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A flexible structural and operational design of steam systems

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A systematic design methodology is developed in this work for synthesizing the steam distribution network (SDN) in chemical process to satisfy period-varying demands. Specifically, the flexible model is developed for the better energy management, and a mixed-integer nonlinear program (MINLP) is formulated to minimize the total annualized cost (TAC) of the network design. For multi-period operation problems, the operation condition varying with time period is adopted in this study. When the structure of network is synthesized, operating conditions allows to be adjusted in company with period to maintain high efficiency of plants. The integration of SDN is achieved by the simultaneous optimization of the configuration and operating conditions. Case studies are presented to demonstrate the feasibility and benefits of the proposed approach.

1. Introduction

Steam-power systems are the main energy supplier for running chemical processing plants. In the system, steam is converted into different types of energy, specifically, electricity and the mechanical power. A large volume of related studies have already been published in the literature. Basically, two distinct approaches were adopted in these works: (a) the heuristics-based thermodynamic design method (Nishio *et al*., 1980; Chou and Shih, 1987) and (b) the model-based optimization method (Papoulias *et al*., 1983; Chang and Hwang, 1996; Bruno *et al*., 1998). The former networks were synthesized with thermodynamic targets for getting the maximum allowable overall thermal efficiency, while the latter were designed with mixed integer linear/nonlinear programs for attaining the minimum TAC. All of them were developed to address the design of SDN assuming that all units operate at full load to satisfy a single set of demands and conditions. However, in many existing chemical processes the common operational feature is varying demands. Since the limitations of these types of studies, methodologies capable for the period-varying demands were developed (Hui and Natori, 1996; Iyer and Grossmann, 1997; Maisa and Qassim, 1997). The proposed model was for the multi-period operation, and the research was only dealing operational problems for existing plants or design problems without simultaneously optimizing unit sizes and loads as continuous functions. More recently, Aguilar et al. (2007b) proposed a MILP

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model to address retrofit and operational problems for utility plants. The linear model was developed while some necessary conditions (e.g., steam properties in steam headers) were pre-determined before running the optimization. Finally, it might loss some feasible results to the better design since this reason. In this paper, the main objective of the study is to develop the flexible model to industrial problems. The model allows for the synthesis and design of SDN and also for the analysis of the existing plants in multi-period problems. Operating parameters are considered as variables and determined in company with time periods. The optimization of SDN is achieved by the simultaneous determination of the configuration and operating conditions. Illustrative examples are provided to demonstrate the benefits of the proposed formulation.

2. Problem Statement

The steam-power plant consists of boilers, steam headers at different pressure level, steam turbines, gas turbines and a deaerator, and it is usually selected as energy supplier in industrial. A general SDN design can be sated as follows: Given a set of boilers, a set of steam headers, a set of steam turbines, a set of gas turbines and a set of electric motors, it is desired to synthesize a cost-optimal SDN that can satisfy the energy demand requirements of chemical processes. The resulting SDN design should include: (1) the number of boilers and their throughputs, (2) the number of turbines and their throughputs, (3) the number of motors and their throughputs, (4) the properties of steam headers of every period, (5) the amount of electricity import/export, (6) the consumption rates of freshwater and fuel and (7) the complete configuration and the operating condition of each unit of every period.

3. Model Formulation

The proposed superstructure of SDN is shown in Figure 1. This superstructure consists of various equipments and depicts the distribution of steam of possible flow connections for all units. Unit performance models adopted in this work are from Aguilar *et al.*, (2007a) and the further discussions of each unit are as follows.

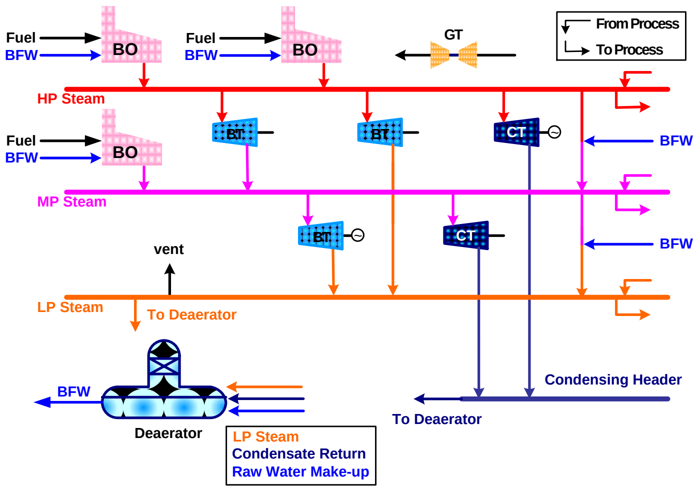

Figure 1: Superstructure for SDN

3.1 Boiler

In the following equations, the subscript b is used to represent a boiler, where the input water comes from the deaerator, and the output steam is sent to steam header at different pressure i. The mass and energy balances of boiler units are derived as follows. There are two types of boilers adopted in this work, which are the multi-fuel boiler (MFB) and the heat recovery steam generator (HRSG). It should be noted that the heat for MFB is only from the fuel and for HRSG is from not only the fuel but also the exhaust gas of gas turbine.

$$f_{bp}^{\mathrm{fw}} = \sum_{i\in I} f_{bip} + \sum_{i\in I} f_{bip}^{\mathrm{bd}} \qquad \forall b \in B, p \in P \tag{1}$$

$$f_{bp}^{\mathrm{fw}} H^{\mathrm{deaer}} + q_{bp} = \sum_{i\in I} f_{bip} H_{ip} + \sum_{i\in I} f_{bip}^{\mathrm{bd}} H_i^{\mathrm{sat,l}} \qquad \forall b \in B, p \in P \tag{2}$$

$$q_{bp} = \sum_{u\in U} \frac{q_{bup}}{B_u} - z_{bp} D^{\mathrm{avg}} \qquad \forall b \in MB, p \in P \tag{3}$$

$$q_{bp} = \mathrm{F}^{\mathrm{rad}} f_{bp} Cp (T_{bp} - T_{bp}^{\mathrm{stack}}) \qquad \forall b \in MH, p \in P \tag{4}$$

$$f_{bp} = \sum_{g\in G} f_{gbp} + \sum_{u\in U} f_{bup} \qquad \forall b \in MH, p \in P \tag{5}$$

3.2 Steam turbine

Steam turbine is assumed without steam loss to simplify the problem and the corresponding energy balance is presented in Eq. 6, where subscript t denotes steam turbine. The performance model of turbines is shown in Eq. 7.

$$f_{i'tip} (H_{ip} - h_{i'tip}) = w_{i'tip} \qquad \forall i', i \in I, t \in T, p \in P \tag{6}$$

$$w_{i'tip} = \Delta H_{i'ip}^{\mathrm{is}} \frac{1 + a_{\mathrm{L}} + b_{\mathrm{L}} \Delta T_{i'i}^{\mathrm{sat}}}{a_2 + a_3 \Delta T_{i'i}^{\mathrm{sat}}} f_{i'tip} - z_{i'tip} [(a_{\mathrm{L}} + b_{\mathrm{L}} \Delta T_{i'i}^{\mathrm{sat}}) W_t^{\max} + (1 + a_{\mathrm{L}} + b_{\mathrm{L}} \Delta T_{i'i}^{\mathrm{sat}} \frac{a_0 + a_1 \Delta T_{i'i}^{\mathrm{sat}}}{a_2 + a_3 \Delta T_{i'i}^{\mathrm{sat}}})]$$

$$\forall i', i \in I, t \in T, p \in P \tag{7}$$

3.3 Deaerator

In this unit water from different sources is held and treated to remove the dissolved gas before being sent to the boiler or let-down unit. The mass and energy balances are given in Eq. 8-10.

$$f_p^{\mathrm{LP}} + f_p^{\mathrm{w}} + f_p^{\mathrm{CT}} + f_p^{\mathrm{C}} = f_p^{\mathrm{deaer}} \qquad \forall p \in P \tag{8}$$

$$f_p^{\mathrm{LP}} H_{I,p} + f_p^{\mathrm{w}} H^{\mathrm{w}} + f_p^{\mathrm{CT}} H_{I+1,p} + f_p^{\mathrm{C}} H_p^{\mathrm{C}} = f_p^{\mathrm{deaer}} H_p^{\mathrm{deaer}} \qquad \forall p \in P \tag{9}$$

$$f_p^{\mathrm{deaer}} = \sum_{b\in B} f_{bp}^{\mathrm{fw}} + \sum_{i\in I} f_{ip}^{\mathrm{LD}} \qquad \forall p \in P \tag{10}$$

3.4 Steam header

Within the SDN there are a lot of streams being mixed in units, and the sum of flows entering a node must equal the total mass leaving. Eq. 11 represents the mass balance for steam headers. For energy balance no matter when two or more steam flows at different conditions are assumed adiabatic mix, Eq. 12 is used to ensure that the total amount of enthalpy entering the header equals that leaving.

$$\sum_{b\in B} f_{bip} + \sum_{\substack{i'\in I \\ i'<i}} \sum_{t\in T} f_{i'tip} + f_{i-1,ip} + f_{ip}^{\mathrm{LD}} + F_{ip}^{\mathrm{PS}} = f_{p}^{\mathrm{LP}} + \sum_{\substack{i'\in I \\ i'>i}} \sum_{t\in T} f_{iti'p} + f_{i,i+1,p} + f_{p}^{\mathrm{vent}} + F_{ip}^{\mathrm{PD}} \qquad \forall i \in I, p \in P \qquad (11)$$

$$\sum_{b\in B} f_{bip} H_{ip} + \sum_{\substack{i'\in I \\ i'<i}} \sum_{t\in T} f_{i'tip} h_{i'tip} + f_{i-1,ip} H_{i-1,p} + f_{ip}^{\mathrm{LD}} H^{\mathrm{deaer}} + F_{ip}^{\mathrm{PS}} H_{ip}^{\mathrm{PS}}$$

$$= \{ f_{p}^{\mathrm{LP}} + \sum_{\substack{i'\in I \\ i'>i}} \sum_{t\in T} f_{iti'p} + f_{i,i+1,p} + f_{p}^{\mathrm{vent}} + F_{ip}^{\mathrm{PD}} \} H_{ip} \qquad \forall i \in I, p \in P \qquad (12)$$

3.5 Objective function

The objective function in the design model is given by the variable cost of equipments, while the operating cost is given by the fuel, water, cooling water and purchased electricity cost.

Table : 1 Global site conditions

Total working hrs	8,600 hrs/y
Fuel oil # 2 LHV	45,000 kJ/kg
Natural gas LHV	50,244 kJ/kg

Table : 2 Site conditions per season

Season	Base	Summer
Fraction of the yrs	67 %	33 %
Electric prices	0.07 $/kWh	0.08 $/kWh
Fuel oil # 2 prices	0.19 $/kg	0.19 $/kg
Natural gas prices	0.22 $/kg	0.22 $/kg
Raw water prices	0.05 $/ton	0.05 $/ton

Table 3: Demands data

Season	Base	Summer
VHP steam demands	112 MW	101 MW
HP steam demands	200 MW	180 MW
MP steam demands	42 MW	38 MW
LP steam demands	70 MW	63 MW
Total steam demands	424 MW	382 MW
Electricity demands	62 MW	68 MW
Condensate return	80 %	80 %
Shaft work demand 1	5.2 MW	5.0 MW
Shaft work demand 2	1.3 MW	1.1 MW
Shaft work demand 3	2.2 MW	2.0 MW
Shaft work demand 4	0.6 MW	0.6 MW

Table 4: Steam header conditions

Pressure (bar)	Temperature (℃)
101	539
20.6	333
4.1	186
2.7	150

4. Case Studies

To demonstrate the application of the MINLP model for SDN design, examples are shown as follows. This case is taken from Aguilar *et al*., (2007b) and three scenarios are considered. The site conditions are presented on Table 1-2, and the demands data/operating conditions are shown on Table 3-4. In the first scenario, the solution procedure suggested by Aguilar et al. (2007b) is followed to integrate the SDN. More specifically, steam header conditions are first determined by the proposed iterative procedure and then a MINLP model is solved accordingly to obtain a SDN with minimum total annualized cost. The resulting network is shown in Figure 2. Its TAC and the corresponding capital investment were found to be is 8.45×10^{7} and 1.11×10^{7} \$/y, respectively. The same SDN design problem is solved in scenario II with simultaneous solution strategy. Specifically, a one step solution strategy is realized to obtain the design with minimum TAC. Note header conditions are determined by running the optimization, and only one condition is allowable during all time periods. The resulting network structure is presented in Figure 3, in which four MFBs, one HRSG and six steam turbines are used. Its TAC and the corresponding capital investment were found to be 8.37×10^{7} and 1.03×10^{7} \$/y, respectively. To demonstrate the capability of proposed flexible model, a case study (scenario III) is performed. The feature of this case is not only that a one step solution strategy is realized but also that conditions are allowed to be adjusted in company with period. The resulting network structure is in Figure 4 and its corresponding TAC is 8.24×10^{7} \$/y.

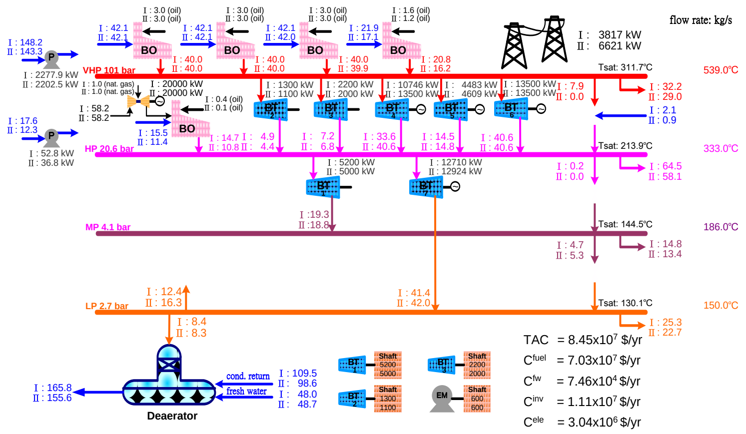

Figure 2: Optimal SDN design for scenario 1.

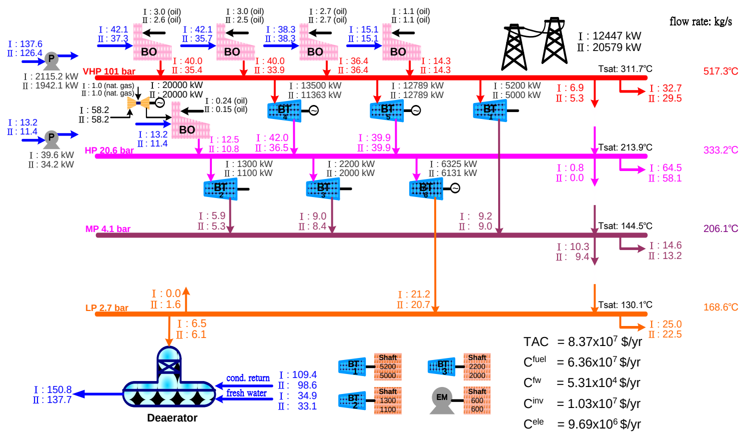

Figure 3: Optimal SDN design for scenario 2.

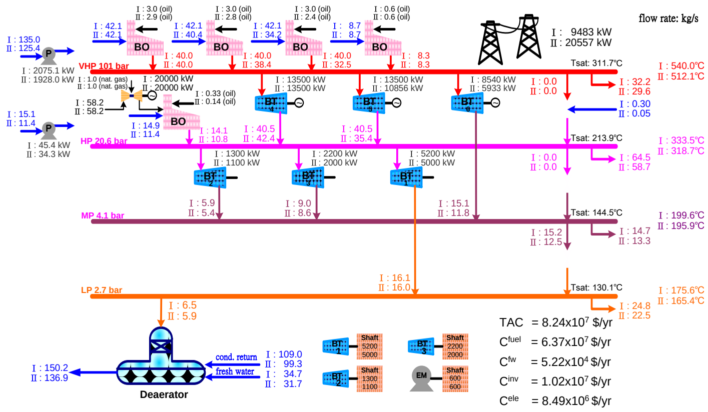

Figure 4: Optimal SDN design for scenario 3

5. Conclusion

A MINLP model for simultaneous optimization of SDN has been proposed in this study. In the application studies, it can be clearly observed that TACs of resulting SDN design are indeed better than previous methods. Theses financial savings are brought not only by adopting flexible design but also by following the proposed simultaneous optimization procedure.

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