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A mathematical approach for retrofit and optimization of total site steam distribution networks

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ABSTRACT

This paper presents a generic mathematical model for retrofitting the steam power plants in an industrial site. The industrial sector under review consists of one steel mill, one oil refinery, and several petrochemical plants, where only small-scale steam integration has been implemented before this study. The relevant unit models in a typical steam power plant are established, and the steam plant retrofit problem is formulated as a mixed-integer nonlinear program (MINLP). Feasible retrofit alternatives suggested by experienced field engineers are investigated in sequence to examine the revenue of those possible modifications. The first scenario examines operational optimization of existent plants; the second option allows installation of one new turbine and replacement of several boilers and turbines with lower efficiency; the third scenario considers using a steam ejector to upgrade the disqualified import steam in the oil refinery. The significant merits from these three retrofit alternatives show that the proposed MINLP formulation has been a great help to enhance the inter-plant steam integration in an industrial sector.

Keywords: Steam power plant; Mathematical programming; Total site integration; Mixed-integer nonlinear programming (MINLP); Process integration; Retrofit; Optimization

1. Introduction

The steam power plant in an industrial site is designed to supply most of the heat and power required by process plants. The steam systems consume a lot of primary fuel sources such as coal, oil, and natural gas. The operational efficiency of the steam systems plays an important role on the domestic energy consumption as well as the greenhouse gas emission.

A lot of studies have been done in the past few decades to improve the thermal efficiency and the greenhouse emission of the steam power plant. Nishio et al. (1980) and Chou and Shih (1987) proposed thermodynamic approach for effective design and synthesis of the plant utility systems. Papoulias and Grossmann (1983) gave a structural optimization approach for targeting and synthesis of the utility systems. Further to the analysis of a single steam power plant, Dhole and Linnhoff (1993) proposed total site integration for a set of processes served by a centralized steam system. The utility system was found one effective tool to implement the total site heat integration (Hui and Ahmad, 1994). Bandyopadhyay et al. (2010) proposed building the site utility grand composite curve to estimate the total site cogeneration potential. The application of the pinch-based total site approach for a large-scale steel plant was reported by Matsuda et al. (2012).

Those insight-based targeting and analyses are effective to maximize the thermal efficiency. The inherent high capital investment required for implementation is usually not focused. To take the optimal capital-energy trade-off into account, Bruno et al. (1998) applied mathematical methods to design the steam plant. A superstructure considering possible configurations in a steam plant was presented and the design problem was formulated as a mixed-integer model involving continuous (process states) and binary (plant configuration) variables. Shang and Kokossis (2004) considered the possibility of steam generation by processes for further improvement

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Indices

$p \in \mathcal{P}$	index for various plants
$s \in \mathcal{S}$	index for time interval
$u \in \mathcal{U}$	index for fuels
$b \in \mathcal{B}_p \subseteq \mathcal{B}$	index for boilers
$e \in \mathcal{E}_p \subseteq \mathcal{E}$	index for steam-jet ejectors
$i \in \mathcal{I}_p \subseteq \mathcal{I}$	index for pressure levels or steam headers
$j \in \mathcal{J}_p \subseteq \mathcal{J}$	index for shaft demands
$t \in \mathcal{T}_p \subseteq \mathcal{T}$	index for steam turbines

Sets

$\mathcal{B}$	$\{b \mid b$ is a boiler, $b = 1, 2, \ldots, B\}$
$\mathcal{BT}$	$\{t \mid t$ is a back-pressure steam turbine, $t = 1, 2, \ldots, BT\}$
$\mathcal{CT}$	$\{t \mid t$ is a condensing steam turbine, $t = 1, 2, \ldots, CT\}$
$\mathcal{E}$	$\{e \mid e$ is a steam ejector, $e = 1, 2, \ldots, E\}$
$\mathcal{I}$	$\{i \mid i$ is a pressure level, $i = 1, 2, \ldots, I\}$
$\mathcal{J}$	$\{j \mid j$ is a shaft demand, $j = 1, 2, \ldots, J\}$
$\mathcal{T}$	$\{t \mid t$ is a steam turbine, $t = 1, 2, \ldots, T\}$
$\mathcal{TE}$	$\{t \mid t$ is a steam turbine for generating electricity, $t = 1, 2, \ldots, TE\}$
$\mathcal{TS}$	$\{t \mid t$ is a steam turbine for producing shaft power, $t = 1, 2, \ldots, TS\}$
$\mathcal{U}$	$\{u \mid u$ is a fuel, $u = 1, 2, \ldots, U\}$

Parameters

C_u	unit cost of fuel u, $ kg^{-1}
C^{cw}	unit cost of cooling water, $ kg^{-1}
$C^{exp,e}$	unit cost of exported electricity, $ kW h^{-1}
$C^{exp,s}$	unit cost of exported steam, $ kg^{-1}
$C^{imp,e}$	unit cost of imported electricity, $ kW h^{-1}
$C^{imp,s}$	unit cost of imported steam, $ kg^{-1}
F_i^{pd}	process demanded steam at header i, kg s^{-1}
F_i^{ps}	steam from process entering header i, kg s^{-1}
H_i^{ps}	enthalpy of steam supplied by processes and delivered at header i, kJ kg^{-1}
$H_i^{sat,l}$	enthalpy of saturated steam at steam header i, kJ kg^{-1}
H_u^{LHV}	low heating value for fuel u, kJ kg^{-1}
H^{da}	enthalpy of water leaving a deaerator, kJ kg^{-1}
R_{ei}	flow ratio of import to carrying steams for ejector e connected to header i
t^{hrs}	total operating time, h
$\Delta T_{ii'}^{sat}$	inlet-outlet saturation temperature difference across turbine, °C
Y_{bu}	a ratio of fuel to all fuels used in boiler b
$W_{ii't}^{d}$	design shaft output, kW
$W_j^{dem,s}$	shaft demand j, kW
$W^{dem,e}$	total electricity demand, kW
N_p^{max}	maximum number of additional units in plant p
φ	fixed blowdown fraction for boilers
η_b	boiler efficiency of steel mill and oil refinery are 0.9 and 0.93 respectively
Ω	an arbitrary larger number
$\overline{\Omega}_b$, $\underline{\Omega}_b$	upper/lower bounds of steam flow rate for boiler b, kg s^{-1}
$\overline{\Omega}_D$, $\underline{\Omega}_D$	upper/lower bounds of steam flow rate for deaerator, kg s^{-1}
$\overline{\Omega}_e$, $\underline{\Omega}_e$	upper/lower bounds of steam flow rate for steam-jet ejector e, kg s^{-1}
$\overline{\Omega}_s$, $\underline{\Omega}_s$	upper/lower bounds of steam flow rate for steam main s, kg s^{-1}
$\overline{\Omega}_t$, $\underline{\Omega}_t$	upper/lower bounds of steam flow rate for steam turbine t, kg s^{-1}
$\overline{\Gamma}_t$, $\underline{\Gamma}_t$	upper/lower bounds of power generation for steam turbine t, kg s^{-1}

Continuous variables

f_b^{bfw}	boiler feed water for boiler b, kg s^{-1}
f_{bi}	steam output from boiler b to steam header i, kg s^{-1}
f_{bi}^{bd}	blowdown water for boiler b at pressure i, kg s^{-1}
f_{bu}	fuel u consumed in boiler b, kg s^{-1}
f_{ei}	steam flow rate from ejector e to header i, kg s^{-1}
f_i^{da}	steam flow rate from header i to deaerator, kg s^{-1}
$f_{ii'}$	steam flow rate from header i to header i', kg s^{-1}
$f_{ii't}$	steam flow rate from header i to header i' through a steam turbine t, kg s^{-1}
$f_{i'ei}$	steam flow rate from header i' to header i via ejector e, kg s^{-1}
f_{is}	steam flow rate from header i to main s, kg s^{-1}
f_i^{ld}	desuperheating boiler feedwater injected into header i, kg s^{-1}
f_i^{vt}	vented steam at header i, kg s^{-1}
f_{sei}	steam flow rate from main s to header i via ejector e, kg s^{-1}
f_{si}	steam flow rate from main s to header i, kg s^{-1}
f_{si}^{pd}	process demanded steam is injected from main s instead of header i, kg s^{-1}
f^c	condensate return, kg s^{-1}
f^w	demineralized water makeup, kg s^{-1}
h_{bi}	enthalpy of steam generated by boiler b entering header i, kJ kg^{-1}
h_{ei}	enthalpy of discharge by ejector e entering header i, kJ kg^{-1}
h_i	enthalpy of steam header i, kJ kg^{-1}
h_{it}	outlet enthalpy of condensing steam turbine t, kJ kg^{-1}
$h_{ii't}$	enthalpy of discharge by steam turbine t entering header i', kJ kg^{-1}
$\Delta h_{ii't}^{is}$	insentropic inlet–outlet enthalpy difference across turbine, kJ kg^{-1}
h_s	enthalpy of steam header s, kJ kg^{-1}
q_b	heat added to the feed water in boiler b, kW
$q_{ii't}^{cw}$	cooling water used for condensing turbine t, kW
$w_{ii't}$	power produced by steam turbine t, kW
w_{tj}	shaft power produced by steam turbine t to shaft demand j, kW
$w^{exp,e}$	electricity exported, kW
$w^{imp,e}$	electricity imported, kW
$\mathbf{x}$	vector of continuous variables

Binary variables

$z_b = 1$	presence of boiler b
$z_{bi} = 1$	connection of boiler b and header i
$z_e = 1$	presence of steam ejector e
$z_{ii't} = 1$	connection of steam turbine t between i and i’ headers
$z_{is} = 1$	connection of steam header i and main s (steam export)