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Periodical replanning with hierarchical repairing for the optimal operation of a utility plant

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Abstract

The integration methodology of periodical replanning and hierarchical repairing is proposed to handle the prediction errors of energy demands in the multiperiod operational planning. The periodical replanning is implemented by the decomposition method. The hierarchical repairing is triggered during the execution interval when prediction errors in energy demands exist. The hierarchical repairing uses the heuristic knowledge. The efficiency indices for utility pumps are introduced to determine the optimal configuration of motors and turbines for running utility pumps without integer programming. Case studies show that the proposed method is more profitable than the periodical replanning. The operational cost is reduced by 0.9–4.0% compared with the cost by the periodical replanning.

Keywords: Periodical replanning; Hierarchical repairing; Multiperiod planning; Prediction error; Knowledge base; Optimization

1. Introduction

A considerable amount of energy is consumed in most of the chemical plants. For this reason, scheduling and planning methodologies for utility plants have been paid much attention by many researchers and process engineers. Heuristic methods as well as scheduling and planning have been developed for the optimal operation of utility plants. In general, the energy demand from a process plant is not constant and is predicted as a fixed value from one period to another. Based on the predicted energy demand, a multiperiod operational plan is calculated. However, the operational plan must be updated for the optimal operation of utility plants because energy demands cannot be predicted exactly in real applications (Yeung, Wong, & Ma, 1998).

There have been many efforts about multiperiod operational planning of utility plants. Nath and Holliday (1985) optimized an industrial utility plant using mixed integer linear programming (MILP). Kalitventzeff (1991) presented mixed integer nonlinear programming (MINLP) formulation for management planning of utility networks. Petracci, Brignole, and Eliceche (1991) established the optimal operation of a utility plant considering variable electricity and fuel cost, different process plant capacities and operating condition. Papalexandri, Pistikopoulos, Kalitventzeff, and Dumont (1996) reviewed researches on optimal operation of utility plants. Hui and Natori (1996) addressed the application of MILP techniques for the optimization of a utility plant. Iyer and Grossmann (1997) proposed a two-stage decomposition algorithm for the multiperiod planning of the utility plant with given demand profiles. Papalexandri, Pistikopoulos, and Kalitventzeff (1998) considered the prediction uncertainty by exploring flexible operating scenarios using predictive planning methods. Iyer and Grossmann (1998) presented an

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Nomenclature

Blr	the set of boilers
C	cost
DU	the set of discontinuously operated units
E	electric power
F	flow rate
f	objective function
H	enthalpy
LD	the set of letdown desuperheaters
LHV	low heating value
N	the number of operating pumps
Q	energy demand
T	the set of prediction horizons
UM	the set of electric motors
$\mathbf{UP}_k$	the set of kth kind of pumps
y	binary variable
z	switch variable

Subscripts

BFW	boiler feed water
CBD	continuous blowdown
con	consumption
E	electricity
ext	extraction
gen	generation
HS	high-pressure steam
in	input flow
LS	low-pressure steam
MS	medium-pressure steam
out	output flow
pur	purchase
SC	condensate
STG	steam turbine generator
SW	spray water
swt	switch
t	time period
VS	very high-pressure steam

Greek letter

η	efficiency

MILP formulation for the synthesis and operational planning of the utility plant for multiperiod operation with varying demands. Lee, Lee, Chang, and Han (1998a, b) showed the hierarchical multiperiod operational optimization for the optimal operational of utility plants. Yi, Han, and Yeo (2000) implemented optimal multiperiod planning by a two-level approach considering the internal energy demands. Kim and Han (2001) proposed a new approach for optimal multiperiod utility plant planning. In the upper level, the optimum configuration of the utility plant is determined by dynamic programming, and in the lower level, nonlinear programming (NLP) is solved for each configuration. Heuristic methods have been developed to minimize the operational cost in utility plants as well (Yoo et al., 1996; Yi, Yeo, Kim, Kim, & Kang, 1998).

Although the optimal operation of utility plants has been studied extensively, most of the previous works have focused on operation in single execution interval without adaptation. However, the operation of a utility plant changes as the demands for the steam or the fuel cost change and these changes should be considered during the planning. Plan update can be accomplished by human intervention, replanning by mathematical programming and repairing by heuristic knowledge. From the optimality point of view, the replanning by mathematical programming is more desired as an update strategy. However, the replanning has difficulties in applying to most industrial planning problems because mathematical programming requires excessive computation time due to many binary variables and it is not straightforward to describe the qualitative features of the real-world problem (Henning & Cerda, 2000). In this paper, the methodology for the optimal operation of utility plants is proposed based on the replanning by mathematical programming and the hierarchical repairing by heuristics. The initial plan of a utility plant is calculated from integer programming, and during the execution interval, the operational plan is repaired by heuristics for optimal operation. Efficiency index of a utility pump (UP) is introduced to obtain the optimal plan without integer programming in the hierarchical repairing system. Case studies show that the proposed method is more profitable than the periodical replanning method.

2. Periodical replanning and hierarchical repairing

When the prediction of energy demands has errors during the operation of a utility plant, either no action can be taken (i.e., the previously established operational plan is used until the next replanning interval) or replanning can be implemented at every prediction error. The former approach is called as periodical replanning and the latter approach is called as continuous replanning. Fig. 1 shows the replanning cycles of a utility plant, where each bar represents an operational plan. Multiperiod operational planning is calculated over six periods that is the planning horizon and the operational plan for the first three periods is executed and the operational plan in the last three

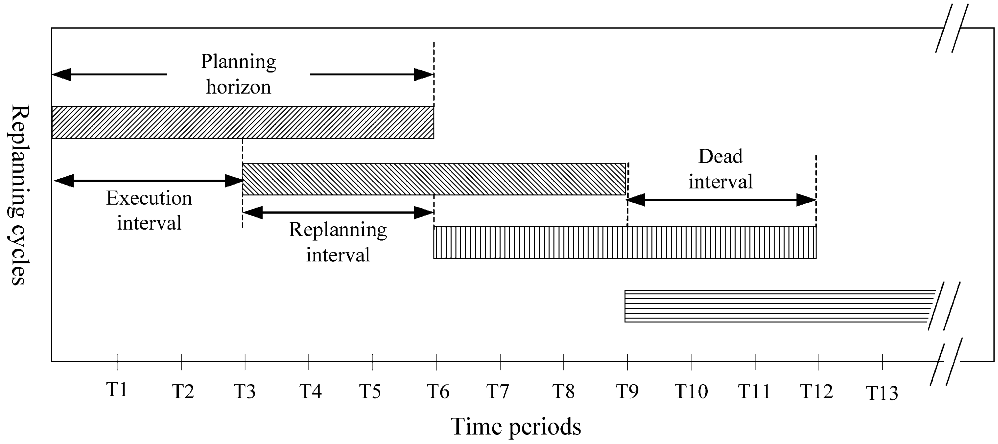


Fig. 1. Periodical replanning cycles in continuous plant.

periods is not executed. The operational plan is updated after every three periods. The first three periods are called *replanning interval* or *execution interval* and the last three periods *dead interval*. A shorter replanning interval leads to a higher replanning frequency. The replanning intervals are the same at all replanning cycles and it is a periodical replanning policy. Periodical replanning is widely used as an updating method.

Another approach for plan update is repairing based on the heuristic knowledge. Because updating a plan using the replanning method requires excessive computation time, many operational constraints and analysis of the results, the repairing by heuristic knowledge is widely used as updating policy (Henning and Cerda, 2000).

Fig. 2 is a simple utility plant as an example to explain the methods of periodical replanning and heuristic-based repairing. The utility plant has a boiler, a steam turbine generator (STG), two utility motors (UMs), three utility turbines (UTs), five UPs, three letdown desuperheaters (LDs) and three steam headers. The performance equation for STG is assumed as

$$F_{STG,\,HS,\,con} - 0.7F_{STG,\,MS,\,ext} - 0.5F_{STG,\,LS,\,ext} - 2.8E_{STG,\,gen} - 18.0 = 0. \quad (1)$$

The STG consumes high-pressure steam (HS), extracts medium-pressure steam (MS), low-pressure steam (LS) and steam condensate (SC), and generates electric power. One of the UP1s is driven by UM1 and the others are driven by UT1s. Two of the UP1s must be operated in normal operation. It is also assumed that all UT1s consume 5.0 t/h steam constantly, and UM1 consumes 1.5 MW electric power constantly. One of the UP2s is driven by UM2 and the other is driven by UT2. One of the UP2s must be operated in normal operation. It is also assumed that UT2 consumes 7.0 t/h steam constantly, and UM2 consumes 2.0 MW electric power constantly.

Fig. 3 shows the predictions and the measurements for energy demand. The solid line represents predictions for energy demand and the dotted line, the measurements for energy demand. It is assumed that all predictions for energy demands are exact except LS prediction at the second period. The initial plan is calculated according to the prediction shown in Fig. 3. Table 1 shows the results for the initial plan. mTnM in Table 1 means that the number of utility pumps is $m+n$: the number of pumps that are driven by utility turbines is m and the number of pumps that are driven by utility motors is n. For example, the number of UP1s in the first period (1T1M) is two; one of them is driven by a utility turbine and the other is driven by a utility motor. The operational mode of UP1s is changed at the second and the third period. However, the operational mode for UP2s is not changed along the prediction horizon. The execution interval for the planning is assumed as four periods. Therefore, the initial plan is fixed until the fourth period although prediction error for energy demand exists at the second period.

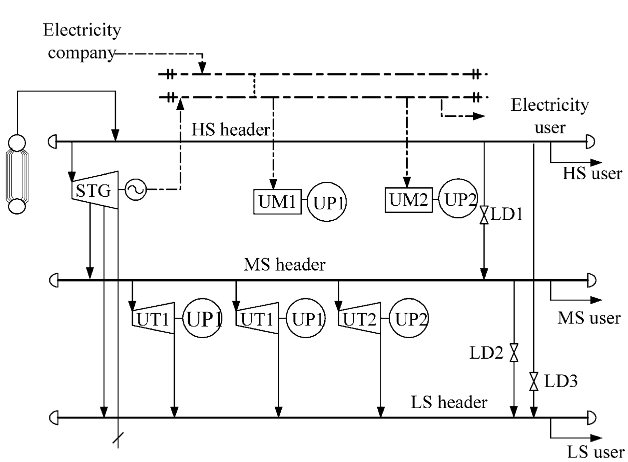


Fig. 2. A simple utility plant.

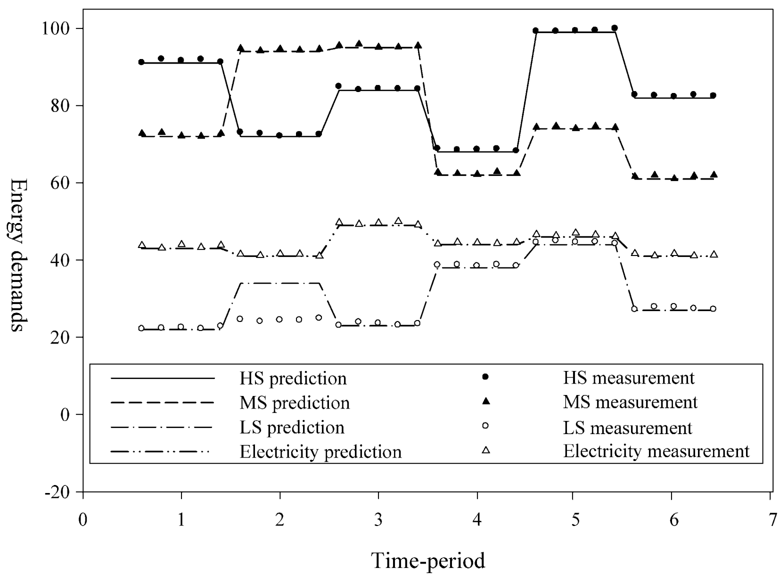


Fig. 3. The predictions and the measurements for energy demands.

Table 1
The results from the initial plan

	Periods					
	1	2	3	4	5	6
Boiler (t/h)	235.0	249.3	252.0	218.0	267.0	220.0
STG						
MS extraction (t/h)	82.0	109.0	105.0	77.0	89.0	76.0
LS extraction (t/h)	5.0	12.0	6.0	16.0	22.0	5.0
SC extraction (t/h)	50.0	49.3	50.0	50.0	50.0	50.0
Generated electricity (MW)	21.1	25.0	23.8	22.5	24.9	20.5
Purchased electricity (MW)	23.4	16.0	26.8	21.5	21.1	20.5
*UP*1	1T1M	2T	1T1M	2T	2T	2T
*UP*2	1T	1T	1T	1T	1T	1T

The initial plan can be updated by hierarchical repairing based on heuristic knowledge. At the second period, LS demand has an error and the initial plan is updated by hierarchical repairing. The hierarchical repairing is performed in a sequential manner; starting from a lower-pressure header to the higher-pressure header. The repairing is composed of the handling of UT, UM, LD and STG. The utility plant in Fig. 2 has two kinds of UPs and a more efficient type of UP should be decided for the optimal operation. If prediction deviation happens in LS demand, a UP1 driven by UT1 is turned off, another UP1 driven by UM1 is turned on, and the amount of LS extraction of STG is reduced to 7.0 t/h, so that prediction error in the LS demand is repaired. However, the repairing of LS demand affects the balance for supply and demand in the MS header. To keep the balance for supply and demand in the MS header, the amount of MS extraction from STG must be reduced to 104.0 t/h. Therefore, the amount of steam consumption in STG is 160.3 t/h and the electric power generation in STG is 23.57 MW, which is calculated by (1). The repairing of MS header balance also affects the balance for supply and demand in the HS header. To keep the balance for supply and demand in the HS header, the amount of steam generation in the boiler must be changed to 239.3 t/h. As the demand for internal electric power increases by 1.5 MW and the amount of electric power generation is 23.57, the purchase of the electric power must be increased to 18.93 MW to keep the balance of supply and demand in electric power. Therefore, the operational cost by repairing of UP1 is $239.3C_{HS,\,gen} + 18.93C_{E,\,pur}$. The initial plan shown in Table 1 can be also repaired by UP2. If a UP2 driven by UM2 is turned on, another UP2 driven by UT2 is turned off, and the amount of LS extraction from STG is reduced to 9.0 t/h, the prediction error in the LS demand can be repaired. The repairing of the MS header resulted from the repairing of the LS demand can be implemented by reducing the amount of MS to 102.0 t/h. Therefore, the amount of steam consumption in STG is 160.3 t/h and the generation of electric power is 23.71 MW. To keep the balance for supply and demand in the HS header, the amount of steam generation in the boiler must be changed to 239.3 t/h. As the demand for internal electric power increases by 2.0 MW and the amount of electric power generation is 23.61 MW, the purchase of electric power must be increased to 19.29 MW to keep the balance for supply and demand in the electric power. Therefore, the operational cost by repairing of UP2 is $239.3C_{HS,\,gen} + 19.29C_{E,\,pur}$. As the operational cost from changing the driving force of UP1 is smaller than the one from UP2, UP1 is more efficient when LS demand has decreased compared with the prediction of energy demand. Because the repairing is based on the heuristic knowledge, the updated result by the repairing may be suboptimal compared with the periodical replanning. However, the repairing can be more effective when the prediction error exists during the execution interval because periodical replanning does not update among the execution intervals.

3. Efficiency index of UP

If the change of driving force for UP from UM to UT reduces the operating cost, the UP is defined as an *efficient utility pump* and UT as an *efficient driving force*. If the change of driving force for UP from UT to UM reduces the operating cost, the UP is defined as the efficient UP and UM is the efficient driving force. The *efficiency index* of UP is a quantitative measure that represents the efficiency of UP in a given process condition and is defined as follows:

$$\text{Efficiency index} = \frac{\text{(Mode change cost)}}{\text{(Original cost)}}. \qquad (2)$$

The original cost is calculated by adjusting the extraction of STG and LD without changing the driving forces of UPs, and the mode change cost is calculated by turning on/off UPs and then adjusting the amount of extraction for STG and LD. If the value of the efficiency index is smaller than 1.0, UP is efficient; otherwise, it is not efficient. As the value of the efficiency index is smaller, the UP becomes more efficient. As an example, consider the simple utility plant shown in Fig. 2 whose operating conditions are given in Table 2. The amounts of steam and electricity consumption are identical to those in Section 2. The amounts of steam supplies to the HS and the MS headers are the same as the amounts of steam demands in the HS and the MS headers, respectively. However, the amount of steam demand in the LS header is larger than that of steam supply by 5.0 t/h, and the deficient steam can be supplied by changing the operating conditions of UP1s, UP2s, STG and LDs. The deficient amount of LS can be supplied by increasing the steam release in LD3 without handling the driving forces of UPs. The resulting operation cost, the original cost in this example, is $320.0C_{HS,\,gen} + 16.93C_{E,\,pur}$. The deficient amount of LS can be also supplied by changing the mode of UP1 and the releases of LDs. Turning on the UT1, which was idle keeps the balance of LS header. UM1 that was operated must be turned off because the number of operated UP1s must be equal to two, which reduces the consumption of the internal electric power by 1.5 MW. To keep the balance of MS header, the release of LD1 must be increased to 25.0 t/h, which makes the amount of steam generation in the boiler 320.0 t/h. Therefore, the mode change cost by UP1s is $320.0C_{HS,\,ge} + 15.43C_{E,\,pur}$. The mode change cost by UP2s can be obtained following the same procedure and the resulting cost is $320.0C_{HS,\,gen} + 14.93C_{E,\,pur}$. Therefore, the efficiency index of UP1 is $(320.0C_{HS,\,gen} + 15.43C_{E,\,pur})/(320.0C_{HS,\,gen} + 16.93C_{E,\,pur})$ and the efficiency index of UP2 is $(320.0C_{HS,\,gen}+14.93C_{E,\,pur})/(320.0C_{HS,\,gen}+16.93C_{E,\,pur})$. Because both efficiency indices are smaller than 1.0, the hierarchical repairing needs to be implemented; otherwise, no repairing is needed. However, the efficiency

Table 2
The operating conditions to explain efficiency index of UP

Units	Min.	Operating condition	Max.
Boiler (t/h)	0.0	315.0	400.0
STG			
HS consumption (t/h)	100.0	195.0	230.0
MS extraction (t/h)	70.0	130.0	150.0
LS extraction (t/h)	5.0	40.0	40.0
SC extraction (t/h)	3.0	25.0	50.0
Electricity (MW)	10.0	23.57	25.0
*LD*1 (t/h)	5.0	20.0	30.0
*LD*2 (t/h)	3.0	10.0	15.0
*LD*3 (t/h)	2.0	5.0	10.0
*UP*1		1T1M	
*UP*2		1M	
HS demand (t/h)		95.0	
MS demand (t/h)		135.0	
LS demand (t/h)		65.0	
E purchase (t/h)		16.93	

index for UP2 is smaller than the efficiency index for UP1, thus, the hierarchical repairing by UP2 is more profitable than UP1 when LS demand increases.

4. Integration of periodical replanning with hierarchical repairing

The periodical replanning and the hierarchical repairing can be integrated for the optimal operation of a utility plant. The integration methodology is shown in Fig. 4. Multiperiod operational planning is implemented periodically off-line based on economic information, demand predictions over the prediction horizon and process database. In multiperiod operational planning, the optimal plan for a utility plant over the planning horizon is determined by integer programming. The transition costs and switch costs must be included in the multiperiod planning problem because frequent and large operational changes between periods make operational plan suboptimal for the entire planning horizon. At the end of execution interval, operational plan is updated by periodical replanning. It is the same as the initial multiperiod operational planning except for shifting the planning horizon. When the current time reaches the end of the current period except the end of execution interval, the energy demand of the utility plant is predicted to examine whether the operational plan is feasible or optimal for the current energy demand. The energy demands of the utility plant are predicted just before the next period starts as shown in Fig. 4. Because the demands predicted just before the next period will be more accurate compared to those predicted at several periods ago, it is assumed that the energy demands of the utility plant for the subsequent periods may be easily predicted just before the period where hierarchical repairing is implemented, and the predicted values have small errors than those predicted at several periods ago. The plan repairing is triggered mainly by two types of events: infeasibility and optimality. If an operational plan is infeasible, the plan must be repaired to be feasible under the process condition in the current period. Although the plan is feasible, plan repairing may be needed when the plan is not optimal for the given energy demand in the current period. This can be easily detected by the existence of an efficient UP. If a UP exists whose efficiency index is smaller than 1.0, the plan repairing is triggered; otherwise, a utility plant is operated according to the operational plan under the varying energy demands. For the hierarchical repairing, heuristic knowledge is used to obtain the optimal driving forces of UPs without mathematical programming.

5. Case study

5.1. Process description

Fig. 5 shows a process flow diagram for an industrial utility plant. The steam generation unit is composed

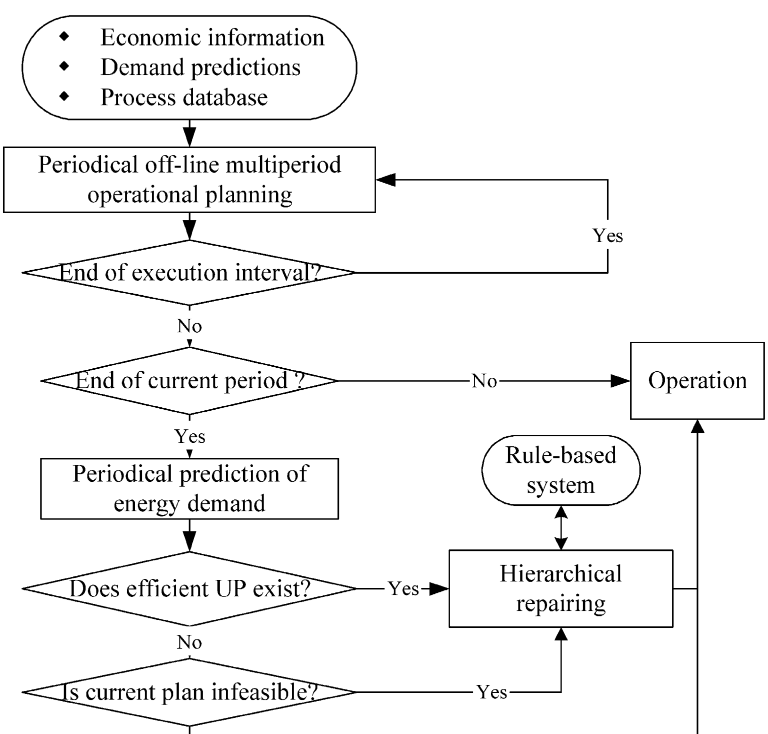


Fig. 4. The integration methodology of the periodical replanning and the hierarchical repairing for the optimal operation.

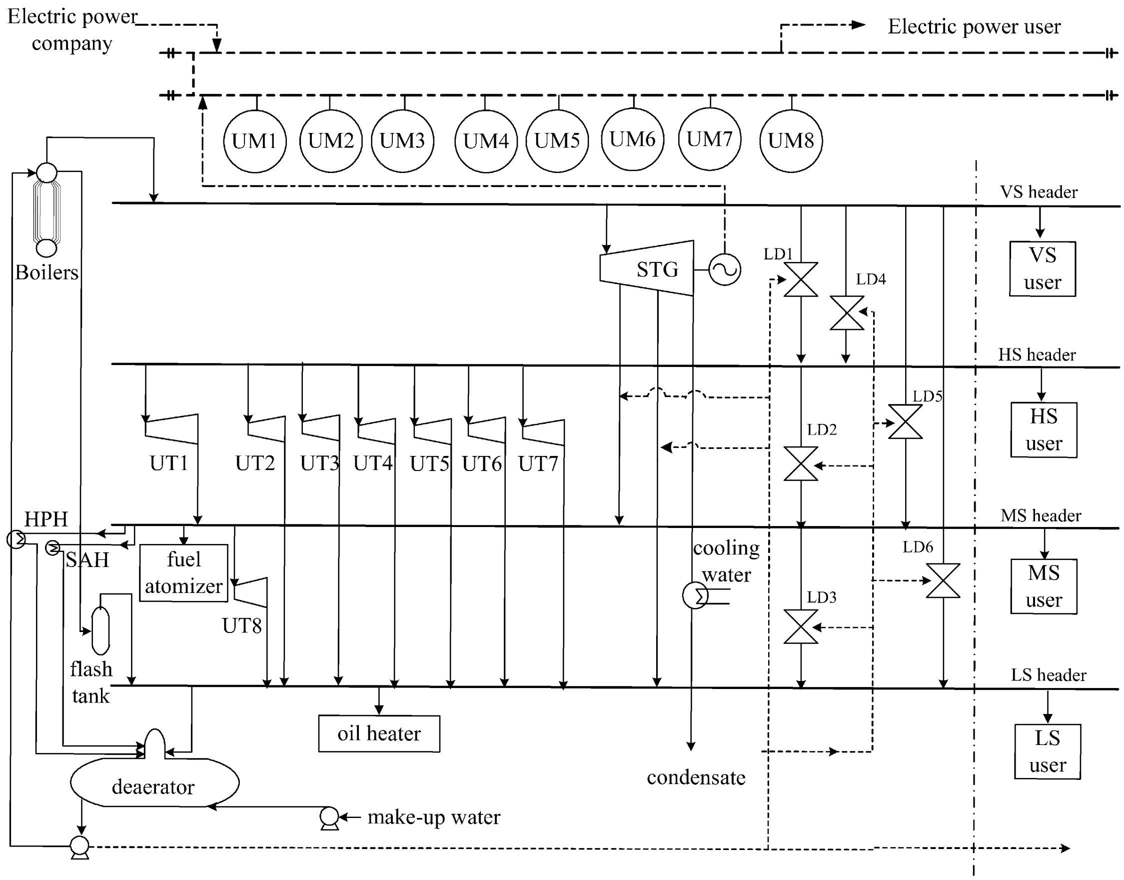


Fig. 5. The schematic diagram to show the process flow of an industrial utility plant.

of four boilers, a high-pressure feed-water heater (HPH), a steam air heater (SAH), a deaerator, an oil heater and a fuel atomizer. The HPH, the SAH and the fuel atomizer consume MS, and the deaerator and the oil heater consume LS. The boilers produce very high-pressure steam (VS) only to be fed into a VS header. VS is fed into a STG that generates electric power and extracts MS, LS and SC. The number of each operating UP must be fixed to supply steam and electricity to the process. Table 3 shows the numbers of installed UPs, the amounts of steam and the electric power consumption to drive them. For example, the number of UP1s is eight, and four of them are driven by UT1s and the others are driven by UM1s. UT1s consume 50.3 t/h of steam and UM1s consume 1770.0 kW of electric power constantly if they are operated. There are four different kinds of steam headers according to their temperature and pressure. Four boilers can supply the entire amount of steam required in the processes and utility plant. Electric power must be purchased to meet the electricity demand because the STG cannot generate enough electric power to be used in the process and utility plant.

Table 3
The driving forces of UPs and steam/power consumptions in UTs/UMs

Process equipment	Driving force	Steam turbine (t/h)	Electric motor (kW)
UT1,UM1	4T4M	50.3	1770.0
UT2,UM2	1T2M	2.1	90.0
UT3,UM3	1T1M	7.6	220.0
UT4,UM4	4T4M	8.1	560.0
UT5,UM5	4T2M	17.3	1250.0
UT6,UM6	4T4M	4.6	250.0
UT7,UM7	2T2M	9.6	540.0
UT8,UM8	2T1M	2.3	45.0

5.2. *The formulation of multiperiod operational planning problem*

The multiperiod operational planning of a utility plant is decomposed into two levels. At the upper level, the amount of steam generation and electric power purchase is minimized by integer programming. At the lower level, the rate of fuel consumption is minimized by NLP. In the upper level planning, the objective function consists of the total cost over all periods. Total cost is composed of the operating costs of a utility plant and the switch costs for all periods. The operating costs are composed of the costs of steam generation, spray water, and purchased electric power. The optimization problem can be defined as

$$\text{Minimize } f = \sum_{t\in\mathbf{T}}\left[\sum_{i\in\mathbf{Blr}} C_{i,VS,\,t}F_{i,VS,\,gen,t} + \sum_{i\in\mathbf{LD}} C_{SW,\,t}F_{i,SW,\,t} + C_{E,t}E_{pur,t} + \sum_{i\in\mathbf{DU}} C_{swt,i}z_{i,t,t+1}\right] \quad (3)$$

$$\text{Subject to} \quad \sum_{i\in\mathbf{Blr}} F_{i,VS,gen,t} - F_{STG,VS,con,t} - \sum_{i=LD1,LD4} F_{i,VS,in,t} = Q_{VS}, \quad (4)$$

$$\sum_{i=LD1,LD4} F_{i,HS,out,t} - \sum_{i=UT1}^{UT7} y_{i,t}F_{i,HS,in,t} - F_{LD2,HS,in,t} = Q_{HS}, \quad (5)$$

$$y_{UT1,t}F_{UT1,MS,out,t} + F_{STG,MS,ext,t} + \sum_{i=LD2,LD5} F_{i,MS,out,t} - \sum_{\substack{i=HPH,SAH,\\ \text{fuel atomizer}}} F_{i,MS,con,t} - y_{UT8,t}F_{UT8,MS,in,t} - F_{LD3,MS,in,t} = Q_{MS}, \quad (6)$$

$$\sum_{i=UT2}^{UT8} y_{i,t}F_{i,LS,out,t} + F_{STG,LS,ext,t} + \sum_{i=LD3,LD6} F_{i,LS,out,t} - \sum_{\substack{i=\text{deaerator},\\ \text{oil heater}}} F_{i,LS,con,t} = Q_{LS} \quad (7)$$

$$F_{STG,VS,con,t} - F_{STG,MS,ext,t} - F_{STG,LS,ext,t} - F_{STG,SC,ext,t} = 0, \quad (8)$$

$$F_{i,\,g1,\,in,\,t} + F_{i,\,SW,\,in,\,t} - F_{i,g2,out,t} = 0, \quad (9)$$

where $i \in \mathbf{LD}$,

$$g1 = \begin{cases} VS & \text{if } i = LD1, LD4, LD5, LD6, \\ HS & \text{if } i = LD2, \\ MS & \text{if } i = LD3, \end{cases},$$

$$g2 = \begin{cases} HS & \text{if } i = LD1, LD4, \\ MS & \text{if } i = LD2, LD5, \\ LS & \text{if } i = LD3, LD6, \end{cases}$$

$$\sum_{i\in\mathbf{Blr}} F_{i,VS,gen,t}H_{i,VS,gen} - F_{STG,VS,con,t}H_{STG,VS,con} - \sum_{i=LD1,LD4} F_{i,VS,in,t}H_{i,VS,in} = Q_{VS}H_{Q,VS}, \quad (10)$$

$$\sum_{i=LD1,LD4} F_{i,HS,out,t}H_{i,HS,out} - \sum_{i=UT1}^{UT7} y_{i,t}F_{i,HS,in,t}H_{i,HS,in} - F_{LD2,HS,in,t}H_{LD2,HS,in} = Q_{HS}H_{Q,HS}, \quad (11)$$

$$y_{UT1,t}F_{UT1,MS,out,t}H_{UT1,MS,out} + F_{STG,MS,ext,t}H_{STG,MS,ext} + \sum_{i=LD2,LD5} F_{i,MS,out,t}H_{i,MS,out} - \sum_{\substack{i=HPH,SAH,\\ \text{fuel atomizer}}} F_{i,MS,con,t}H_{i,MS,con} - y_{UT8}F_{UT8,MS,in,t}H_{UT8,MS,in} - F_{LD3,MS,in,t}H_{LD3,MS,in} = Q_{MS}H_{Q,MS}, \quad (12)$$

$$\sum_{i=UT2}^{UT8} y_{i,t}F_{i,LS,out,t}H_{i,LS,out} + F_{STG,LS,ext,t}H_{STG,LS,ext} + \sum_{i=LD3,LD6} F_{i,LS,out,t}H_{i,LS,out} - \sum_{\substack{i=\text{deaerator},\\ \text{oil heater}}} F_{i,LS,con,t}H_{i,LS,con} = Q_{LS}H_{Q,LS}, \quad (13)$$

$$F_{i,g1,in,t}H_{i,g1,in} + F_{i,SW,in,t}H_{i,SW,in} - F_{i,g2,out,t}H_{i,g2,out} = 0, \quad (14)$$

where $i, g1$ and $g2$ are the same as in Eq. (9).

$$F_{STG,VS,con,t} = p_tF_{STG,MS,ext,t} + q_tF_{STG,LS,ext,t} + r_tE_{STG,gen,t} + s_t, \quad (15)$$

$$\sum_{i\in\mathbf{UP}_k} y_{i,k,t} = N_{k,t} \quad (k = 1, 2, \ldots, 8: \text{ all kinds of pumps}), \quad (16)$$

$$E_{STG,gen,t} + E_{pur,t} \geqslant Q_{E,t} + \sum_{i\in\mathbf{UM}} y_{i,t}E_{i,con,t}, \quad (17)$$

$$z_{t,t+1} \geqslant y_t - y_{t+1}, \quad (18a)$$

$$z_{t,t+1} \geqslant y_{t+1} - y_t, \quad (18b)$$

$$z_{t,t+1} \leqslant 2 - y_t - y_{t+1}, \quad (18c)$$

$$z_{t,t+1} \leqslant y_t + y_{t+1}. \quad (18d)$$

Eqs. (4)–(9) are mass balance equations around four steam headers, the STG and the letdown desuperheaters. Eqs. (10)–(14) are energy balance equations around four steam headers and letdown desuperheaters. Eq. (15) gives the relation among the power generation, steam consumption and steam extraction whose coefficients can be found elsewhere (Lee, Lee, Han, & Chang, 1998). The set **DU** represents the discontinuously operated unit such as UTs, UMs. Therefore, integer variable y is used to represent on/off status of a unit that belongs to **DU**. The utility plant in this study has eight different kinds of

UPs that are driven by UMs and UTs. There is a restriction on the number of operated UPs during the normal operation. The set $\mathbf{UP}_k$ represents the kth kind of UPs and each set, $\mathbf{UP}_k$, must satisfy the criteria (16). Eq. (17) represents constraints for the demand satisfactions of electric power. Eqs. (18a)–(18d) are the relations between on/off variables and switch variables.

In the lower level planning, we have allocated the boiler load according to their efficiencies to minimize the total cost. The total cost is composed of the fuel cost and the boiler transition cost. The multiperiod planning problem can be formulated as

$$\text{Minimize } f = \sum_{t \in \mathbf{T}} \sum_{i \in \mathbf{Blr}} \lfloor C_{i,fuel,t} F_{i,fuel,t} + C_{tran,t} |F_{i,VS,gen,t} - F_{i,VS,gen,t+1}| \rfloor \tag{19}$$

$$\text{Subject to} \quad F_{i,BFW,t} = F_{i,CBD,t} + F_{i,VS,gen,t}, \tag{20}$$

$$F_{i,fuel,t} = \frac{1}{LHV_t} \times \frac{F_{i,CBD,t} H_{i,CBD,t} + F_{i,VS,gen,t} H_{i,VS,gen,t} - F_{i,BFW,t} H_{i,BFW,t}}{\eta_{i,t}}, \tag{21}$$

$$\eta_{i,t} = a_{i,t} F_{i,VS,gen,t}^2 + b_{i,t} F_{i,VS,gen,t} + c_{i,t}. \tag{22}$$

The subscript i represents the ith boiler. Eq. (20) is the mass balance around the boilers and (21) can be obtained from energy balance considering thermal efficiency of the boiler. The boiler efficiency of the ith boiler can be expressed as (22). We have obtained the coefficients for the boiler efficiency equation from the regression based on operation data (Lee et al., 1998).

5.3. The heuristic knowledge for hierarchical repairing

Hierarchical repairing is triggered if the prediction errors of energy demand exist during the execution period. Hierarchical repairing is always performed sequentially from LS header to VS header and is composed of the handling of UT, UM, STG and LD. The heuristics for the repairing at each header is shown in Fig. 6(a)–(d).

If the prediction error in the LS demand exists, operation plan must be repaired because the current plan may be infeasible or not optimal under the current condition. To repair the operational plan of LS header, the efficiency indices and efficient driving forces from UP2 to UP8 are calculated and the driving forces for UPs are changed. Generally, the handling of UPs does not satisfy the temperature and the pressure conditions for a steam header because the amounts of steam consumption of UTs are fixed. Therefore, LS extraction of STG, LD3 and LD6 must be adjusted in order to meet the temperature and the pressure conditions of the header. If the prediction errors do not exist or rules succeed in repairing of the LS header, the repairing of MS header is implemented.

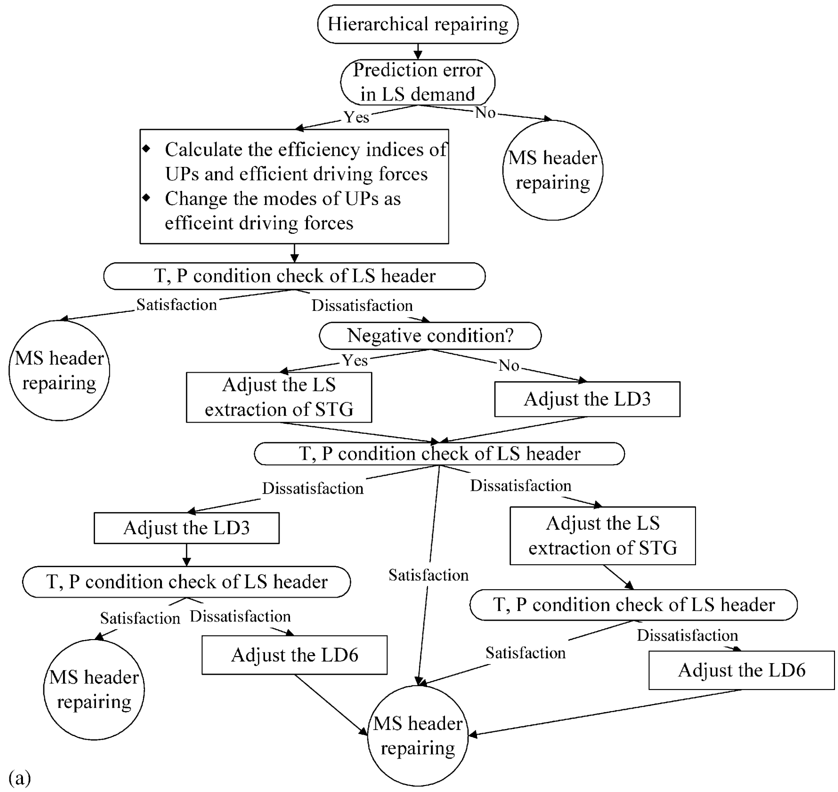
The hierarchical repairing of MS header has the same structure with that of the LS header. If the temperature and pressure in the MS header are within the admissible ranges, HS header repairing is implemented; otherwise, hierarchical repairing searches for the optimal operating condition. To repair the operational plan of MS header, the efficiency index and efficient driving force of UP1 are calculated and the mode of UP1 is changed according to the calculation. MS extraction of STG, LD2 and LD5 must be adjusted to meet the temperature and pressure conditions of MS header because the steam consumption of UT1 is constant.

If the temperature and the pressure of HS header are not within the admissible ranges, the feasibilities of LD1 and LD4 are examined. If they are feasible, flow rates of LD1 and LD4 are changed and VS repairing is implemented. Otherwise, the driving forces from UP1 to UP7 are changed for LD1 and LD4 to be feasible. After changing the driving forces of the UPs in VS repairing, the temperature and the pressure of LS header must be checked because the driving force changes of UPs make steam supply to MS and LS headers change.

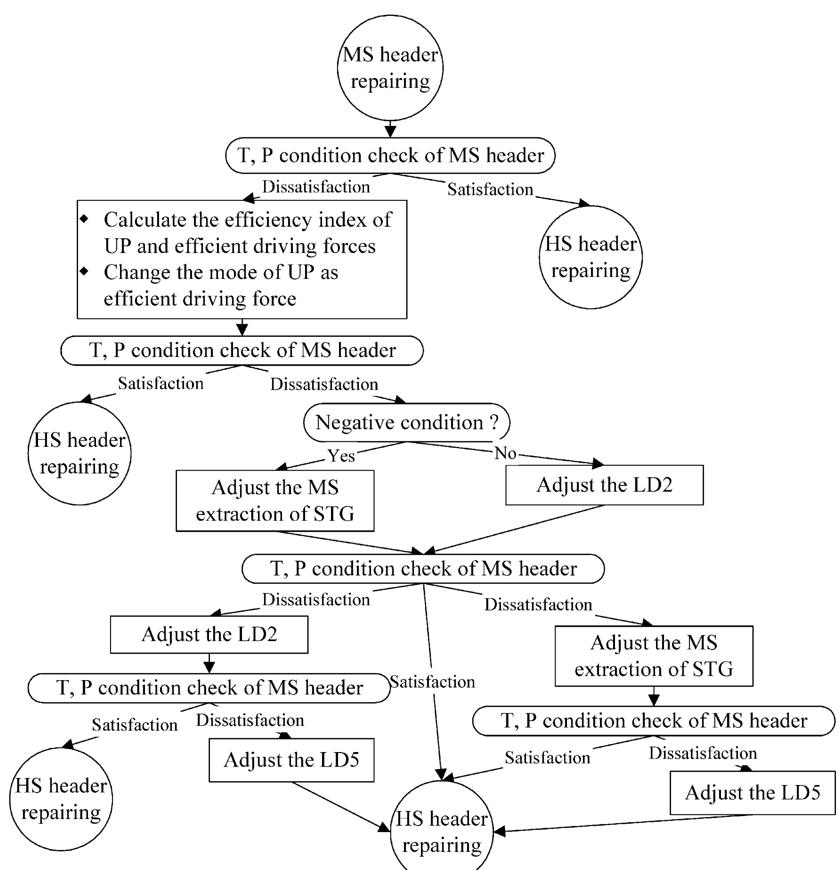
The repairing knowledge base of VS header is usually implemented by the load allocation of the boilers and the driving force changes of UPs. The load allocation is implemented by NLP. In an extreme case, the total requirement for VS can be larger than the maximum operating limit of boilers. In this case, repairing must be implemented all over again from LS header to reduce the total requirement of VS and increase the consumption of electric power, which can be accomplished by changing the driving forces of UPs as UMs.

5.4. Results and discussion

The results of the proposed method are compared with that of periodical replanning. Table 4 shows the demand predictions of steam and electric power for a planning horizon of twelve periods. One time period is 4 h and the execution interval is 28 h in this case study. The signs of HS demands are negative, which mean that the supply of HS from process plants and the utility plant is larger than the demand of HS from process plants. The initial multiperiod operational plan is calculated by the decomposition method based on the prediction shown in Table 4. The result of driving forces of UPs is shown in Table 5 that is calculated by the upper level multiperiod operational planning considering the switch cost of UPs. Fig. 7 shows the result of the optimal profiles of boiler load allocations by the lower level multiperiod operational planning considering the transition cost of boilers. Based on the initial plan,



(a)



(b)

Fig. 6. Heuristic knowledge for the hierarchical repairing of prediction error in the LS header; (b) heuristic knowledge for the hierarchical repairing of prediction error in the MS header; (c) heuristic knowledge for the hierarchical repairing of prediction error in the HS header; (d) heuristic knowledge for the hierarchical repairing of prediction error in the VS header.

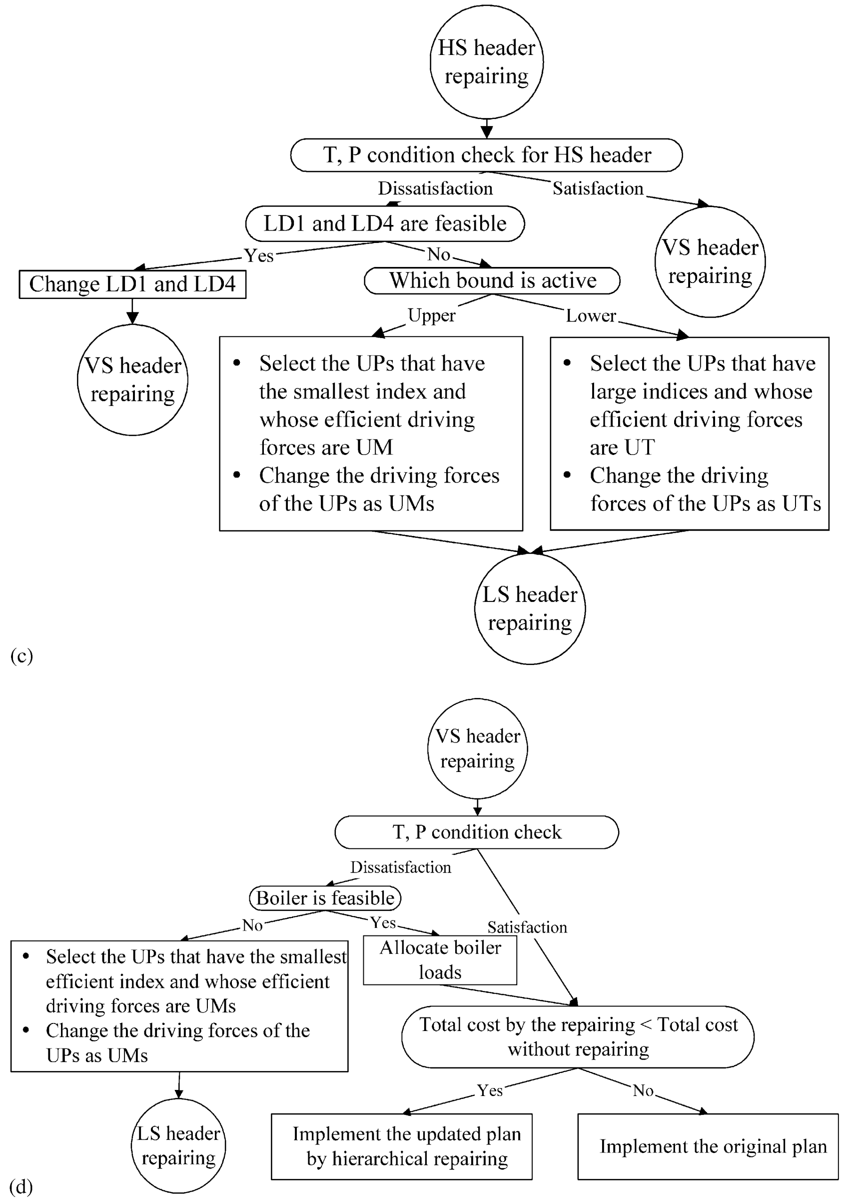


Fig. 6 (*continued*).

Table 4
The demand predictions of steam and electric power for a planning horizon

	1	2	3	4	5	6	7	8	9	10	11	12
VS (t/h)	150	175	160	140	155	165	163	154	168	156	144	151
HS (t/h)	−112	−138	−125	−136	−122	−134	−119	−125	−134	−124	−139	−126
MS (t/h)	204	166	214	179	220	169	210	198	174	201	189	212
LS (t/h)	88	68	96	72	104	75	89	111	71	93	69	92
E (MW)	30	34	31	38	36	32	34	37	31	33	42	38

periodical replanning and hierarchical repairing is implemented under varying energy demands. The execution period of the planning is seven periods. Fig. 8 shows the predictions and the measurements of steam demands, which have prediction errors. Dotted lines represent the measured steam demands and solid lines represent the predicted steam demands along the planning horizon. In the first execution interval, prediction errors in the demands of MS and LS exist from the fourth period to the seventh period. Fig. 9

Table 5
The initial multiperiod plan for UPs

	1	2	3	4	5	6	7	8	9	10	11	12
UP1	3T1M	3T1M	4T	3T1M	4T	3T1M	4T	3T1M	3T1M	3T1M	2T2M	4T
UP2	2M	2M	2M	2M	2M	2M	2M	2M	2M	2M	2M	2M
UP3	1M	1M	1M	1M	1M	1M	1M	1M	1M	1M	1M	1M
UP4	4M	4M	4M	4M	4M	4M	4M	4M	4M	4M	4M	4M
UP5	3T1M	2T2M	2T2M	2T2M	3T1M	2T2M	2T2M	4T	2T2M	3T1M	3T1M	3T1M
UP6	4M	4M	4M	4M	4M	4M	4M	4M	4M	4M	4M	4M
UP7	2M	2M	2M	2M	2M	2M	2M	2M	2M	2M	2M	2M
UP8	1M	1M	1T	1M	1M	1M	1M	1M	1M	1M	1M	1M

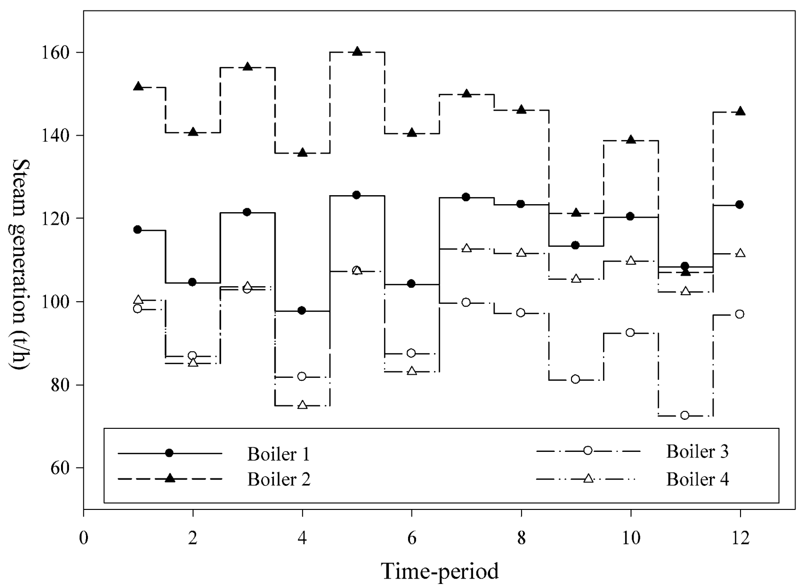


Fig. 7. The results for boiler load allocation.

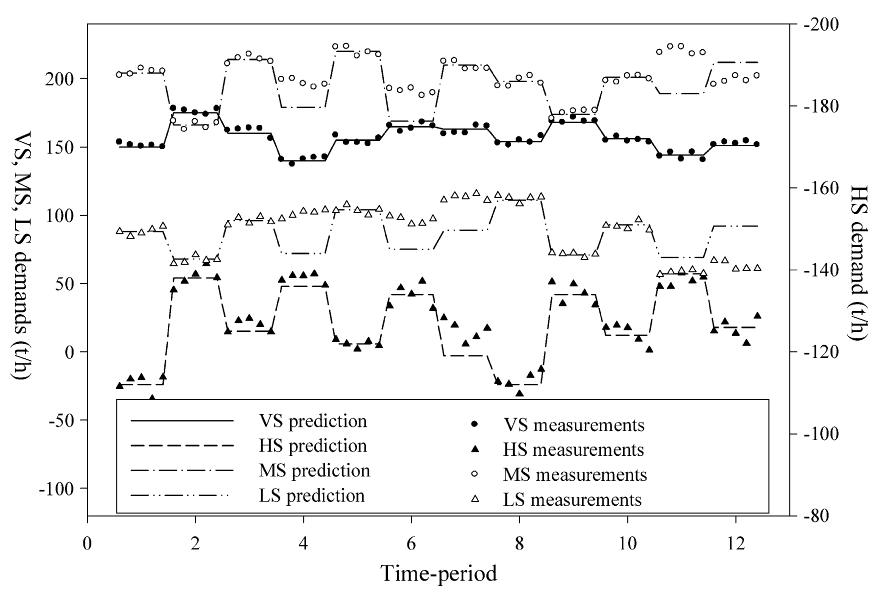


Fig. 8. The predictions and the measured values for steam demands.

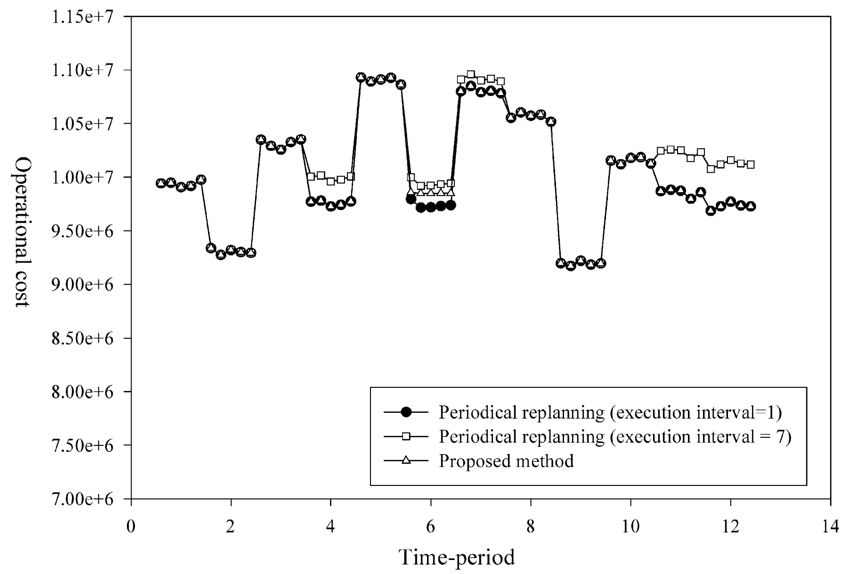


Fig. 9. The comparison of the operational cost by the proposed method with that of periodical replanning.

compares the operational cost by the proposed method with that by periodical replanning. The black circle line shows the operational cost by the periodical replanning whose length of execution interval is one period. The white rectangle line shows the operational cost by the periodical replanning whose length of execution interval is seven periods. The white triangle line is the result by the proposed method. The proposed method updates the initial plan by hierarchical repairing because prediction errors exist from the fourth period to the seventh period. The proposed method has reduced the operational cost by 0.9–2.5% during the first execution interval compared with the result of the periodical replanning whose execution interval is seven periods. The operational cost by the proposed method is almost the same with the cost by the periodical replanning whose execution interval is one period except the sixth period. From the point of optimal operation, the periodical replanning at every period must be favored. However, the replanning at every period requires more computation time and operational constraints. For example, at the sixth period, the driving force of UP5 is updated by the periodical replanning at every period from 2T2M to 4T. However, the proposed method updates the driving force of UP5 from 2T2M to 3T1M. The simultaneous changes of driving forces are not favored in the real operation of industrial utility plants. Generally, the constraints in startups/shutdowns of UPs may change when the prediction errors in energy demands increase. In such case, the adaptive formulation in the replanning problem is very difficult. However, heuristic knowledge can consider the operational constraints during the triggering process of hierarchical repairing.

The proposed method updates the initial plan at the eighth period by the periodical replanning because of the execution interval. The part of the operational results by the proposed method is also compared with that by periodical replanning at the second execution interval in Fig. 9. From the eighth period to the tenth period, prediction errors of energy demand are small and the differences between the operational costs by the proposed method and periodical replannings do not exist. However, prediction errors of energy demand exist from the eleventh period. Therefore, the hierarchical repairing updates the initial plan at the eleventh period. The proposed method reduced the operational cost by 3.0–4.0% compared with the periodical replanning whose execution interval is the seventh period. The operational cost by the proposed method has little difference with the result by the periodical replanning at every period.

6. Conclusions

The periodical replanning integrated with the hierarchical repairing is proposed to handle the prediction errors of energy demands in the multiperiod operational planning at utility plants. The hierarchical repairing can reduce the operational cost compared with the conventional method because the conventional method does not have any updating method during the execution intervals. The proposed method is more profitable than the periodical replanning when prediction errors in energy demands exist. The operational cost is reduced by 0.9–2.5% during the first execution intervals and 3.0–4.0% during the second execution interval. The proposed method is also gives almost the same result by the periodical replanning whose execution interval is one period.

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