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The Integration of Complete Replanning and Rule-Based Repairing for Optimal Operation of Utility Plants

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Abstract−The integration methodology of complete replanning and plan repairing is proposed to handle the prediction errors for energy demands during multiperiod operational planning. Complete replanning is implemented periodically and plan repairing is triggered during the execution interval. The plan repairing is constructed by a rule-based system because of real-time limitations. The efficiency index of a utility pump is introduced to determine startup/shutdown of equipment without integer programming in plan repairing. Case studies show that the proposed method is more profitable than the conventional replanning method. The total operating costs are reduced by 0.3-9.0% compared with the conventional replanning method.

Key words: Multiperiod Operational Planning, Prediction Error, Plan Repairing, Replanning, Rule-based System

INTRODUCTION

Most chemical plants consume a considerable amount of energy; thus, multiperiod operational planning of utility plants has been studied extensively. In conventional multiperiod operational planning, the operational plan is fixed during the execution interval in the planning horizon [Jang and Babu, 1987]. However, energy demand cannot be predicted exactly in real applications, and the prediction error in multiperiod operational planning makes it difficult for the conventional method to obtain a true optimum. In this situation, the operational plan must be updated for optimal operation.

A plan update can be accomplished in several ways: relying on human intervention, plan repairing, and complete replanning. The distinction between plan repairing and complete replanning is fundamental. Plan repairing involves changing the operational plan as little as possible to obtain optimal operation. Complete replanning generates an operational plan all over again. Re-generation of an entire plan is rarely achievable in a real-time environment and requires much computation time [Belz and Mertens, 1996]. Complete replanning is useful when prediction error is so large that the off-line re-generation of the entire plan can save operating cost. Therefore, off-line complete replanning is implemented periodically for optimal operation [Yeung et al., 1998]. In contrast to complete replanning, plan repairing is preferred in a real-time environment when the prediction error is not so large that off-line replanning is not required, but the current plan is not optimal.

There has been much research 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 et al. [1991] established the optimal operation of a utility plant considering variable electricity and fuel cost, different process plant capacities and operating condition. Ito et al. [1994] proposed an optimization method for the operation of a cogeneration plant. The method combines the dynamic programming with mixed integer programming. Papalexandri et al. [1996] reviewed researches on optimal operation of utility plants. Hui and Natori [1996] addressed the application of MILP techniques for the optimization of the 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 et al. [1998] considered the prediction uncertainty by exploring flexible operating scenarios using predictive planning methods. Iyer and Grossmann [1998] presented MILP formulation for the synthesis and operational planning of the utility plant for multiperiod operation with varying demands. Kim et al. [1999] proposed a new approach for optimal multiperiod utility plant planning. At the upper level, the optimum configuration of the utility plant is determined by dynamic programming, and at the lower level, nonlinear programming (NLP) is solved for each configuration that is decided at the upper level. Yi et al. [2000] implemented optimal multiperiod planning by two-level approach considering the internal energy demands. Strouvalis et al. [2000] proposed the customized solver for the operational planning scheduling of utility systems. Heuristic methods have been developed to minimize the operational cost in utility plants as well [Yoo et al., 1996; Yi et al., 1998].

Many studies for the optimal operation of utility plants have been implemented. However, investigation results focused on only a single execution interval. A utility plant is operated continuously and there exist sequences of many execution intervals. Therefore, the study of single execution interval is not proper for a utility plant. In addition, the above studies considered prediction errors by a predictive way. However, the real world cannot be predicted exactly and entirely [Spalazzi, 1998], and an operational plan must be updated because of uncertainty [Yeung, 1998]. In this paper, the integration methodology of complete replanning and rule-based plan

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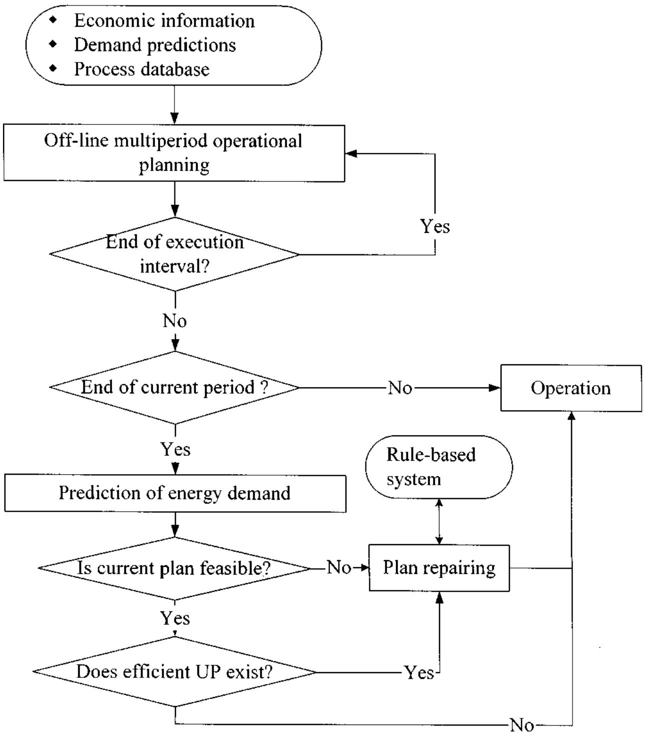

Fig. 1. Plan updating strategy for the handling of prediction errors.

repairing is proposed for a continuously operated utility plant in the presence of prediction errors. Case studies are examined and the results show that the proposed method is more profitable than the conventional method.

INTEGRATION METHODOLOGY

The integration methodology of complete replanning and rule-based plan repairing is shown in Fig. 1. Off-line multiperiod operational planning is implemented by using economic information, demand predictions over the horizon and process database. In multiperiod operational planning, the optimal plan of a utility plant over 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 an operational plan suboptimal for the entire planning horizon. At the end of an execution interval, the operational plan is updated periodically by complete replanning. It is the same as off-line multiperiod operational planning except for shifting planning horizon. If the current period is not the end of an execution interval, it is examined whether or not the current period ends. If the current period ends, energy demand is predicted to examine whether the operational plan determined from off-line multiperiod operational planning is feasible or optimal for the current energy demand. The plan repairing is mainly triggered by two types of events: infeasibility and optimality. If the operational plan is infeasible, the plan must be updated 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 on the energy demand in the current period. This can be easily detected by the existence of an efficient utility pump (UP). If a UP exists that has

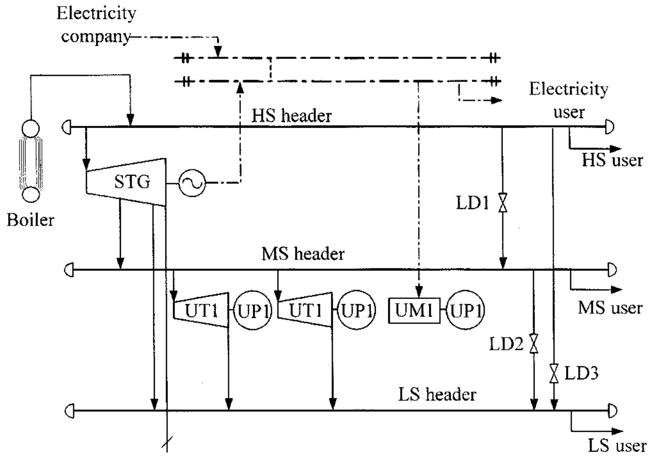

Fig. 2. The process flow diagram of a simple utility plant to explain efficient UP.

positive efficiency index, the plan repairing is triggered; otherwise, a utility plant is operated according to operational plan under the varying energy demands.

For plan repairing, a rule base is used because of real-time limitations. The rule base is constructed to reduce operational cost by changing the operational modes of UPs. Based on the fixed modes that are calculated from the off-line multiperiod operational planning and plan repairing, a utility plant is operated under varying energy demands.

EFFICIENCY INDEX OF UP

If the change of driving force of UP from utility motor (UM) to utility turbine (UT) reduces operating cost, it is defined as the efficient UP and UT as efficient driving force. If the change of driving force of UP from UT to UM reduces operating cost, it is defined as the efficient UP and UM is efficient driving force. As an example, consider the simple utility plant shown in Fig. 2. The utility plant has a boiler, a steam turbine generator (STG) governed by (1), three letdown desuperheaters (LDs) and a kind of UPs.

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

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 UP1s must be operated in normal case. It is also assumed that all UT1s consume 5.0 t/h steam constantly if they are operated, and UM1 consumes 1.5 MW electric power constantly if it is operated. The operating condition is shown in Table 1. As manifested in Table 1, 5.0 t/h of LS is needed. If a UP1 that stood by is turned on and another UP1 driven by UM1 is turned off, then additional 5.0 t/h steam can be supplied to LS header through the UT1 and 5.0 t/h steam is needed in MS header. The MS extraction of STG must increase to 135.0 t/h to maintain the pressure and temperature conditions of MS header. Therefore, the amount of steam consumption must be 198.5 t/h that is calculated by (1) and the steam generation in the boiler must be 318.5 t/h. As the demand of internal electric power decreases by 1.5 MW, the purchase of electric power must be reduced to 15.43

Table 1. The operating condition of a simple utility plant to explain efficient UP

Units	Minimum	Operating condition	Maximum
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
LD1 [t/h]	5.0	20.0	30.0
LD2 [t/h]	3.0	10.0	15.0
LD3 [t/h]	2.0	5.0	10.0
UP1		1T1M	
HS demand [t/h]		95.0	
MS demand [t/h]		135.0	
LS demand [t/h]		65.0	
E purchase [t/h]		16.93	

MW. Therefore, the operational cost is 318.5$C_{HS,gen}$+15.43$C_{E,pur}$.

Without changing the mode of UP, LS can be supplied by LD or STG. However, LS extraction of STG cannot supply enough steam because of the operating limit. Therefore, LD1, LD2 and LD3 must be manipulated. If the flow rates of LD1 and LD2 increase to 25.0 t/h and 15.0 t/h, respectively, the operating cost is 320.0$C_{HS,gen}$+16.93$C_{E,pur}$. Because operating cost calculated by changing the mode of UP is less than the cost calculated without changing the mode of UP, the UP1 is efficient and efficient driving force of UP1 is UT1.

However, if we want to repair the operational plan of a utility plant, we must define the index to determine which UP is more efficient than others. The efficiency index of UP is a quantitative measure that will indicate how much efficient UP is in a given process condition and defined as follows:

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

The original cost is calculated by adjusting the flow rate of continuous equipment without changing the mode of the discontinuous equipment, and the mode change cost is calculated by turning on/off the discontinuous equipment and adjusting the flow rate of the continuous equipment. If the sign of the efficiency index is positive, UP is efficient; otherwise, it is not efficient. As the value of the efficiency index is larger, the UP becomes more efficient. As an example, consider the simple utility plant shown in Fig. 3. The utility plant has a boiler, an STG governed by (1), three LDs and two kinds of UPs. It is assumed that one of the UP1 driven by UT1 and another UP1 driven by UM1 are operated, and the third UP1 driven by UT1 stands by. It is also assumed that UT1 consumes 5.0 t/h steam constantly if it is operated, and UM1 consumes 1.5 MW electric power constantly if it is operated. It is assumed that UP2 driven by UT2 is not operated and UP2 driven by UM2 is operated. UT2 consumes 7.0 t/h constantly if it is operated and UM2 consumes 2.0 MW constantly if it is operated. The operating condition is same as Table 1 except the electricity demand. In Fig. 1, the external electric power demand is 39.0 MW and internal electric power demand is 1.5 MW. However, the external electric power demand is 37.0 MW and internal electric power demand is 3.5 MW in Fig. 2. From the operating condition, it is manifested that 5.0 t/h of LS is needed. If UP1 that stood by is turned on, the operating cost is 318.5$C_{HS,gen}$+15.43$C_{E,pur}$, that is, the mode change cost of UP1. If the UP2 that stood by is turned on, the operating cost is 317.9$C_{HS,gen}$+14.93$C_{E,pur}$, that is, the mode change cost of UP2. The original cost is identical with the example of Fig. 1. Therefore, the efficiency index of UP1 is (1.5$C_{HS,gne}$+1.5$C_{E,pur}$)/(320.0$C_{HS,gen}$+16.93$C_{E,pur}$) and the efficiency index of UP2 is (2.1$C_{HS,gen}$+2.0$C_{E,pur}$)/(320.0$C_{HS,gen}$+16.93$C_{E,pur}$). Because the efficiency index of UP2 is larger than the efficiency index of UP1, turning on UT2 is more economical than UT1 when LS demand increases.

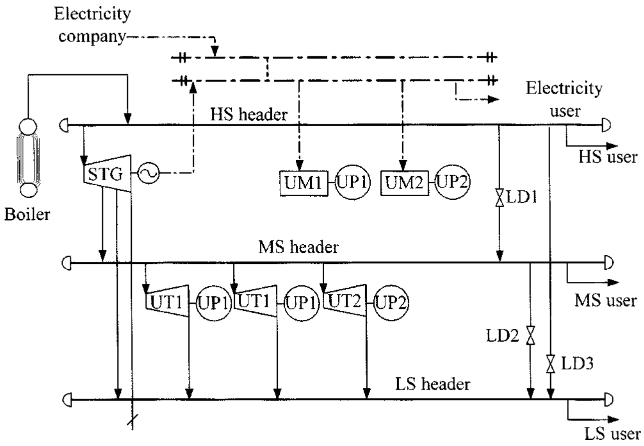

Fig. 3. The process flow diagram of a simple utility plant to explain efficiency index.

CASE STUDIES

1. Process Description

Fig. 4 shows the process flow diagram of an industrial utility plant. The steam generation unit consists of four boilers, high pressure feed water heaters (HPH), steam air heaters (SAH), deaerators, oil heaters, and fuel atomizers. HPH, SAH and fuel atomizers consume MS, and deaerators and oil heaters consume LS supplied. The boilers produce only very high pressure steam (VS) to be fed to a VS header. VS is fed into STG that generates electric power and extracts MS, LS and SC. The numbers of operating UPs must be fixed to supply utilities to the process and utility plant. Table 2 shows the numbers of installed UPs, the amounts of steam and electric power consumption to drive them. For example, the number of UP5s is six; four of them are driven by UT5s and the others are driven by UM5s. UT5s consume 50.26 t/h of steam and UM5s consume 1770.0 kW of electric power constantly if they are operated. The steam headers are four different kinds 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 STG cannot generate enough electric power to be used in the process and utility plant.

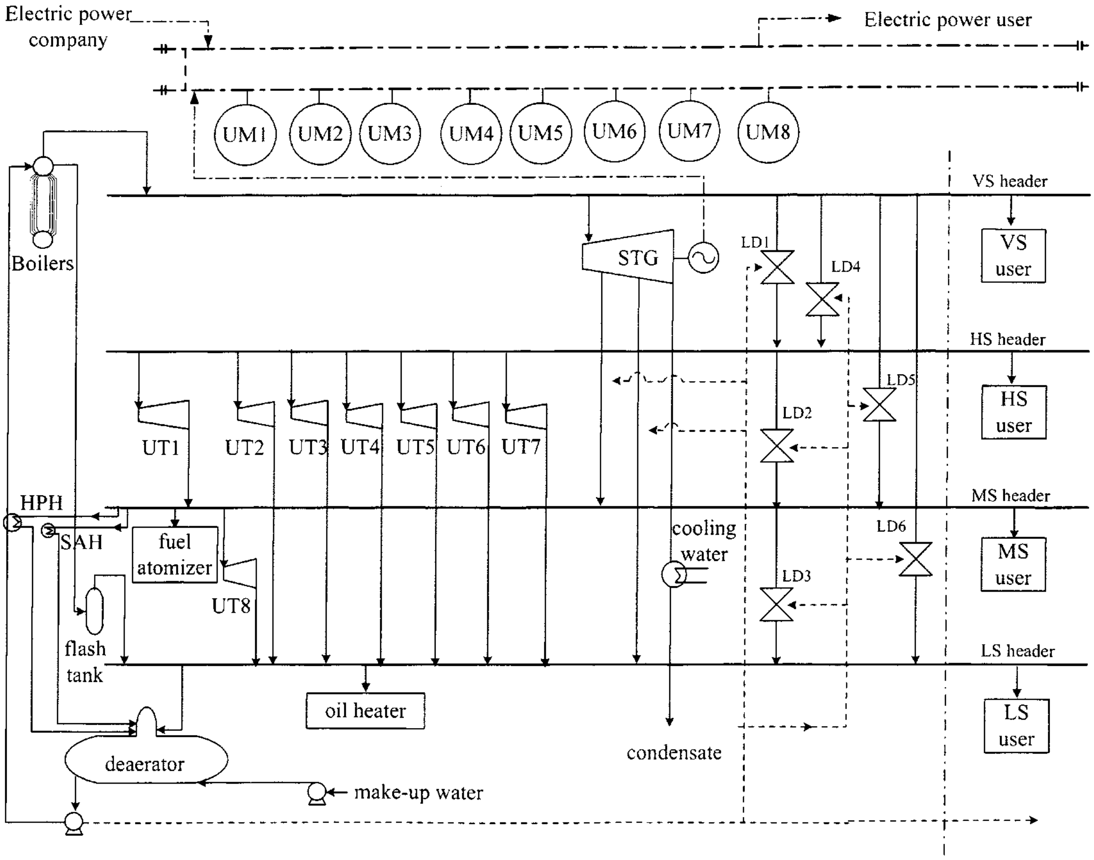

Fig. 4. The process flow diagram of an industrial utility plant.

Table 2. 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	50.26	1770.0
UT2, UM2	1T2M	2.13	90.0
UT3, UM3	1T1M	7.59	220.0
UT4, UM4	4T4M	8.12	560.0
UT5, UM5	4T2M	17.29	1250.0
UT6, UM6	4T4M	4.60	250.0
UT7, UM7	2T2M	9.61	540.0
UT8, UM8	2T1M	2.34	45.0

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, minimum steam generation and electric power purchase are calculated by MINLP. At the lower level, minimum fuel consumption rate is calculated by NLP.

2-1. The Upper Level Planning Problem

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 cost is constituted by the steam generation cost, spray water cost and purchased electric power cost. The optimization problem can be defined as:

Minimize

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

Subject to

$$\sum_{i\in CU}F_{i,in,t}+\sum_{i\in DU}y_{i,t}F_{i,in,t}-\sum_{i\in CU}F_{i,out,t}-\sum_{i\in DU}y_{i,t}F_{i,out,t}=0 \quad (4)$$

$$\sum_{i\in CU}F_{i,in,t}H_{i,in,t}+\sum_{i\in DU}y_{i,t}F_{i,in,t}H_{i,in,t}-\sum_{i\in CU}F_{i,out,t}H_{i,out,t}$$
$$-\sum_{i\in DU}y_{i,t}F_{i,out,t}H_{i,out,t}=0 \quad (5)$$

$$F_{STG,VS,con,t}=p_tF_{STG,MS,ext,t}+q_tF_{STG,LS,ext,t}+r_tE_{STG,gen,t}+s_t \quad (6)$$

$$\sum_{i\in P_k}y_{i,k,t}=N_{k,t} \text{ (k: all kinds of pumps)} \quad (7)$$

$$E_{STG,gen,t}+E_{pur,t}\geq E_{dmd,t}+\sum_{i\in M}y_{i,t}E_{i,con,t} \quad (8)$$

$$F_{i,spp,t}\geq F_{i,dmd,t} \text{ (i: all steam grades)} \quad (9)$$

$$z_{t,t+1}\geq y_t-y_{t+1} \quad (10a)$$

$$z_{t,t+1}\geq y_{t+1}-y_t \quad (10b)$$

$$z_{t,t+1}\leq 2-y_t-y_{t+1} \quad (10c)$$

$$z_{t,t+1}\leq y_t+y_{t+1} \quad (10d)$$

Eqs. (4) and (5) are mass and energy balance equations in the utility plant. The set **CU** represents the continuously operated unit. The set **DU** represents the discontinuously operated unit such as UTs, UMs. Therefore, integer variable y is used to represent on/off status of the units that belong to **DU**. Eq. (6) gives the relation among power generation, steam consumption, and steam extraction of STG. Details on the coefficient used in (6) can be found elsewhere [Lee et al., 1998]. The utility plant considered in the present study has eight different kinds of UPs that are driven by UMs and UTs. The numbers of each kind of operated UPs have criteria for the normal operation of the utility plant. The set $\mathbf{P}_k$ represents the k-th kind of UPs and each set of $\mathbf{P}_k$ must satisfy the criteria N_k in (7). Eqs. (8) and (9) represent the demand satisfactions of electric power and steam, respectively. Eqs. (10a)-(10d) are the relations between on/off status variables and switch variables and are well defined by Papalexandri et al. [1998].

2-2. The Lower Level Planning Problem

In the lower level planning, we have allocated the boiler load according to efficiencies to minimize the total cost. The total cost is composed of the fuel cost and boiler transition cost. The total amounts of generated VS in four boilers are determined from the solution of the upper level problem. The multiperiod planning problem can be formulated as:

Minimize

$$f=\sum_{t\in \mathbf{T}}\sum_{i\in \mathbf{Blr}}[C_{i,fuel,t}F_{i,fuel,t}+C_{tran,t}|F_{i,VS,gen,t}-F_{i,VS,gen,t+1}|] \qquad (11)$$

Subject to

$$F_{i,BFW,t}=F_{i,CBD,t}+F_{i,VS,gen,t} \qquad (12)$$

$$F_{i,fuel,t}=\frac{1}{LHV_t}\frac{F_{i,CBD,t}H_{i,CBD,t}+F_{i,VS,t}H_{i,VS,gen,t}-F_{i,BFW,t}H_{i,BFW,t}}{\eta_{i,t}} \qquad (13)$$

$$\eta_{i,t}=a_{i,t}F^2_{i,VS,gen,t}+b_{i,t}F_{i,VS,gen,t}+c_{i,t} \qquad (14)$$

$$\sum_{i\in \mathbf{Blr}}F_{i,VS,gen,t}\geq F_{VS,gen,t} \qquad (15)$$

The subscript i represents the i-th boiler. Eq. (12) is the mass balance around the boiler, and (13) can be obtained from energy balance considering thermal efficiency of the boiler. The boiler efficiency of the i-th boiler can be expressed as (14). We have obtained the coefficients for the boiler efficiency equation from the regression based on operational data [Lee et al., 1998]. Total VS demand obtained from the upper level problem must be supplied from the boilers, as represented in (15).

3. The Rule Base for Plan Repairing

There exist many types of prediction errors affecting optimal operation of utility plants. Sources of prediction errors can be classified into energy demand and equipment performance. The prediction errors of energy demand can be further split into timing and quantity. The timing error of energy demand refers to the shift in required amount from a period to another. The quantity error of energy demand refers to inaccurate prediction. The prediction errors of equipment performance result from the deterioration or scaling of process equipment. Timing errors can be recovered by moving, swapping and deleting the plan. Planning errors concerned with prediction quantity and equipment performance require complex repairing strategies considering the efficiency indices of UPs.

Figs. 5(a) and 5(b) show the rule-based hierarchies for selecting repairing strategy. Fig. 5(a) is the hierarchy to determine simple repairing strategy such as deleting, moving and swapping. A deleting plan can be used when energy demand prediction of some periods does not occur due to production cancellation. A moving plan (i.e., introducing a delay to the unit configurations and operating conditions) is employed when energy requirements are delayed in a simple manner. A swapping plan can be employed when the energy demands are exchanged. These methods are easily applicable if the production plans are cancelled, delayed and exchanged. If prediction errors mentioned above do not happen, complex repairing strategies are triggered.

Fig. 5(b) shows the rule-based hierarchies to implement complex repairing. The complex repairing of multiperiod operational plan is always accomplished from LS header to VS header. It is composed of the handling of UT, UM, STG, LD and boilers. The heuristics for the repairing at each header can be summarized as follows:

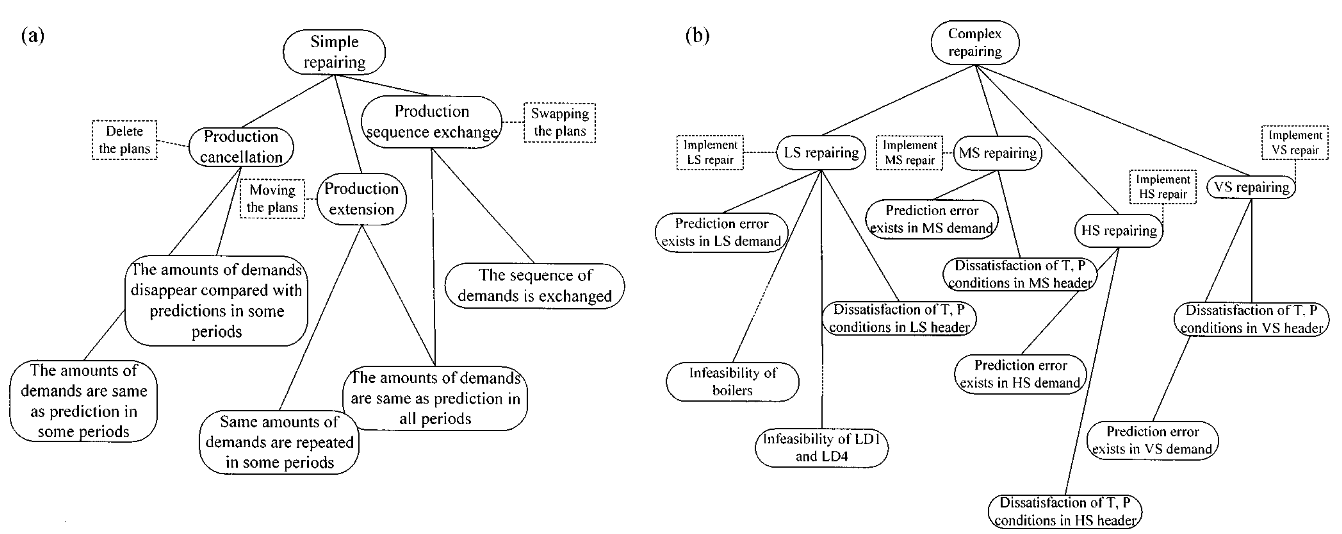

Fig. 5. (a) Rule-based hierarchy to select simple repairing strategy. (b) Rule-based hierarchy to select complex repairing strategy.

LS header:
1st. Mode changes of UP2-UP8
2nd. LS extraction of STG
3rd. LD from MS header to LS header
4th. LD from VS header to LS header

MS header:
1st. Mode change of UP1
2nd. MS extraction of STG
3rd. LD from HS header to MS header
4th. LD from VS header to MS header

HS header:
1st. LD from VS header to HS header
2nd. Mode changes of UP1-UP7

VS header:
1st. Boiler load allocation
2nd. The change of driving forces of UP1-UP8

If prediction error concerned with LS exists, the operational plan must be repaired because the current plan may be infeasible or a more optimal plan may exist under the current conditions. To repair the operational plan of the LS header, the efficiency indices and efficient driving forces from UP2 to UP8 are calculated and the configurational modes of UPs are changed. Generally, the handling of UPs does not satisfy the temperature and pressure conditions of a 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 pressure conditions of the header. If prediction errors do not exist or rules succeed in repairing of LS header, the repairing of MS header is implemented.

The complex repairing of the MS header has the same structure as that of the LS header. If prediction error exists, HS header repairing is implemented; otherwise, the rule-based system searches the repairing strategies of the HS header. To repair the operational plan of the 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 the MS header because the steam consumption of UT1 is constant.

If prediction error concerned with HS exists, 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 configurational modes from UP1 to UP7 are changed for LD1 and LD4 to be feasible. After the repairing of the UPs, the repairing of the LS header must be implemented all over again because the mode changes of UPs make steam supply to MS and LS headers change.

The repairing rule base of the VS header is usually implemented by the load allocation of boilers and mode changes of UPs. The load allocation is implemented by NLP. The problem formulation is the same as the lower-level planning formulation except time horizon. In the repairing stage, time horizon is reduced from the present time. In an extreme case, total requirement of 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 total requirement of VS and increase electric power consumption, which can be accomplished by changing the driving forces of UPs as UMs.

Table 3. The demand prediction of steam and electric power

Period	1	2	3	4	5	6	7
VS [t/h]	150.0	175.0	160.0	140.0	155.0	165.0	166.0
HS [t/h]	−112.0	−138.0	−125.0	−139.0	−122.0	−134.0	−119.0
MS [t/h]	204.0	166.0	214.0	179.0	220.0	169.0	210.0
LS [t/h]	88.0	40.0	96.0	36.0	95.0	41.0	89.0
E [MW]	30.0	34.0	31.0	38.0	36.0	32.0	34.0

Table 4. The optimal plan of UPs

	1	2	3	4	5	6	7
UP1	3T1M	2T2M	3T1M	2T2M	3T1M	2T2M	3T1M
UP2	2M	2M	2M	2M	2M	2M	2M
UP3	1M	1M	1M	1M	1M	1M	1M
UP4	4M	4M	1T3M	4M	2T2M	4M	4M
UP5	3T1M	2T2M	3T1M	2T2M	3T1M	2T2M	3T1M
UP6	4M	4M	4M	4M	4M	4M	4M
UP7	2M	2M	2M	2M	2M	2M	2M
UP8	1M	1M	1M	1M	1M	1M	1M

RESULTS AND DISCUSSION

The results of the proposed method are compared with the results of conventional multiperiod planning. Table 3 shows the demand predictions of steam and electric power for a planning horizon of seven periods. The signs of HS demands are negative, which means that HS supply from process plants is larger than HS demand. The multiperiod operational plan is calculated by the decomposition method. Table 4 shows the optimal plan of UPs by the upper-level multiperiod planning considering switch cost. Fig. 6 shows the results of the optimal boiler load profiles by the lower-level multiperiod planning considering the transition cost of boilers. Based on the results of the multiperiod operational plan, a utility plant is operated under the varying energy demands.

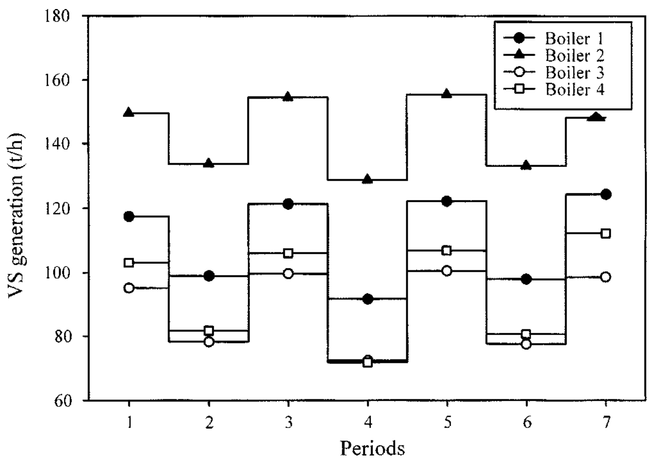

Fig. 6. The results of boiler load allocations.

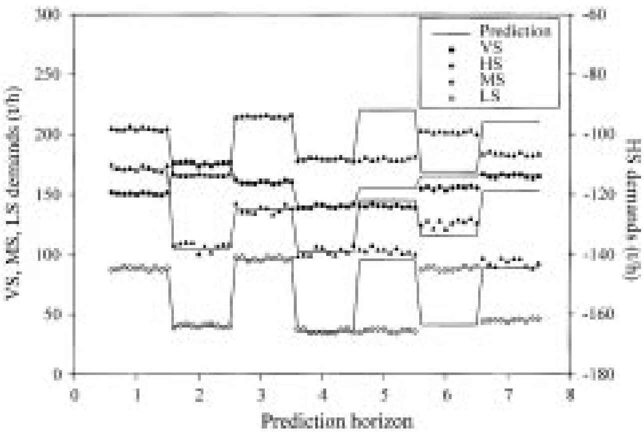

Fig. 7. The predictions and measured values of steam demands to represent timing errors.

Fig. 7 shows the predictions and the measurements of steam demands, which have timing errors. Dotted graphs represent the measured steam demands and solid graphs represent the predicted steam demands along the prediction horizon. The prediction error of electric power demand does not exist. The measured values of steam demands in the fourth period are delayed until the fifth period. In the initiation of the fifth period, the operating conditions and configurations must be replaced with the plan of the fifth period. However, replacing the operational conditions and configurations with the plan of the fifth period causes infeasible or suboptimal. These problems can be solved by moving the plan of the fourth period to the fifth period. Fig. 8 compares the results of the proposed method with the conventional method. The plan of the fourth period is delayed by the rule-based repairing system. However, the conventional method has only a periodical replanning system, and a utility plant is operated with the plan of the fifth period that is calculated from the multiperiod operational planning. Fig. 8 shows that the operational costs by the proposed method are less than the costs by the conventional method. The operational costs is reduced by 1.0-9.0%.

Fig. 9 shows the predictions and measurements of steam demands, which have quantity errors. Quantity errors of energy demands are more general to occur and difficult to recover than the timing errors of energy demands. Dotted graphs represent the measured steam demands and solid graphs represent the predicted steam demands. The prediction error of electric power demand does not exist. Fig. 9 shows the discrepancies between measurements and predictions from the fifth period to the seventh period. The plan from the fifth period to the seventh period must be modified for optimal operation. Table 5 shows the results of complex repairing from the fifth period to the seventh period. In the fifth period, the configuration of UP5 is updated from 3T1M to 2T2M, and the configuration of UP4 is not revised because the efficiency index of UP5 is larger than the value of UP4. The efficiency indices of the remaining UPs are not calculated because all of them are driven by Ums, and LS demand is reduced when compared with prediction. UP1 is not used to repair the plan because the efficiency index of UP1 has a negative sign. In the sixth period, any repairing operation is not implemented because the plan is feasible although discrepancies exist between the predictions and measurements. In the seventh period, the efficiency index of UP4 is not calculated because all of the UP4s are driven by UMs and LS demand is reduced when compared with the prediction. The configuration of UP5 is updated from 3T1M to 2T2M because the efficiency index of UP5 has a positive value. The change of driving force of UP1 in the seventh period is infeasible operation; therefore, the configuration of UP1 in the seventh period is not revised.

Fig. 10 compares the results of the proposed method with those of the conventional method. From the first period to the fourth period, the operational costs are identical because prediction errors do not exist and the plan repairing is not required. In the fifth period and the seventh period, the proposed method is more economical than the conventional method because prediction errors exist and

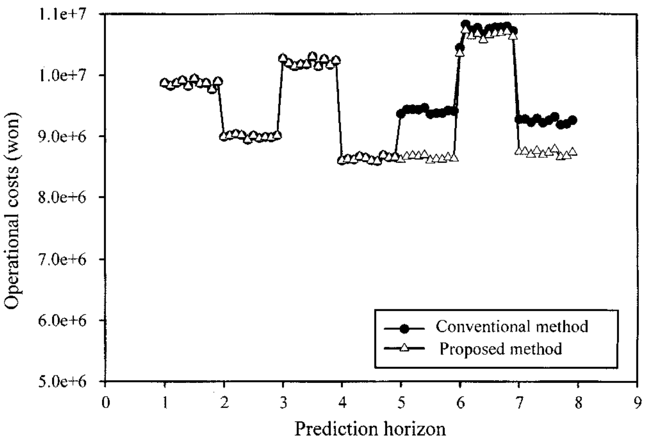

Fig. 8. The comparison of the proposed method with the conventional method in timing errors.

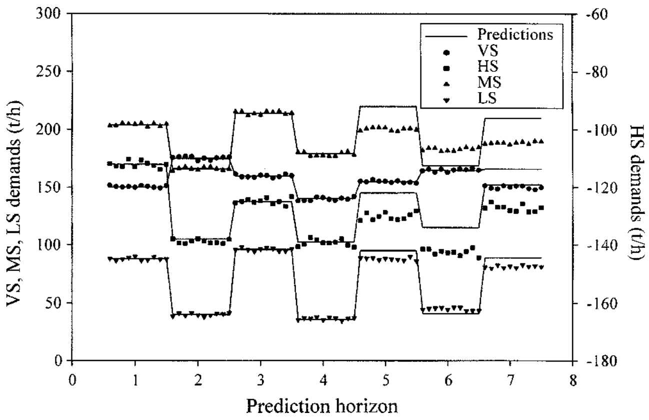

Fig. 9. The predictions and measured values of steam demands to represent quantity errors.

Table 5. The results of plan repairing and efficiency indices

	UP1		UP4		UP5	
	Driving forces	Efficiency index	Driving forces	Efficiency index	Driving forces	Efficiency index
5	3T1M	-1.06×10^{-1}	2T2M	6.65×10^{-3}	2T2M	9.56×10^{-3}
6			Feasible plan			
7	3T1M	Infeasible	Not calculated		2T2M	1.27×10^{-3}

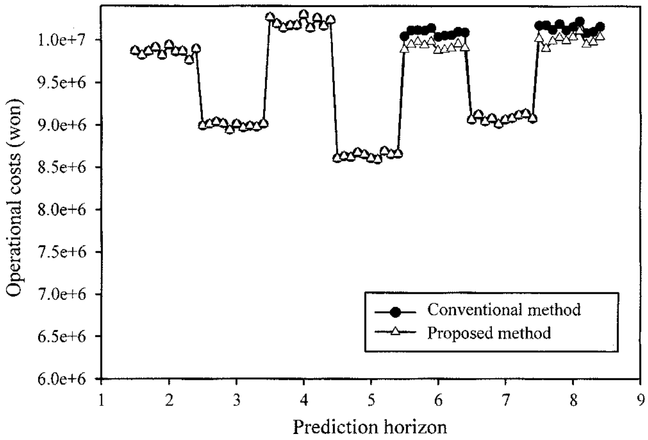

Fig. 10. The comparison of the proposed method with the conventional method in quantity errors.

the plan is updated by the repairing scheme. However, the operational costs of the proposed method and the conventional method have little difference in the sixth period. In the sixth period, the plan is not repaired because the operational plan is feasible although prediction errors exist. The operational cost saving is about 0.6-2.0% compared with the conventional method when quantity prediction errors exist.

CONCLUSIONS

The integration methodology of complete replanning and plan repairing is proposed to handle the prediction errors for energy demands during multiperiod operational planning in utility plants. Periodical complete replanning and rule-based repairing is very important because the future cannot be predicted entirely and exactly. The proposed method is more profitable than the conventional method when timing and quantity prediction errors exist. The operational cost was reduced by 1.0-9.0% under the timing errors in energy prediction and 0.6-2.0% under the quantity errors energy prediction compared with the conventional method.

ACKNOWLEDGMENTS

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NOMENCLATURE

Blr : the set of boilers
C : cost [won]
CU : the set of continuously operated units
DU : the set of discontinuously operated units
E : electric power [MW]
F : flow rate [t/h]
f : objective function
LHV : low heating value [kcal/kg]
M : the set of electric motors
N : the number of operating pump
$\mathbf{P}_k$: the set of k-th kind of pumps
T : the set of prediction horizons
y : binary variable
z : switch variable

Greek Letter

η : efficiency

Subscripts

BFW : boiler feed water
CBD : continuous blowdown
con : consumption
dmd : demand
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
spp : supply
STG : steam turbine generator
SW : spray water
swt : switch
t : time period
VS : very high pressure steam

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