CHEMICAL ENGINEERING TRANSACTIONS

VOL. 45, 2015

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Sharifah Rafidah Wan Alwi, Jun Yow Yong, Xia Liu

ISBN 978-88-95608-36-5; **ISSN** 2283-9216

DOI: 10.3303/CET1545183

Multi-objective Optimization on Driving Options for Rotating Equipment in Process Industries to Make Trade-offs between Economy and Environmental Impacts

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In process industries, steam turbines and electric motors are usually selected to be the choice of drivers for pumps and compressors. The economy of the drivers is usually one of the critical factors when the decisions of drives for pumps and compressors are made. In this work, we proposed a multi-objective optimization model to simultaneously minimize the total annual costs and environmental impacts. In the proposed model, the capital and operational costs for the drivers were included in the economic objective and the environmental impacts was measured by the indexes of Eco-indicator 99. The driving system in a diesel hydrotreating unit was taken as a case study to exemplify the proposed method. Under the circumstances of fixed and variable prices of electricity and steam, the influences on Pareto fronts and trade-off points were obtained and discussed. Results show that the steam turbines are favorable in the driving system when the environmental impacts are mainly considered. The drives option schemes are sensitive to the change of electricity and steam prices, and the environmental impacts of the drives option should not be ignored.

1. Introduction

In process industries, pumps and compressors are commonly employed to deliver fluids or increase pressure. Steam turbines and electric motors are usually selected to be the choice of drivers for pumps and compressors (Hugot, 2014). The drives option of the driving system in a plant is of importance to determine utility consumption, capital cost and operational cost as well.

Conventionally, the economy of the drivers is one of the critical factors when the decisions of drives for pumps and compressors are made. For example, the objective of the drives option is to minimize total annual cost (TAC) of driving systems. Oh and Yeo (2008) obtained the minimum TAC of the driving system through appropriate application of electric motors and steam turbines by solving a mixed integer nonlinear programming (MINLP) problem. Li et al. (2014) proposed a MINLP model to optimize a steam system in a chemical plant that contains multiple direct drive steam turbines by considering electric power as the alternative energy source for lower-level mechanical power demands. However, these previous studies mainly focused on the economy of the drives option instead of considering impacts of both economy and environment. Furthermore, the influence of different electricity and steam prices on the drives option is often ignored.

To deal with the problems mentioned above, we proposed a multi-objective optimization model aiming at simultaneously minimizing the economic objective and environmental objective of the drives option for rotating equipment in process Industries. In the model, life cycle assessment (LCA) method is used to quantify the environmental impacts. Moreover, the influences of different electricity and steam prices on the drives option are also analysed and discussed.

Please cite this article as: Wu L., Liu Y. , Kang L., 2015, Multi-objective optimization on driving options for rotating equipment in process industries to make trade-offs between economy and environmental impacts, Chemical Engineering Transactions, 45, 1093-1098 DOI:10.3303/CET1545183

2. Multi-objective optimization model

2.1 Economic objective

For a driving system with M electric motors and N steam turbines, the total annual cost for the drives option is chosen as the economic objective, which contains the capital cost of the electric motors and steam turbines and the operating cost of utilities consumed by these drivers. It can be expressed as

$$TAC = \left(f_m \sum_{i=1}^{M} C_i^m + f_t \sum_{j=1}^{N} C_j^t \right) + \left(u^{elec} C^{elec} + u^{hs} C^{hs} - u^{ls} C^{ls} \right) \quad (1)$$

where f_m and f_t denote the spare factors of the electric motor and steam turbine; C_i^m and C_j^t represent the annualized investment cost of motor and steam turbine, [CNY·y^{-1}]. CNY is the currency of China. u^{elec}, u^{hs} and u^{ls} are the annual consumption of electricity, [kWh·y^{-1}], the annual consumption amount of high pressure steam and low pressure steam, [t·y^{-1}]. C^{elec}, C^{hs} and C^{ls} represent the price of electricity, [CNY·kWh^{-1}], the prices of high pressure steam and low pressure steam, [CNY·t^{-1}]. Since the low pressure steam discharged from the steam turbine is usually delivered to the low pressure steam header, the total operating cost should take out the cost of low pressure steam.

The annualized investment cost of the electric motor and the steam turbine can be calculated by (Chen and Lin, 2012)

$$C_i^m = 9766.1 + 166.457 W_i^m \quad (2)$$

$$C_j^t = 497723.4 + 110.117 W_j^t \quad (3)$$

where W_i^m denotes the driving power of the i th electric motor, kW, and W_j^t denotes the driving power of the j th steam turbine in the driving system, [kW].

The electricity consumption in the driving system can be calculated by

$$u^{elec} = \sum_{i=1}^{M} \frac{W_i^m}{\eta_i} t \quad (4)$$

where t is the annual operating time, and η_i is the efficiency of the i th electric motor.

The consumption of the high pressure steam in the driving system can be expressed as

$$u^{hs} = \sum_{j=1}^{N} \frac{W_j^t}{\eta_j} t \bigg/ \left(H^{hs} - H^{ls} \right) \quad (5)$$

where H^{hs} and H^{ls} are the enthalpies of high pressure steam and low pressure steam, [kJ·t^{-1}]; η_j denotes the efficiency of the j th steam turbine.

Assume that the leakage and loss of steam are ignored. Then the amount of low pressure steam equals to the amount of the high pressure steam consumed by the steam turbines. That is

$$u^{hs} = u^{ls} \quad (6)$$

2.2 Environmental objective

Life cycle assessment (LCA) is a method to quantitatively assess the environmental impacts of goods and processes from “cradle to grave.”(Hellweg and Canals, 2014) The impacts of the consumed electricity and steam on the eco-system can be measured by the indexes in Eco-indicator 99 (Goedkoop and Spriensma, 2000), which is based on LCA. According to the instructions of Eco-indicator 99, the environmental impacts of the consumed electricity and steam can be expressed as

$$Env = u^{elec} DAM^{elec} + u^{hs} DAM^{hs} - u^{ls} DAM^{ls} \quad (7)$$

where DAM denotes the damage factor of utilities, which can be obtained from the database of Eco-indicator 99 (Sander Hegger, 2010). The units are [Pt·kWh^{-1}] for electricity and [Pt·t^{-1}] for steam.

2.3 Trade-off between the economic objective and the environmental objective

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

$$\mu_o^s = \left(O_o^{\max} - O_o^s\right) \Big/ \left(O_o^{\max} - O_o^{\min}\right) \tag{8}$$

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

The membership function of each Pareto-optimal solution can be expressed as

$$\mu^s = \sum_o \varpi_o \mu_o^s \tag{9}$$

where ϖ_o is the weight value of the o th objective function that is optional for decision makers. Then the trade-off solution is the one corresponding to the maximum of μ^s .

3. Case study

In this section, the driving system in a diesel hydrotreating (HDT) unit with an annual processing capacity of 3.2 × 10^6 t is taken as an example to simultaneously minimize its TAC and the environmental objective. Figure 1 shows the flowchart of the HDT unit. Table 1 lists the rated powers of pumps and compressors. The damage factors of utilities are given in Table 2. The enthalpy of the high pressure steam and the one of the low pressure steam are 3.189 kJ·t^{-1} and 2.777 kJ·t^{-1}. The annual running time of the unit is 8,400 h. To simplify the calculations, we assume the efficiencies of electric motors and steam turbines to be 75 % and 65 %.

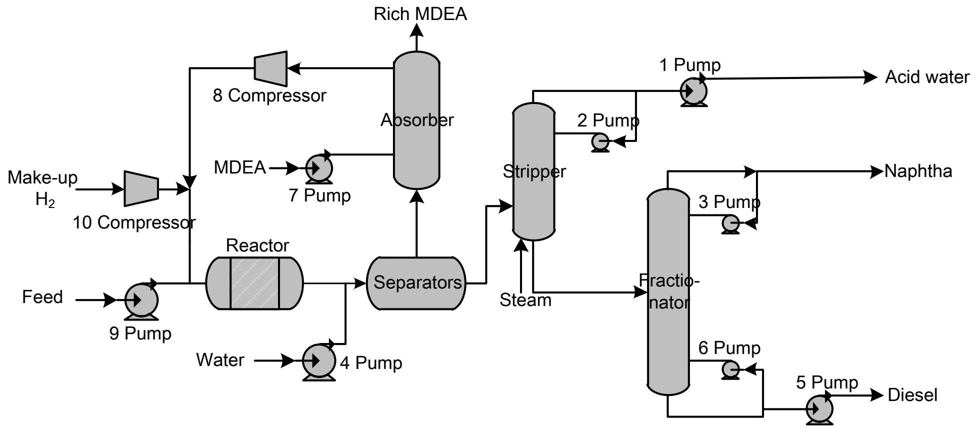

Figure 1: The flowchart of a diesel HDT unit

Table 1: The rated powers of pumps and compressors

No.	Pump or compressor	Rated power/ kW
1	Sour water pump	9.9
2	Reflux pump of stripper	29.2
3	Reflux pump of fractionator	47.8
4	Water pump	76.5
5	Refined diesel pump	215
6	Circulating pump of fractionator	414
7	Poor MEDA pump	497
8	Cycle hydrogen compressor	1,960
9	Feed pump	2,277
10	Make-up hydrogen compressor	2,800

Table 2: Damage factors of electricity and steam

	DAM^{elec} / Pt·kWh^{-1}	DAM^{hs} / Pt·t^{-1}	DAM^{ls} / Pt·t^{-1}
Damage factor	0.7873	15.009	13.07

3.1 Drives option at the fixed prices of electricity and steam

Assume that the electricity price is 0.52 CNY·kWh^{-1}, and the price of high pressure and low pressure steam are 120 CNY·t^{-1} and 90 CNY·t^{-1}. The proposed multi-objective optimization model was solved by the ε-constraint method implemented by the software package GAMS, where the weight values of the two objectives in Eq(9) are 0.5. The maximum value of Eq(9) is the trade-off point. The obtained Pareto front of the two objectives is shown in Figure 2, and the schemes of drives option are listed in Table 3.

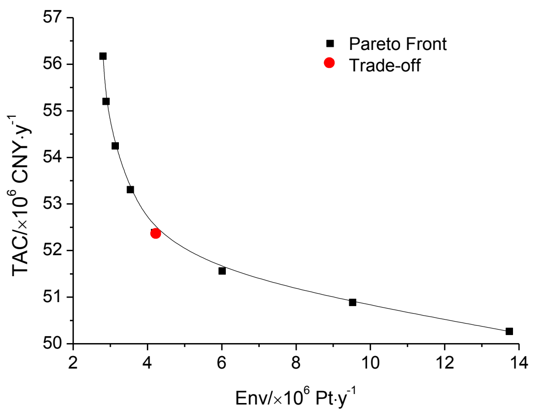

Figure 2: Pareto front of TAC and the environmental objective

Figure 2 indicates that the economic and environmental objectives present an opposite trend. TAC reaches its minimum of 50.26 × 10^6 CNY while the annual environmental impacts are the maximum of 13.74 × 10^6 Pt. On the contrary, the annual environmental impacts gets the minimum of 2.805 × 10^6 Pt while TAC reaches its maximum of 56.17 × 10^6 CNY. The red dot in Figure 2 denotes the trade-off solution, which corresponds to the TAC of 5.238 × 10^7 CNY and the annual environmental impact of 4.191 × 10^6 Pt. The schemes of drives option of the three cases are listed in Table 3.

Table 3: Schemes of drives option at fixed electricity and steam prices

No.	1	2	3	4	5	6	7	8	9	10
Min TAC	M	M	M	M	M	M	M	T	T	T
Min Env	T	T	T	T	T	T	T	T	T	T
Trade-off	M	M	M	M	T	T	T	T	T	T

Note: The number coincides with the number in Table 1; M and T denote the electric motor and the steam turbine.

When the TAC of the driving system is selected as the dominant objective, Table 3 indicates that motor-driven pumps or compressors are highly recommended when the rated powers are less than 500 kW. In this case, the high investment cost of steam turbines can be compensated by the less operating cost of steam. On the other hand, when the environmental objective is mainly considered, the steam turbine-driven pumps or compressors are recommended because the environmental impacts of steam are less than that of electricity. However, the motor-driven rotating equipment could be a better choice when their rated powers are less than 80 kW, which corresponds to the trade-off point.

3.2 Drives option under different electricity price

Since the electricity price varies with the fuel price, it is necessary to study the influence of utility prices change on the drives option.

Figure 3 shows the Pareto fronts of economy and environmental objectives for drives option varying with the electricity prices varying from 0.49 CNY·kWh^{-1}, 0.55 CNY·kWh^{-1} to 0.65 CNY·kWh^{-1}. As shown in Figure 3, the minimum TAC increases and the maximum environmental impacts decrease with the increase of electricity price. In other words, the Pareto optimal solutions and trade-off solution are dramatically dependent on the electricity price. The optimal schemes of drives option are given in Table 4. These results indicate that the steam turbines will reduce both TAC and environmental impacts of the driving system as the electricity price increases.

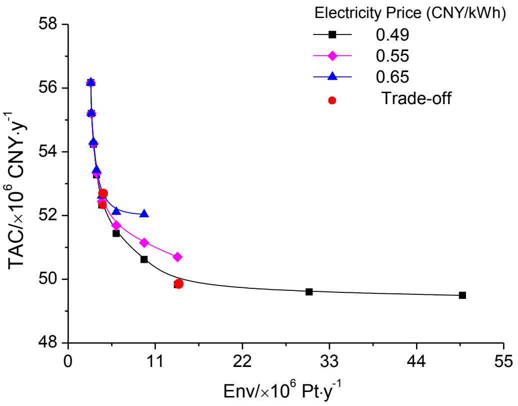

Figure 3: Pareto fronts under different electricity price

Table 4: Schemes of drives option under different electricity price

Electricity Price/ CNY·kWh^{-1}	No.	1	2	3	4	5	6	7	8	9	10
	Min TAC	M	M	M	M	M	M	M	M	M	T
0.49	Min Env	T	T	T	T	T	T	T	T	T	T
	Trade-off	M	M	M	M	M	M	M	T	T	T
	Min TAC	M	M	M	M	M	M	M	T	T	T
0.55	Min Env	T	T	T	T	T	T	T	T	T	T
	Trade-off	M	M	M	M	T	T	T	T	T	T
	Min TAC	M	M	M	M	M	M	T	T	T	T
0.65	Min Env	T	T	T	T	T	T	T	T	T	T
	Trade-off	M	M	M	M	T	T	T	T	T	T

3.3 Drives option under different steam price

The change of steam prices will also affect the drives option in the driving system.

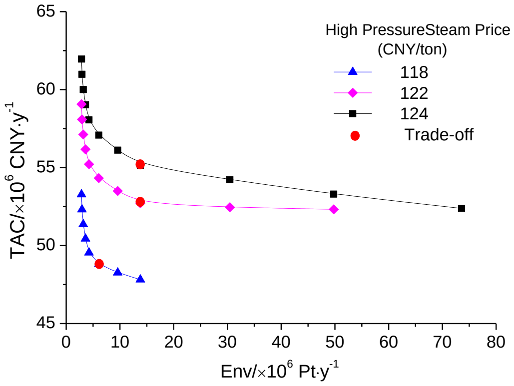

Figure 4 Pareto fronts under different steam prices

Likewise, as shown in Figure 4, we can also obtain the Pareto fronts of TAC and environmental objective for drives option with high pressure steam prices changing from 118 CNY·t^{-1}, 122 CNY·t^{-1} to 124 CNY·t^{-1}, whereas the low pressure steam price holds constant of 90 CNY·t^{-1}.

As shown, both the minimum TAC and maximum environmental impacts increase as the price of high pressure steam increases from 118 CNY·t^{-1} to 124 CNY·t^{-1}. This trend is opposite to that presented in Figure 3. When the price of high pressure steam increases, the steam turbines would increase the TAC and reduce the environmental impacts. Therefore, the variation of high pressure steam price has intensive influences on the Pareto front and trade-off solution as well. The schemes of drives option after optimization are given in Table 5.

Table 5: Schemes of drives option under different steam prices

HP Steam Price / CNY·t^{-1}	No.	1	2	3	4	5	6	7	8	9	10
	Min TAC	M	M	M	M	M	M	M	T	T	T
118	Min Env	T	T	T	T	T	T	T	T	T	T
	Trade-off	M	M	M	M	T	T	T	T	T	T
	Min TAC	M	M	M	M	M	M	M	M	M	T
122	Min Env	T	T	T	T	T	T	T	T	T	T
	Trade-off	M	M	M	M	M	M	M	T	T	T
	Min TAC	M	M	M	M	M	M	M	M	M	M
124	Min Env	T	T	T	T	T	T	T	T	T	T
	Trade-off	M	M	M	M	M	M	M	T	T	T

4. Conclusions

In this work, we proposed a multi-objective optimization model to simultaneously minimize the economic objective and environmental objective of the drives option for rotating equipment in process Industries, in which the environmental impacts of the driving system are measured by the indexes of Eco-indicator 99. The influences of fixed and variable prices of the electricity and steam on the schemes of drives option in the driving system are analyzed and discussed. The results for the driving system in a diesel hydrotreating unit show that appropriate drives option could reduce both the TAC and environmental impacts. When the environmental impacts are mainly considered, the steam turbines are favorable in the driving system. The variations of electricity and steam prices should be taken into consideration due to the fact that the drives option scheme is sensitive to these changes.

Acknowledgements

The authors gratefully acknowledge funding by the project (No.21376188 and No.2015GY095) sponsored by the Natural Science Foundation of China and the Industrial Science & Technology Planning Project of Shaanxi Province.

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