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Development of Models for the Prediction of Electric Power Supply-Demand and the Optimal Operation of Power Plants at Iron and Steel Works.

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ABSTRACT

In order to achieve stable and efficient use of energy at iron and steel works, a model for the prediction of supply and demand of electric power system is developed on the basis of the information on operation and particular patterns of electric power consumption. The optimal amount of electric power to be purchased and the optimal fuel allocation for the in-house electric power plants are also obtained by a mixed-integer linear programming(MILP) and a nonlinear programming (NLP) solutions, respectively. The validity and the effectiveness of the proposed model are investigated by several illustrative examples. The simulation results show the satisfactory energy saving by the optimal solution obtained through this reseach.

1. INTRODUCTION

A steel plant uses various forms of energy in large quantities and about 40% of the energy requirement in the production process is supplied from the by-product gases generated at the upstream processes. Wide fluctuations in energy supply and demand are a burden on operators and make economic energy management difficult. Thus the role of the Energy Center is to minimize energy cost by centralized energy management. In fact, the Energy Center which we are concerned has managed in the past energy-saving and stable energy supply with a reasonable success. But in recent years it has shown some functional drawbacks and the needs for improving the system functions to reflect the changed energy environment.

A most important function of the Energy Center is the prediction of proper energy management schedule so as to minimize the total energy cost. This existing function was redeveloped to achieve more stable energy supply and optimal control of energy use at steelworks. This paper describes two representative examples: one is a prediction of total electric power supply-demand using the information on operation and particular electric power consumption pattern for some unit plants within a specified period and the other is the optimal energy supply system for the in-house electric power plants using mathematical programming techniques.

2. GENERAL DESCRIPTION ON ENERGY MANAGEMENT

The steelworks uses various forms of energy, such as electric power, steam, oil, coal, Blast Furnace Gas (BFG), Coke Oven Gas (COG), Lintz Donawiz Gas (LDG) at many energy consuming plants of which the number is about fifty for the case of this study. By-product gases can be utilized to replace electric power and oil to be purchased. The portion of energy replacement can be decided depending on the operating conditions and the gas holders are used to balance the production and the consumption rates of by-product gases.

Figure 1 shows a simplified overall diagram of energy flow focusing on by-product gases, oil, and electricity. By-product gases are used within the steelworks, and the surplus by-product gases, after the consumption at many unit plants, are stored in the gas holders or supplied to the in-house electric power plants. Three types of by-product gases (BFG, LDG, COG) are very useful energy sources due to their high calorie contents and very closely related to the amount of oil consumption and electric power generation at the in-house power plants. The in-house electric power plants, consisting of five sites having different capacities, use oil and by-product gases as fuel. The electric power is provided in two ways: the electric power purchased from outside company and generated at the in-house electric power plants whose capacity is about 80% of total electric power demand at steelworks.

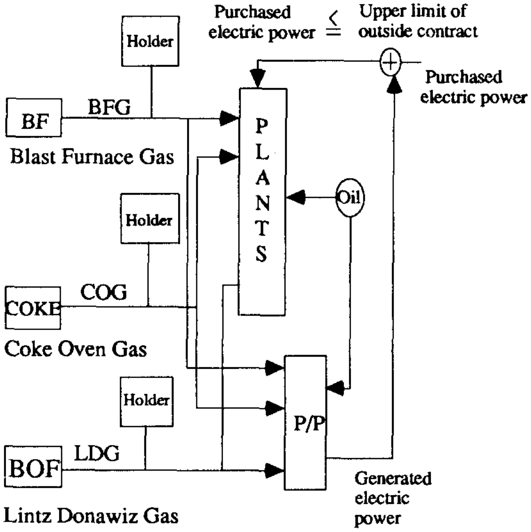


Fig. 1 The diagram of energy flows

3. A PREDICTION OF TOTAL ELECTRIC POWER CONSUMPTION

The key problems of electric power management for steelworks are how to predict the electric power consumption of various unit plants as accurately as possible. From the prediction of total electric power consumption, the operators can conduct appropriate energy management to minimize energy cost and supply stable energy to works. In the case that the electric power consumption exceeds the limit of contracted electric power purchase from the electric power company, electric power generation can be increased to the maximum capacity at the in -house power plants. If it is not sufficient, electric power consumption restriction to some unit plants should be imposed inevitably so as not to suffer from serious economic loss caused by breaking the contract.

After analyzing the operation data and the existing prediction procedure, we developed the following model. The electric power loads can be divided into two large groups by the degree of loads variation according to the operation condition. One is electric power loads at upper-stream plants of steel making process: raw materials treating facilities, iron-making plant, continuous casting plant, etc. The loads of these plants are nearly constant with time at each particular operating condition so that electric power consumption can be simply predicted using the information on operation such as shut down, routine operation, or unexpected accident. The other is electric power loads at milling plants: cold rolling mill, hot strip mill, stainless steel making plant, plate mill, etc. The loads at milling region are fluctuating severely with time and have very complicated patterns according to operation conditions. Therefore it is not sufficient to predict electric power using only the information on operation at milling plants. Thus we use the rolling schedule and the pattern of electric power consumption for some plants.

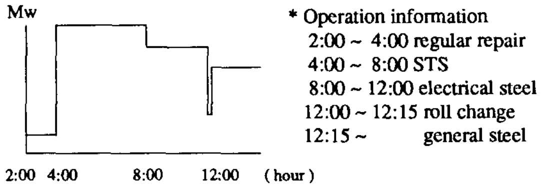
3.1 Hot Strip Mill (HSM)

The aim of the hot rolling process is to reprocess slabs to make strips with specified dimensions and mechanical properties. Actual operation data shows that electric loads are closely related to milling materials, milling thickness, and pitch (the time interval between two consecutive slabs to be extracted). To develop a model, the milling materials were classified into six classes by the characteristic material properties and investigated about their relationship to milling loads, milling time, and slab' thickness. Then the average electric power consumption as function of slab' thickness is obtained for each class. Our simulation utilizes the information on the adjacent operation schedules of hot strip mill, and a satisfactory prediction of electric power consumption is achieved by using those information compared to the existing prediction strategy (Fig. 2).

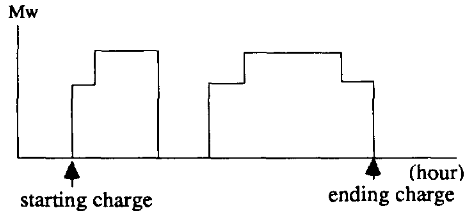
3.2 Stainless steel making plant

Electric loads of electric furnace are fluctuating severely but the other facility's electric loads are nearly constant at the stainless steel making plant. The electric furnace is a continuous batch process and its pattern of electric power consumption is somewhat regular per charges. Using the starting time of charges and particular pattern of electric power consumption, we obtained a good prediction of electric power consumption (Fig. 2).

By summing up all the predicted electric loads according to the information on operation and the prediction model, a satisfactory prediction of total electric power consumption is obtained for the specific planning period which is eight hours.



(a) hot strip mill



(b) stainless steel making plant

Fig. 2 Model of determining electric power consumption

4. ECONOMICAL ENERGY ALLOCATION AT THE IN-HOUSE POWER PLANTS

The fundamental concept of economical energy allocation is to minimize the energy cost without creating obstruction to the production operation of steelworks. Therefore the present energy environment such as operation of by-product gas holders and fuel use strategy at in-house electric power plants should be reflected as much as possible for the purpose of more stable energy supply and effective use of energy. An optimal energy allocation is achieved by two step calculation: the amount of electric power to be purchased is first determined, and then the economical fuel allocation for the in-house power plants is decided so as to satisfy the required electric power generation.

4.1 Determination of an optimal amount of electric power to be purchased

The amount of electric power to be purchased is determined by considering the total electric power consumption, available amount of by-product gases, the unit price of electric power to be purchased, fuel cost, and gas holder conditions. The cost for electric power to be purchased varies according to three time zones light, normal, or peak time for each day reflecting the variation of electric loads. When the amount of electric power to be generated exceeds that of total electric power demand at steelworks, the surplus electric power can be sold to an outside electric company, its unit price also varies according to the time zones. Therefore basic policy was to store by-product gases at light time zone and to use at normal and peak time zones to suppress the usuage of electric power to be purchased. But, under the present operating conditions, the capacities of gas holders are not enough to control the rates of by-product gas consumption at particular time zones, therefore a stable operation of gas holders are being crucial factor for the energy management. Figure 3 shows the prices of electric power.

With these conditions in mind, we determine an optimal amount of electric power to be purchased and by-product gas usuage for the in-house electric power plants. The entire period of schedule is divided into n periods according to the prediction of by-product gas production and consumption rates at the steelworks. By-product gas flow rates are assumed as constant in any given period. The constraints and objective function are formulated as follows:

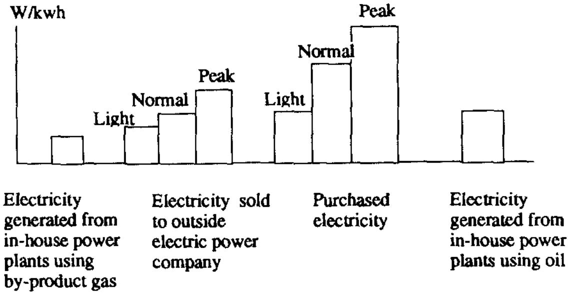


Fig. 3 The electricity unit prices

a) Constraints for the electric power generation

The amount of electric power generated is roughly a linear function of consumed fuels and process steam. Upper and lower limits of fuel consumptions are employed since each in-house power plants have different capacity and uses different fuel.

$$P_G = f(q_{Bi}, q_{Ci}, q_{Li}, q_{Oi}, S_{Pi}, S_{Bi})$$

$$P_{Ti} - P_L \leq P_{Gi} - P_{REi} + P_{ABi} \leq P_{Ti}$$

$$P_{MINi} \leq P_{Gi} \leq P_{MAXi}$$

$$q_{BMINi} \leq q_{Bi} \leq q_{BMAXi}$$

$$q_{CMINi} \leq q_{Ci} \leq q_{CMAXi}$$

$$q_{LMINi} \leq q_{Li} \leq q_{LMAXi}$$

$$q_{OMINi} \leq q_{Oi} \leq q_{OMAXi}$$

b) Constraints for gas holders

In design, the amount of gas in the holder is allowed to fluctuate within the upper and lower limits of the holders. The operators, however, keep the gas holder levels within the specified ranges for stable operation of gas holders. Thus gas holders practically have different upper and lower limits for operation. To reflect these conditions, we assign a penalty when gas holder level going to deviate from these practical limits. In case that the amount of by-product gases exceeds gas holder capacity, by-product gased can be emitted to air. But this condition is suppressed by assigning a cost to the amount of by-product gases to be emitted which reflects the effects of air pollutions.

$$V_{BMIN} \leq V_{Bi} + \sum_{i=1}^{n} \alpha\, (q_{BTi} - q_{Bi} - q_{BOUTi} + q_{BABi}) \leq V_{BMAX}$$

$$V_{CMIN} \leq V_{Ci} + \sum_{i=1}^{n} \alpha\, (q_{CTi} - q_{Ci} - q_{COUT} + q_{CABi}) \leq V_{CMAX}$$

$$V_B^L \leq V_{Bi} \leq V_B^U$$

$$V_C^L \leq V_{Ci} \leq V_C^U$$

c) Objective function

The objective function consists of the following items:

i) unit prices of electric power to be purchased and to be sold to an outside electric company

ii) penalty for the gas holder levels deviating from the practical limits

iii) cost of by-product gas emission to air

iv) cost of electric power and by-product gas owing to their consumption restriction

By summing up above items, the objective function to be minimized is as follows:

$$\begin{aligned} z = \sum_{i=1}^{n} \{ & C_E\,(P_{Ti} - P_{Gi}) + C_{RE}\,P_{REi} + C_G\,P_G \\ & + C_{REi}\,P_{REi} + C_{PAB}\,P_{ABi} + C_{BOUT}\,q_{BOUT} \\ & + C_{COUTP}\,q_{COUT} + C_{BAB}\,q_{BAB} + C_{CAB}\,q_{CAB} \\ & + p_{B+}\,V_B^{+} + p_{B-}\,V_B^{-} + p_{C+}\,V_C^{+} + p_{C-}\,V_C^{-} \} \end{aligned}$$

4.2 An optimal energy allocation at the in-house electric power plants

Using the amount of electric power to be generated and available by-product gases at the previous step, the optimal fuel allocation for the in-house electric power plants are calculated. The amount of by-product gases to the in-house electric power plants fluctuates with time; a stable supply of gas, however, is desired and frequent changes of the fuel types for boilers should be avoided. So it is important to determine optimal gas supply strategy to the in-house electric power plants up to a certain point of time in advance from employable holdups of by-product gases. The in-house electric power plants consist of 11 boilers and 8 turbine generators. Each boiler has different capacity and characteristic relationships between fuel types and the amount of steam generated. The steam, generated from boiler #1 to boiler #4, is gathered at a steam header. From this steam header, the steam used by the blast furnaces and low pressure steam to steelworks are supplied. Turbine generators also have different capacities and nonlinear relationships between the amount of steam and electric power generated. The objective function is to minimize the cost of the electric power generated.

The optimal allocation of fuels and steam are determined up to eight hours in advance. To simplify a mathematical formulation, minimal amount of fuels required to operate boilers are decided before solving a nonlinear programing. The constraints and objective functions are as follows:

a) Constraints for boilers

fuel usage: $\sum f_{Xi} = F_{XALL}$

$f_{MINi} \leq f_{Xi} \leq f_{MAXi}$

steam generation: $S_{MINi} \leq S_i \leq S_{MAXi}$

characteristic relationships between the fuels consumed and the staem generated :

$$S_i = f(q_{Bi}, q_{Ci}, q_{Li}, q_{Oi}, Q_B, Q_C, Q_L, O_O)$$

b) Constraints for turbine generators

steam balance: $S_{Ti} = \sum S_i - \sum S_H$

(for steam header type)

$S_{Tj} = S_j$

(for directly connected type,)

steam usage: $S_{TMINi} \leq S_{Ti} \leq S_{TMAXi}$

required process steam:

$S_{PMINi} \leq S_{Pi} \leq S_{PMAXi}$

power generation: $P_{MINi} \leq P_i \leq P_{MAXi}$

characteristic relationships between the steam consumed and the electric power generated :

$$P_i = f(S_{Ti}, S_{Pi})$$

c) constraints for tie-line

$TL_{MIN} \leq P_{R-2} + P_{P2-1} \leq TL_{MAX}$

$P_D + P_{R-2} + P_{P2-1} = P_{RS/S} + P_{1S/S}$

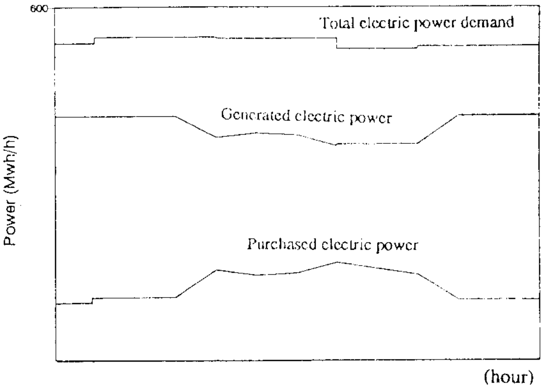
d) Objective function

$z = \min C_S (P_S, q_B, q_C, q_L, q_O)$

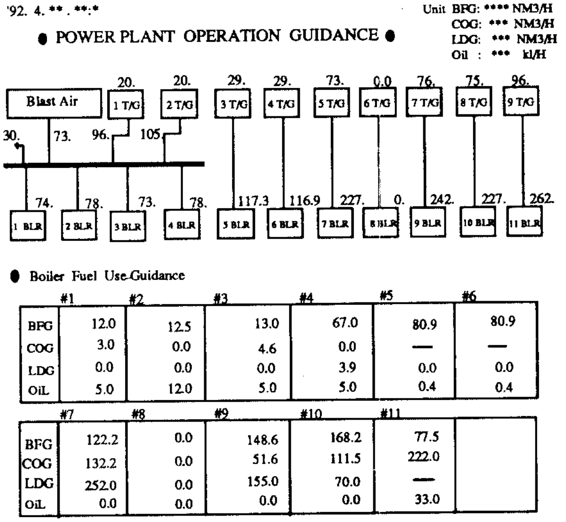
5. AN EXAMPLE OF CALCULATION

In order to investigate the validity and effectiveness of the formulation, off-line numerical calculations have been performed for several illustrative examples which correspond to the actual operation data. The numerical calculation has been made using commercial optimizer, LINDO(Linear INteractive Discrete Optimizer), to solve mixed-integer linear programming, and GINO(General INteractive Optimizer), to solve nonlinear program-ming, installed on VAX 8800.

First, we predict the total electric power consumption using the information on operation for each unit plant and determine the amount of electric power to be purchased, then obtain an optimal fuel and steam allocation at in-house electric power plants. Fig. 4 shows a solution obtained by the mathematical formulation with the actual operation data. It is observed that gase holder levels of our simulation show moderate changes compared to the real operation data which fluctuated widely. And additional reduction of oil usage is possible when compared to the actual required oil usuage. Similar improvement has been obtained for the other examples. It is concluded from several examples which were investigated that present mathematical models describe the essential function of the actual system with a sufficient degree of reliability.



(a) the amount of electric power



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● POWER PLANT OPERATION GUIDANCE ●

Unit BFG: **** NM3/H
COG: *** NM3/H
LDG: *** NM3/H
Oil : *** kl/H

● Boiler Fuel Use-Guidance

	#1	#2	#3	#4	#5	#6
BFG	12.0	12.5	13.0	67.0	80.9	80.9
COG	3.0	0.0	4.6	0.0	—	—
LDG	0.0	0.0	0.0	3.9	0.0	0.0
OiL	5.0	12.0	5.0	5.0	0.4	0.4

	#7	#8	#9	#10	#11	
BFG	122.2	0.0	148.6	168.2	77.5	
COG	132.2	0.0	51.6	111.5	222.0	
LDG	252.0	0.0	155.0	70.0	—	
OiL	0.0	0.0	0.0	0.0	33.0	

(b) an optimal fuel allocation at in-house power plants

Fig. 4 calculation results using the developed models

6. CONCLUSION

In this study, we discussed how to predict total electric power supply-demand at steelworks and an optimal energy allocation for the in-house electric power plants. An improved electric power prediction has been obtained by using the information on operation. The problem of determining the amount of electric power to be purchased and optimal energy allocation has been formulated as a mixed-integer linear, and a nonlinear model and optimal solutions are obtained by using MILP and NLP techniques. By providing guidance to the operators from the developed models, additional energy saving and more stable energy supply to the steelworks is expected.

NOMENCLATURE

P_G : electric power to be generated
P_T : total electric power demand
P_{RE} : electric power to the outside electric company
P_{AB} : electric power restriction to plants
P_A : limit of contracted electric power to be purchased
q_B, q_C, q_L, q_O: flow rates of by-product gases and oil
α : correction factor
q_{BOUT}, q_{COUT} : by-product gas emitted to air
q_{BAB}, q_{CAB} : by-product gas use restriction
V_B, V_C : gas holder levels
V_B^U, V_C^U, V_B^L, V_C : upper and lower limits of gas holder levels
C_E, C_{RE}, C_G, C_{PAB} : unit cost of electricity
C_{BOUT}, C_{BOUT}, C_{BAB}, C_{CAB} : unit cost of by-product gas
p_{B+}, p_{B-}, p_{C+}, p_{C-} : penalty for the gas holder levels deviating from practical limits
F_{XAL} : total fuel quantity to the in-house electric power plants
f_X : fuel flow rate
S, S_T, S_P : steam flow rate
Q_B, Q_c, Q_L, Q_O : calorie contents of fuel
$P_{R\text{-}2}$, $P_{P2\text{-}1}$: electric power transmission quantity
P_D , $P_{R\text{-}2}$, $P_{P2\text{-}1}$: electric power quantity at substation
$P_{RS/S}$, $P_{1S/S}$: electric power quantity at switching station
C_S : unit cost of electric power generated

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