Applied Thermal Engineering xxx (2013) 1–10

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Retrofit of steam power plants in a petroleum refinery

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HIGHLIGHTS

- A steam system model is developed for the analysis of existing steam power plant in a refinery.
- Optimization and retrofit strategies are taken into account to improve the site performance.
- The best energy utilization is determined by the optimization.

ARTICLE INFO

Article history:
Received 17 October 2012
Accepted 1 April 2013
Available online xxx

Keywords:
Steam system
Total site integration
Optimization
Retrofit
MINLP

ABSTRACT

A comprehensive mathematical model is developed for the operational optimization and retrofit of industrial steam systems. The problem of maximizing the cost reduction given by the difference in annual operating costs minus the annualized investment cost of the retrofit is formulated as a mixed integer nonlinear program (MINLP) based on a collection of unit models. The steam power plant of a traditional petroleum refinery is analyzed and retrofitted based on the proposed MINLP formulation. The operating conditions are firstly optimized to investigate whether there is room for improvement without modifying existent units or layout. Thereafter, retrofit possibilities on internal steam turbine or layout are taken into account to enhance steam utilization efficiency. Feasible method for inspiring the total site steam integration among adjacent companies is finally deliberated, where the steam ejector is adopted to upgrade the lower pressure import steam for being directed into the existent steam headers. The results of various degrees of retrofit on the steam system of a practical refinery verify the applicability of the proposed approach.

1. Introduction

Steam systems are a major fuel consumer in industry and the main energy supplier for industrial process plants. Modern steam systems are typically designed for combined heat and power generation (or cogeneration). Numerous investigations have been conducted in the past few decades to improve the energy performance of steam systems.

Methodologies for obtaining the optimal steam system configurations can be broadly divided into heuristics with thermal targets and mathematical optimization techniques. Heuristic methods for the synthesis of steam systems were first studied by Nishio et al. [1]. Chou and Shih [2] also applied the thermodynamic approach to the design of plant utility systems. The objective of their approaches is to achieve the maximum thermal efficiency of the plants. However, such designs normally require high capital investment and are therefore not necessarily attractive from the point of view of total cost. To establish the optimal capital-energy trade-off, Bruno et al. [3] proposed mathematical optimization methods for designing steam plants, taking into account different conflicting objectives (e.g. operating and capital costs). All the possible configurations are systematically considered with a superstructure, and the corresponding optimization models are mixed-integer programs involving continuous and discrete (binary) variables.

For multi-period operation of utility systems, Hui and Natori [4] developed a mixed-integer linear programming (MILP) technique incorporating discrete decisions such as turning equipment on and off. Iyer and Grossmann [5] later presented a decomposition algorithm, in which a two-stage approach involving the solution of the MILP subproblems was developed along with the shortest path algorithm to reduce the computational expense. In addition, Maia and Qassim [6] used simulated annealing to synthesize utility systems with variable demands. Micheletto et al. [7] focused on operational optimization of the utility system of a practical oil refinery.

Dhole and Linnhoff [8] proposed total site integration for a set of processes served by a centralized steam system, with a targeting approach developed for sites consisting of multiple processes. This approach was then extended by Hui and Ahmad [9], and it was shown that reducing exergy losses in heat exchanger networks will ultimately benefit power generation in steam systems. Klemeš

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http://dx.doi.org/10.1016/j.applthermaleng.2013.04.001

et al. [10] extended the targeting and design methodology for reduction of fuel, power and CO_2 on total sites. Bandyopadhyay et al. [11] proposed using 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 presented by Matsuda et al. [12]. Abadi et al. [13] studied the integration methodology for the steam power plant and the process utility system. Ghannadzadeh et al. [14] developed a new shaft work targeting model for the estimation of cogeneration potential prior to the design of the total site utility system. In addition, a numerical technique for total site sensitivity analysis was developed by Liew et al. [15] to assess the impact of operational changes on a cogeneration system. Recently, the total site concept has been extended to a broader set of entities, including various industrial entities, commercial and service buildings and residential areas [16].

Apart from targeting, network design for steam systems with total site integration was performed by Papoulias and Grossmann [17], who combined the MILP models and the transshipment model for the simultaneous synthesis of utility and heat recovery systems. It was mentioned that this strategy does not include energy transfer from the process plant to the utility plant. Shang and Kokossis [18] later considered the possibility of steam generation by processes so that the total site performance can be improved further. Similar work has also been addressed by Chen and Lin [19], with steam header levels automatically determined by optimization. In addition, Varbanov et al. [20] used a similar technique to address the cost-effective de-carbonization problem. Note that the above-mentioned works have focused mainly on the design of steam systems. To overcome this limitation, Chen and Lin [21] recently presented simultaneous network design of steam and heat recovery systems, and emphasized its application on chemical plants [22].

For total site energy integration in industrial sectors, the basic idea is business cooperation in an attempt to share resources (e.g. materials, water, energy, etc.) efficiently to reduce waste and pollution, increase economic gains and improve environmental performance for sustainable development. Mattila et al. [23] assessed the total environmental impacts of an industrial symbiosis. Zhang et al. [24] developed an approach to early planning and design of the total site around an oil refinery. The proposed methodology can model the energy and material flows between the prospective members and quantify the benefits of integrating different firms. For total site heat integration, it is essential to determine the amounts of sources or energy to be imported or exported before practical implementation. This is no doubt a challenge for the companies because they would have to analyze a series of scenarios for decision making, and the alternatives involve changes of operation and various retrofits of the existent layout. Fortunately, this difficulty can readily be dealt with through the application of total site integration techniques, assuming that sources can be imported or exported within an industrial park.

In this paper, the objective is to develop a steam system model to analyze and assess existing steam power plants. The model will be able to handle the general operation, retrofit and total site steam integration problem.

2. Problem definition

The problem studied in this article focuses on the optimization and retrofit of an existent steam power plant in a traditional refinery. Fig. 1 shows the plant layout and current operating conditions. There are three boilers producing steam at 101 (B1 and the site boiler) and 20.6 bar (B3), four levels of steam headers (101 bar, 20.6 bar, 4.5 bar and condensate) and four steam turbines (ST1 for generating electricity and ST2-ST4 for providing shaft power). Although the site boiler at the refinery complex produces 208.3 t/h of steam (101 bar) for self use, the steam plant still has to provide three levels of steam and electricity to satisfy heating and power demands of the refinery processes. Currently, the steam plant imports 35 t/h of medium pressure steam (18 bar and 215 °C) from an adjacent steel mill for local heating. The import flow rate may be increased to 120 t/h if the steam can be upgraded to 20.6 bar and 260 °C. In order to improve the efficiency of steam utilization and promote total site steam integration, it is desired to examine the existing steam system and propose feasible solutions to increase steam import from the steel mill, where steam is produced at a much lower cost than in the refinery. For comprehensive studies, this work involves operational optimization of the existent steam plant and exploring its retrofit possibilities. The former is to improve the performance of the current layout, while the latter provides additional options to overcome the limitations of the existent system.

3. Model formulation

In order to take into account various operational optimization and retrofit options efficiently, a mixed-integer nonlinear programming (MINLP) model is developed for the refinery steam system. As mentioned earlier, the goal would be to import more steam from the adjacent steel mill. This steam system model is based on a collection of unit models shown in Fig. 2, which consists of boilers $b \in \mathcal{B}$ (Fig. 2(a)) to produce different levels of steam, steam turbines $t \in \mathcal{T}$ (Fig. 2(b)) to provide shaft power or generate electricity, and headers $i \in \mathcal{I}$ (Fig. 2(c)) for steam distribution. These unit models collectively act as a superstructure to represent an existing steam system and its retrofit options. The proposed model is comprised mainly of mass and energy balance equations and logical constraints representing flow rate and capacity limits as well as the interconnection of units.

Modeling equations associated with boilers, steam turbines, steam headers and shaft demands ($j \in \mathcal{J}$) are presented below. It is first assumed that the imported level i steam can directly be used in the process, in which case the process steam demand (F_i^{pd}) will be reduced by the amount of steam import ($f_i^{\mathrm{imp,s}}$).

Eqs. (1) and (2) describe the mass and energy balances for header i. As shown in Fig. 2(c), the inlet streams may be steam from boilers b (f_{bi}), steam turbines t connected to higher pressure headers i' ($f_{i'it}$), the higher pressure header i' ($f_{i'i}$), process supply (F_i^{ps}) or import ($f_i^{\mathrm{imp,s}}$), or may be water through the let-down station (f_i^{ld}); while the outlet steam of header i may be discharged to the lower pressure header i' through turbine t ($f_{ii't}$), dispatched to meet the process demand (F_i^{pd}), vent to the environment (f_i^{vent}) or exported ($f_i^{\mathrm{exp,s}}$) to neighboring sites.

$$\sum_{b\in\mathcal{B}} f_{bi} + \sum_{\substack{i'\in\mathcal{I}\\ i'<i}} \sum_{t\in\mathcal{T}} f_{i'it} + \sum_{\substack{i'\in\mathcal{I}\\ i'<i}} f_{i'i} + f_i^{\mathrm{ld}} + F_i^{\mathrm{ps}} = \sum_{\substack{i'\in\mathcal{I}\\ i'>i}} \sum_{t\in\mathcal{T}} f_{ii't} + \sum_{\substack{i'\in\mathcal{I}\\ i'>i}} f_{ii'} + F_i^{\mathrm{pd}} - f_i^{\mathrm{imp,s}} + f_i^{\mathrm{vent}} + f_i^{\mathrm{exp,s}} \quad \forall i\in\mathcal{I} \tag{1}$$

$$\sum_{b\in\mathcal{B}} f_{bi}h_{bi} + \sum_{\substack{i'\in\mathcal{I}\\ i'<i}} \sum_{t\in\mathcal{T}} f_{i'it}h_{i'it} + \sum_{\substack{i'\in\mathcal{I}\\ i'<i}} f_{i'i}h_{i'} + f_i^{\mathrm{ld}}H^{\mathrm{deaer}} + F_i^{\mathrm{ps}}H_i^{\mathrm{ps}} = \left(\sum_{\substack{i'\in\mathcal{I}\\ i'>i}} \sum_{t\in\mathcal{T}} f_{ii't} + \sum_{\substack{i'\in\mathcal{I}\\ i'>i}} f_{ii'} + F_i^{\mathrm{pd}} - f_i^{\mathrm{imp,s}} + f_i^{\mathrm{vent}} + f_i^{\mathrm{exp,s}} \right) h_i \quad \forall i\in\mathcal{I} \tag{2}$$

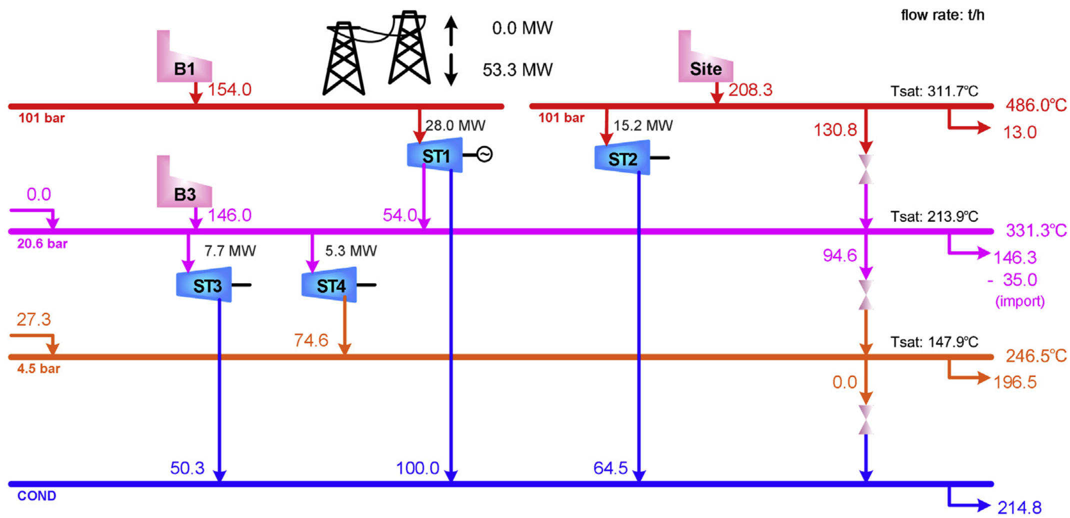

Fig. 1. Steam distribution network for the existent plant.

Eq. (3) defines the mass balance for boiler b: the feed water flow rate ($f_b^{\rm bfw}$) is equal to the amount of steam produced (f_{bi}) plus the blowdown flow rate ($f_{bi}^{\rm bd}$). The blowdown water is extracted as saturated liquid, and its flow rate is assumed to be a fixed fraction (φ) of the steam production, as given in Eq. (4). Eq. (5) describes the energy balance for boiler b. The fuel consumption (f_{bu}) is given by Eq. (6), where Z_{bu} is a binary parameter indicating whether fuel u is used in boiler b ($Z_{bu}=1$) or not ($Z_{bu}=0$), η_b the efficiency of boiler b, and $H_u^{\rm LHV}$ the low heating value of fuel u.

$$f_b^{\rm bfw} = \sum_{i\in\mathcal{I}} f_{bi} + \sum_{i\in\mathcal{I}} f_{bi}^{\rm bd} \quad \forall b\in\mathcal{B} \tag{3}$$

$$f_{bi}^{\rm bd} = \varphi f_{bi} \quad \forall b\in\mathcal{B},\ i\in\mathcal{I} \tag{4}$$

$$f_b^{\rm bfw} H^{\rm deaer} + q_b = \sum_{i\in\mathcal{I}} f_{bi} h_{bi} + \sum_{i\in\mathcal{I}} f_{bi}^{\rm bd} H_i^{\rm sat,l} \quad \forall b\in\mathcal{B} \tag{5}$$

$$f_{bu} = \frac{Z_{bu} q_b}{\eta_b H_u^{\rm LHV}} \quad \forall b\in\mathcal{B},\ u\in\mathcal{U} \tag{6}$$

The steam turbine performance model adopted in this work can be found in Aguilar et al. [25]. Rated turbine performance is usually reported as curves on an isentropic efficiency versus flow rate plot (e.g. Ref. [26]) so that the design shaft power and steam mass flow through a turbine can be determined graphically. If this information is used to plot the isentropic power against the real shaft output, the resulting trends are linear and can be represented with linear equations. To incorporate both rated and part-load operation of the equipment into mathematical expressions, the Willans' Line concept [27] can be exploited, given that it represents part-load turbine performance with a linear equation. Eqs. (7)–(11) present the performance model, in which the shaft power produced by steam turbine t between headers i and i' ($w_{ii't}$) is a function of its unit size ($W_{ii't}^{\rm d}$), unit load ($f_{ii't}$) and inlet–outlet steam conditions, namely the isentropic enthalpy difference ($\Delta h_{ii't}^{\rm is}$) and the saturation temperature difference ($\Delta T_{ii'}^{\rm sat}$). The numerical values of those regression coefficients are shown in Table 1.

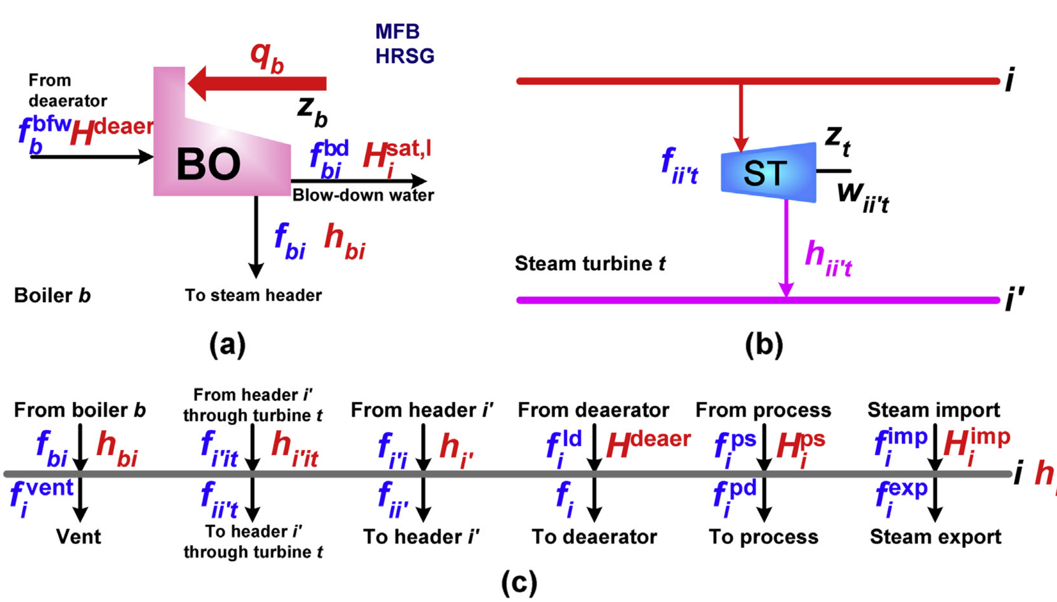

Fig. 2. Unit models for a typical steam distribution network: (a) boiler (b) steam turbine (c) steam header.

Table 1
Regression coefficients for the steam turbine model.

	Back-pressure turbines ($t\in\mathcal{BT}$)	Condensing turbines ($t\in\mathcal{CT}$)	Units
a_0	10.000000	−0.000021	kW
a_1	7.000000	0.297263	kW/°C
a_2	1.312466	1.601699	–
a_3	−0.000910	−0.001596	1/°C
a_L	0.224361	−0.010000	–
b_L	−0.000777	0.000326	1/°C

$$w_{ii't} = \Delta h^{\text{is}}_{ii't}\frac{L_{ii''}+1}{B_{ii'}}f_{ii't} - L_{ii'}W^{\text{d}}_{ii't} - (L_{ii'}+1)\,\frac{A_{ii'}}{B_{ii'}} \quad \forall i,\ i'\in\mathcal{I},\ t\in\mathcal{T} \tag{7}$$

$$f_{ii't}h_{ii't} = f_{ii't}\left(h_i - 0.838\Delta h^{\text{is}}_{ii't}\right) + 809.721 \quad \forall i,\ i'\in\mathcal{I},\ t\in\mathcal{T} \tag{8}$$

$$A_{ii'} = a_0 + a_1\Delta T^{\text{sat}}_{ii'} \quad \forall i,\ i'\in\mathcal{I} \tag{9}$$

$$B_{ii'} = a_2 + a_3\Delta T^{\text{sat}}_{ii'} \quad \forall i,\ i'\in\mathcal{I} \tag{10}$$

$$L_{ii'} = a_{\text{L}} + b_{\text{L}}\Delta T^{\text{sat}}_{ii'} \quad \forall i,\ i'\in\mathcal{I} \tag{11}$$

Eq. (12) represents the cooling water requirement ($q^{\text{cw}}_{ii't}$) for a condensing steam turbine to enhance its performance:

$$q^{\text{cw}}_{ii't} = f_{ii't}(h_{ii't} - h_{i't}) \quad \forall i,\ i'\in\mathcal{I},\ t\in\mathcal{CT} \tag{12}$$

where $h_{ii't}$ and $h_{i't}$ are the enthalpies of the outlet steam of condensing turbine t and its condensate to header i'.

For steam turbines employed to satisfy shaft demands ($W^{\text{dem,s}}_j$), Eqs. (13) and (14) ensure that the actual power delivered by drivers attached to a common shaft meets the corresponding demand:

$$\sum_{\substack{i,i'\in\mathcal{I}\\ i<i'}} w_{ii't} = \sum_{j\in\mathcal{J}} w_{tj} \quad \forall t\in\mathcal{TS} \tag{13}$$

$$\sum_{t\in\mathcal{TS}} w_{tj} = W^{\text{dem,s}}_j \quad \forall j\in\mathcal{J} \tag{14}$$

where w_{tj} is the shaft power from turbine t to demand j. Eq. (15) depicts the overall power balance for the steam system, in which there are also steam turbines generating electricity to satisfy the power demand ($W^{\text{dem,e}}$). Note that electricity import ($w^{\text{imp,e}}$) and export ($w^{\text{exp,e}}$) are considered as there can be a power deficit or surplus.

$$\sum_{\substack{i,i'\in\mathcal{I}\\ i<i'}}\sum_{t\in\mathcal{TE}} w_{ii't} + w^{\text{imp,e}} = W^{\text{dem,e}} + w^{\text{exp,e}} \tag{15}$$

In addition, it is assumed that the electricity generated by the steam system cannot be exported unless all the device and process demands are satisfied. This is ensured by Eq. (16), which prevents the electricity import and export from occurring at the same time. Eqs. (17) and (18) are introduced to correlate the binary variables with the continuous variables, with Ω being a large enough upper bound.

$$z^{\text{imp,e}} + z^{\text{exp,e}} \le 1 \tag{16}$$

$$w^{\text{imp,e}} \le \Omega z^{\text{imp,e}} \tag{17}$$

$$w^{\text{exp,e}} \le \Omega z^{\text{exp,e}} \tag{18}$$

Logical constraints using binary variables are imposed to limit the interconnection of units. Eq. (19) states that an existing boiler b ($z_b = 1$) generates one level of steam, and therefore one connection exists between the boiler and a steam header (one nonzero z_{bi}). Similarly, Eq. (20) states that an operating steam turbine t ($z_t = 1$) can deliver power to one shaft demand (at most one nonzero z_{tj}). Eq. (21) ensures that a turbine works between a higher and a lower pressure headers ($z_{ii't} = 1$).

$$z_b = \sum_{i\in\mathcal{I}} z_{bi} \quad \forall b\in\mathcal{B} \tag{19}$$

$$z_t \ge \sum_{j\in\mathcal{J}} z_{tj} \quad \forall t\in\mathcal{T} \tag{20}$$

$$z_{ii't} \le z_t \le \sum_{\substack{i,i'\in\mathcal{I}\\ i<i'}} z_{ii't} \quad \forall i,i'\in\mathcal{I}, i<i', t\in\mathcal{T} \tag{21}$$

The following constraints represent the upper and lower limits for the flow rates and the amounts of power produced/delivered:

$$\underline{\Omega}_b z_{bi} \le f_{bi} \le \overline{\Omega}_b z_{bi} \quad \forall b\in\mathcal{B},\ i\in\mathcal{I} \tag{22}$$

$$\underline{\Omega}_t z_{ii't} \le f_{ii't} \le \overline{\Omega}_t z_{ii't} \quad \forall i,\ i'\in\mathcal{I},\ i<i',\ t\in\mathcal{T} \tag{23}$$

$$\underline{\Gamma}_t z_{ii't} \le w_{ii't} \le \overline{\Gamma}_t z_{ii't} \forall i,\ i'\in\mathcal{I},\ i<i',\ t\in\mathcal{T} \tag{24}$$

$$\underline{\Gamma}_t z_{tj} \le w_{tj} \le \overline{\Gamma}_t z_{tj} \quad \forall j\in\mathcal{J},\ t\in\mathcal{TS} \tag{25}$$

where $\underline{\Omega}_b$, $\underline{\Omega}_t$ and $\underline{\Gamma}_t$ are lower bounds; $\overline{\Omega}_b$, $\overline{\Omega}_t$ and $\overline{\Gamma}_t$, upper bounds.

The retrofit of steam systems may involve adding new units, which are mostly boilers and turbines in refinery cases. Eq. (26) is then introduced to limit the maximum number of additional units:

$$\sum_{b\in\mathcal{B}^*} z_b + \sum_{t\in\mathcal{T}^*} z_t \le N^{\max} \tag{26}$$

where $\mathcal{B}^*$ and $\mathcal{T}^*$ are the sets of new boilers and turbines respectively.

In the case that the import steam can directly be utilized in the process, the objective function for steam system optimization and retrofitting is to maximize the cost reduction given by the difference in annual operating cost (AOC) minus the annualized investment cost of the retrofit ($J^{\text{AIC}}_{\text{ret,P1}}$):

$$\mathbf{P1}: \max_{\boldsymbol{x}_{P1},\boldsymbol{z}_{P1}\in\boldsymbol{\Omega}_{P1}} J_{P1} = J^{AOC}_{base} - J^{AOC} - J^{AIC}_{ret,P1}$$

$$J^{AOC} = \left(\sum_{b\in\mathcal{B}}\sum_{u\in\mathcal{U}} C_u f_{bu} + \sum_{i,i'\in\mathcal{I}}\sum_{t\in\mathcal{TC}} C^{cw} q^{cw}_{ii't} + \sum_{i\in\mathcal{I}} C^{imp,s}_i f^{imp,s}_i \right.$$
$$\left. - \sum_{i\in\mathcal{I}} C^{exp,s}_i f^{exp,s}_i + C^{imp,e} w^{imp,e} - C^{exp,e} w^{exp,e} \right) t^{hrs}$$

$$J^{AIC}_{ret,P1} = A\sum_{b\in\mathcal{B}^*}\left(z_b C^{fix}_b + C^{var}_b \sum_{i\in\mathcal{I}} f_{bi} \right) + A\sum_{t\in\mathcal{T}^*}\left(z_t C^{fix}_t + C^{var}_t \sum_{i,i'\in\mathcal{I}} f_{ii't} \right)$$

where $\boldsymbol{x}_{P1}$ and $\boldsymbol{z}_{P1}$ are vectors of the continuous and binary variables respectively, $\boldsymbol{\Omega}_{P1}$ a feasible solution space defined by the constraints, and A the annualization factor. The numerical value of A will be 0.2 in the following case studies.

$$\boldsymbol{x}_{P1} \equiv \left\{ \begin{array}{c} f^{bfw}_b, f_{bi}, f^{bd}_{bi}, f_{bu}, f_{ii'}, f_{ii't}, f^{ld}_i, f^{vent}_i, f^{imp,s}_i, f^{exp,s}_i, \\ h_{bi}, h_i, h_{ii't}, \Delta h^{is}_{ii't}, q_b, q^{cw}_{ii't}, w_{ii't}, w_{tj}, w^{imp,e}, w^{exp,e} \\ \forall b\in\mathcal{B}, i, i'\in\mathcal{I}, j\in\mathcal{J}, t\in\mathcal{T}, u\in\mathcal{U} \end{array} \right\}$$

$$\boldsymbol{z}_{P1} \equiv \left\{ \begin{array}{l} z_b, z_t, z_{bi}, z_{tj}, z_{ii't}, z^{imp,e}, z^{exp,e} \\ \forall b\in\mathcal{B}, i, i'\in\mathcal{I}, j\in\mathcal{J}, t\in\mathcal{T}, u\in\mathcal{U} \end{array} \right\}$$

$$\Omega_{P1} = \{\boldsymbol{x}_{P1}, z_{P1} | \text{Eqs.}(1)-(26)\}$$

With the use of binary variables and the presence of bilinear terms in the energy balance equations, model **P1** is an MINLP.

For other cases where the import steam is not qualified to be directly utilized, a simple and economical way of improving its quality is needed. Given the investment and maintenance costs, it is proposed to use steam ejector(s). Let f_{ei} be the steam flow rate from steam-jet ejector e to steam header i, and $f_{iei'}$ the flow rate of high pressure level i steam used in ejector e to upgrade the low pressure import steam to level i (or the steam flow rate from header i to i' via ejector e). Thus, the mass and energy balances for header i, Eqs. (1) and (2), are rewritten as in Eqs. (27) and (28):

$$\sum_{b\in\mathcal{B}} f_{bi} + \sum_{\substack{i'\in\mathcal{I}\\ i'<i}}\sum_{t\in\mathcal{T}} f_{i'it} + \sum_{\substack{i'\in\mathcal{I}\\ i'<i}} f_{i'i} + f^{ld}_i + F^{ps}_i + \sum_{e\in\varepsilon} f_{ei}$$
$$= \sum_{\substack{i'\in\mathcal{I}\\ i'>i}}\sum_{t\in\mathcal{T}} f_{ii't} + \sum_{\substack{i'\in\mathcal{I}\\ i'>i}} f_{ii'} + F^{pd}_i + f^{vent}_i + f^{exp,s}_i + \sum_{\substack{i'\in\mathcal{I}\\ i'>i}}\sum_{e\in\varepsilon} f_{iei'} \quad \forall i\in\mathcal{I} \tag{27}$$

$$\sum_{b\in\mathcal{B}} f_{bi}h_{bi} + \sum_{\substack{i'\in\mathcal{I}\\ i'<i}}\sum_{t\in\mathcal{T}} f_{i'it}h_{i'it} + \sum_{\substack{i'\in\mathcal{I}\\ i'<i}} f_{i'i}h_{i'} + f^{ld}_i H^{deaer} + F^{ps}_i H^{ps}_i$$
$$+ \sum_{e\in\varepsilon} f_{ei}h_{ei} = \left(\sum_{\substack{i'\in\mathcal{I}\\ i'>i}}\sum_{t\in\mathcal{T}} f_{ii't} + \sum_{\substack{i'\in\mathcal{I}\\ i'>i}} f_{ii'} + F^{pd}_i + f^{vent}_i \right.$$
$$\left. + f^{exp,s}_i + \sum_{\substack{i'\in\mathcal{I}\\ i'>i}}\sum_{e\in\varepsilon} f_{iei'} \right) h_i \quad \forall i\in\mathcal{I} \tag{28}$$

The following constraints describe the mass and energy balances for steam-jet ejector e. Eq. (29) states that the low pressure import steam ($f^{imp,s}_{i''}$) may be upgraded to different levels i through ejectors e. The steam flow from ejector e to header i (f_{ei}) is comprised of the upgraded import steam ($f^{imp,s}_{i''ei}$) and the used high pressure steam ($f_{i'ei}$), as given in Eqs. (30) and (31).

$$f^{imp,s}_{i''} = \sum_{\substack{i\in\mathcal{I}\\ i<i''}}\sum_{e\in\varepsilon} f^{imp,s}_{i''ei} \quad \forall i''\in\mathcal{I} \tag{29}$$

$$f_{ei} = \sum_{\substack{i''\in\mathcal{I}\\ i''>i}} f^{imp,s}_{i''ei} + \sum_{\substack{i'\in\mathcal{I}\\ i'<i}} f_{i'ei} \quad \forall e\in\varepsilon, i\in\mathcal{I} \tag{30}$$

$$f_{ei}h_{ei} = \sum_{\substack{i''\in\mathcal{I}\\ i''>i}} f^{imp,s}_{i''ei}H^{imp,s}_{i''} + \sum_{\substack{i'\in\mathcal{I}\\ i'<i}} f_{i'ei}h_{i'} \quad \forall e\in\varepsilon, i\in\mathcal{I} \tag{31}$$

For any ejector to make level i steam, the entrainment ratio ($R_{i''i'i}$) is defined in Eq. (32) as the ratio of the level i'' to level i steam flow rate:

$$R_{i''i'i} \geq \frac{f^{imp,s}_{i''ei}}{f_{i'ei}} \quad \forall e\in\varepsilon, i, i', i''\in\mathcal{I}, i'<i<i'' \tag{32}$$

In addition, Eqs. (33)–(35) are imposed to limit the connections of steam ejectors. As stated, an ejector is only allowed to use steam at a high pressure level i' to upgrade the import steam at a low pressure (level i'') to a medium level i.

$$z_e \geq \sum_{i''\in\mathcal{I}} z_{i''i'ei} \quad \forall e\in\varepsilon, i', i\in\mathcal{I}, i'<i \tag{33}$$

$$z_e \geq \sum_{i'\in\mathcal{I}} z_{i''i'ei} \quad \forall e\in\varepsilon, i'', i\in\mathcal{I}, i''>i \tag{34}$$

$$z_e \geq \sum_{i\in\mathcal{I}} z_{i''i'ei} \quad \forall e\in\varepsilon, i'', i'\in\mathcal{I}, i''>i' \tag{35}$$

The flow rate constraints for ejectors are given by Eqs. (36)–(38):

$$\underline{Q}_e \sum_{i'\in\mathcal{I}} z_{i''i'ei} \leq f^{imp,s}_{i''ei} \leq \overline{Q}_e \sum_{i'\in\mathcal{I}} z_{i''i'ei} \quad \forall e\in\varepsilon, i'', i\in\mathcal{I}, i''>i \tag{36}$$

$$\underline{Q}_e \sum_{i''\in\mathcal{I}} z_{i''i'ei} \leq f_{i'ei} \leq \overline{Q}_e \sum_{i''\in\mathcal{I}} z_{i''i'ei} \quad \forall e\in\varepsilon, i', i\in\mathcal{I}, i'<i \tag{37}$$

$$\underline{Q}_e \sum_{i'',i'\in\mathcal{I}} z_{i''i'ei} \leq f_{ei} \leq \overline{Q}_e \sum_{i'',i'\in\mathcal{I}} z_{i''i'ei} \quad \forall e\in\varepsilon, i\in\mathcal{I} \tag{38}$$

In cases where the import steam is to be upgraded, the objective function is also to maximize the cost reduction:

$$\mathbf{P2}: \max_{\boldsymbol{x}_{P2},\boldsymbol{z}_{P2}\in\boldsymbol{\Omega}_{P2}} J_{P2} = J^{AOC}_{base} - J^{AOC} - J^{AIC}_{ret,P2}$$

$$J^{AIC}_{ret,P2} = J^{AIC}_{ret,P1} + A\sum_{e\in\varepsilon}\left(z_e C^{fix}_e + C^{var}_e \sum_{e\in\varepsilon}\sum_{i\in\mathcal{I}} f_{ei} \right)$$

$$\boldsymbol{x}_{P2} \equiv \boldsymbol{x}_{P1} \cup \left\{ f^{imp,s}_{i''}, f^{imp,s}_{i''ei}, f_{i',ei}, f_{ei}, h_{ei} \quad \forall e\in\varepsilon, i, i', i''\in\mathcal{I} \right\}$$

$$\boldsymbol{z}_{P2} \equiv \boldsymbol{z}_{P1} \cup \{ z_e, z_{i''i'ei} \quad \forall e\in\varepsilon, i, i', i''\in\mathcal{I} \}$$

$$\boldsymbol{\Omega}_{P2} = \{\boldsymbol{x}_{P2}, \boldsymbol{z}_{P2} | \text{Eqs.}(3)-(38)\}$$

This model (**P2**) is also an MINLP.

4. Industrial case study

A real steam system in a petroleum refinery is considered for operational optimization and retrofits to demonstrate the application of the proposed model. Fig. 1 shows the current layout and operating conditions of the steam system, with the demands data shown in Tables 2 and 3. The steam system has three boilers, four levels of steam headers and four steam turbines. Note that there are two 101-bar headers operating separately. In addition, the steam production rate of the site boiler (208.3 t/h) is fixed. As for the steam turbines, ST1 is used for power generation (28 MW), while ST2-ST4 for providing shaft power. The process supplies 27.3 t/h of low pressure steam to the 4.5-bar header, and 35 t/h of steam (18 bar and 215 °C) is imported from a neighboring steel mill as a result of total site steam integration. Even though the import steam is below the medium pressure level of 20.6 bar, it can be used for heating. Therefore, the medium pressure steam demands are reduced from 146.3 to 111.3 t/h. The annual operating cost for the current conditions is 299.3 M$/y, as shown in Table 4.

Four sequential scenarios are analyzed, involving optimization of operating conditions (scenario 1), modification (scenario 2) and addition of units (scenario 3), and steam quality upgrading (scenario 4). Thus, model **P1** is solved for scenarios 1–3 and **P2** for scenario 4. In each scenario the model is implemented in the GAMS environment [28] on a Core 2, 2.53 GHz, 1.00 GB RAM processor with BARON as the MINLP solver [29].

4.1. Scenario 1: optimization of the existing steam system

In this scenario, the objective is to optimize the operation of the steam system without changing its layout. Hence, adding new equipment is currently not allowed (i.e. $N^{\max} = 0$). To reflect the layout in Fig. 1, the values of structural binary variables (i.e. z_b, z_t, z_{bi}, z_{tj} and $z_{ii't}$) are predefined. In addition, $z^{\text{imp,e}} = 1$ and $z^{\text{exp,e}} = 0$ are set beforehand because typical petroleum refineries always need to import electricity. For clarity, these variables are divided into three sets: $\boldsymbol{z}_{\text{P1}}^{\text{v,S1}}$ contains all binaries to be determined by optimization, $\boldsymbol{z}_{\text{P1}}^{1,\text{S1}}$ contains those set to one, and $\boldsymbol{z}_{\text{P1}}^{0,\text{S1}}$ those set to zero.

$$\boldsymbol{z}_{\text{P1}}^{\text{v,S1}} = \phi$$

$$\boldsymbol{z}_{\text{P1}}^{1,\text{S1}} = \left\{ \begin{array}{c} z^{\text{imp,e}}; z_{b=1}, z_{b=2}, z_{b=3}; z_{t=1}, z_{t=2}, z_{t=3}, z_{t=4}; \\ z_{bi=11}, z_{bi=22}, z_{bi=33}; z_{tj=21}, z_{tj=32}, z_{tj=43}; \\ z_{ii't=131}, z_{ii't=151}, z_{ii't=252}, z_{ii't=353}, z_{ii't=344} \end{array} \right\}$$

$$\boldsymbol{z}_{\text{P1}}^{0,\text{S1}} = \boldsymbol{z}_{\text{P1}} - \boldsymbol{z}_{\text{P1}}^{\text{v,S1}} - \boldsymbol{z}_{\text{P1}}^{\text{v,S1}}$$

where $b \in \mathcal{B} = \{1\text{–}3\}$ denotes boiler B1, the site boiler B2 and boiler B3; $t \in \mathcal{T} = \{1\text{–}4\}$, turbines ST1–ST4; $i \in \mathcal{I} = \{1\text{–}5\}$, headers of 101 bar for B1 and for the site boiler, 20.6 bar, 4.5 bar and condensate; and $j \in \mathcal{J} = \{1\text{–}3\}$, shaft demands 1–3. Note that $\boldsymbol{z}_{\text{P1}}^{\text{v,S1}}$ is an empty set. Therefore, the model can be solved as a nonlinear program (NLP) by treating all binary variables as parameters.

Fig. 3 shows the optimized operating conditions. The optimization result suggests that boiler B1 should produce more steam (increased from 154 to 199.4 t/h) for turbine ST1 to generate more electricity (increased from 28 to 33.1 MW). Thus, the power import can be reduced from 53.3 to 48.2 MW. The optimized steam system has an annual operating cost of 297.2 M$/y, which corresponds to a 2.1 M$/y cost reduction compared to the initial case. However, it can be observed that the flow rates of the let-down stations are still high because the optimization is limited by the existent layout: the steam production rate of the site boiler is fixed (208.3 t/h), and turbines ST2–ST4 cannot use more let-down steam because they are only in charge of satisfying shaft demands 1–3 (15.2, 7.7 and 5.3 MW). Hence, the following scenarios will focus on the retrofit of the existing system to further improve steam utilization.

Table 2
Site conditions of the refinery.

Total working hours	8000 h/yr
Fuel oil LHV	42,800.4 kJ/kg
Electric price	0.13 $/kWh
Steam price	36 $/t
Fuel price	824.3 $/t

Table 3
Steam and power demands of the refinery.

Steam demands (101.0 bar)	13.0	t/h
Steam demands (20.6 bar)	146.3	t/h
Steam demands (4.5 bar)	196.5	t/h
Power demands	81.3	MW
Shaft demand 1	15.2	MW
Shaft demand 2	7.7	MW
Shaft demand 3	5.3	MW

4.2. Scenario 2: modification of steam turbine ST1

The second scenario evaluates the benefit of modifying the existing units without adding new equipment. For simplicity, boiler B1 and the site boiler as well as all steam headers are not considered for retrofitting. The modification of turbines ST2–ST4 is also excluded because they are designed to provide given amounts of shaft power. Meanwhile, turbine ST1 generates 33.1 MW of electricity and discharges 20.6-bar steam and condensate. By consulting the manufacturer, it is known that turbine ST1 can be modified to discharge steam at 20.6 and 4.5 bar. In addition, the necessity of using boiler B3 is doubtful, because it is operating at its minimum capacity (Fig. 3). Hence, B3 and ST1 are the only units to be retrofitted, and **P1** is then solved with the inclusion of their potential changes. The binary sets for this scenario are as follows:

$$\boldsymbol{z}_{\text{P1}}^{\text{v,S2}} = \{ z_{b=3}; z_{bi=33}; z_{ii't=131}, z_{ii't=141}, z_{ii't=151} \}$$

$$\boldsymbol{z}_{\text{P1}}^{1,\text{S2}} = \left\{ \begin{array}{l} z^{\text{imp,e}}; z_{b=1}, z_{b=2}; z_{t=1}, z_{t=2}, z_{t=3}, z_{t=4}; \\ z_{bi=11}, z_{bi=22}; z_{tj=21}, z_{tj=32}, z_{tj=43}; \\ z_{ii't=252}, z_{ii't=353}, z_{ii't=344} \end{array} \right\}$$

$$\boldsymbol{z}_{\text{P1}}^{0,\text{S2}} = \boldsymbol{z}_{\text{P1}} - \boldsymbol{z}_{\text{P1}}^{\text{v,S2}} - \boldsymbol{z}_{\text{P1}}^{1,\text{S2}}$$

Fig. 4 shows the optimal design for scenario 2. Note that turbine ST1 is modified and now discharges 4.5-bar steam to meet the low pressure steam demands. Consequently, there is no let-down flow between the 20.6- and 4.5-bar headers, and boiler B3 is switched off. Converting ST1 from a condensing turbine to an extractive turbine results in a significant reduction in fuel consumption. However, the power generation is less than that in scenario 1, and

Table 4
Summary of the refinery case study.

(M$/y)	Current	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual operating cost	299.3	297.2	261.8	257.8	254.0
Fuel cost	229.9	232.9	190.7	193.2	169.5
Steam cost	10.1	10.1	10.1	10.1	26.7
Power cost	54.0	48.8	58.2	51.7	54.8
CW cost	5.4	5.4	2.8	2.9	3.1
Cost saving to previous scenario (M$)	–	2.1	35.4	4.0	3.8
Installed cost (M$)	–	–	10.0	5.0	5.0
Payback (y)	–	–	0.28	1.25	1.32

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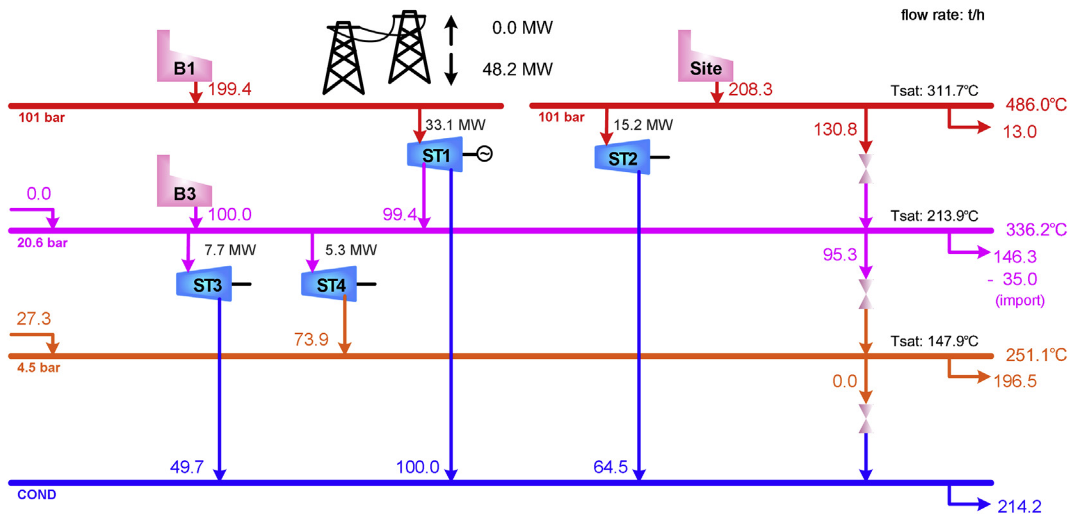

Fig. 3. Operational optimization for the existent plant (scenario 1).

therefore more electricity (increased from 48.2 to 57.5 MW) is imported from the public grid. Such a retrofit requires an estimated investment of 10 M$ and gives a 35.4 M$/y reduction (−11.9%) in operating cost compared to scenario 1. With payback time being only 0.28 y, this is considered economically worthwhile.

4.3. Scenario 3: addition of new equipment

Having modified turbine ST1, the inclusion of an additional unit (i.e. $N^{\max} = 1$) is considered in this scenario for further improvement. Given the high let-down flow rate between the 101- and 20.6-bar headers, it is proposed to add a new steam turbine (denoted by ST5) in between to generate electricity. This gives the following binary sets:

$$\begin{aligned}
\boldsymbol{z}_{\mathrm{P1}}^{\mathrm{v,S3}} &= \{z_{t=5}; z_{ii't=235}\} \\
\boldsymbol{z}_{\mathrm{P1}}^{1,\mathrm{S3}} &= \boldsymbol{z}_{\mathrm{P1}}^{1,\mathrm{S2}} \cup \{z_{ii't=131}, z_{ii't=141}\} \\
\boldsymbol{z}_{\mathrm{P1}}^{0,\mathrm{S3}} &= \boldsymbol{z}_{\mathrm{P1}} - \boldsymbol{z}_{\mathrm{P1}}^{\mathrm{v,S3}} - \boldsymbol{z}_{\mathrm{P1}}^{1,\mathrm{S3}}
\end{aligned}$$

where $t = 5$ denotes turbine ST5. Note that adding a new boiler is not considered because the steam demands can be met even having an existing boiler shut down.

The optimal solution for scenario 3 is shown in Fig. 5, where turbine ST5 is used to generate 6.4 MW of electricity, and the let-down flow rate between the 101- and 20.6 bar headers is reduced to 58.1 t/h. The steam from turbines ST1 and ST5 is used to satisfy the medium pressure (20.6 bar) steam demands. Note that the power generation of the steam plant is increased from 23.8 to 30.3 MW and less electricity (51 MW) is imported. The resulting saving on the operating cost is 4 M$/y compared to scenario 2, and the required capital investment is estimated at 5 M$ with payback time of 1.25 y.

4.4. Scenario 4: upgrading the import steam

Based on the retrofit in scenario 3, this scenario considers the case that the import steam is not qualified to satisfy the medium pressure steam demands. Hence, upgrading the import steam would be needed. The amount of steam (18 bar and 215 °C) available from the neighboring steel mill is 120 t/h. For utilization, the import steam needs to be upgraded to at least 20.6 bar and 260 °C. The steam from boiler B1 (101 bar and 486 °C) can be used as the high pressure steam to upgrade the low pressure import steam in an ejector at an entrainment ratio of 3.76. Design procedures of

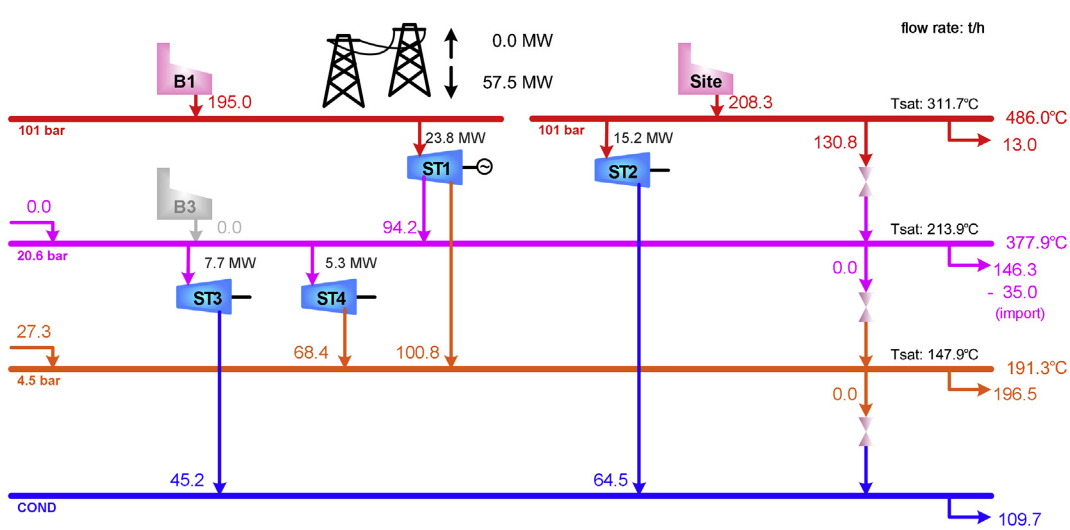

Fig. 4. Optimal steam distribution network for scenario 2.

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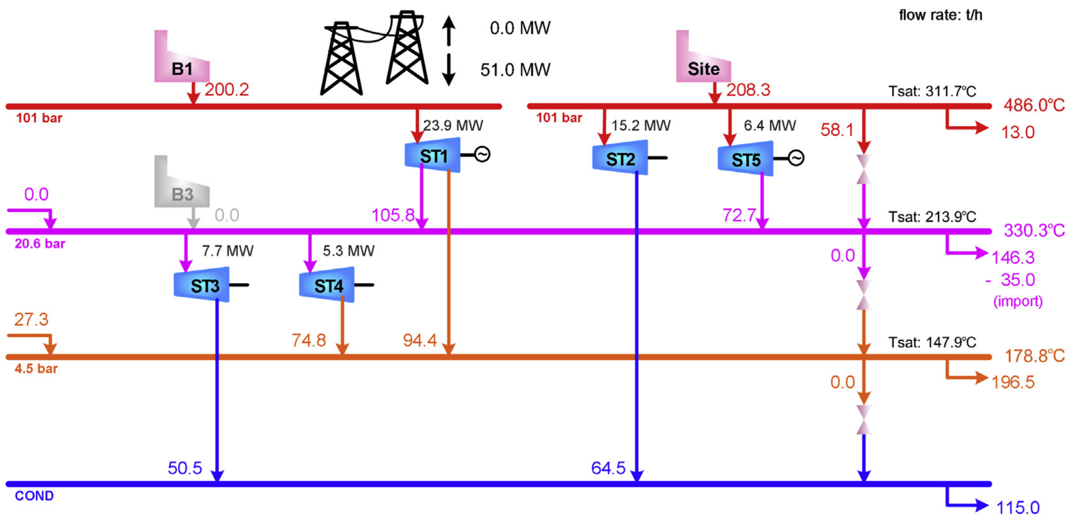

Fig. 5. Optimal steam distribution network for scenario 3.

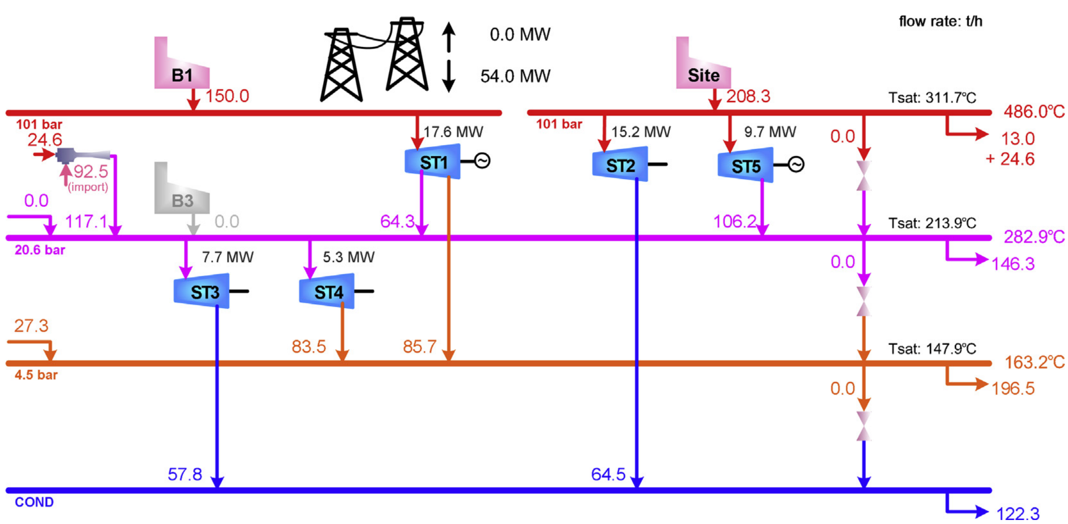

Fig. 6. Optimal steam distribution network for scenario 4.

steam ejectors can be found in Perry's Handbook [30]. The binary sets for this scenario are as follows:

$$
\begin{aligned}
\mathbf{z}_{P2}^{v,S4} &= \{z_{e=1}; z_{i''i'ei=4113}\} \\
\mathbf{z}_{P2}^{1,S4} &= \mathbf{z}_{P1}^{1,S3} \cup \{z_{t=5}; z_{ii't=235}\} \\
\mathbf{z}_{P2}^{0,S4} &= \mathbf{z}_{P2} - \mathbf{z}_{P2}^{v,S4} - \mathbf{z}_{P2}^{1,S4}
\end{aligned}
$$

where $e \in \varepsilon = \{1\}$ denotes the ejector; $i \in \mathcal{I} = \{1\text{–}6\}$, pressure levels of 101 bar, 101 bar, 20.6 bar, 18 bar, 4.5 bar and condensate.

Fig. 6 shows the optimal design obtained by solving model **P2**. The steam ejector is used to make qualified medium pressure (20.6 bar) steam from 24.6 t/h of the high pressure (101 bar) steam and 92.5 t/h of the imported low pressure (18 bar) steam. Consequently, the steam production of boiler B1 is decreased from 200.2 to 150 t/h. Note that all let-down flow rates are zero, which indicates complete utilization of steam energy without waste. The site generates 33.6% of the electricity required, and the deficit is made up by power import from the public grid. The annual operating cost of the steam plant is 254 M$/y, or a 1.5% reduction (−3.8 M$/y) compared to scenario 3. In summary, the result suggests increasing steam import from the neighboring plant and thereby reducing the production of high pressure steam from the boiler. The cost of a steam ejector can be taken as 5 M$ although it is actually less expensive than a steam turbine. This gives the payback time of 1.32 y.

The optimization results for all scenarios are summarized in Table 4. Here, we analyze different circumstances and evaluate the potential benefits of various retrofit potentialities. The results show that various degrees of retrofit can break the limitation to improve total site performance.

5. Conclusion

The steam power plant of a petroleum refinery is studied in this article. Based on the proposed unit models, a comprehensive mathematical model is presented for analysis and design of the steam power plant, where the design problem is formulated as a mixed-integer nonlinear program (MINLP). The assessment of existent steam power plant in a refinery can be fulfilled by the proposed comprehensive steam system model, which includes the operational optimization, retrofit of existent units, and import steam integration. The results show that the existent layout limits the steam utilization performance. Hence, the retrofit strategy is adopted to break this limitation, and the site performance can be improved. Significant reduction has achieved in operating cost by 13.8% in the studied case, where an existent condensing turbine is modified into an extractive turbine, and one new steam turbine is adopted for generating electricity. In addition, by applying integration technique, the corresponding cost saving is up 15.1%. This work can be accomplished by the steam ejector to enhance lower grade imported steam to the desired level, which improves the usability of steam import. The payback time for the retrofit cases is lower than 0.5 year, which shows the suggestions given by the proposed model are promising to enhance the efficiency of steam system in a refinery.

Acknowledgements

Financial support of the National Science Council of ROC under grants NSC100-3113-E-002-0094 and NSC 101-3113-E-002-004- is appreciated.

Nomenclature

Indices:

b index for boilers
e index for steam-jet ejectors
i index for pressure levels or steam headers
j index for shaft demands
t index for steam turbines
u index for fuels

Sets:

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

Parameters:

$C_i^{\mathrm{exp,s}}$ unit cost of exported i level steam, \$ kg^{-1}
$C_i^{\mathrm{imp,s}}$ unit cost of imported i level steam, \$ kg^{-1}
C_u unit cost of fuel u, \$ kg^{-1}
C^{cw} unit cost of cooling water, \$ kg^{-1}
$C^{\mathrm{exp,e}}$ unit cost of exported electricity, \$ kW h^{-1}
$C^{\mathrm{imp,e}}$ unit cost of imported electricity, \$ kW h^{-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}
$H_i^{\mathrm{imp,s}}$ enthalpy of imported i level steam, kJ kg^{-1}
H_i^{ps} enthalpy of steam supplied by processes and delivered at header i, kJ kg^{-1}
H_u^{LHV} low heating value for fuel u, kJ kg^{-1}
$H_u^{\mathrm{sat,l}}$ enthalpy of saturated steam at steam header i, kJ kg^{-1}
H^{deaer} enthalpy of water leaving a deaerator, kJ kg^{-1}
$R_{i''i'i}$ flow ratio of i'' level import steam over i' level carrying steam
t^{hrs} total operating time, h
$\Delta T_{ii'}^{\mathrm{sat}}$ inlet-outlet saturation temperature difference across turbine (°C)
$W_{ii't}^{\mathrm{d}}$ design shaft output (kW)
$W_j^{\mathrm{dem,s}}$ shaft demand j, kW
$W^{\mathrm{dem,e}}$ total electricity demand, kW
Ω an arbitrary larger number
φ fixed blowdown fraction for boilers
η_b boiler efficiency (0.93)
$\overline{\Omega}_b, \underline{\Omega}_b$ upper/lower bounds of steam flow rate for boiler b, kg s^{-1}
$\overline{\Omega}_e, \underline{\Omega}_e$ upper/lower bounds of steam flow rate for ejector e, 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, kW
$\boldsymbol{z}_{\mathrm{P1}}^{*,\dagger}$ set of binary parameters assigned to $* \in \{0, 1\}$ in scenario $\dagger$ of **P1**, $\dagger \in$ {S1,S2,S3}
$\boldsymbol{z}_{\mathrm{P2}}^{*,\mathrm{S4}}$ set of binary parameters assigned to $* \in \{0, 1\}$ in scenario S4, **P2**

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}
$f_{ii't}$ steam flow rate from header i to header i' through a steam turbine t, kg s^{-1}
$f_{ii't}$ steam flow rate from header i to header i', kg s^{-1}
$f_{i'ei}$ steam flow rate from header i' to header i via ejector e, kg s^{-1}
$f_i^{\mathrm{exp,s}}$ steam export flow rate from header i, kg s^{-1}
$f_i^{\mathrm{imp,s}}$ steam import flow rate to header i, kg s^{-1}
$f_{i''ei}^{\mathrm{imp,s}}$ steam import flow rate of i'' level to header i via header e, kg s^{-1}
f_i^{ld} desuperheating boiler feed water injected into header i, kg s^{-1}
f_i^{vent} vented steam at header i, 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}
$h_{ii't}$ enthalpy of discharge by steam turbine t 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}
$\Delta h_{ii't}^{\mathrm{is}}$ insentropic inlet–outlet enthalpy difference across turbine (kJ/kg)
J^{AOC} the annual operating cost of the optimized steam system
$J_{\mathrm{base}}^{\mathrm{AOC}}$ the annual operating cost of the base steam system
$J_{\mathrm{ret},\dagger}^{\mathrm{AIC}}$ the annual installed cost of retrofitted steam system, $\dagger \in$ {**P1**, **P2**}
$q_{ii't}^{\mathrm{cw}}$ 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
$w^{\mathrm{exp,e}}$ electricity exported, kW
$w^{\mathrm{imp,e}}$ electricity imported, kW
$\boldsymbol{x}_{\mathrm{P1}}, \boldsymbol{x}_{\mathrm{P2}}$ vectors for continuous variables in **P1** and **P2**

Binary variables:

z_{bi} 1 denotes connection of boiler b and header i
z_b 1 denotes presence of boiler b

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z_e	1 denotes presence of steam ejector e
$z_{i''i'ei}$	1 denotes i'' pressure steam is brought by i' pressure steam via ejector e to header
$z_{ii't}$	1 denotes connection of steam turbine t between i and i' headers
z_{tj}	1 denotes connection of steam turbine t and shaft demand j
z_t	1 denotes presence of steam turbine t
$z^{\mathrm{exp,e}}$	1 denotes presence of electricity export
$z^{\mathrm{imp,e}}$	1 denotes presence of electricity import
$\boldsymbol{z}_{\mathrm{P1}}$, $\boldsymbol{z}_{\mathrm{P2}}$	vectors for binary variables in **P1** and **P2**
$\boldsymbol{z}_{\mathrm{P1}}^{\mathrm{v},\dagger}$	set of binary variables in scenario † of **P1**, $\dagger \in$ {S1,S2,S3}
$\boldsymbol{z}_{\mathrm{P2}}^{\mathrm{v,S4}}$	set of binary variables in scenario S4, **P2**, $\dagger \in${S1,S2,S3}

References

[1] M. Nishio, J. Itoh, K. Shiroko, T. Umeda, A thermodynamic approach to steam-power system design, Ind. Eng. Chem. Process Des. Dev. 19 (1980) 306–312.

[2] C.-C. Chou, Y.-S. Shih, A thermodynamic approach to the design and synthesis of plant utility systems, Ind. Eng. Chem. Res. 26 (1987) 1100–1108.

[3] J.C. Bruno, F. Fernandez, F. Castells, I.E. Grossmann, A rigorous MINLP model for the optimal synthesis and operation of utility plants, Trans. IChemE 76 (1998) 246–258.

[4] C.-W. Hui, Y. Natori, An industrial application using mixed-integer programming technique: a multi-period utility system model, Comput. Chem. Eng. 20 (1996) S1577–S1582.

[5] R.R. Iyer, I.E. Grossmann, Optimal multiperiod operational planning for utility systems, Comput. Chem. Eng. 21 (1997) 787–800.

[6] L.O.A. Maia, R.Y. Qassim, Synthesis of utility systems with variable demands using simulated annealing, Comput. Chem. Eng. 21 (1997) 947–950.

[7] S.R. Micheletto, M.C.A. Carvalho, J.M. Pinto, Operational optimization of the utility system of an oil refinery, Comput. Chem. Eng. 32 (2008) 170–185.

[8] V.R. Dhole, B. Linnhoff, Total site targets for fuel, co-generation, emissions, and cooling, Comput. Chem. Eng. 17 (Suppl) (1993) S101–S109.

[9] C.W. Hui, S. Ahmad, Total site heat integration using the utility system, Comput. Chem. Eng. 18 (8) (1994) 729–742.

[10] J. Klemeš, V.R. Dhole, K. Raissi, S.J. Perry, L. Puigjaner, Targeting and design methodology for reduction of fuel, power and CO_2 on total sites, Appl. Therm. Eng. 17 (1997) 993–1003.

[11] S. Bandyopadhyay, J. Varghese, V. Bansal, Targeting for cogeneration potential through total site integration, Appl. Therm. Eng. 30 (2010) 6–14.

[12] K. Matsuda, S. Tanaka, M. Endou, T. Iiyoshi, Energy saving study on a large steel plant by total site based pinch technology, Appl. Therm. Eng. 43 (2012) 14–19.

[13] S.K. Abadi, M.H.K. Manesh, M. Amidpour, A.A. Hamidi, Integration of steam power plant with process utility system, Chem. Eng. Trans. 29 (2012) 133–138.

[14] A. Ghannadzadeh, S. Perry, R. Smith, Cogeneration targeting for site utility systems, Appl. Therm. Eng. 43 (2012) 60–66.

[15] P.Y. Liew, S.R.W. Alwi, P.S. Varbanov, Z.A. Manan, J. Klemeš, A numerical technique for total site sensitivity analysis, Appl. Therm. Eng. 40 (2012) 397–408.

[16] S. Perry, J. Klemeš, I. Bulatov, Integrating waste and renewable energy to reduce the carbon footprint of locally integrated energy sectors, Energy 33 (2008) 1489–1497.

[17] S.A. Papoulias, I.E. Grossmann, A structural optimization approach in process synthesis Part III: total processing systems, Comput. Chem. Eng. 7 (1983) 723–734.

[18] Z. Shang, A. Kokossis, A transhipment model for the optimisation of steam levels of total site utility system for multiperiod operation, Comput. Chem. Eng. 28 (2004) 1673–1688.

[19] C.L. Chen, C.Y. Lin, A flexible structural and operational design of steam systems, Appl. Therm. Eng. 31 (2011) 2084–2093.

[20] P. Varbanov, S. Perry, J. Klemeš, R. Smith, Synthesis of industrial utility systems: cost-effective de-carbonisation, Appl. Therm. Eng. 25 (2005) 985–1001.

[21] C.L. Chen, C.Y. Lin, Design and optimization of steam distribution systems for steam power plants, Ind. Eng. Chem. Res. 50 (2011) 8097–8109.

[22] C.L. Chen, C.Y. Lin, Design of entire energy system for chemical plants, Ind. Eng. Chem. Res. 51 (2012) 9980–9996.

[23] T.J. Mattila, S. Pakarinen, L. Sokka, Quantifying the total environmental impacts of an industrial symbiosis – a comparison of process-, hybrid and input–output life cycle assessment, Environ. Sci. Technol. 44 (2010) 4309–4314.

[24] X. Zhang, S.A.H. Stromman, C. Solli, E.G. Hertwich, Model-centered approach to early planning and design of an eco-industrial park around an oil refinery, Environ. Sci. Technol. 42 (2008) 4958–4963.

[25] O. Aguilar, S.J. Perry, J.-K. Kim, R. Smith, Design and optimization of flexible utility systems subject to variable conditions, Part 1: Modelling Framework, Chem. Eng. Res. Des. 85 (2007) 1136–1148.

[26] S.M. Walas, Chemical Process Equipment: Selection and Design, Elsevier, 1990.

[27] E.F. Church (Ed.), Steam Turbines, third ed., McGraw-Hill, New York, 1950.

[28] GAMS Development Corporation, GAMS: a User's Guide (2008). Washington, DC.

[29] GAMS Development Corporation, GAMS: The Solver Manuals (2007). Washington, DC.

[30] McGraw-Hill Companies, Perry's Chemical Engineer's Handbook, Seventh ed., 1999.

Please cite this article in press as: C.-L. Chen, et al., Retrofit of steam power plants in a petroleum refinery, Applied Thermal Engineering (2013), http://dx.doi.org/10.1016/j.applthermaleng.2013.04.001