A novel MILP model for plantwide multiperiod optimization of byproduct gas supply system in the iron- and steel-making process is proposed. Compared with the previous optimization model, proposed approach simultaneously optimizes the byproduct gas holder levels and gas distribution among conflicting objectives. Both integer and continuous variables are used in determining the optimal fuel load change according to the fuel types. Objectives include the minimization of the unfavorable byproduct gas emission or shortage, oil consumption, the number of turn on/off of the burner, maintaining the normal holder levels, and maximizing fuel usage efficiency. Case study results show that the proposed model finds the optimal solution in terms of total cost reduction and the different optimization model structure makes the solution more applicable than the previous approach.

Keywords: plantwide; multi-period optimization; MILP; discrete fuel load change; holder level control; iron and steel making process.

INTRODUCTION

An iron- and steel-making process is one of the most energy-intensive processes, whose energy cost constitutes about 20% of the total operation cost. Thus, efficient use of energy is very important to reduce the total operation cost. Unlike other energy sources used in the iron- and steel-making process such as oil, electricity and liquefied natural gas, byproduct gases are continuously generated during the production of iron and steel without additional cost, and cannot be stored for a long time. Therefore, the efficient management of byproduct gases plays a central role in the energy cost reduction in the iron- and steel-making process.

Imbalances between the amount of the generation and consumption exist over a short timescale because the production and consumption of the byproduct gases are irregular. Byproduct gasholders exist to solve the temporal imbalances. However, because of the limit on holder capacity, temporary excesses or shortages of byproduct gas occur. As shown in Figure 1, the excess or shortage of byproduct gases can be adjusted by changing the supply of byproduct gases from gasholders to power plant, where byproduct gases are used to generate process steam and electricity. In the power plant, each boiler has different efficiencies. Therefore, the optimal operation that prevents the loss of byproduct gases and efficient distribution of byproduct gases is an indispensable issue in the process.

Although much research has been done on the optimization of iron- and steel-making processes, it has mainly been on scheduling and production planning problems, and few research works have been reported on the optimization of the byproduct gas supply and distribution. Akimoto et al. (1991) proposed a MILP (mixed integer linear programming) approach, where the holder level control and the optimal distribution of byproduct gases are considered. The optimization model reflects process constraints by assigning appropriate penalty functions for the situation that is not preferred, such as excess or shortage of byproduct gases, oil usage, fluctuation of gas amount in the holder, simultaneous changeover of fuels etc. Fukuda et al. (1986) proposed an optimal energy distribution control method for the steel works by energy demand forecasting and optimization. An ARMAX (autoregressive moving average with exogenous variable) model was used for forecasting and a gradient descent method was used for optimization. Bemporad and Morari 1999 proposed a framework for modeling and controlling the mixed logical dynamical systems, and applied it to the gas supply system at steel works. Sinha et al. (1995) used MILP to optimally allocate the resource for profit maximization, and a significant amount of benefit was reported by applying it to Tata Steel.

Consideration of the startup and shutdown costs in the optimization formulation was introduced into the optimization modeling. Hui and Natori (1996) presented a mixed integer programming model for industrial utility system that includes startup and shutdown costs to find optimum solutions by introducing equipment startup and shutdown costs. Iyer and Grossmann (1997, 1998)
Figure 1. (a) The flow network for BFG, CFG and LDG in the iron- and steel-manufacturing plant. (b) The flow network for COG and mixed gas in the iron- and steel-manufacturing plant.
proposed the bilevel decomposition method to solve the multiperiod optimization problem for utility plant and considered the switching cost between periods. Kim and Han (2002) proposed a heuristics combined dynamic programming approach to solve the multiperiod planning problem for utility plant. Yi et al. (2000) also used this concept in a planning problem. Singh et al. (2000) proposed time horizon-based real-time optimization (RTO) approach for the gasoline blending process, which is similar to model predictive control (MPC). A Blending horizon and a stochastic model of disturbances were incorporated into the optimization model.

In this paper, a novel MILP model for plantwide multiperiod optimization is proposed for the simultaneous optimization of byproduct gas holder level control and byproduct gas distribution. The proposed approach simultaneously optimizes the byproduct gas holder levels and gas distribution by finding the optimal tradeoff among conflicting objectives. Both integer variables and continuous variables are used in determining the optimal fuel load change according to the fuel types. Objectives include the minimization of the unfavorable byproduct gas emission or shortage, oil consumption, the number of on/off turns of the burner, maintaining the normal holder levels, and maximizing fuel usage efficiency. A case study was performed to verify the usefulness of the proposed approach.

This article is organized as follows. The networks for byproduct gas supplies and optimal management of byproduct gases are presented first. In the next section, the previous researches about the optimal management for byproduct gas systems are reviewed. The formulation for optimal byproduct gas management is described in the following section using MILP. Then the results by the proposed method are discussed, and the performances are compared with those by the previous method. Finally, a concluding remark is presented to show the effectiveness of the proposed method for byproduct gas management.

BYPRODUCT GAS SUPPLY SYSTEM AND PROBLEM SCOPE

Figure 1(a) and (b) shows the networks for byproduct gas supplies in the iron- and steel-making process for this study. There are four kinds of byproduct gases in iron- and steel-making plants: blast furnace gas (BFG); COREX furnace gas (CFG); coke oven gas (COG); and Linze–Donawitz gas (LDG). BFG and CFG are byproducts from the operations of a blast furnace and a COREX furnace during the production of pig iron, respectively. COG is a byproduct from the operation of a coke oven during the production of coke and LDG is a byproduct from the operation of a basic oxygen furnace during the production of steel. In Figure 1(a), the solid line shows BFG flow, the dotted line CFG flow and the dash-dotted line LDG flow. BFG is byproduced in five blast furnaces and consumed in coke plants and power plants. The remaining BFG is pressurized and then mixed with COG and LDG in the first and second mixers. CFG is byproduced in a COREX furnace, and is consumed in the fifth and sixth power plants. The remaining amount of COG is mixed with BFG directly. LDG is byproduced in basic oxygen furnaces at steel-making plants. LDG generated in the first steel-making plant is consumed in the first and second power plants. However, LDG generated in the second steel-making plant is pressurized, then consumed in a low-pressure boiler and power plants, and mixed with BFG and COG in the mixers. Figure 1(a) shows the schematic diagram of COG and the mixed gas flows. Solid lines represent the flow network for COG, and dotted lines represent the flow network for the mixed gas of BFG, COG, LDG and CFG. COG is byproduced in four coke plants, and consumed in blast furnaces, power plants, chemical plants, steel-making plants, etc. The remaining COG is pressurized and mixed with BFG and LDG. The mixed gas is consumed in the plate rolling mills, wire rod rolling mills, hot strip mills, etc.

The patterns of the generation and consumption of each byproduct gas are different from each other. Some of byproduct gases are generated irregularly, and others with a constant generation pattern. Because of the combination of the limited capacity of byproduct gas holders and irregular generation of byproduct gases, excess or shortage of byproduct gases at the holder can happen, which results in an economic loss. Larger byproduct gas supply than the demand makes the gas holder exceed its capacity, and then byproduct gas must be emitted to the environment. These imbalances are compensated for by moving byproduct gases from each gas holder to the power plant. Byproduct gases are used as fuel to generate steam that is used for process steam and generating electricity. The consumption of byproduct gases at the steel-making plant is according to the steel production schedule, and there is little flexibility for changing the amount of byproduct gas consumption. The changes in byproduct gas consumption in boilers charges the amount of steam generation in boilers, which means fuel load changes. When the byproduct gases are insufficient to supply for generation the required amount of electricity, oil can be used for production of electricity, but it is not preferable because additional fuel cost is incurred. Each boiler in the power plant has different characteristics such as capacities, efficiencies and available fuel types. For the optimal management of byproduct gases following conditions are required:

1. The holder level of each byproduct gas should be maintained within the operation range to avoid unfavorable byproduct gas emission and holder booster trip;
2. Minimum number of startup/shutdown of burners in the boiler;
3. Minimum amount of oil consumption;
4. Minimum deviation from the normal holder operation level;
5. Maximization of electricity production by the distribution of byproduct gases.

PREVIOUS RESEARCH ON BYPRODUCT GAS MANAGEMENT

Little researches has been done on the optimal management of byproduct gases in iron- and steel-making plants. Byproduct gases are generated during the process of iron ore and consumed as energy sources in downstream processes and power plants. Discrepancies between the amounts of generation and consumption of byproduct...
gases result in fluctuating holder levels and the demand for steam and electricity at the power plant is changing due to the process demand. Therefore, optimal management of byproduct gases in iron- and steel-making plants has to be determined by considering two aspects: one is to maintain the holder level at an appropriate level and the other is to distribute the byproduct gases in an optimal way so that the total cost for holder part and power plant part might be minimized. Previous research on the optimal management of byproduct gases in an iron- and steel-making plants had focused on only one aspect of gas holder level control and byproduct gas distribution to boilers. Akimoto et al. (1991) used MILP to control the level of gas holders and determine the total flow rates of byproduct gases to boilers. Only the holder parts were considered in determining the optimal solution, but the solution should be found by including both the holder part and power plant part as a whole to minimize the total cost. They did not consider the efficiencies of boilers so that only total flow rates of byproduct gases to boilers were determined. Binary variables were applied to represent the on/off status of boilers that consume C gas only. However, industrial boilers in an iron- and steel-making plants consumes four kinds of byproduct gases in general, and binary variables must be used to represent the on/off status of boilers that consume all kinds of product gases. Furthermore, industrial boilers in iron- and steel-making plants have many burners in a boiler, and binary variables must be used to represent the on/off status of burners in boilers. Formulation of binary variables to denote the on/off status of burners makes the operation of gas holder smooth, but the results cannot be implemented in industrial boilers because the load of an industrial boiler cannot be changed continuously. The load of an industrial boiler is changed discontinuously at the amount of burner capacities in a boiler.

For the optimal management of byproduct gases for an industrial iron- and steel-making plants, the level of gasholder for byproduct gases must be maintained around the normal operating conditions and byproduct gases must be distributed to each boiler considering efficiencies of boilers. Boilers are operated as burner levels and each burner is operated discontinuously. For the optimal distribution of byproduct gases to each boiler, not only the flow rates of byproduct gases but also the on/off status of burners in boilers must be determined.

MATHEMATICAL FORMULATION FOR OPTIMAL BYPRODUCT GAS MANAGEMENT

Optimal management of byproduct gas networks in an iron- and steel-making plant has two objectives. The first objective is to maximize the benefit from the production of electric power in power plant with minimum purchase for oil consumption. The second objective is to minimize the fluctuation of the gasholder levels from normal operating condition to prevent byproduct gas emission due to excess supplies and mechanical trouble of gasholders due to excess demands. Much research for byproduct gas management has used binary variables to represent the on/off status of boilers. However, binary variables must be used to represent the on/off status of burners in an industrial boiler. Penalty terms are used in objective functions to minimize the fluctuation of the gasholder levels from normal operating condition. The weights of penalties are imposed using the piece-wide linear curves.

Objective Function

Total cost for objective function is composed of oil consumption cost, penalty costs and power generation benefit. Penalty costs consists of byproduct gas emission penalty, high/low operation penalty of gasholders, holder level deviation penalty, boiler on/off penalty and burner on/off penalty in the same boiler.

\[
\text{Min} \sum_{i=1}^{P} \sum_{t=1}^{T} \left( C_{\text{Oil}} f_{i,t}^{\text{Oil}} + \sum_{G} W_{\text{HH}} G_{i,t}^{\text{HG}} + \sum_{G} W_{\text{L}} G_{i,t}^{\text{LG}} + \sum_{G} W_{\text{SW}} G_{i,t}^{\text{S}} \Delta h_{i,t}^{G} + \sum_{G} \sum_{i=1}^{N} \sum_{t=1}^{T} \left[ W^S (ibn_{i,t}^{G} + ibf_{i,t}^{G}) \right] + W^S (ibn_{i,t}^{G} + ibf_{i,t}^{G}) \right) - \sum_{i=1}^{P} \left( \text{elect} (p_{G_{\text{gen},i}} - PD_{i}) \right) \]

The objective is to minimize fuel cost, penalty costs and the purchased power cost during the planning horizon \(P\). The first term in the objective function represents oil consumption cost for all boilers during planning horizon \(P\). Gasholder levels must be maintained at the normal operating condition, \(GH_{i,t}^{G}\), shown in Figure 2. Deviation from the normal operating condition is not preferable in the industrial iron- and steel-making plant to prevent byproduct gas emission and mechanical trouble. Therefore, the penalty cost must be imposed to the objective function for stable operation of gasholders. The second term is penalty cost for byproduct emission when the level of a gasholder exceeds the holder capacity, \(GH_{i,t}^{G}\). The third term is penalty cost when holder levels are larger than high bound, \(GH_{i,t}^{G}\) and the fourth term is penalty cost when holder levels are smaller than low bound, \(GH_{i,t}^{G}\). The fifth term is penalty cost when holder levels are fluctuated above the normal operation condition, \(GH_{i,t}^{G}\), and the sixth term is penalty cost when holder levels are fluctuated below normal operation condition, \(GH_{i,t}^{G}\). The fifth term is penalty cost when holder levels are larger than high bound, \(GH_{i,t}^{G}\) and the fourth term is penalty cost when holder levels are smaller than low bound, \(GH_{i,t}^{G}\). The fifth term is penalty cost when holder levels are fluctuated above the normal operation condition, \(GH_{i,t}^{G}\), and the sixth term is penalty cost when holder levels are fluctuated below normal operation condition, \(GH_{i,t}^{G}\). The seventh term represents the penalty cost when boilers are started up or shut down. The eighth term in the objective function is the penalty cost when more than two burners in the same boiler are started up or shut down. The last term is the benefit from electricity generation in power plants.

Optimization variables are the number of byproduct gas burners used at each time at each boiler \(n^{G}_{i,t}\), and supplied oil flow rate \(f_{i,t}^{\text{Oil}}\) during the planning horizon \(P\). Unlike the
previous research works (Akimoto et al., 1991; Bemporad and Morari, 1999; Sinha et al., 1995), both integer variables and continuous variables are used as optimization variables. Figure 4 shows the schematic diagram of the combined burner system at the boiler in the power plant and its relationship with the optimization variable. At each boiler, multiple burners exist to introduce several types of byproduct gases and oils. Because a relatively large amount of byproduct gas change is required to adjust the holder level, and frequent fuel load change is not ideal for the stable operation of the boiler, fuel load change for the byproduct gases is made by burner level, not continuously. Therefore, integer variables are used to determine the optimum number of byproduct gas burners to be used at each boiler. For the oil flow rates, it changes in a continuous way because oil is used to supplement the insufficient heat energy, and continuous variables are used to represent the fuel load change of oil.

**Constraints**

**Material balances for holders and boilers**

\[ h_i^G = h_{i-1}^G + \left( F_{\text{pred,gen}}^G - F_{\text{pred,con}}^G - \sum_{i}^{NB} \Delta f_{ij}^G \right) \times \Delta t \quad \text{for } \forall G, t \]  

(2)

\[ \Delta f_{ij}^G = U_j^G(N_j^G - N_{j-1}^G) \Delta t \quad \text{for } \forall G, i, t \]  

(3)

\[ f_{ij}^{\text{sum}} = f_{ij}^{\text{gen}} + f_{ij}^{\text{con}} \quad \text{for } \forall i, t \]  

(4)

where \( \Delta f_{ij}^G \) is load change of byproduct gas \( G \) in \( i \)th boiler from time \( t - 1 \) to time \( t \). The amount of gas in each holder at time \( t \), \( h_i^G \), is equal to the amount of byproduct gases at time \( t - 1 \), \( h_{i-1}^G \), and the difference between the generation and the consumption of byproduct gases at the steel-making plant minus the sum of byproduct gas load change at the \( i \)th boiler, \( \Delta f_{ij}^G \). The mass balance equations are calculated from the initial time of

![Figure 2. Risk-averse region-based holder operation penalty.](image)

![Figure 3. Penalty functions for the gas amount deviation.](image)
planning to the final time of planning. The load change of byproduct gas is made in a discrete way, which is the amount of the byproduct gas load change at the \( t \)th boiler \( \omega_{i,t} \), as given in equation (3). Full load burner usage is assumed when byproduct gas fuel load change is made, which is normal in real operation. The amount of steam produced is equal to the sum of the amount of process steam and inlet to the turbine [equation (4)].

\[
\sum_{G} f_{i,t}^{G} C_{G}^{G} + f_{i,t}^{\text{coal}} C_{\text{coal}}^{G} = \frac{H_{\text{steam}}^{i,t} - H_{\text{water}}^{i,t}}{\eta_{i,t}^{G}} \quad \text{for } \forall i, t \tag{5}
\]

The sum of energy supplied to each boiler multiplied by the efficiencies of each boiler is equal to the total enthalpy change from water to steam in all boilers. The electricity generation at each turbine for each period should satisfy the demands for process steam and electricity for all periods.

\[
f_{i,t}^{\text{coal},j} = f_{i,t}^{\text{coal}} H_{t}^{i,t} \eta_{i,t}^{G} \quad \text{for } \forall i, t \tag{6}
\]

Energy balances for boilers and turbines

\[
\sum_{G} f_{i,t}^{G} C_{G}^{G} + f_{i,t}^{\text{coal}} C_{\text{coal}}^{G} = \frac{H_{\text{steam}}^{i,t} - H_{\text{water}}^{i,t}}{\eta_{i,t}^{G}} \quad \text{for } \forall i, t
\]

Boilers and turbines have their own operation ranges for stable operation, and the optimization should be made to satisfy these operation constraints.

\[
G_{\text{H}_{\text{L},t}} \leq \frac{h_{i,t}^{G} - s_{i,t}^{G} - s_{i,t}^{G} - s_{i,t}^{G}}{G_{\text{H},t} - s_{i,t}^{G}} \leq G_{\text{H}_{\text{H},t}} \quad \text{for } \forall G, t \tag{11}
\]

\[
G_{\text{H}_{\text{L},t}} \leq \frac{h_{i,t}^{G} - s_{i,t}^{G} - s_{i,t}^{G}}{G_{\text{H},t} - s_{i,t}^{G}} \leq G_{\text{H}_{\text{H},t}} \quad \text{for } \forall G, t \tag{12}
\]

\[
\Delta h_{i,t}^{G} = n_{\text{mod},i,t}^{G} - n_{\text{mod},i,t-1}^{G} \quad \text{for } \forall G, i, t \tag{16}
\]

Penalties are imposed on the deviation of the gas amount from the normal operating condition of holder level, \( G_{\text{H},t}^{G} \).

Equation (11) prevents the holder level from being operated below \( G_{\text{H}_{\text{L},t}}^{G} \) for all byproduct gases. Therefore, the holder booster trip is strictly prohibited as a hard constraint by equation (11) because of its enormous economic loss. Slack variables related to holder level deviations (\( s_{i,t}^{G} \) and \( s_{i,t}^{G} \)) are cumulative and more than one can have a non-zero value.

\[
G_{\text{H}_{\text{L},t}} \leq s_{i,t}^{G} \leq G_{\text{H}_{\text{H},t}} \quad \text{for } \forall G, t \tag{13}
\]

\[
G_{\text{H}_{\text{L},t}} \leq s_{i,t}^{G} \leq G_{\text{H}_{\text{H},t}} \quad \text{for } \forall G, t \tag{14}
\]

Boilers and turbines have their own operation ranges for stable operation, and the optimization should be made to satisfy these operation constraints.

\[
G_{\text{H}_{\text{L},t}} \leq s_{i,t}^{G} \leq G_{\text{H}_{\text{H},t}} \quad \text{for } \forall G, t \tag{17}
\]

Penalties are imposed on the deviation of the gas amount from the normal operating condition of holder level, \( G_{\text{H},t}^{G} \).

Equation (11) prevents the holder level from being operated below \( G_{\text{H}_{\text{L},t}}^{G} \) for all byproduct gases. Therefore, the holder booster trip is strictly prohibited as a hard constraint by equation (11) because of its enormous economic loss. Slack variables related to holder level deviations (\( s_{i,t}^{G} \) and \( s_{i,t}^{G} \)) are cumulative and more than one can have a non-zero value.

Fuel input limitation to each boiler

\[
F_{i,t}^{G,\text{min}} \leq f_{i,t}^{G} \leq F_{i,t}^{G,\text{max}} \quad \text{for } \forall i, t \tag{15}
\]

Fuel input limitation to each boiler

\[
F_{i,t}^{G,\text{min}} \leq f_{i,t}^{G} \leq F_{i,t}^{G,\text{max}} \quad \text{for } \forall i, t
\]

Auxiliary equations

\[
\Delta h_{i,t}^{G} = n_{\text{mod},i,t}^{G} - n_{\text{mod},i,t-1}^{G} \quad \text{for } \forall G, i, t \tag{16}
\]

\[
sw_{i,t}^{G} + sw_{i,t}^{G} \geq 0 \quad \text{for } \forall G, i, t \tag{17}
\]

The produced steam and electricity at each period should satisfy the demands for process steam and electricity for all periods.

\[
\sum_{i=1}^{N_{B}} p_{\text{water}}^{i,t} \geq p_{D,t} \quad \text{for } \forall t
\]

Equation (5)The produced steam and electricity at each period should satisfy the demands for process steam and electricity for all periods.

\[
\sum_{i=1}^{N_{B}} p_{\text{water}}^{i,t} \geq p_{D,t} \quad \text{for } \forall t
\]
Equations (16)–(18) represent the number of burner turns on/off using slack variables. Number of turn on at time $t$ is expressed by $sw_{i,t}^G$, and the number of turns off is expressed by $sw_{i,t}^G$. The initial number of burners running $G$ byproduct gas at the $i$th boiler $n_{i,0}^G$ is determined by the number of burners running at the current time. Equations (19)–(22) represent the number of burner changes at the same boiler for each byproduct gas. The binary variables $ibn_{i,t}^G$, $ibn_{i,t}^G$, represent the two and three burners turn-on status, and $ibf_{i,t}^G$, $ibf_{i,t}^G$, represent two and three burner turn-off status at the same boiler during the same period, respectively. When these slack variables have values of 1, this means a simultaneous multiple fuel load change, and a penalty is imposed.

**CASE STUDY**

A case study was performed using the simulated model of the networks for byproduct gas in the iron- and steel-making process. For prediction of the given holder level change, and steam and electricity demands, optimum solution was found using the proposed multiperiod plantwide optimization formulation and the results were compared with those of the previous approach (Akimoto et al., 1991; Bemporad and Morari, 1999). To compare the performance of the proposed approach with the previous approach, it was assumed that the distribution of the total adjusting byproduct gases determined from the previous approach was distributed to each boiler considering efficiencies, demand for steam and electricity, and the number of turns on/off of the burner with the continuous fuel load change.

Figure 5 shows the networks for byproduct gases for the case study. The system is composed of byproduct gas holders, oil tank, boilers and turbines. Boiler numbers 1 and 2 supply process steam, and electricity is generated using turbines. Available fuels are two types of byproduct gases and oil. The planning period is five periods, and each period is 5 min. Table 1 shows operation limits of each byproduct gas holders and Table 2 shows efficiencies of boilers and turbines. Table 3 shows the capacity of the byproduct gas burners. Cost data for objective function, low heating values for byproduct gases and consumption ranges for byproduct gases in boilers are represented in Tables 4–6, respectively. Figure 6 shows the electricity and process demand during the planning horizon. The simulation study was implemented on a Pentium IV 1.6GHz with

- **Table 1.** Operation limits of byproduct gas holders.

<table>
<thead>
<tr>
<th>Gas A</th>
<th>Gas B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low–low $(m^3)$</td>
<td>40,000</td>
</tr>
<tr>
<td>Low $(m^3)$</td>
<td>50,000</td>
</tr>
<tr>
<td>Center $(m^3)$</td>
<td>70,000</td>
</tr>
<tr>
<td>High $(m^3)$</td>
<td>90,000</td>
</tr>
<tr>
<td>High–high $(m^3)$</td>
<td>100,000</td>
</tr>
</tbody>
</table>

- **Table 2.** Efficiencies of each boiler and turbines.

<table>
<thead>
<tr>
<th>Boiler 1</th>
<th>Boiler 2</th>
<th>Boiler 3</th>
<th>Boiler 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boilers</td>
<td>0.8</td>
<td>0.85</td>
<td>0.82</td>
</tr>
<tr>
<td>Turbines</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

- **Table 3.** Byproduct gas burner capacity, $m^3 h^{-1}$

<table>
<thead>
<tr>
<th>Boiler 1</th>
<th>Boiler 2</th>
<th>Boiler 3</th>
<th>Boiler 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas A burner</td>
<td>27,000</td>
<td>27,000</td>
<td>27,000</td>
</tr>
<tr>
<td>Gas B burner</td>
<td>10,000</td>
<td>10,000</td>
<td>10,000</td>
</tr>
</tbody>
</table>

Figure 5. Byproduct gas supply system for case study.
512 MB RAM, and What’s Best 5.0 (Lindo Systems Inc.) was used for the MILP solver. The MILP problem had 304 continuous variables, 202 binary variables and 405 constraints, but it was solved within 5 min average computation time.

Figure 7 shows the prediction of byproduct gas amount in each holder. It shows that gas A is expected to increase and gas discharge is expected at time period 5. Meanwhile, gas B holder level operates at a lower level, and it is expected to go to the lower risky region at time period 3. Therefore, the situation requires adequate operations during the planning horizon to avoid gas discharge and holder booster trip, thus minimizing the total operation cost.

A different optimum solution has been found due to the different optimization model structure. Figures 8 and 9 show byproduct gas fuel load change by the previous and proposed approaches, respectively. The result shows that the proposed approach performs three burner turns on/off (gas A burner turn off at the first period, and gas B burner turn on at the second period), while the previous approach involves six fuel load changes. (gas A burner turn off at the first period, and gas B turn on at the second and third period). Another difference is that the fuel load changes by the proposed approach have whole numbers of burner turns on/off while the previous one shows fractional numbers of burner turns on/off, which is not good in terms of implementation. This result comes from the difference in the optimization model structure. The result also shows that the fuel load change is performed by considering the efficiency of the boiler. When the fuel load is increased, the most efficient burner (burner in no. 4 boiler) is first turned on, and then the next efficient one (burner in no. 2 boiler) turns on. However, when reducing the fuel load, the most

---

**Table 4. Cost data for objective function.**

<table>
<thead>
<tr>
<th></th>
<th>Cost data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil cost</td>
<td>200,000</td>
</tr>
<tr>
<td>Electricity cost</td>
<td>5150</td>
</tr>
<tr>
<td>Penalty for high-high holder level</td>
<td>4300</td>
</tr>
<tr>
<td>Penalty for high holder level</td>
<td>10</td>
</tr>
<tr>
<td>Deviation penalty from normal operation</td>
<td>0.4</td>
</tr>
<tr>
<td>Penalty for low holder level</td>
<td>4</td>
</tr>
<tr>
<td>Boiler on/off penalty</td>
<td>130,000</td>
</tr>
<tr>
<td>Simultaneous on/off penalty for burners</td>
<td>200,000</td>
</tr>
</tbody>
</table>

**Table 5. Low heating values for byproduct gases.**

<table>
<thead>
<tr>
<th></th>
<th>Low heating values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas A</td>
<td>750.0</td>
</tr>
<tr>
<td>Gas B</td>
<td>2000.0</td>
</tr>
</tbody>
</table>

**Table 6. Consumption ranges for byproduct gases of boilers.**

<table>
<thead>
<tr>
<th></th>
<th>First boiler</th>
<th>Second boiler</th>
<th>Third boiler</th>
<th>Fourth boiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum for gas A</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Maximum for gas A</td>
<td>84,000</td>
<td>84,000</td>
<td>84,000</td>
<td>84,000</td>
</tr>
<tr>
<td>Minimum for gas B</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Maximum for gas B</td>
<td>6000</td>
<td>6000</td>
<td>6000</td>
<td>6000</td>
</tr>
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</table>

---

**Figure 6. Process steam and electricity demand.**

**Figure 7. Byproduct gas amount prediction.**

**Figure 8. Optimal byproduct gas burner turns on/off change by the previous approach.**

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inefficient one (burner in no. 1 boiler) first turned off, and then the next inefficient one turned off. It was assumed that the efficiency of the burner is the same in the same boiler.

Figure 9 shows the comparison of result holder level change by applying the optimum fuel load change. The result shows that both holder levels fluctuate within the operation limit during the planning horizon, but the proposed approach shows larger deviations than the previous approach. This is because the proposed one determines the optimum point by considering the penalty for the frequent burner turns on/off and discrete load change while the previous approach does not consider the frequent fuel load change.

Table 7 shows the total cost comparison of the two approaches. The result shows that oil was not used, holder booster trip and byproduct gas emission did not occur, and simultaneous changeover did not occur in both results. The difference was in the switching cost, deviation, and the amount of electricity generated. The previous approach shows the small deviation cost, and slightly more profit from electricity generation, but loses more by the frequent burner operation. This approach focuses on the reduction of oil use, maintaining the normal operation gas amount related to the byproduct gas holder unit, while not enough consideration was given to the optimal operation of the power plant usage. The proposed approach finds the optimum solution among the different objectives, and it shows the reduced total cost compared with the previous approach. Although the optimum solution can change for the different penalty coefficients by reflecting the changing situation of operation, such as fuel price change, the proposed approach finds the optimum solution for the determined set of weights for each cost term. The optimum burner load changes for each period change for the holder level prediction, and the sensitivity of the optimum solution is influenced by holder level prediction (which expected to be uncertain), present holder level, byproduct gas burner capacity etc.

The determination of the weights for each cost is difficult and is subjective. Therefore, many optimum solution sets exist for the different set of weights, which reflects the relative importance among objectives. A Pareto plot can be used to determine the appropriate optimum solution set for the different set of weights. Figure 11 shows the Pareto plot for power generation that should be maximized and the holder level penalty cost that should be minimized. The manager can choose an appropriate optimum solution from the Pareto plot by reflecting their experience on the relative weights between conflicting objectives.

Figure 9. Optimal byproduct gas burner turns on/off change by proposed approach.

Figure 10. Comparison of byproduct gas fuel load change.

Figure 11. Pareto plot of optimum solution.

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<thead>
<tr>
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<th>Previous</th>
<th>Proposed</th>
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<tr>
<td>Oil consumption cost</td>
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<tr>
<td>Holder booster trip penalty</td>
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<td>0</td>
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<tr>
<td>Unfavorable byproduct gas emission</td>
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<td>0</td>
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<tr>
<td>High operation penalty</td>
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<td>Low operation penalty</td>
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<tr>
<td>Deviation penalty</td>
<td>441,875</td>
<td>573,125</td>
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<tr>
<td>Burner switching cost</td>
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<td>300,000</td>
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<tr>
<td>Electricity generation benefit</td>
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<td>-317,727</td>
</tr>
<tr>
<td>Total cost</td>
<td>620,541</td>
<td>555,897</td>
</tr>
</tbody>
</table>

*Total cost for planning horizon.

Table 7. Total cost comparison* (Won).
CONCLUSION

In this research, a simultaneous multiperiod optimization model for holder level control and the byproduct gas distribution was proposed. By simultaneously optimizing the holder level range control and boiler operation by finding optimal trade-off among conflicting objectives, the total cost was reduced compared with the previous approach which mainly focusing on the holder level control and the reduction of oil consumption. The reflection on real operation of performing different fuel load changes according to fuel types leads to the new optimization model, and it successively finds the optimum solution. The case study results show the total cost reduction where unfavorable byproduct gas emission and equipment trip are minimized, and optimal allocation of byproduct gas considering the efficiencies of the boilers is made. The optimum solution by the proposed approach shows good performance in terms of total cost reduction by plant-wide optimization and operation-easy value that can be used.

NOMENCLATURE

Sets

\( i \)
boiler (\( i = 1, \ldots, NB \))

\( j \)
period (\( j = 1, \ldots, Nt \))

\( t \)
byproduct gas types (G = BFG, COG, LDG, CFG)

Parameters

\( C_{\text{Oil}} \)
unit fuel cost, \( \text{won} \cdot \text{ton}^{-1} \)

\( C_{\text{elec}} \)
unit electricity cost, \( \text{won} \cdot \text{MWh}^{-1} \)

\( C_{G} \)
low heating value of byproduct gas \( G \), \( \text{kcal m}^{-3} \)

\( F_{\text{max},G} \)
minimum flow rate of byproduct gas \( G \) into boiler \( i \)

\( F_{\text{Max,}G} \)
maximum flow rate of byproduct gas \( G \) into boiler \( i \) at time \( t \), \( \text{ton h}^{-1} \)

\( F_{\text{Min,}G} \)
minimum flow rate of steam produced at boiler \( i \)

\( F_{\text{Max}} \)
maximum flow rate of steam produced at boiler \( i \) at time \( t \), \( \text{ton h}^{-1} \)

\( F_{\text{Min}} \)
minimum flow rate of steam produced at boiler \( i \) at time \( t \), \( \text{ton h}^{-1} \)

\( F_{\text{Min},G} \)
minimum flow rate of steam produced at boiler \( i \) at time \( t \), \( \text{ton h}^{-1} \)

\( F_{\text{Max},G} \)
maximum flow rate of steam produced at boiler \( i \) at time \( t \), \( \text{ton h}^{-1} \)

\( F_{\text{Min,}G} \)
minimum flow rate of steam produced at boiler \( i \) at time \( t \), \( \text{ton h}^{-1} \)

\( F_{\text{Max}} \)
maximum flow rate of steam produced at boiler \( i \) at time \( t \), \( \text{ton h}^{-1} \)

\( F_{\text{Min}} \)
minimum flow rate of steam produced at boiler \( i \) at time \( t \), \( \text{ton h}^{-1} \)

\( G_H \)
predicted amount of byproduct gas consumption at time \( t \), \( \text{Nm}^3 \cdot \text{h}^{-1} \)

\( G_{\text{PP,gen稠}} \)
predicted amount of byproduct gas generation at time \( t \), \( \text{Nm}^3 \cdot \text{h}^{-1} \)

\( G_H \)
minimum required byproduct gas amount in holder \( G \) at time \( t \), \( \text{Nm}^3 \)

\( G_H \)
low operation byproduct gas amount in holder \( G \) at time \( t \), \( \text{Nm}^3 \)

\( G_H \)
normal operation byproduct gas amount in holder \( G \) at time \( t \), \( \text{Nm}^3 \)

\( G_H \)
high operation byproduct gas amount in holder \( G \) at time \( t \), \( \text{Nm}^3 \)

\( G_H \)
maximum allowable byproduct gas amount in holder \( G \) at time \( t \), \( \text{Nm}^3 \)

\( N \)
number of current operating burner at boiler \( i \)

\( P_D \)
power demand at time \( t \), \( \text{MW h} \)

\( \Delta T \)
time period, \( \text{min} \)

\( U_G \)
byproduct gas load change unit amount of \( G \) burner at the time \( t \), \( \text{Nm}^3 \cdot \text{h}^{-1} \)

\( W_{G} \)
penalty weight for unfavorable byproduct gas emission of \( G \) type, \( \text{won} \cdot \text{Nm}^3 \cdot \text{h}^{-1} \)

\( W_{G} \)
penalty weight for high operation of byproduct gas holder, \( \text{won} \cdot \text{Nm}^3 \cdot \text{h}^{-1} \)

\( W_{G} \)
penalty weight for low operation of byproduct gas holder, \( \text{won} \cdot \text{Nm}^3 \cdot \text{h}^{-1} \)

\( W_{G} \)
penalty weight for gas amount deviation over the normal value of gas amount at the \( G \) gas holder, \( \text{won} \cdot \text{Nm}^{-3} \)

\( W_{G} \)
penalty weight for gas amount deviation over the normal value of gas amount at the \( G \) gas holder, \( \text{won} \cdot \text{Nm}^{-3} \)

\( W_{G_{SW}} \)
penalty weight for \( G \) byproduct gas burner turn on/off switching, \( \text{won} \cdot \text{switching}^{-1} \)

\( W_{2i} \)
penalty weight for two burners simultaneous switching in the same boiler, \( \text{won} \cdot \text{switching}^{-1} \)

\( W_{3i} \)
penalty weight for three burners simultaneous switching in the same boiler, \( \text{won} \cdot \text{switching}^{-1} \)

\( \eta_{b,i}^B \)
turbine efficiency of boiler \( i \)

\( \eta_{b,i}^T \)
turbine efficiency of turbine \( j \)

Continuous variables

\( f_{i,t}^{\text{Oil}} \)
flow rate of oil into boiler \( i \) at time \( t \), \( \text{ton h}^{-1} \)

\( f_{i,t}^{G} \)
flow rate of byproduct gas \( G \) into boiler \( i \) at time \( t \), \( \text{ton h}^{-1} \)

\( f_{i,t}^{G_{SW}} \)
flow rate change of byproduct gas \( G \) into boiler \( i \) from time \( t \) to time \( t + 1 \), \( \text{ton h}^{-1} \)

\( f_{i,t}^{\text{steam}} \)
flow rate of steam produced at boiler \( i \) at time \( t \), \( \text{ton h}^{-1} \)

\( f_{i,t}^{\text{steam,process}} \)
flow rate of steam into process from boiler \( i \) at time \( t \), \( \text{ton h}^{-1} \)

\( f_{i,t}^{\text{water}} \)
flow rate of water into boiler \( i \) at time \( t \), \( \text{ton h}^{-1} \)

\( h_{G} \)
byproduct gas amount in holder \( G \) at time \( t \), \( \text{Nm}^3 \)

\( h_{G} \)
high operation amount of byproduct gas at the \( G \) gas holder at time \( t \), \( \text{Nm}^3 \)

\( h_{G} \)
low operation amount of byproduct gas at the \( G \) gas holder at time \( t \), \( \text{Nm}^3 \)

\( h_{G} \)
byproduct gas amount deviation at time \( t \) at \( G \) gas holder above the average gas amount, \( \text{Nm}^3 \)

\( h_{G} \)
byproduct gas amount deviation at time \( t \) at \( G \) gas holder below the average gas amount, \( \text{Nm}^3 \)

General integer variables

\( n_{i,t}^{\text{on}} \)
number of operating burner at boiler \( i \) at time \( t \)

\( h_{G} \)
change of the number of operating burner at boiler \( i \) from time \( t \) to time \( t + 1 \)

\( s_{G_{sw}}^{i,t} \)
number of \( G \) gas burner turn on at boiler \( i \) at time \( t \)

\( s_{G_{off}}^{i,t} \)
number of \( G \) gas burner turn off at boiler \( i \) at time \( t \)

Binary integer variables

\( i_{b,i}^{t} \)
1 if one \( G \) gas burner turned on at boiler \( i \) at time \( t \)

0 else

\( i_{b,\text{on}}^{t} \)
1 if two \( G \) gas burners simultaneously turned on at the same boiler \( i \) at time \( t \)

0 else

\( i_{b,\text{on}}^{3} \)
1 if three \( G \) gas burners simultaneously turned on at the same boiler \( i \) at time \( t \)

0 else

\( i_{b,\text{off}}^{t} \)
1 if \( G \) gas burner turned off at boiler \( i \) at time \( t \)

0 else

\( i_{b,\text{on}}^{2} \)
1 if two \( G \) gas burners simultaneously turned off at the same boiler \( i \) at time \( t \)

0 else

\( i_{b,\text{on}}^{3} \)
1 if three \( G \) gas burners simultaneously turned off at the same boiler \( i \) at time \( t \)

0 else

REFERENCES


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