Multi-objective Optimization for Design of a Steam System with Drivers Option in Process Industries

Le Wu\textsuperscript{a}, Yongzhong Liu\textsuperscript{a,b,*}, Xiaoqiang Liang\textsuperscript{a}, Lixia Kang\textsuperscript{a}

\textsuperscript{a} Department of Chemical Engineering, Xi’an Jiaotong University, Xi’an, Shaanxi, 710049, P. R. China

\textsuperscript{b} Key Laboratory of Thermo-Fluid Science and Engineering, Ministry of Education, Xi’an, Shaanxi, 710049, P. R. China

*Corresponding Author
Phone: +86-29-82664752
Fax: +86-29-83237910
E-mail: yzliu@mail.xjtu.edu.cn
Abstract

In process industries, a steam system is usually constructed to satisfy the demands of steam and electricity in a plant, in which steam turbines and electric motors are commonly used to drive rotating equipment, such as pumps and compressors. In this paper, a multi-objective optimization model for the design of a steam system with drivers option for rotating equipment is proposed to simultaneously minimize the economic and environmental objectives. It features that the energy performances of steam turbines and electric motors are embedded in the model, and the environmental impacts caused by both the material of equipment and the utilities consumption in the system are evaluated by life cycle assessment method. A steam system of the hydrotreating units in a refinery is taken as a case study to demonstrate the application of the proposed method. The Pareto front of the economic and environmental objectives is obtained, and three scenarios on the Pareto front are analyzed and discussed. Results show that appropriate drivers option can effectively reduce both the economic and environmental impacts of the steam system. In addition, the preference of steam turbines and electric motors in the system is intensively dependent on the two objectives. Consequently, the drivers option for the power demand in a plant should be determined before the entire steam system is designed and optimized.

Keywords: Multi-objective optimization; Steam system; Drivers option; Life cycle analysis
Highlights

- A multi-objective optimization of a steam system with drivers option is proposed.
- Appropriate drivers option can reduce both the economic and environmental impacts.
- The drivers option should be optimized before the steam system is determined.
- A steam system for hydrotreating units is used to exemplify the proposed method.
1. Introduction

In process industries, a steam system provides driving power for rotating equipment, such pumps and compressors in a refinery, and satisfies the demand of heating as well. The drivers for the rotating equipment are usually electric motors and steam turbines (Favi et al., 2012; Hugot, 2014). The electric motors consume electricity to drive rotating equipment, whereas the steam turbines consume high pressure steam. Drivers option affects demands and balance of electricity and steam in the steam system of a plant. Therefore, it is imperative to optimize the drivers option for the plant before the configuration of the steam system is determined.

For the steam system with fixed electricity and steam demands, the thermodynamics-based methods and model-based methods are commonly adopted to optimize the operational parameters of steam systems, which include boilers, steam turbines and multiple steam headers. The thermodynamics-based methods focus mainly on increasing the energy utilization efficiency and exploiting the benefit from maximum process to process integration (Li et al., 2014). On the basis of thermodynamic losses and the irreversibility of utility systems, a design method was proposed by Nishio et al.(1980). Dhole and Linnhoff (1993) introduced a graphical method to reach the maximum heat recovery and minimum cost of utilities of the cogeneration of heat and power system (Klemeš et al., 1997). All these studies mentioned the energy usage of the steam system, but the optimization of the capital cost and operating cost is usually ignored.

In principle, the model-based methods can overcome this drawback and attain a better solution of the steam system (Varbanov et al., 2004). Papoulias and Grossmann (1983) proposed a mixed-integer linear programming model (MILP) to optimize the steam system configuration considering the selection of boilers and the inlet and exhaust pressure of steam turbines, which also satisfies the demand of heat and power in the system. Based on this
MILP model, Bruno et al. (1998) presented a more rigorous mixed-integer nonlinear programming model (MINLP). The optimal configuration and relevant parameters can be obtained by solving the model. Mavromatis and Kokossis (1998) developed a more rigorous estimation of power produced by steam turbines. In recent, Luo et al. (2011) proposed a superstructure of a steam system containing the multiple extractions steam turbines. The energy consumption and boiler feed water can be simultaneously reduced in the steam system. Sun and Liu (2015) discussed the reliability and flexibility of a steam system. Subsequently, the steam system is important for the regular operations and energy savings of a plant. (Alkaya and Demirer, 2015)

Different drivers options affect the demand of different utilities. Drivers option for the power demand in a plant should be determined before the entire steam system is designed. Furthermore, with the development of small-scale steam turbines, it makes possible to drive pumps and compressors with low rated power. Li et al. (2014) presented that the operating cost can be reduced by using the steam turbines to drive the rotating equipment in a steam system. Oh and Yeo (2008) proposed an MINLP model and illustrated that the appropriate drivers option for the rotating equipment may lead to dramatic decrease of operating cost. Wu et al. (2015) presented that appropriate drivers option can reduce both the TAC and environmental impacts. However, in their work, the design of the steam system was not considered.

In these abovementioned studies, however, all of problems solved were based on the retrofit problems of the steam system with drivers option rather than the design ones, which is much more important for energy conservation of a plant. Furthermore, when the steam system is used to satisfy the demands of electricity and steam in a plant, which consumes a large amount of primary energy, coal, oil or natural gas, for examples, and large amount of CO₂ and SO₂ will be discharged. (Boix et al., 2015) This triggers severe environmental problems.
Hence, the environmental impacts of a steam system should be taken into consideration when the steam system is designed. Meanwhile, the effect of drivers option on environmental impacts should also be analyzed because the drivers in the system consume a lot of secondary energy, electricity and steam. In addition, the environmental impacts of drivers are dependent on the drivers option in the system. In this context, when a steam system is designed for a plant, it is significant importance of considering the drivers option and their effects on the economic and the environmental impacts.

In this work, a multi-objective optimization model was proposed to simultaneously minimize the economic objective and environmental objective of a steam system with drivers option for rotating equipment in a plant, in which life cycle assessment (LCA) method is used to quantify the environmental impacts. The remainder of this paper is organized as follows. In section 2, the multi-objective optimization model for a steam system with drivers option is presented. In section 3, the effect of drivers option on the economic and environmental impacts of the steam system in a practical refinery is illustrated and discussed. Finally, the conclusions of this work are drawn in section 4.

2. Multi-objective optimization model for a steam system with drivers option

2.1 Superstructure

Fig. 1 presents a superstructure of a steam system containing drivers option for pumps and/or compressors in a process system. Two types of drivers, i.e. electric motors and steam turbines, are used to drive pumps and compressors in the system. The driving power of the electric motors can be obtained from the power grid or the generators driven by steam turbines in the system. On the other hand, the steam turbines that are used to drive the generators, pumps and compressors intake higher pressure steam from the steam system and discharge lower pressure steam to the relevant steam headers. As shown in the figure, there
are four pressure levels in the steam headers, i.e., the super-high pressure (SP), the high pressure (HP), the medium pressure (MP) and the low pressure (LP). In the system, the boilers generate the steam at two high pressure levels, SP steam and HP steam. Furthermore, the steam system is required to meet the power demand of rotating equipment, \( W_p \), the steam for heating and stripping, \( S_o \), and the basic electricity demand, \( P_0 \), which can also be purchased from the power grid outside.

On the basis of this superstructure, aiming at simultaneously minimizing the economic objective and environmental objective, a multi-objective optimization model of a steam system with drivers option is proposed. After the model is solved, the following information can be obtained: (1) the drivers option for rotating equipment in the plant; (2) the power source to satisfy the demand of the basic electricity and the electric motors; (3) the flow rate and pressure of the inlet and exhaust steams for driving steam turbines; (4) the flow rate and the pressure of the inlet and exhaust steams for driving turbines of generators; (5) the flow rate and the pressure of the outlet steam of the boilers in the system.

2.2 Economic objective

The total annual cost (TAC) includes the capital cost (CC) and the operating cost (OC). That is

\[
TAC = CC + OC
\]  

The capital cost includes the investment cost of \( i \) boilers (b), \( j \) generators (g) and driving turbines of generators (gt), \( k \) electric motors (m) and \( l \) steam turbines (t). That can be expressed as

\[
CC = \sum_{i=1}^{f_i} C_i^b + \sum_{j=1}^{f_j} \left( C_j^g + f_j^{gt} C_j^{gt} \right) + \sum_{k=1}^{f_k} z_{k,p} f_k^m C_k^m + \sum_{l=1}^{f_l} z_{l,p} f_l^t C_l^t
\]  

where \( f \) denotes the spare factor of equipment; \( C \) is the capital cost or the utility prices, in US$·y\(^{-1}\), US$·t\(^{-1}\) or US$·kWh\(^{-1}\); \( z_{k,p} \) is a binary variable, which denotes that the \( p^{th} \)
rotating equipment is driven by the $k^{th}$ electric motor; $z_{i,p}$ is a binary variable, which denotes that the $p^{th}$ rotating equipment is driven by the $l^{th}$ steam turbine.

On the other hand, the operating cost includes the fuel for boilers (BF), the feed water of boiler (BW), the purchased electricity (PE) and the purchased steam (PS). It can be expressed as

$$OC = \left( F^{BF}C^{BF} + F^{BW}C^{BW} + F^{PE}C^{PE} + F^{PS}C^{PS} \right) AOT$$  \hspace{1cm} (3)

where $F$ denotes the flow rate of the utilities, in t·h$^{-1}$ or kWh·h$^{-1}$; AOT is the annual operating time, in h·y$^{-1}$.

2.2.1 The capital cost

The capital cost of the boiler is related to the flow rate and pressure of the outlet steam. It can be written as (Bruno et al., 1998)

$$C_{i}^{b} = 4.954 \left( F_{i}^{BS} \right)^{0.77} \left( 1.3794 - 0.5438BP_{i} + 0.1879BP_{i}^{2} \right)$$  \hspace{1cm} (4)

where $F^{BS}$ denotes the flow rate of outlet steam from the boiler, in t·h$^{-1}$; BP is the pressure of the steam from the boiler, in MPa. This pressure should not be less than the pressure of the relevant steam headers.

The investment of generator can be calculated by (Bruno et al., 1998):

$$C_{j}^{g} = 8.141 + 0.6495W_{j}^{g}$$  \hspace{1cm} (5)

where $W_{j}^{g}$ denotes the generated power of the generator, in kW;

The cost of steam turbine is relevant to the driving power (Bruno et al., 1998). It can be expressed as

$$C_{i}^{t} = 81.594 + 18.052W_{i}^{t}$$  \hspace{1cm} (6)

where $W_{i}^{t}$ denotes the driving power of the steam turbine, in kW;

The capital cost of the super high pressure steam turbine can be calculated by the capital
cost of the normal steam turbine multiplying the material factor (Seider et al., 2006). It can be written as
\[
C_{t}^{\text{ TSA }} = f_{\text{ mat }} \left( 81.594 + 18.052 W_{t}^{\text{ TSA }} \right)
\]
(7)

where \( f_{\text{ mat }} \) denote the material factor, which is 1.2 in general cases.

The capital cost of electric motor is related to its driving power. It can written as (Bruno et al., 1998)
\[
C_{k}^{\text{ m }} = 9,766.1 + 166.457 W_{k}^{\text{ m }}
\]
(8)

where \( W_{k}^{\text{ m }} \) denote the driving power of the electric motor, in kW.

2.2.2 The operating cost

The fuel cost for boilers can be calculated by the following equation:
\[
F_{\text{ BF }} = \sum_{i} \left[ \left( \sum_{k} z_{i,j,k,p} W_{p} / \eta_{k}^{m} \eta_{j}^{s} + \sum_{l} z_{i,l,p} W_{l} / \eta_{l}^{s} + z_{i,j} P_{0} / \eta_{j}^{s} + z_{i} S_{0} / \Delta H_{S_{0}} \right) / \eta_{b} \right]
\]
(9)

where \( z_{i,j,k,p} \) is a binary variable, which denotes that the \( p^{th} \) rotating equipment is driven by the \( k^{th} \) electric motor, whose power comes from the \( j^{th} \) generator driven by steam turbine, in which the inlet steam is from the \( i^{th} \) boiler; \( W_{p} \) denotes the power demand of rotating equipment, which is a known parameter, in kW; \( z_{i,l,p} \) is a binary variable, which denotes the existence of connection among boiler, steam turbine and rotating equipment; \( z_{i,j} \) is a binary variable, which represents that the power source of the base electricity demand is from the \( j^{th} \) generator driven by steam turbine, in which the inlet steam of the steam turbine is from the \( i^{th} \) boiler; \( \Delta H_{S_{0}} \) is the total enthalpy difference between the steam and the feed water in the boiler, in MJ·t\(^{-1}\); \( z_{i} \) is a binary variable, which denotes that the steam of heating and stripping comes from the \( i^{th} \) boiler; \( \eta_{b} \) is the efficiency, \%.
The consumption of the purchased electricity can be calculated by

\[ F_{\text{PE}} = \sum_k W_k^m \left(1 - z_{j,k,p}\right) + P_0 \left(1 - z_{i,j}\right) \]  

(11)

where \( z_{j,k,p} \) is a binary variable, which denotes that the \( p \)th rotating equipment is driven by the \( k \)th electric motor, whose power comes from the \( j \)th generator driven by steam turbine.

The purchase steam is calculated by

\[ F_{\text{PS}} = S_0 \left(1 - z_{i}\right) \]  

(12)

### 2.3 Environmental objective

Life cycle assessment (LCA) is a systematical method to quantitatively evaluate the environmental impacts of goods and processes from “cradle to grave.” Eco-indicator 99 (Mark Goedkoop, 2000) is used to assess the environmental impacts of the system of interest because it is an endpoint LCA method (Dreyer et al., 2003).

According to the evaluation scope in Fig. 1, the Eco-indicator 99 method is used to evaluate the environmental impacts of a steam system in following four steps, as shown in Fig. 2.

1. Goal and scope definition

This step defines the goal of the work, system boundaries, allocation methods and impact categories. The total annual environmental impact (TAEI) includes two parts, which are similar to the TAC, i.e., the total impacts of equipment (TIE) that is caused by the material of equipment and the total impacts of the operating process (TIO) that is caused by the utilities consumption. It can be expressed as

\[ TAEI = TIE + TIO \]  

(13)

2. Inventory analysis

In this phase, the relevant inputs and outputs of mass and energy associated with the
steam system are used to calculate the environmental impacts. The impacts contain the utilities consumed and the manufacture material of equipment.

3. Impact assessment

In the third step, the impacts of the utilities and material are calculated. The impact of equipment (IE) includes boilers, generators, driving turbines of generators, electric motors and steam turbines in the system. It can be written as

\[
TIE = \left( \sum_{i=1}^{b} f_i^{IE} IE_i^b + \sum_{j=1}^{g} \left( f_j^{IE} IE_j^g + f_j^{IE} IE_j^g \right) + \sum_{k=1}^{gt} z_{k,p} f_k^{m} IE_k^m + \sum_{l=1}^{t} z_{l,p} f_l^{ie} IE_l^i \right) LS 
\]

where LS denotes the life span of equipment, in years.

The impact of the equipment is correlated with its weight and material. It can be expressed as

\[
IE_i^b = m_i^b D^{St} 
\]

where \( m \) is the weight of the equipment, in tonne. According to the manufacturing experience and the previous work (Seider et al., 2006; Vaskan et al., 2012), the weight of a boiler is linear to its outlet steam flow rate when the pressure of the outlet steam is constant. For other equipment, such as generators, steam turbines and electric motors, their weights have a linear relation with their mechanical power. \( D \) denotes the damage factor of the material, in \( \text{pt} \cdot \text{t}^{-1} \), which can obtain from the database of Eco-indicator 99 (Hegger and Hischier, 2010).

The generator and electric motor are mainly made by stainless steel and copper. Generally, the steel takes 90% weight, whereas the rest is copper (Yan et al., 2006). The environmental impacts of the generators and the electric motors can be calculated by

\[
IE_j^g = 0.9 m_j^g D^{St} + 0.1 m_j^g D^{Co} 
\]

\[
IE_k^m = 0.9 m_k^m D^{St} + 0.1 m_k^m D^{Co} 
\]

The environmental impact of steam turbines is expressed as
When the super high pressure steam is used as the inlet steam, the steam turbine should bear the higher pressure. The environmental impacts of the super high pressure steam turbine can be calculated as

$$IE_i^{\text{t,ss}} = m_i^{\text{l,ss}} D^{\text{ss}}$$ (19)

The environmental impacts of the operation process are the impacts of the fuel, feed water, the purchased electricity and steam.

$$TOI = \left( F_{\text{BF}}^{\text{BF}} D_{\text{BF}}^{\text{BF}} + F_{\text{BW}}^{\text{BW}} D_{\text{BW}}^{\text{BW}} + F_{\text{PE}}^{\text{PE}} D_{\text{PE}}^{\text{PE}} + F_{\text{PS}}^{\text{PS}} D_{\text{PS}}^{\text{PS}} \right) AOT$$ (20)

4. Interpretation

The results of the life cycle assessment are then analysed in this step. And a set of conclusions and recommendations for the steam system are proposed.

2.4 Constraints

2.4.1 Mass balance

For a boiler in the system, the outlet steam flow rate is equal to the flow rate of the feed water, i.e.

$$F_{i}^{\text{BW}} = F_{i}^{\text{BS}}$$ (21)

For each pressure level of the steam headers, the flow rate of outlet steam is equal to the flow rate of inlet steam, i.e.

$$F_{P,\text{in}}^{\text{S}} = F_{P,\text{out}}^{\text{S}}$$ (22)

where the subscript $P$ denotes the pressure level of the steam header.

For a steam turbine, the flow rate of inlet steam from the $P$ level steam header is equal to the flow rate of exhaust steam to the $P'$ level steam header, i.e.

$$F_{P,i}^{\text{S}} = F_{P',j}^{\text{S}}$$ (23)

In the system, the total flow rates of the outlet steam of boilers and the purchased steam
should be no less than the demand of the steam for heating and stripping in the system, i.e.

\[
\sum_i F_i^{BS} + F_i^{PS} \geq S_0
\]  

(24)

**2.4.2 Energy balance**

For a boiler, a generator, and a steam turbine, the following energy balances should be satisfied.

\[
F_i^{BF} H_i^{BF} \eta_i^b + F_i^{BW} H_i^{BW} = F_i^{BS} H_i^{BS}
\]  

(25)

\[
F_p^s (H_{p,j}^s - H_{p',j}^s) / \eta_j^g = W_j^g
\]  

(26)

\[
W_j^g = \sum_k z_{j,k,p} W_p / \eta_k^m \eta_j^g
\]  

(27)

\[
F_p^s (H_{p,j}^s - H_{p',j}^s) = W_i^t
\]  

(28)

\[
W_i^t = W_p / \eta_i^t
\]  

(29)

where \( H \) is the enthalpy of streams, in MJ·t\(^{-1}\).

For an electric motor, it satisfies

\[
W_k^m = W_p / \eta_k^m
\]  

(30)

For the power grid, the following equation should be satisfied.

\[
\sum_j W_j^g + F_p^{PE} = \sum_k W_k^m + P_0
\]  

(31)

In addition, these binary variables satisfy

\[
\sum_k z_{k,p} + \sum_i z_{i,p} = 1
\]  

(32)

\[
\sum_i z_{i,k,p} = z_{i,p}
\]  

(33)

\[
\sum_j z_{j,k,p} = z_{k,p}
\]  

(34)

\[
\sum_i z_{i,j,k,p} = z_{j,k,p}
\]  

(35)
2.5 Trade-off between economic objective and environmental objective

For a multi-objective optimization problem, each optimal solution on the Pareto front can be considered as a trade-off solution between the economic and environmental objectives. To choose a trade-off solution from the Pareto front, a linear membership function was used to describe weights of the objective functions, which can be expressed as (Agrawal et al., 2008)

\[ \mu_o^s = \left( \frac{O_o^{\text{max}} - O_o^s}{O_o^{\text{max}} - O_o^{\text{min}}} \right) \]

where \( O_o^{\text{max}} \) and \( O_o^{\text{min}} \) denote the maximum and minimum values of the \( o^{\text{th}} \) objective function among all solutions. \( O_o^s \) denotes the \( s^{\text{th}} \) solution of the \( o^{\text{th}} \) objective function.

The membership function of each optimal solution can be expressed as:

\[ \mu^s = \sum_o \sigma_o \mu_o^s \]

where \( \sigma_o \) is the weight value of the \( o^{\text{th}} \) objective function that is optional for decision makers. Then the trade-off solution is the one corresponding to the maximum of \( \mu^s \).

3. Case study

3.1 Fundamental data of hydrotreating units in a refinery

Take a refinery with the primary processing capability of 8 Mt (million tons) crude oil per year as an example. In this refinery, a diesel HDT unit with annual processing capability of 2.6 Mt and a gasoline HDT unit with annual processing capability of 1.4 Mt are expanded and designed. The existing boilers in the refinery cannot meet the requirement of the two newly designed HDT units. Therefore, the steam system should be re-designed. In this case, the multi-objective design method is used to design the steam system with the drivers option of the two HDT units.

The existing steam headers in the refinery are at the super high pressure (SP) level, the high pressure (HP) level, the medium pressure (MP) level and the low pressure (LP) level. In
the steam system, the SP steam is used to generate electricity or drive steam turbines, and the HP steam usually drives the steam turbines. The MP steam is often used for stripping or heating, and the LP steam is usually for heating. Furthermore, the steam turbines discharge the exhaust steam to the MP steam level, whereas the driving turbines of generators usually intake the SP steam and discharge the exhaust steam to the MP steam level. The properties of these steam headers are listed in Table 1.

In the two newly designed HDT units, there are 15 pumps and 4 compressors, as shown in Fig. 3. The power demands of the pumps and compressors are listed in Table 2. The basic demand of electricity in the system is 600 kW, and the stripping steam is 6 t·h⁻¹. The annual operating time of the units is 8,400 h. The efficiency of the boiler is 80 %. The total efficiencies of the generators driven by steam turbines are 58 %. The transmission efficiency of all electric motors is 80%. The efficiencies of electric motors (Yan et al., 2006) and steam turbines (Bruno et al., 1998) are presented in Table 3. In addition, the life span of boilers, generators, electric motors and steam turbines are assumed to 20 years. The spare factors are one.

The damage factors (Hegger and Hischier, 2010) and the prices of the utilities are listed in Table 4.

3.2 Results and discussion

On the basis of the fundamental data mentioned above, the proposed multi-objective optimization model was solved by the $\varepsilon$-constraint method implemented on the platform of software package GAMS (V24.1), in which the solver BARON was used. Then the Pareto front of the two objectives is obtained, as shown in Fig. 4. The drivers option for pumps and compressors in the system can be obtained accordingly. The configurations of the steam system in three different scenarios, i.e. Scenario A, Scenario B, and Scenario C, as marked in Fig. 4, are given in Fig. 5, Fig. 6, and Fig. 7, respectively. The results in these scenarios will
be further explained and discussed later.

As shown in Fig. 4, the economic objective and the environmental objective present an opposite trend. With the increase of the environmental impacts, the TAC of the system reduces sharply at the beginning, then decreases slowly and become flat at last. In Fig. 4, Scenario A denotes the operation of the system with the minimum TAC of $3.114 \times 10^6 \text{ US}\$\cdot\text{y}^{-1}$, while the TAEI are maximum of $8.376 \times 10^5 \text{ Pt}\cdot\text{y}^{-1}$. Scenario B denotes the operation of the system with the minimum TAEI of $7.410 \times 10^5 \text{ Pt}\cdot\text{y}^{-1}$ and the maximum TAC of $5.640 \times 10^6 \text{ US}\$\cdot\text{y}^{-1}$. Scenario C denotes that the operation of the system is at a trade-off point when the weight values of the two objectives in Eq.(33) are both assumed to be 0.5. In this scenario, the TAC of the system is $3.435 \times 10^6 \text{ US}\$\cdot\text{y}^{-1}$, whereas the TAEI of the system is $7.54 \times 10^5 \text{ Pt}\cdot\text{y}^{-1}$.

**Scenario A: The minimum TAC**

Fig. 5 presents the configuration of steam system and the drivers option of Scenario A with the minimum TAC in Fig. 4. It can be seen in Fig. 5 that the steam turbines are recommended as the drivers for the power demand of rotating equipment over 1,250 kW; whereas the electric motors are highly recommended for the power demand less than 1,071 kW. When the power demands of the rotating equipment are between 1,071 kW and 1,250 kW, the drivers option have little effect on the TAC of the system. At the same time, in this scenario, the steam system discharges $0.474 \text{ t}\cdot\text{h}^{-1}$ HS steam and $7.992 \text{ t}\cdot\text{h}^{-1}$ MS steam to the relevant steam headers, which satisfies the demand of MS steam in other units of the refinery.

**Scenario B: The minimum TAEI**

Fig. 6 shows the configuration of steam system and the drivers option of Scenario B with the minimum TAEI in Fig. 4. It can be seen from Fig. 6 that the steam turbines are favorable choices as the drivers when the environmental objective is focused due to the fact that the low
efficiency of the generator leads to more fuel to be consumed and hence aggravates the 
environmental impacts. In this scenario, the steam system discharges 0.222 t·h⁻¹ HS steam and 
9.191 t·h⁻¹ MS steam to the relevant steam headers, which satisfies the demand of MS steam 
in other units of the refinery.

**Scenario C: The trade-off between economic and environmental objectives**

Fig. 7 presents the configuration of steam system and the drivers option of *Scenario C* 
with a compromise between the economic objective and the environmental objective in Fig. 4. 
As shown in Fig. 7, the steam turbines are preferred for the power demand of rotating 
equipment over 211 kW, whereas the electric motors are preferred for the power demand less 
than 140 kW. When the power demand of the rotating equipment is between 140 kW and 211 
kW, the drivers option have little effects on the economic and environmental impacts of the 
system. In this scenario, the steam system discharges 0.003 t·h⁻¹ HS steam and 8.884 t·h⁻¹ MS 
steam to the relevant steam headers, which satisfies the demand of MS steam in other units of 
the refinery.

Table 5 presents the composition of the TAC and the TAEI in *Scenario C*. In this case, 
the capital cost and the operating cost in TAC are at the same order of magnitude. The 
investment of steam turbines, $1.045 \times 10^6$ US$·y⁻¹, takes the maximum proportion in the 
capital cost, whereas the fuel cost, $1.443 \times 10^6$ US$·y⁻¹, is the maximum cost in the operating 
cost. In contrast, it can also be seen that the environmental impacts caused by the operation of 
the system are much larger than that caused by the material of equipment.

4. Conclusions

In process industries, a steam system is commonly constructed to satisfy the demands of 
steam in various levels and electricity in a plant. It is of significant importance to determine 
the drivers option for rotating equipment before the configuration of the steam system is
designed and optimized because the drivers option affects demands and balance of steam and electricity in the steam system, in which a large amount of primary energy is consumed and thus severe environmental issues occur owing to the emissions of pollutants and greenhouse gases. Hence, the economic and environmental impacts of a steam system should be simultaneously taken into consideration when the steam system is designed and optimized.

In this paper, a multi-objective optimization model for the design of a steam system with drivers option for rotating equipment is proposed to simultaneously minimize the economic and environmental objectives. Under a superstructure of the steam system with drivers option, the energy performances of steam turbines and electric motors are embedded. It also features that Eco-indicator 99, which is an endpoint LCA method, is used to evaluate the environmental impacts caused by both the material of equipment and the utilities consumption in the system.

The steam system of the hydrotreating units in a refinery is taken as a case study to demonstrate the application of the proposed method. The Pareto front of the two objectives is obtained by the $\varepsilon$-constraint method. Furthermore, three scenarios on the Pareto front are analyzed and discussed, including the scenario of the minimum TAC of the system, the scenario of the minimum TAEI of the system, and the scenario of trade-off between the two objectives. The results show that appropriate drivers option can effectively reduce both the economic and environmental impacts of the steam system. Moreover, as shown in the three scenarios, the preference of steam turbines and electric motors in the system is intensively dependent on the objectives that the decision maker attaches. In addition, for different cases in the steam system, the criteria that clarify the favorable selection of steam turbines or electric motors in the drivers option can also be obtained by the proposed method.

Consequently, the determination of the drivers option should be performed before the steam system in a plant is designed and optimized.
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Nomenclature

Parameters

\[\text{AOT} = \text{annual operating time, h} \cdot \text{y}^{-1}\]
\[C^m_k = \text{the capital cost of electric motors, US$} \cdot \text{y}^{-1}\]
\[C^t_k = \text{the capital cost of steam turbines, US$} \cdot \text{y}^{-1}\]
\[D = \text{the damage factor of equipment material, pt} \cdot \text{t}^{-1}\]
\[f = \text{the spare factor of equipment}\]
\[f_{\text{mat}} = \text{the material factor}\]
\[H = \text{the enthalpy of utilities, MJ} \cdot \text{t}^{-1}\]
\[IE^m_k = \text{the impacts of electric motors, pt}\]
\[IE^t_k = \text{the impacts of steam turbines, pt}\]
\[m^m_k = \text{the weight of electric motors, t}\]
\[m^t_k = \text{the weight of steam turbines, t}\]
\[\text{LS} = \text{the life span of the equipment, y}\]
\[P_0 = \text{the basic electricity demand, kW}\]
\[S_0 = \text{the basic steam demand, t} \cdot \text{h}^{-1}\]
\[W_p = \text{the power demand of rotating equipment, kW}\]
\[W^m_k = \text{the driving power of electric motors, kW}\]
Variable

\( W_i \) = the driving power of steam turbines, kW

\( B_{Pi} \) = the pressure of the steam from the \( i^{th} \) boiler, MPa

\( C \) = the capital cost of equipment or prices of utilities, US\$\cdot y^{-1}, US\$\cdot t^{-1} \) or US\$\cdot kWh^{-1}

\( CC \) = the capital cost, US\$\cdot y^{-1}

\( C^b_i \) = the capital cost of boilers, US\$\cdot y^{-1}

\( C^g_j \) = the capital cost of generators, US\$\cdot y^{-1}

\( C^{gs}_j \) = the capital cost of generators’ driving turbines, US\$\cdot y^{-1}

\( F \) = the flow rate of utilities, t\cdot h^{-1} \) or kWh\cdot h^{-1}

\( IE^b_i \) = the impacts of boilers, pt

\( IE^g_j \) = the impacts of generators, pt

\( IE^{gs}_j \) = the impacts of generators’ driving turbines, pt

\( m^b_i \) = the weight of boilers, t

\( m^g_j \) = the weight of generators, t

\( m^{gs}_j \) = the weight of generators’ driving turbines, t

\( OC \) = the operating cost, US\$\cdot y^{-1}

\( O^s_o \) = the \( s^{th} \) solution of the \( o^{th} \) objective function

\( TAC \) = total annual cost, US\$\cdot y^{-1}

\( TAEI \) = total annual environmental impacts, pt\cdot y^{-1}

\( TIE \) = the total annual impact of equipment, pt\cdot y^{-1}

\( TIO \) = the total annual impact of operation, pt\cdot y^{-1}

\( W^g_j \) = the generated power of generators, kW
**Binary variable**

\[ z = \text{binary variable} \]

**Greeks**

\[ \eta = \text{the efficiency, \%} \]
\[ \mu = \text{the linear membership function} \]
\[ \sigma = \text{the weight value of the objective functions} \]

**Superscripts**

\[ b = \text{boiler} \]
\[ BF = \text{the fuel for boilers} \]
\[ BW = \text{the feed water of boilers} \]
\[ Co = \text{Copper} \]
\[ g = \text{generator} \]
\[ gt = \text{generator driven by steam turbine} \]
\[ m = \text{electric motor} \]
\[ \text{max} = \text{maximum value} \]
\[ \text{min} = \text{minimum value} \]
\[ PE = \text{the purchased electricity} \]
\[ PS = \text{the purchased steam} \]
\[ S = \text{steam} \]
\[ St = \text{stainless steel} \]
\[ ss = \text{the steel can stand super high pressure} \]
\[ t = \text{steam turbine} \]
t, ss = the super high pressure steam turbine

Subscripts

0 = the basic demand of the utilities
i = number of boilers
in = inlet steam
j = number of generators or driving turbines of generators
k = number of electric motors
l = number of steam turbines
o = the objective functions
out = outlet steam
P = the pressure level of the steam header
p = number of power demand equipment

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The environmental impacts of system

Assessment and analysis

Goal and scope definition

Inventory analysis

Impact assessment

Interpretation

Utilities impacts

Equipment impacts

Utilities

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Table 1 The properties of steam headers in the refinery

<table>
<thead>
<tr>
<th>Pressure rating</th>
<th>SP</th>
<th>HP</th>
<th>MP</th>
<th>LP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure/MPa</td>
<td>10.8</td>
<td>3.5</td>
<td>1.0</td>
<td>0.35</td>
</tr>
<tr>
<td>Temperature/°C</td>
<td>540</td>
<td>386</td>
<td>180</td>
<td>140</td>
</tr>
<tr>
<td>Enthalpy/MJ·t⁻¹</td>
<td>3,465</td>
<td>3,189</td>
<td>2,777</td>
<td>2,733</td>
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</table>
Table 2 The power demand of pumps and compressors in the system

<table>
<thead>
<tr>
<th>Pump or compressor</th>
<th>Power demand/kW</th>
<th>No.</th>
<th>Pump or compressor</th>
<th>Power demand/kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oily water pump</td>
<td>2.7</td>
<td>D1</td>
<td>Oily water pump</td>
<td>3</td>
</tr>
<tr>
<td>Reflux pump of stripper</td>
<td>11</td>
<td>D2</td>
<td>Sour water pump</td>
<td>3.5</td>
</tr>
<tr>
<td>Water pump</td>
<td>14</td>
<td>D3</td>
<td>Reflux pump of stripper</td>
<td>9</td>
</tr>
<tr>
<td>Reflux pump of fractionator</td>
<td>40</td>
<td>D4</td>
<td>Reflux pump of fractionator</td>
<td>22.7</td>
</tr>
<tr>
<td>Refined gasoline pump</td>
<td>82.5</td>
<td>D5</td>
<td>Water pump</td>
<td>58</td>
</tr>
<tr>
<td>Make-up hydrogen compressor</td>
<td>103</td>
<td>D6</td>
<td>Poor MEDA pump</td>
<td>140</td>
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<tr>
<td>Feed pump</td>
<td>122</td>
<td>D7</td>
<td>Circulating pump of fractionator</td>
<td>211</td>
</tr>
<tr>
<td>Cycle hydrogen compressor</td>
<td>1164</td>
<td>D8</td>
<td>Refined diesel pump</td>
<td>235</td>
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<tr>
<td>D9</td>
<td></td>
<td>D9</td>
<td>Feed pump</td>
<td>1071</td>
</tr>
<tr>
<td>D10</td>
<td></td>
<td>D10</td>
<td>Cycle hydrogen compressor</td>
<td>1250</td>
</tr>
<tr>
<td>D11</td>
<td></td>
<td>D11</td>
<td>Make-up hydrogen compressor</td>
<td>1715</td>
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</tbody>
</table>
Table 3 The efficiencies of electric motors and steam turbines

<table>
<thead>
<tr>
<th>Power demand/kW</th>
<th>η/%&lt;br/&gt;&lt;br/&gt;</th>
<th>90</th>
<th>92</th>
<th>95</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;100</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

The total efficiencies of steam turbines

<table>
<thead>
<tr>
<th>Inlet pressure/MPa</th>
<th>η&lt;sub&gt;i&lt;/sub&gt; = c (a − W&lt;sup&gt;i&lt;/sup&gt;) / (b + W&lt;sup&gt;i&lt;/sup&gt;)</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>-378.0419</td>
<td>758.8181</td>
<td>0.8223</td>
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</tr>
<tr>
<td>10.8</td>
<td>0.5658</td>
<td>3.4434×10&lt;sup&gt;-4&lt;/sup&gt;</td>
<td>-1.4713×10&lt;sup&gt;-9&lt;/sup&gt;</td>
<td></td>
</tr>
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</table>
Table 4 The damage factors and prices of utilities and materials

<table>
<thead>
<tr>
<th></th>
<th>Fuel / MJ$^{-1}$</th>
<th>Water / t$^{-1}$</th>
<th>Electricity / kWh$^{-1}$</th>
<th>Steel / t$^{-1}$</th>
<th>Stainless Steel / t$^{-1}$</th>
<th>Copper / t$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage factor / Pt</td>
<td>0.006422</td>
<td>0.05005</td>
<td>0.7873</td>
<td>1,245.5</td>
<td>1,374.3</td>
<td>3,658</td>
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<tr>
<td>Price / US$</td>
<td>0.00347</td>
<td>0.413</td>
<td>0.159</td>
<td></td>
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<td></td>
</tr>
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Table 5 The composition of the TAC and the TAEI in Scenario C

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Operation</th>
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<tbody>
<tr>
<td>Boiler</td>
<td>US$·y⁻¹</td>
</tr>
<tr>
<td>Generator</td>
<td>0.00916</td>
</tr>
<tr>
<td>Generator Turbine</td>
<td>1.450</td>
</tr>
<tr>
<td>Motor</td>
<td>0.504</td>
</tr>
<tr>
<td>Turbine</td>
<td>10.450</td>
</tr>
<tr>
<td>Fuel</td>
<td>14.430</td>
</tr>
<tr>
<td>Water</td>
<td>0.0627</td>
</tr>
<tr>
<td>Electricity</td>
<td>0</td>
</tr>
</tbody>
</table>

TAC/×10⁵ US$·y⁻¹

<table>
<thead>
<tr>
<th>TAC/×10² Pt·y⁻¹</th>
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</thead>
<tbody>
<tr>
<td>6.914</td>
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<tr>
<td>0.00916</td>
</tr>
<tr>
<td>1.450</td>
</tr>
<tr>
<td>0.504</td>
</tr>
<tr>
<td>10.450</td>
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<tr>
<td>14.430</td>
</tr>
<tr>
<td>0.0627</td>
</tr>
<tr>
<td>0</td>
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</tbody>
</table>

TAEI/×10² Pt·y⁻¹

<table>
<thead>
<tr>
<th>TAEI/×10² Pt·y⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.620</td>
</tr>
<tr>
<td>7.430</td>
</tr>
<tr>
<td>2.362</td>
</tr>
<tr>
<td>9.319</td>
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<tr>
<td>10.250</td>
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<tr>
<td>7,418.096</td>
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<tr>
<td>62.694</td>
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<tr>
<td>0</td>
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