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# Applying the multi-objective approach for operation strategy of cogeneration systems under environmental constraints

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## Abstract

This paper presents a multi-objective approach based on evolutionary programming to solve the economical operation of cogeneration system under emission constraints. A multi-objective function including the minimization of cost and multi-emission is formulated in this paper. The cost model includes fuels cost and tie-line energy. The emissions with CO<sub>2</sub>, SO<sub>x</sub>, and NO<sub>x</sub> were derived as a function of fuel enthalpy. All constraints including fuel mix, operational constraints, and emission constraints must be met in the optimization process. The steam output, fuel mix, and power generations will be found by considering the time-of-use dispatch between cogeneration systems and utility companies. Data of an industrial cogeneration system was used to illustrate the effectiveness of the proposed method. © 2002 Elsevier Science Ltd. All rights reserved.

*Keywords:* Cogeneration systems; Evolutionary programming; Multi-objective approach; Time-of-use

## 1. Introduction

Cogeneration systems have now become an important power source to the industry. It offers a reliable, efficient, and an economic mean to supply both thermal and electrical energy. It can be constructed in urban areas and used as distributed electrical energy sources. Applications of cogeneration systems are still growing. More experience will be needed in improved operations for more energy saving.

For effective operations, many strategies had been developed in Refs. [1–6]. Those strategies mainly dealt with the operating cost regardless of emissions constraints. The passage of the Clean Air Act Amendments of 1990 [7] has forced utilities to modify their operating strategies to meet environmental standards set by legislation. In recent years, some strategies including emission dispatching and fuel switching have been developed in Refs. [8–13]. These techniques intended to reduce both the emission and the operational cost. In addition, some multi-objective algorithms [14–16] were successfully applied to solve bi-objective environmental/economic problem regarding minimization of operational cost and the total emission of NO<sub>x</sub>/SO<sub>x</sub>/CO<sub>2</sub>. The multi-emission, such as CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub>,

etc. are not all taken into account. In search procedure, it easily enables the decision makers (DMs) to alternative a paerto-optimal solution. DMs are not able to adjust single-emission dependent upon their importance.

Owing to the conflicting and non-commensurable natures of fuel cost and emission control, a trade-off between economy and environment needs to be considered in the optimization process. A single-objective function seems inappropriate for this problem. An efficient and reliable technique is needed to solve this problem. This paper presents a multi-objective approach with evolutionary programming (EP) approach [17] to solve the problem. In interactive nature, the DM could easily seek alternatives to find a satisfactory strategy.

In this paper, the fuel consumption and steam output will first be measured. Curve fitting method [18] was used to get the Input–Output (I/O) curve for the heat input and the steam generation output. A multi-fueled unit model was formulated to get the I/O curve for units burning mixed fuels. The emissions with CO<sub>2</sub>, SO<sub>x</sub>, and NO<sub>x</sub> were derived as a function of fuel enthalpy. The operation problem of cogeneration systems is formulated as a multi-objective non-differentiable optimization problem. The objectives considered in this paper include the minimization of operation cost, SO<sub>x</sub> emission, NO<sub>x</sub> emission, and CO<sub>2</sub> emission. The improvement of one objective can be reached only by the reduction of the other. The optimization

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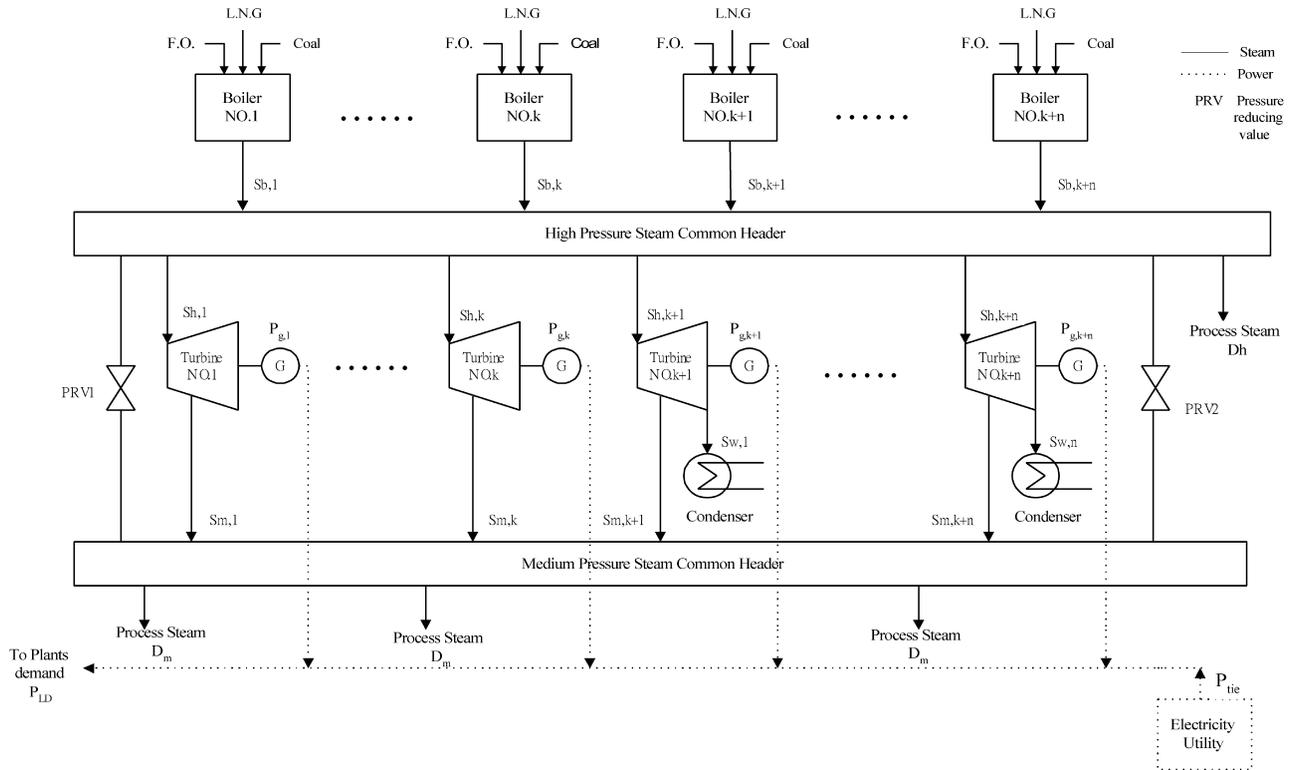


Fig. 1. The diagram of the cogeneration system.

technique of the EP is relied on to solve the multi-objective problem efficiently. This approach will provide a set of flexible best selection for operation dispatch by following the instructions of DMs.

## 2. Problem formulation

Fig. 1 shows the diagram of a cogeneration system with common medium pressure steam headers. The system has  $n$  extraction-condenser steam turbines for power generation. There are  $n$  back-pressure steam turbine,  $k$  extraction-condenser steam turbine and  $k+n$  steam boilers. The fuels including F.O., L.N.G., and coal were used in each boiler. Various models are needed as follows.

### 2.1. I/O cost curve of boilers

It is assumed that the I/O curve of a boiler is a 3rd order polynomial, we have

$$F_{bi}(S_{bi}(t)) = A_0 + A_1 \times S_{bi}(t) + A_2 \times S_{bi}^2(t) + A_3 \times S_{bi}^3(t) \quad (1)$$

where

$F_{bi}(S_{bi}(t))$ : consumed enthalpy of the  $i$ th boiler at time  $t$  (MBTU/H).

$S_{bi}(t)$ : steam output of the  $i$ th boiler at time  $t$  (T/H).  
 $A_0, A_1, A_2, A_3$ : coefficients of the I/O operation curve.

With mixed fuel used, a proper model needs to be developed. The dual-fueled unit model was formulated in Ref. [19]. Eq. (2) is used to represent a unit burning three fuels simultaneously. We have

$$F_{bT}(S_b(t)) = F_{b1}(S_b(t)) \times (\lambda_1(t) + \eta_{1/2} \times \lambda_2(t) + \eta_{1/3} \times \lambda_3(t)) \quad (2)$$

where

$F_{bT}(S_b(t))$ : total consumed enthalpy at time  $t$  (MBTU/H).  
 $F_{b1}(S_b(t))$ : consumed enthalpy of fuel 1 at time  $t$  (MBTU/H).  
 $\eta_{1/2}$ : the efficiency ratio of fuel 1/fuel 2.  
 $\eta_{1/3}$ : the efficiency ratio of fuel 1/fuel 3.  
 $\lambda_1(t), \lambda_2(t), \lambda_3(t)$ : the mixed ratio of fuel 1, 2, and 3 at time  $t$  with  $\lambda_1(t) + \lambda_2(t) + \lambda_3(t) = 1$ .

The I/O cost curve of boilers can be described by

$$FBC_T(t) = F_{bT}(S_b(t)) \times BC_T(t) \quad (3)$$

$$BC_T(t) = BC_1 \times \lambda_1(t) + BC_2 \times \lambda_2(t) + BC_3 \times \lambda_3(t) \quad (4)$$

where

$FBC_T(t)$ : the total operation cost of boilers at time  $t$  (NT\$).

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