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Optimal operation of the integrated district heating system with multiple regional branches

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Abstract−This paper presents an optimal management model for structural and operational optimization of an integrated district heating system (DHS) with multiple regional branches. A DHS consists of energy suppliers and consumers, district heating pipelines and heat storage facilities in a region. The integrated DHS considered in this paper consists of 11 regional DHS branches. In the optimal management system, production and consumption of heat, transport and storage of heat at each regional DHS are taken into account. The optimal management system is formulated as a mixed integer linear programming (MILP), where the objective is to minimize the overall cost or to maximize the profits of the integrated DHS by generating electricity while satisfying the operation constraints of heat units and networks, as well as fulfilling heating demands from consumers. Evaluation of the operation cost is based on daily operations for two months (during August and December) at each DHS located in Seoul and Gyeonggi-do in Korea. Results of numerical simulations show the increase of energy efficiency due to the introduction of the present optimal operation system.

Key words: Optimization, District Heating System, MILP, Unit Commitment, Integrated District Heating System

INTRODUCTION

A district heating system (DHS) is a complex system consisting of a large number of energy suppliers and consumers, district heating pipelines and heat storage facilities in a region. A DHS plays an important part 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 a significant economical potential. DHSs fulfill a significant part of energy demand, especially in Nordic countries such as Iceland,, Finland, Denmark, Norway, etc. Korea began to employ DHSs in 1987. 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 DHSs 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. In this work, a model for the optimal operation of a DHS to increase energy efficiency is developed. Since a heat generation and a network distribution system are main constituents of a DHS, it is obvious that the optimization of a DHS should be based upon the optimization of the heat generation system and of the network distribution system to give the integrated optimal operating system. More specifically, it is suggested to partition the optimization of the entire system into a scheduling among different heat producing units followed by a control problem for the distribution network in order to make the solution of the optimization problem feasible.

The main role of an optimal operation system for a DHS is to minimize the operation cost of the DHS or to maximize the profits of the DHS by generating electricity while satisfying the constraints of the system as well as fulfilling heating demands from consumers. Nordic countries have been showing active research activities in this area for last decade. Due to the existence of time delays in the heat supply, the operation of a DHS is highly dependent upon time-varying demands of customers and the energy distribution network. Moreover, the heat storage as well as the heat loss to the environment should be considered in the operation. To take into account all of these effects, a nodal method was presented to resolve the problem of determination of the supply temperature and the amount of the heat supply. This method is based on the modeling of the heat generation system and the energy distribution network, and was applied to simulate the heat flow and the temperature distribution in a DHS [1]. As a heat source of DHS, a cogeneration heat plant (CHP), peak load boiler (PLB), an incinerator and geothermal heat generation can be used.

A typical optimization problem for a DHS consists of modeling of the heat generation system and the energy distribution network and employment of an MILP algorithm [2]. Results of evaluation of manufacturing costs in a DHS were reported to show the optimal heat generation and optimal operation of a heat distribution network [3]. As the energy efficiency is increased due to the utilization of energy distribution networks in DHSs, the optimization of energy distribution networks has been paid much attention by many researchers. In the formulation of optimization problems, models for generation and consumption of electricity and heat, a model for fuel transmission to generation plants, a flow transportation model within district heating pipeline networks and a heat storage model

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are incorporated to give a mixed integer linear programming (MILP) problem so that consumers, suppliers, designers and operators can make decisions in different situations [4]. Recently, many researchers tried to apply optimized models in the planning and scheduling of new DHSs as well as in the operation of existing DHSs. They used a linear programming (LP) model in the planning and scheduling of DHSs including CHP to determine optimal operating costs while satisfying demands of heat and electricity of regional customers [6].

In the construction of an optimal operation system for a DHS, consideration of heat generation and storage facilities, constraints on the operation of distribution networks and satisfaction of consumers is equivalent to the constraints in the optimization of large scale electricity generation systems which were employed to supply energy prior to DHSs. Many researchers have investigated the optimal operation of electricity generation systems where the primary purpose is to minimize costs of electricity generation while fulfilling demands from consumers. A piecewise linear function was used to compute operation costs of electricity generation plant incorporating start-up and shutdown costs [5,7,8].

In this paper an integrated optimal operation system is developed for the heat generation systems and heat distributed networks of the DHSs located in Gyeonggi-do, Korea. Most of the results on the optimization study for DHSs reported so far are concerned with single DHS, while an integrated DHS consisting of multiple regional DHSs (branches) is considered in this work. The overall cost of actual operation of DHSs is compared with that of optimal operation of DHSs by employing the present integrated optimal operation system to analyze energy efficiency. In the optimization, much stress is laid on how to take into account heat demands from various regional branches and how to incorporate constraints on heat generation and storage facilities. As the basis of computation, we selected a typical cold day (one day in December) as a sample for highest heat demand and a typical hot day (one day in August) as a sample for least heat demand. Hourly numerical simulations were performed for each selected day based on the present MILP model.

OPTIMIZATION

1. Formulation of DHS Optimization Problem

1-1. Description of DHS

The basic configuration of a DHS being considered in this work is shown in Fig. 1. A DHS consists of heat generation and storage facilities including CHP, PLB and ACC. As we can see from Fig. 1, a DHS forms a closed-loop in which heat is generated, supplied, recovered and supplied again. The heat generated from CHP or PLB is directed to heat exchangers, where the temperature is increased to a desired supply temperature and heat is supplied to consumers. The CHP generates heat and electricity simultaneously, while PLBs produce heat only.

The heat distribution network connected and managed by DHSs includes primary (supplier) heat networks, secondary (consumer)

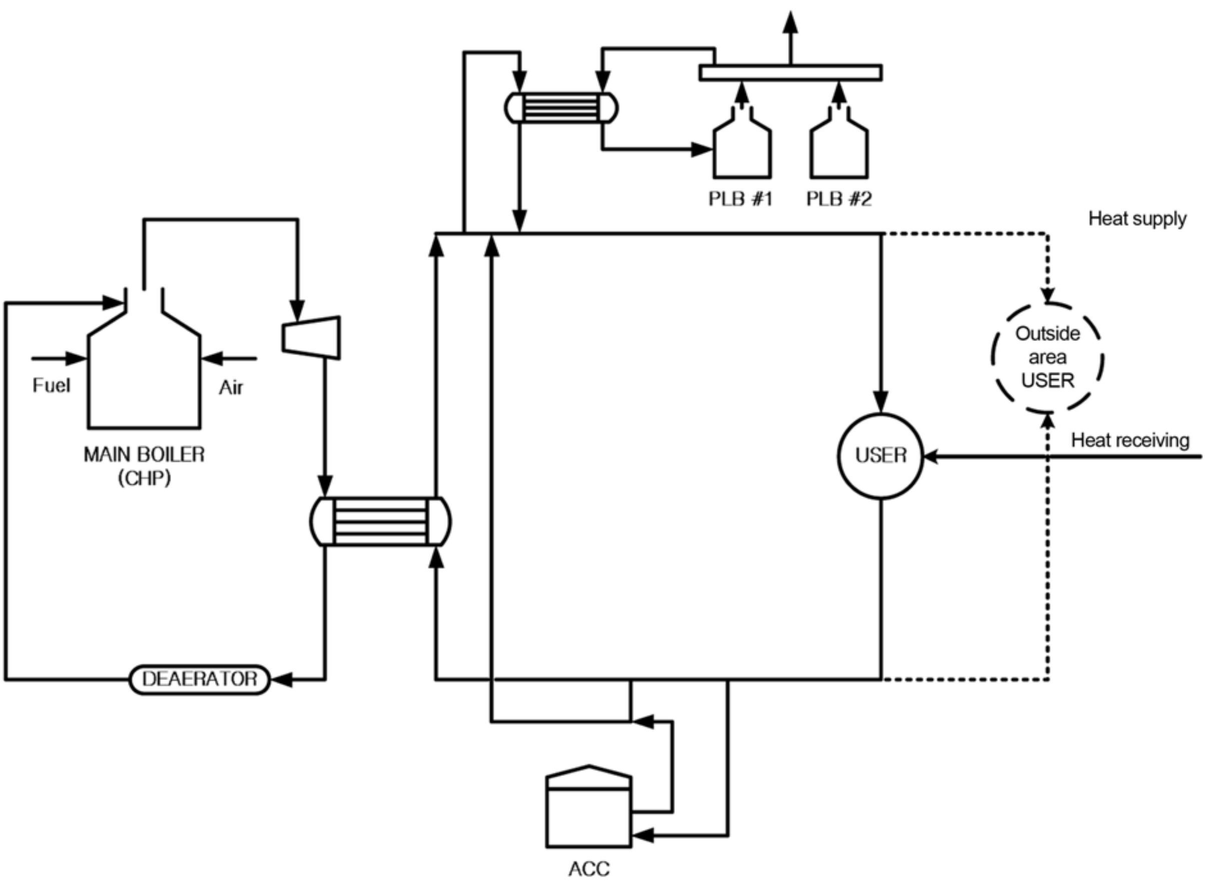

Fig. 1. Basic configuration of a DHS.

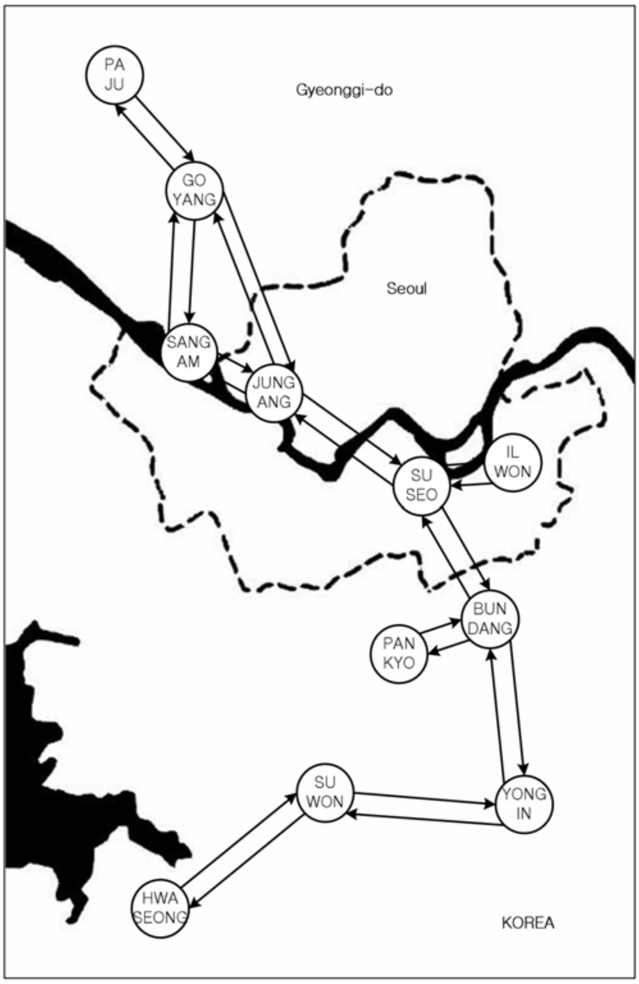

Fig. 2. A schematic diagram of heat distribution network in Gyeonggi-do, Korea.

heat networks and interconnected networks. The integrated DHS considered in this work consists of 11 regional DHSs among which three DHSs (Paju, Pankyo, Hwaseong) were planned to be operational in April, 2009. Each regional DHS is interconnected via 22 distribution networks. Fig. 2 and Table 1 show the basic structure of the interconnected DHS networks.

1-2. Objective of the Optimization

The primary objective of the optimal operation system for the integrated DHS is to minimize operation cost or to maximize the profits obtained, especially from the sales of electricity while fulfilling heat demand from consumers and satisfying various constraints consisting of operating conditions of heat generation and storage facilities. The optimal operation system for the integrated DHS proposed in this work is constructed in terms of MILP and the objective function can be represented as the following:

$$\text{Minimize} \sum_{b=1}^{nbBranch} \mathrm{OC(b)} - \mathrm{ES(b)} \quad \text{or} \tag{1}$$

$$\text{Maximize} \sum_{b=1}^{nbBranch} \mathrm{ES(b)} - \mathrm{OC(b)} \tag{2}$$

Subject to: (Constraints of each regional DHS (branch) and networks)

Table 1. Interconnection of each regional DHS

No.	Network (A→B)	
	A	B
1	Suwon	Yongin
2	Yongin	Suwon
3	Yongin	Bundang
4	Bundang	Yongin
5	Bundang	Suseo
6	Suseo	Bundang
7	Suseo	Ilwon
8	Ilwon	Suseo
9	Suseo	Jungang
10	Jungang	Suseo
11	Jungang	Sangam
12	Sangam	Jungang
13	Sangam	Goyang
14	Goyang	Sangam
15	Jungang	Goyang
16	Goyang	Jungang
17	Goyang	Paju
18	Paju	Goyang
19	Pankyo	Bundang
20	Bundang	Pankyo
21	Hwaseong	Suwon
22	Suwon	Hwaseong

Table 2. ID number for each regional DHS

No.	Branch
1	Suwon
2	Yongin
3	Bundang
4	Suseo
5	Ilwon
6	Jungang
7	Sangam
8	Goyang
9	Paju
10	Pankyo
11	Hwaseong

where b denotes each regional DHS, and OC and ES represent operating cost of each DHS and sales of electricity, respectively. The regional DHSs considered in this work are shown in Fig. 2 and Table 2.

1-3. Heat Production Cost and Electricity Sales

The operating cost of the integrated DHS is defined as the difference between the sum of costs of total regional DHSs and the amount of total electricity sales at those regional branches. The operating cost of a regional DHS is defined as the sum of the operating costs of CHP and heat generation facilities. The transportation cost of heat among regional DHSs is not included in the computation of the total operating cost. The operating cost of a regional DHS is given by

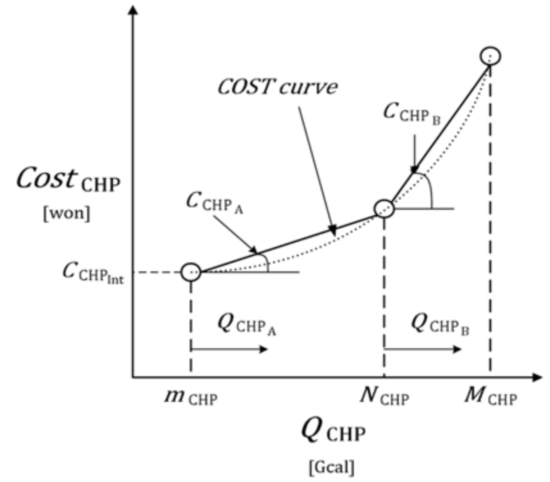

Fig. 3. Operating cost function of a CHP.

$$OC(b) = \sum_{t\in T}\sum_{c\in C} Cost_{CHP}(b,c,t) + \sum_{t\in T}\sum_{u\in U} Q_{Unit}(b,u,t)\times C_{Unit}(b,u) \quad \forall b\in B \quad (3)$$

where $Cost_{CHP}$ represents the operation cost of CHP and Q and C_{Unit} denote the amount of heat generation and the unit operating price of each unit, respectively. The amount of electricity sales at each regional DHS can be represented as

$$E(b) = \sum_{t\in T}\sum_{c\in C} P_{CHP}(b,c,t)\times SMP \quad (4)$$

where P_{CHP} denotes the amount of electricity generated at CHPs and SMP is the marginal unit price. Values of terms in Eq. (3) and Eq. (4) are dependent upon the CHPs and heat generation facilities. The operating cost of heat generation facilities is given by the amount of heat generation multiplied by unit fuel price. The operating cost of a CHP can be represented in the form of a quadratic function depending upon the amount of heat generation. Fig. 3 shows the profile of the operating cost of a CHP. To avoid nonlinearity exhibited by the operating cost of a CHP, the operating interval can be divided into subintervals having equal marginal cost to get piecewise linear forms as shown in Fig. 3.

In Fig. 3, m_{CHP} denotes the minimum heat generation during CHP operation and M_{CHP} is the maximum heat generation. N_{CHP} is an intermediate breakpoint between linear approximations with different limit cost depending upon the heat generation. Therefore, we can see that Q_{CHP}, the amount of heat generated from a CHP, is given by Eq. (5).

$$Q_{CHP}(b,c,t)=Q_{CHP_A}(b,c,t)+Q_{CHP_B}(b,c,t)+m_{CHP}(b,c)\times Y_{CHP}(b,c,t) \quad \forall b\in B, c\in C, t\in T \quad (5)$$

where b represents each regional DHS, c denotes each CHP at the corresponding DHS, and t is time. Y_{CHP}, representing the operational status of a CHP, is a binary variable taking 0 or 1. In Eq. (5), Q_{CHP_A} is 0 at m_{CHP} and then increases up to N_{CHP}. Similarly, Q_{CHP_B} is 0 at N_{CHP} and then increases up to M_{CHP}. Both Q_{CHP_A} and Q_{CHP_B} are subject to the following constraints.

$$Q_{CHP_A}(b,c,t)\le[N_{CHP}(b,c)-m_{CHP}(b,c)]\times Y_{CHP}(b,c,t) \quad \forall b\in B, c\in C, t\in T \quad (6)$$

$$Q_{CHP_B}(b,c,t)\le[M_{CHP}(b,c)-N_{CHP}(b,c)]\times Y_{CHP}(b,c,t) \quad \forall b\in B, c\in C, t\in T \quad (7)$$

We can see that the cost function of the CHP shown in Fig. 3 is represented by Eq. (8).

$$Cost_{CHP}(b,c,t)=C_{CHP_{Ini}}(b,c,t)\times Y_{CHP}(b,c,t)+C_{CHP_A}(b,c,t)\times Q_{CHP_A}(b,c,t)+C_{CHP_B}(b,c,t)\times Q_{CHP_B}(b,c,t) \quad \forall b\in B, c\in C, t\in T \quad (8)$$

In Eq. (8), C_{CHP_A} and C_{CHP_B} represent limit costs at each heat generation subinterval, and $C_{CHP_{Ini}}$ denotes the minimum operating cost in the operation of CHP.

2. Constraints on Heat Units and Networks

2-1. Heat Demand and Generation

Fulfillment of heat demand from consumers by adjusting the amount of heat generation and heat supply through distributed networks as well as heat storage and transmission is the basic operating constraint in the optimizations of the integrated DHS. This condition can be summarized as Eq. (9).

$$D(b,t)\le Q(b,t)+\Delta Q_{Acc}(b,t)+Q_{Nin}(b,t)-Q_{Nout}(b,t) \quad \forall b\in B, t\in T \quad (9)$$

where

$$Q(b,t) = \sum_{c=1}^{nbCHP} Q_{CHP}(b,c,t) + \sum_{s=1}^{nbPLBso} Q_{PLBso}(b,s,t) + \sum_{w=1}^{nbPLBwg} Q_{PLBwg}(b,w,t) + \sum_{n=1}^{nbInc} Q_{Inc}(b,n,t) + \sum_{g=1}^{nbGRB} Q_{GRB}(b,g,t) + \sum_{a=1}^{nbHan} Q_{Han}(b,a,t) = \sum_{h=1}^{nbHU} Q_{HU}(b,h,t)$$

$$\Delta Q_{Acc}(b,t) = \sum_{j=1}^{nbAcc} \{Q_{Acc}(b,j,t) - Q_{Acc}(b,j,t-1)\}$$

$$Q_{Nin}(b,t) = \sum_{i=1}^{nbNin} Q_{Nin}(b,i,t)$$

$$Q_{Nout}(b,t) = \sum_{o=1}^{nbNout} Q_{Nout}(b,a,t)$$

In the above relations, Q_{HU} is the amount of heat generation from all heat generation facilities in each DHS including CHP, and Q_{Nin} and Q_{Nout} denote the amount of heat transmission through interconnected distribution networks, respectively. ΔQ_{Acc} represents changes in the heat accumulator. Application of Eq. (9) depends upon the characteristics of each DHS. For example, the DHS in Suwon area does not accept electricity outside the area and the corresponding term (Q_{Han}) is excluded from Eq. (9).

The heat units (HU) used to supply heat to fulfill demands of customers include CHP, PLBso, PLBwg, GRB and MHP. In each heat unit, there exist the minimum and maximum amount of hourly heat generation that consist of an operating range to be satisfied. The operational status of a heat unit is represented by an integer 0 (not being operated) or 1 (being operated). The overall constraints for heat units can be represented as Eq. (10).

$$Y_{HU}(b,h,t)\times m_{HU}(b,h)\le Q_{HU}(b,h,t)$$
$$Y_{HU}(b,h,t)\times M_{HU}(b,h)\le Q_{HU}(b,h,t) \quad \forall b\in B, h\in H, t\in T \quad (10)$$

where Y_{HU} denotes the operating status (i.e., on/off status), and m_{HU} and M_{HU} represent the minimum and maximum hourly heat generation for the heat unit, respectively. In general, the value of m_{HU} is greater than 0. The amount of heat generation in heat units should not show abrupt variations for safe operation. The variations in the

Table 3. CHP operation data

Branch no.	Productivity					Unit cost [won]			Coefficient for power generation function [kW/Gcal], [kW]	
	Heat [Gcal/h]			Power [kW/h]						
	Min	Inter.	Max	Min	Max	Initial	A	B	A1	A2
1	35	53	71	14000	43200	1566215	34749	54749	811.11	−14388.85
9	82	242	402	171000	515000	3669418	34749	54749	1075	82850
10	46	86	126	49000	146000	2058454	34749	54749	1212.5	−6775
11	76.6	236.6	396.6	170600	511800	3427773.4	34749	54749	1066.25	88625.25

Table 4. Productivity of heat and unit operation prices for each unit

(a) PLBso

Branch no.	Productivity										Unit cost [won/Gcal]
	Minimum [Gcal/h]					Maximum [Gcal/h]					
	E1	E2	E3	E4	E5	E1	E2	E3	E4	E5	
1	35	35				77	77				46050
2	40	40				102	102				48545
3	15	15				51	51				39328
4	11	11	31	31	31	34	34	103	103		59722
5	20	20				102	102				59722
7	1					53					47097
8	20	20				51	51				41847

(b) PLBso

Branch no.	Productivity												Unit cost [won/Gcal]
	Minimum [Gcal/h]						Maximum [Gcal/h]						
	E1	E2	E3	E4	E5	E6	E1	E2	E3	E4	E5	E6	
1	20.6	20.6	6.88	6.88			103.2	103.2	34.4	34.4			62195
2	30	30	30	20	20	20	103	103	103	68	68	68	61725
3	40						103						60638
4	1	1					20	20					61461
5	20	20					103	103					61456
7	20						103						61456
8	20	20		15			103	103	86				61456

(c) Incinerator, GRB, Hanjun and MHP

Type	Branch no.	Productivity						Unit cost [won/Gcal]
		Minimum [Gcal/h]			Maximum [Gcal/h]			
		E1	E2	E3	E1	E2	E3	
Incinerator	1	7	7		15	15		11847
	2	1	1		2	2		11847
	5	15	15	15	32	32	32	11321
	7	5	5	5	20	10	15	11847
	8	1			16			11672
GRB	7	1	1		25	25		10571
Hanjun	3	165	175		450	280		30459
	6	1	1		129	240		39444
	8	1			823			32896
MHP	9	1			50			10571
	11	1			50			10571

E: Equipment

amount of heat generation in heat units should be confined within certain range, which is usually given by the maximum hourly generation multiplied by safety factor as shown in Eq. (11).

$$Q_{HU}(b, h, t)-Q_{HU}(b, h, t-1)\leq(b, h)\times M_{HU}(b, h)$$
$$Q_{HU}(b, h, t-1)-Q_{HU}(b, h, t)\leq S_{HU}(b, h)\times M_{HU}(b, h)$$
$$\forall b\in B, h\in H, t\in T \quad (11)$$

where S_{HU} denotes the safety factor for the corresponding heat unit.

Once the operation of a heat unit begins, the operational status should be maintained at least for a certain time period defined as the minimum up time (Mut). Similarly, if the operation of a heat unit is terminated, the un-operational status should be maintained at least for a certain time period defined as the maximum down time (Mdt). Each heat unit has its own Mut and Mdt to be satisfied as represented by Eqs. (12) and (13) which behave as constraints on heat units.

$$[Y_{HU}(b, h, t)-Y_{HU}(b, h, t-1)]+[Y_{HU}(b, h, t+k-1)-Y_{HU}(b, h, t+k)]\leq 1$$
$$\forall b\in B, h\in H, t\in T, k\in[1, 2, \ldots, Mut_{HU}(b, h)-1] \quad (12)$$

$$[Y_{HU}(b, h, t-1)-Y_{HU}(b, h, t)]+[Y_{HU}(b, h, t+k)-Y_{HU}(b, h, t+k-1)]\leq 1$$
$$\forall b\in B, h\in H, t\in T, k\in[1, 2, \ldots, Mut_{HU}(b, h)-1] \quad (13)$$

The amount of the electricity generated from a CHP which produces heat and electricity simultaneously is a function of heat generated as given by Eq. (14).

$$P_{CHP}(b, c, t)=A1(b, c)\times Q_{CHP}(b, c, t)+A2(b, c)\times Y_{CHP}(b, c, t)$$
$$\forall b\in B, c\in C, t\in T \quad (14)$$

where A1 is the gradient of the linear function representing the relationship between the amount of heat production and electricity generation, and A2 is the interception of y-axis. Production of electricity has to satisfy the constraint defined by the minimum and maximum amount of hourly electricity generation as given by Eq. (15).

$$mP_{CHP}(b, c)\leq P_{CHP}(b, c, t)\leq MP_{CHP}(b, c) \qquad \forall b\in B, c\in C, t\in T \quad (15)$$

where mP_{CHP} and MP_{CHP} are the minimum and maximum hourly generation of electricity respectively.

2-2. Heat Distribution Networks

The constraints on heat distribution networks in DHSs involve constraints on the amount of heat transmission through interconnected networks as well as those on Mut's and Mdt's for the networks. These constraints are similar to Eqs. (10) to (13). The direction of heat transfer is also limited. Eq. (16) represents the constraint on the heat transmission.

$$Z(r, t)\times m_{Net}(r)\leq Q_{Net}(r, t)$$
$$Z(r, t)\times M_{Net}(r)\leq Q_{Net}(r, t) \qquad \forall r\in R, t\in T \quad (16)$$

where Z represents the operational status of a network (i.e., on/off) and r denotes each connected network as shown in Fig. 2 and Table 1. Constraints on the variations in the amount of heat transmission among networks are given by Eq. (17).

Table 5. Heat transfer of networks

Network no.	Heat transfer [Gcal/h]		Network no.	Heat transfer [Gcal/h]	
	Min	Max		Min	Max
1	5	100	12	5	53
2	5	100	13	5	50
3	5	100	14	5	50
4	5	100	15	5	60
5	20	100	16	5	60
6	20	100	17	5	100
7	20	120	18	5	100
8	20	120	19	5	100
9	5	42	20	5	100
10	5	42	21	5	100
11	5	53	22	5	100

Table 6. Mut, Mdt and safety ratio for each heat unit and interconnected network

Equipment	Minimum up time [h]	Maximum down time [h]	Safety ratio [-]
CHP	4	4	0.75
PLBso	4	4	0.75
PLBwg	3	3	0.75
Inc	4	4	0.75
GRB	3	3	0.75
Hanjun	6	3	0.75
MHP	3	3	0.75
Network	6	3	0.75

Table 7. Heat storage unit (Acc)

Branch no.	Storage [Gcal]				Safety factor [Gcal/h]
	Minimum		Maximum		
	E1	E2	E1	E2	
1	1475		2300		65
2	0	0	350	350	63
5	0	0	267.5	267.5	66
6	0		528		66
8	0		1000		211

E: Equipment

Table 8. System marginal prices (Aug. and Dec.)

Time	SMP [won/kW]		Time	SMP [won/kW]	
	Aug.	Dec.		Aug.	Dec.
1	50.05	85.37	13	68.9	79.89
2	18.93	74.1	14	68.24	79.89
3	18.75	73.44	15	68.24	84.3
4	18.56	73.35	16	68.24	79.89
5	18.47	73.35	17	68.24	86.02
6	18.56	73.35	18	68.24	86.02
7	18.93	73.67	19	68.24	88.91
8	19.06	74.2	20	68.24	85.24
9	62.02	74.63	21	68.24	80.13
10	63.96	80.13	22	67.59	80.13
11	76.61	86.02	23	63.37	88.91
12	68.24	89.02	24	60.47	88.91

$$Q_{Net}(r,t)-Q_{Net}(r,t-1)\le S_{Net}(r)\times m_{Net}(r)$$
$$Q_{Net}(r,t-1)-Q_{Net}(r,t)\le S_{Net}(r)\times M_{Net}(r) \qquad \forall r\in R, t\in T \quad (17)$$

The constraints on Mut and Mdt of interconnected networks are given by Eqs. (18) and (19), respectively.

$$[Z(r,t)-Z(r,t-1)]+[Z(r,t+k-1)-Z(r,t+k)]\le 1$$
$$\forall r\in R, t\in T, k\in[1,2,\ldots,ZMut(r)-1] \quad (18)$$

$$[Z(r,t-1)-Z(r,t)]+[Z(r,t+k)-Z(r,t+k-1)]\le 1$$
$$\forall r\in R, t\in T, k\in[1,2,\ldots,ZMdt(r)-1] \quad (19)$$

In the integrated DHS considered in this work, there are 22 interconnected networks. A network line is defined as the interconnected network between two regional DHSs. For example, the interconnected networks R12 and R21 in Fig. 2 between Suwon and Youngin are network lines between these two areas. This condition can be represented as Eq. (20).

$$\sum_{k=2n-1}^{2n} Z(k,t)\le 1 \qquad \forall n\in[1,2,\ldots,nbNet/2], t\in T \quad (20)$$

2-3. Heat Storage Units

There exist the minimum and maximum amount of heat that can be stored in a heat storage unit. Thus the constraint on a heat storage unit can be written as Eq. (21).

$$m_{Acc}(b,j)\le Q_{Acc}(b,j,t)\le M_{Acc}(b,j) \qquad \forall b\in B, j\in J, t\in T \quad (21)$$

The constraints on the variations of the amount of heat stored in a heat storage unit are given by Eq. (22).

$$Q_{Acc}(b,j,t)-Q_{Acc}(b,j,t-1)\le S_{Acc}(b,j)$$
$$Q_{Acc}(b,j,t-1)-Q_{Acc}(b,j,t)\le S_{Acc}(b,j) \qquad \forall b\in B, j\in J, t\in T \quad (22)$$

where S_{Acc} represents a permissible amount of possible variations. A heat storage unit has to store a certain amount of heat to prepare for abnormal or urgent situations. This condition can be written as Eq. (23).

$$Q_{Acc}(b,j,t^{Initial})=Q_{Acc}(b,j,t^{Final}) \qquad \forall b\in B, j\in J, t\in T \quad (23)$$

where $t^{Initial}$ and t^{Final} mean the starting and the final time for a given operating period. In this work, the operating period is set to 24 hours.

3. Numerical Simulation

Among 22 DHSs, several DHSs were selected to apply the optimization system presented in this work. Table 3 shows CHP operation data to be used to estimate the production capability and operating cost. Table 4 shows the minimum and maximum amounts of hourly heat generation and unit price of operation for each heat generation facility. Table 5 shows the minimum and maximum amount of hourly heat transfer among interconnected regional DHSs. The minimum up time and maximum down time for each heat generation facility and interconnected network as well as the safety factor for variations in the amount of heat generation and heat transmis-

Table 9. Heat demands from customers

(a) August

Time	Branch number										
	1	2	3	4	5	6	7	8	9	10	11
1	22	29	31	44	0	15	3	22	28	12	15
2	22	20	23	31	0	15	3	21	20	12	15
3	17	20	27	27	0	15	2	16	25	8	15
4	19	20	27	27	0	12	1	12	26	4	12
5	18	21	26	27	0	12	1	10	25	4	12
6	20	22	24	29	0	12	1	12	23	4	12
7	28	37	45	33	0	14	2	16	43	8	14
8	30	38	69	47	0	14	5	35	64	20	14
9	37	38	73	58	0	14	7	68	66	28	14
10	39	38	79	58	0	13	7	96	72	28	13
11	36	34	86	59	0	22	8	112	78	32	22
12	33	29	94	57	0	18	7	106	87	28	18
13	28	30	85	56	0	10	7	103	78	28	10
14	29	28	86	65	0	11	6	94	80	24	11
15	31	30	83	61	0	14	7	91	76	28	14
16	29	32	83	60	0	14	7	85	76	28	14
17	29	31	79	53	0	16	7	82	72	28	16
18	25	29	77	65	1	16	6	81	70	25	17
19	26	29	73	50	8	14	6	62	59	32	22
20	31	26	72	36	18	14	6	57	48	42	32
21	30	29	47	38	18	14	6	55	23	42	32
22	32	31	44	39	18	17	6	46	20	42	35
23	29	34	39	31	22	16	7	46	10	50	38
24	26	33	31	22	17	18	5	41	9	37	35

(b) December

Time	Branch number										
	1	2	3	4	5	6	7	8	9	10	11
1	356	368	422	368	249	233	24	594	350	273	332
2	322	319	432	367	236	223	22	565	366	258	300
3	315	311	429	351	226	231	21	535	366	247	294
4	303	313	418	344	215	237	21	531	355	236	282
5	304	314	420	344	222	233	20	531	360	242	284
6	309	316	429	366	227	252	20	512	369	247	289
7	352	332	504	360	233	283	21	544	441	254	331
8	373	339	537	365	260	311	22	603	471	282	351
9	346	320	541	347	265	338	23	646	472	288	323
10	299	325	516	347	238	305	21	633	453	259	278
11	253	326	510	352	218	291	18	575	456	236	235
12	219	328	443	355	204	278	18	528	389	222	201
13	208	323	426	318	188	274	16	473	378	204	192
14	211	316	427	311	198	287	16	464	379	214	195
15	217	304	416	312	175	262	16	446	368	191	201
16	218	269	424	291	188	250	16	450	376	204	202
17	276	287	458	299	191	251	16	461	410	207	260
18	312	332	463	334	216	276	20	497	403	236	292
19	346	336	461	354	251	284	21	550	398	272	325
20	372	350	499	351	252	285	23	590	430	275	349
21	374	365	504	362	163	283	25	615	429	188	349
22	379	375	506	350	284	277	26	623	428	310	353
23	390	367	533	348	296	270	27	638	452	323	363
24	380	369	531	342	290	251	25	629	456	315	355

[unit: Gcal]

sion are shown in Table 6. Here the safety ratio represents variation rates in the amount of heat production or transmission and is denoted as S_{HU} and S_{Net} in Eq. (11) and (17), respectively. The constraints on variation rates in the amount of heat production and transmission are given by the multiplication of the safety ratio with the maximum amount of heat production and transmission. Table 7 shows data for the minimum and maximum amount of hourly heat storage in Acc as well as corresponding safety index, which represents the limiting amount for variations in heat accumulation or transmission and is denoted by S_{Acc} in Eq. (22). The system marginal costs in August and December to be taken into account in the computation of electricity sales are shown in Table 8. Table 9 shows hourly heat demands from customers in August and December for one day at 11 DHS branches.

The effectiveness of the optimization system for the integrated DHS developed in this work could be evaluated by estimating total operating cost or profits. For comparison we chose a single day in December and in August considering the maximum hourly variation in the amount of heat demand from customers. For the two selected days, the total operating cost and electricity sales were computed by using the optimization system and compared with actual operation data. Results of numerical simulations are highly dependent upon the initial operating type of regional DHSs. In simulations, all the values of heat generations and heat transmission among networks were assumed to be one half of their maximum values. Since Eq. (12), (13), (18) and Eq. (19) are not affected by the initial states of Mut and Mdt, we can include the following relations.

$$(T_{HU}^{on}(b,h,t-1)-Mut_{HU}(b,h))\times(Y_{HU}(b,h,t-1)-Y_{HU}(b,h,t)\geq 0 \quad \forall b\in B, h\in H, t\in[1,2,\ldots,Mut_{HU}(b,h)] \quad (24)$$

$$(T_{HU}^{off}(b,h,t-1)-Mdt_{HU}(b,h))\times(Y_{HU}(b,h,t)-Y_{HU}(b,h,t-1)\geq 0 \quad \forall b\in B, h\in H, t\in[1,2,\ldots,Mdt_{HU}(b,h)] \quad (25)$$

$$(T_{Net}^{on}(r,t-1)-ZMut(r))\times(Z(r,t-1)-Z(r,t)\geq 0 \quad \forall r\in R, t\in[1,2,\ldots,ZMut(r)] \quad (26)$$

$$(T_{Net}^{off}(r,t-1)-ZMdt(r))\times(Z(r,t)-Z(r,t-1)\geq 0 \quad \forall r\in R, t\in[1,2,\ldots,ZMdt(r)] \quad (27)$$

The initial operation status of Mut and Mdt of heat generation facilities is considered in Eq. (24) and (25). Similarly, the initial oper-

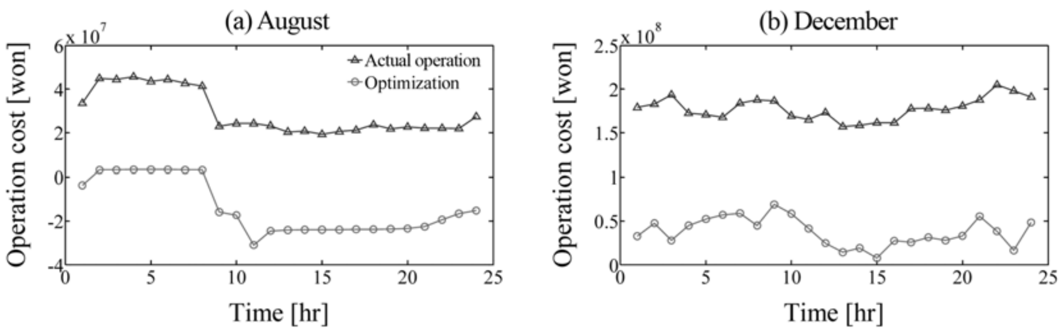

Fig. 4. The operation cost of simulation (optimization) and actual operations in August and December.

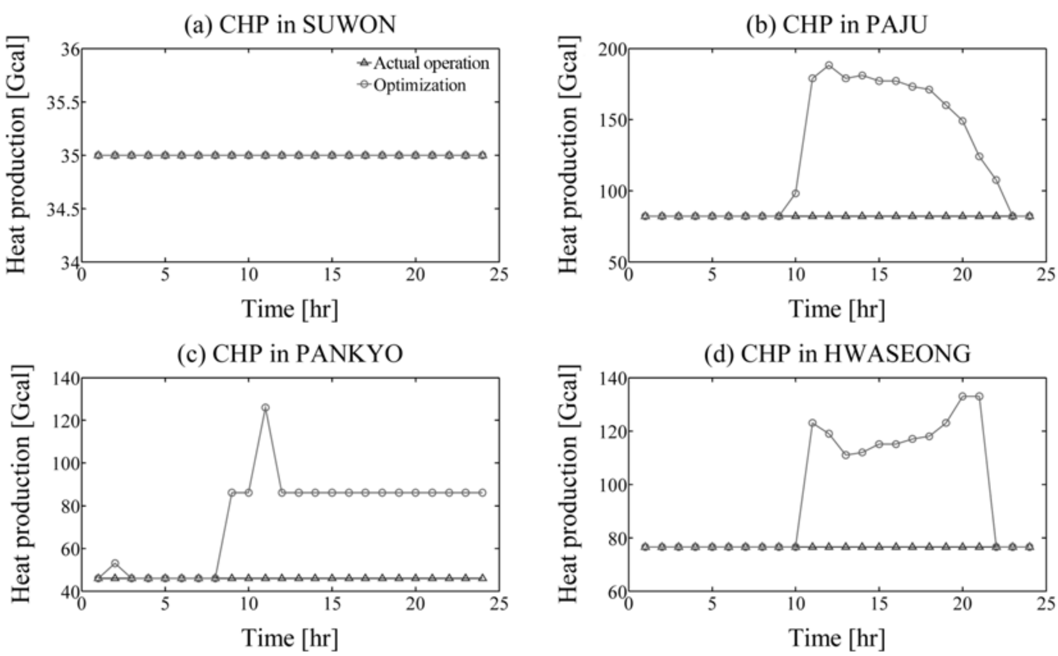

Fig. 5. Comparison between simulations (optimization) and operation of CHP (August).

ation status of Mut and Mdt of interconnected networks is considered in Eq. (26) and (27). T_{HU}^{on} and T_{HU}^{off} represent the duration times for heat generation facilities to be on/off status, while T_{Net}^{on} and T_{Net}^{off} represent the duration times for interconnected networks to be on/off status. The optimization problem consists of 23,180 constraints and 5,487 variables. CPLEX 11.0 of ILOG, Inc. was used to solve the optimization problem.

4. Results and Discussion

The total operating costs as well as total profits between the operation of DHS based on the proposed optimization system and actual operation of DHS were compared. Results for the optimization system were obtained not from actual application but from numerical simulations. As shown in Fig. 4, we can see much reduction in the operating costs both in August and December. For example, in De-

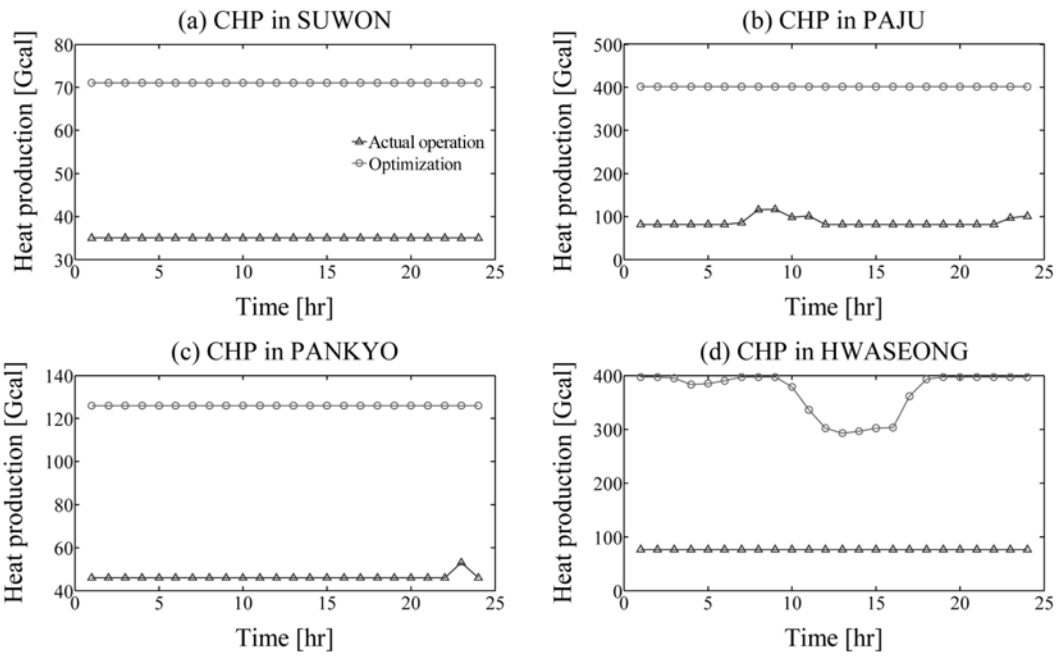

Fig. 6. Comparison between simulations (optimization) and operation of CHP (December).

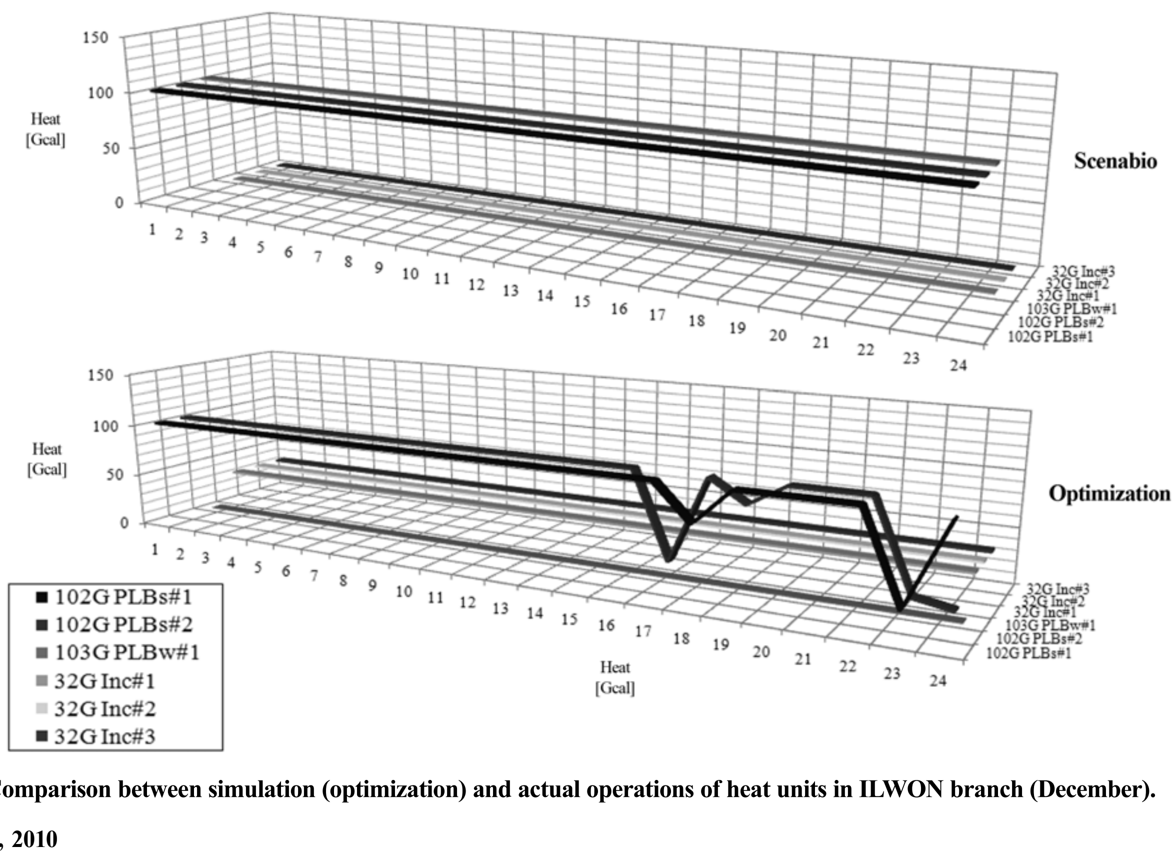

Fig. 7. Comparison between simulation (optimization) and actual operations of heat units in ILWON branch (December).

Table 10. Comparison between simulation (optimization) and actual operations of heat units in ILWON branch (December)

(a) Actual operations

Time	Heat units					
	102G PLBso #1	102G PLBso #2	103G PLBwg #1	32G Inc. #1	32G Inc. #2	32G Inc. #3
1	**102**	**102**	**103**	0	0	0
2	**102**	**102**	**103**	0	0	0
3	**102**	**102**	**103**	0	0	0
4	**102**	**102**	**103**	0	0	0
5	**102**	**102**	**103**	0	0	0
6	**102**	**102**	**103**	0	0	0
7	**102**	**102**	**103**	0	0	0
8	**102**	**102**	**103**	0	0	0
9	**102**	**102**	**103**	0	0	0
10	**102**	**102**	**103**	0	0	0
11	**102**	**102**	**103**	0	0	0
12	**102**	**102**	**103**	0	0	0
13	**102**	**102**	**103**	0	0	0
14	**102**	**102**	**103**	0	0	0
15	**102**	**102**	**103**	0	0	0
16	**102**	**102**	**103**	0	0	0
17	**102**	**102**	**103**	0	0	0
18	**102**	**102**	**103**	0	0	0
19	**102**	**102**	**103**	0	0	0
20	**102**	**102**	**103**	0	0	0
21	**102**	**102**	**103**	0	0	0
22	**102**	**102**	**103**	0	0	0
23	**102**	**102**	**103**	0	0	0
24	**102**	**102**	**103**	0	0	0

(b) Optimization

Time	Heat units					
	102G PLBso #1	102G PLBso #2	103G PLBwg #1	32G Inc. #1	32G Inc. #2	32G Inc. #3
1	**102**	**102**	0	**32**	**32**	**32**
2	**102**	**102**	0	**32**	**32**	**32**
3	**102**	**98**	0	**32**	**32**	**32**
4	**102**	**21**	0	**32**	**32**	**32**
5	**102**	**98**	0	**32**	**32**	**32**
6	**102**	**102**	0	**32**	**32**	**32**
7	**102**	**102**	0	**32**	**32**	**32**
8	**102**	**102**	0	**32**	**32**	**32**
9	**102**	**102**	0	**32**	**32**	**32**
10	**102**	**102**	0	**32**	**32**	**32**
11	**102**	**102**	0	**32**	**32**	**32**
12	**102**	**98**	0	**32**	**32**	**32**
13	**98**	**102**	0	**32**	**32**	**32**
14	**102**	**102**	0	**32**	**32**	**32**
15	**57**	**102**	0	**32**	**32**	**32**
16	**102**	**102**	0	**32**	**32**	**32**
17	**102**	**102**	0	**32**	**32**	**32**
18	**102**	**26**	0	**32**	**32**	**32**
19	**102**	**102**	0	**32**	**32**	**32**
20	**102**	**102**	0	**32**	**32**	**32**
21	**102**	**102**	0	**32**	**32**	**32**
22	**102**	**102**	0	**32**	**32**	**32**
23	**102**	**93**	0	**32**	**32**	**32**
24	**102**	**102**	0	**32**	**32**	**32**

[unit: Gcal]

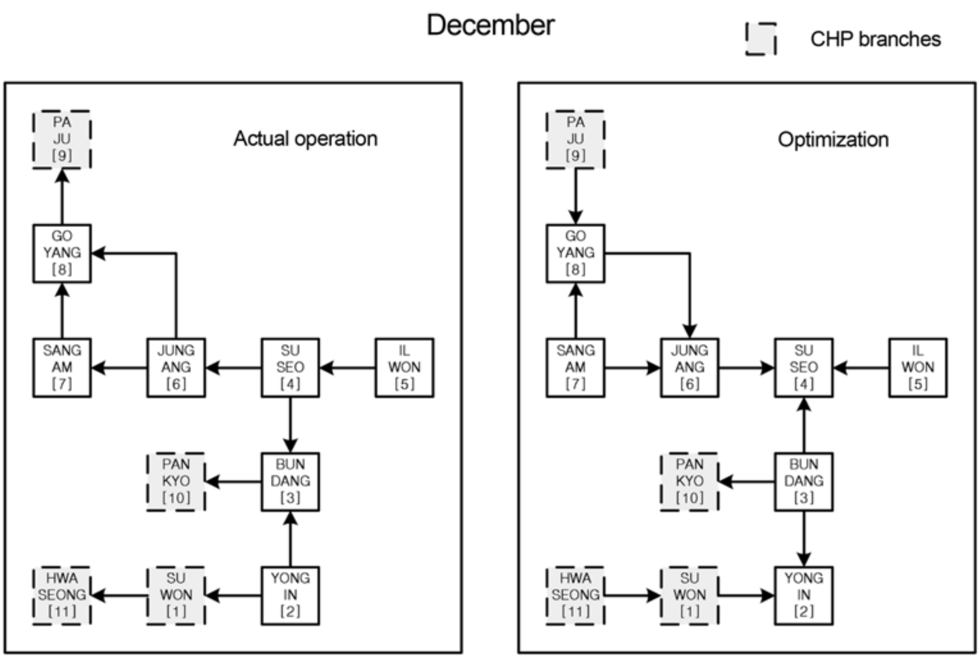

Fig. 8. Heat flows in DH Network system.

Table 11.Comparison between simulation (optimization) and actual operations of heat transfer in KDH system

(a) Actual operations

Time	Network number																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	0	100	100	0	0	100	0	120	29	0	21	0	50	0	60	0	63	0	0	57	0	5
2	0	82	100	0	0	100	0	110	19	0	19	0	50	0	60	0	79	0	0	42	0	5
3	0	100	100	0	0	100	0	74	0	0	18	0	50	0	60	0	79	0	0	31	0	36
4	0	100	100	0	0	100	0	67	0	0	18	0	50	0	60	0	68	0	0	20	0	100
5	0	99	100	0	0	100	0	67	0	0	17	0	50	0	60	0	73	0	0	26	0	100
6	0	100	100	0	0	100	0	89	0	0	17	0	50	0	60	0	70	0	0	31	0	81
7	0	100	100	0	0	100	0	83	0	0	18	0	50	0	60	0	100	0	0	38	0	100
8	0	100	100	0	0	100	0	113	25	0	19	0	50	0	60	0	100	0	0	66	0	100
9	0	100	100	0	0	100	0	108	38	0	20	0	50	0	60	0	100	0	0	72	0	100
10	0	100	100	0	0	100	0	112	42	0	18	0	50	0	60	0	100	0	0	43	0	99
11	0	87	100	0	0	100	0	98	23	0	15	0	50	0	60	0	100	0	0	20	0	100
12	0	38	100	0	0	100	0	120	42	0	15	0	50	0	60	0	90	0	0	6	0	100
13	0	5	100	0	0	100	0	53	12	0	13	0	50	0	60	0	91	0	0	0	0	96
14	0	5	100	0	0	100	0	51	17	0	13	0	50	0	60	0	92	0	0	0	0	99
15	0	72	100	0	0	100	0	40	5	0	13	0	50	0	60	0	81	0	0	0	0	100
16	0	73	100	0	0	100	0	20	6	0	13	0	50	0	60	0	89	0	0	0	0	100
17	0	100	100	0	0	100	0	22	0	0	13	0	50	0	60	0	100	0	0	0	0	100
18	0	83	100	0	0	100	0	52	0	5	17	0	50	0	60	0	100	0	0	20	0	98
19	0	100	100	0	0	100	0	72	0	5	18	0	50	0	60	0	100	0	0	56	0	54
20	0	64	100	0	0	100	0	66	0	8	20	0	50	0	60	0	100	0	0	59	0	67
21	0	100	100	0	0	100	0	52	0	33	22	0	50	0	60	0	100	0	0	72	0	100
22	0	100	100	0	0	100	0	68	0	5	23	0	50	0	60	0	100	0	0	94	0	96
23	0	100	100	0	0	100	0	66	0	5	24	0	50	0	60	0	100	0	0	100	0	85
24	0	100	100	0	0	100	0	65	0	0	22	0	50	0	60	0	100	0	0	99	0	95

(b) Simulation (optimization)

Time	Network number																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	78	0	0	100	100	0	0	20	0	42	0	53	28	0	0	60	0	100	0	100	100	0
2	11	0	0	98	100	0	0	23	0	42	0	53	30	0	0	60	0	85	0	100	100	0
3	65	0	0	100	100	0	0	20	0	42	0	53	31	0	0	60	0	85	0	100	100	0
4	100	0	0	100	100	0	0	31	0	42	0	53	31	0	0	60	0	96	0	100	100	0
5	65	0	0	100	100	0	0	103	0	42	0	53	32	0	0	60	0	91	0	100	100	0
6	0	0	0	100	100	0	0	73	0	42	0	53	32	0	0	60	0	82	0	100	100	0
7	0	0	0	100	100	0	0	120	0	42	0	53	31	0	0	60	0	10	0	100	100	0
8	0	0	0	95	100	0	0	104	0	42	0	53	30	0	0	60	0	5	0	100	95	0
9	5	0	0	91	100	0	0	120	0	42	0	53	29	0	0	60	0	5	0	100	100	0
10	80	0	0	100	100	0	0	62	0	42	0	53	31	0	0	60	0	18	0	100	100	0
11	100	0	0	100	100	0	0	120	0	42	0	53	34	0	0	60	0	15	0	100	100	0
12	83	0	0	100	100	0	0	120	0	42	0	53	34	0	0	60	0	62	0	97	100	0
13	100	0	0	100	100	0	0	108	0	42	0	53	36	0	0	60	0	73	0	79	100	0
14	100	0	0	100	100	0	0	120	0	42	0	53	36	0	0	60	0	72	0	89	100	0
15	73	0	0	100	100	0	0	120	0	42	0	53	36	0	0	60	0	83	0	66	100	0
16	72	0	0	100	100	0	0	120	0	42	0	53	36	0	0	60	0	75	0	79	100	0
17	14	0	0	100	100	0	0	81	0	42	0	53	36	0	0	60	0	41	0	82	100	0
18	5	0	0	100	100	0	0	0	0	42	0	53	32	0	0	60	0	48	0	100	100	0
19	74	0	0	100	100	0	0	0	0	42	0	53	31	0	0	60	0	53	0	100	100	0
20	5	0	0	100	100	0	0	0	0	42	0	53	29	0	0	60	0	21	0	100	97	0
21	23	0	0	100	100	0	0	0	0	42	0	53	27	0	0	60	0	22	0	100	97	0
22	0	0	0	100	100	0	0	0	0	42	0	53	26	0	0	60	0	23	0	100	93	0
23	0	0	0	99	100	0	20	0	0	42	0	53	25	0	0	60	5	0	0	100	83	0
24	0	0	0	100	100	0	58	0	0	42	0	53	27	0	0	60	5	0	0	100	91	0

[unit: Gcal]

cember, the daily operating cost obtained from the optimization system is 902,259,799 won, which compares well with 4,262,903,950 won of actual operation.

Fig. 5 and Fig. 6 show hourly operating types of CHPs at four regional areas in August and December for one day. The main difference in the operation types of the optimization system and actual operation is that each DHS operated by the integrated optimization system produces heat and electricity as much as possible to maximize electricity sales, while hourly heat generation is maintained to the minimum level in the actual operation.

Fig. 7 and Table 10 show the operating status in December at Ilwon DHS branch which does not have a CHP. In the optimal operation (numerical simulations), the heat demand from customers is fulfilled by the incinerator and PLBso. This type of operation is supported by the fact that the operating cost of the incinerator is relatively low and that the operating cost of PLBso is lower than that of PLBwg. In the actual operation, the heat demand from customers is fulfilled both by PLBso and PLBwg.

Fig. 8 and Table 11 show the heat transmission among the interconnected networks in December. In the optimal operation (numerical simulations), heat is mainly generated at the regional DHS branches with CHPs and excess heat is transported to other branches with heat deficit. In contrast to this type of optimal operation, heat is transported from the DHS branches without CHPs to those with CHPs in actual operation. Exceptionally, Pankyo DHS branch with CHPs receives heat from other branches in the optimal operation because heat demand from customers in the area exceeds the capacity of heat generation.

CONCLUSIONS

The operation of regional district heating systems (DHSs) needs to be optimized in order to improve the economics and efficiency. In contrast to the optimization of each regional DHS separately, the optimization problem of the integrated DHSs in a relatively large area is tackled in this work. The optimal operation system for the integrated DHSs was developed in the form of an MILP configuration and was investigated to validate the effectiveness of the optimal operation system. In the optimization, the total operation cost of the integrated DHSs is minimized or the total profit of DHS is maximized, while heat demands from customers and operation constraints of heat units and interconnected networks are fulfilled. From the results of numerical simulations, it was found that the optimal operating system for the integrated DHSs shows reduction of energy cost compared to conventional operation.

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NOMENCLATURE

A1 : ratio of power generation function [kW/Gcal]
A2 : constant of power generation function [kW]
B : set of branches [-]
C : set of CHPs [-]
C_{CHP_A} : marginal cost of CHP at A section [won/Gcal]
C_{CHP_B} : marginal cost of CHP at B section [won/Gcal]
$C_{CHP_{Ini}}$: cost at minimum heat of CHP [won]
C_{Unit} : unit cost of units [won/Gcal]
$Cost_{CHP}$: operation cost of CHP [won]
D : heat demand of consumer [Gcal]
ES : electrical Sales of branch [won]
H : set of heat units [-]
J : set of accumulators [-]
m_{Acc} : minimum heat storage of Acc [Gcal]
m_{CHP} : minimum heat production of CHP [Gcal]
m_{HU} : minimum heat production of heat unit [Gcal/h]
m_{Net} : minimum transfer heat of network [Gcal/h]
M_{Acc} : maximum heat storage of Acc [Gcal]
M_{CHP} : maximum heat production of CHP [Gcal/h]
M_{HU} : maximum heat production of heat unit [Gcal/h]
M_{Net} : maximum transfer heat of network [Gcal/h]
mP_{CHP} : minimum power generation of CHP [kW/h]
MP_{CHP}: naximum power generation of CHP [kW/h]
Mdt_{HU} : minimum down time of heat unit [h]
Mut_{HU} : minimum up time of heat unit [h]
nbAcc : number of accumulators [-]
nbBranch : number of branches [-]
nbCHP: number of CHPs [-]
nbGRB: number of GRBs [-]
nbHan: number of Hanjun supplies [-]
nbHU : number of heat units [-]
nbInc : number of incinerators [-]
nbNet : number of network [-]
nbNin : number of incoming networks to branch [-]
nbNout : number of exporting networks from branch [-]
nbPLBso : number of PLBso [-]
nbPLBwg : number of PLBwg [-]
nbUnit : number of units [-]
N_{CHP} : intermediate heat of CHP [Gcal]
OC : iperation cost of branch [won]
P_{CHP} : power generation of CHP [kW]
Q : heat production of unit [Gcal]
Q_{Acc} : heat storage of Acc [Gcal]
Q_{CHP} : heat production of CHP [Gcal]
Q_{CHP_A} : heat production of CHP at A section [Gcal]
Q_{CHP_B} : heat production of CHP at B section [Gcal]
Q_{GRB} : heat production of GRB [Gcal]
Q_{Han} : supplied heat from Hanjun [Gcal]
Q_{HU} : heat production of heat unit [Gcal]
Q_{Inc} : heat production of incinerator [Gcal]
Q_{Net} : heat transfer of network [Gcal]
Q_{Nin} : incoming heat to a branch [Gcal]
Q_{Nout} : exporting heat from a branch [Gcal]
Q_{PLBso} : heat production of PLBso [Gcal]
Q_{PLBwg}: heat production of PLBwg [Gcal]
Q_{Unit} : heat production of unit [Gcal]
R : set of networks [-]
S_{Acc} : safety factor of heat storage in Acc [Gcal/h]

S_{HU} : safety ratio of heat change of heat unit [-]
S_{Net} : safety ratio of heat change of network [-]
SMP : system marginal price [won/kW]
$t^{Initial}$: initial time of time periods [-]
t^{Final} : final time of time periods [-]
T : set of time periods [-]
T_{HU}^{off} : time duration for which HU has been off [h]
T_{Net}^{off} : time duration for which Net has been off [h]
T_{HU}^{on} : time duration for which HU has been on [h]
T_{Net}^{on} : time duration for which Net has been on [h]
Y_{CHP} : on/off signals of CHP [-]
Y_{HU} : on/off signals of heat unit [-]
Z : on/off signals of network [-]
ZMdt : minimum down time of network [h]
ZMut : minimum up time of network [h]

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