# Target and Synthesis of Cogeneration System

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## Abstract

Appropriate design of a cogeneration system requires understanding of interactions between various processes and utility system of a process plant. This paper introduces a new method to estimate cogeneration potential based on the total site profile by introducing "detailed shaft-work targeting model." The proposed model accounts for the variation of efficiency of a steam turbine with capacity, inlet pressure, exit pressure, degree of superheat as well as the part load operation. Maximum possible cogeneration potential is addressed through mathematical optimisation using superstructure of steam turbines satisfying required process heat load. The proposed methodology is illustrated through an example.

**Keywords:** Cogeneration, targeting, steam turbine, efficiency.

## 1. Introduction

Cogeneration system satisfies the heat and power demands of different processes in a chemical process plant. A typical cogeneration system consists of boilers for steam production and turbines for power generation. Processes are either users or generators of steam at different levels. The major issue is steam load distribution for appropriate generation of power. It is important to estimate cogeneration potential in a process plant ahead of detailed design. In recent years, concepts and methods have been developed for optimising energy systems ranging from heat recovery systems for individual processes to total site energy systems.

Dhole and Linnhoff (1993) introduced a simple exergetic model to estimate cogeneration potential for the total site. This method assumes that the isentropic efficiency of a steam turbine is constant over different operating range. Raissi (1994) proposed a temperature- enthalpy (*T–H*) model based on the Salisbury (1942) approximation, which states that the specific heat load of the steam (difference of the enthalpy at the inlet condition and the saturated liquid enthalpy at the inlet pressure) remains approximately constant during the expansion. This model cannot respond to variations in load, size, or operating conditions.

Marvomatis and Kokossis (1998) presented a more accurate shaft-work targeting model, known as the turbine hardware model (THM). It is based on the concepts of (i) the Willan's relationship, (ii) typical maximum efficiency plots, (iii) fixed percentage of internal losses to maximum power and (iv) the equivalence of a complex turbine to a cascade of simple turbines. Major disadvantages are that THM model doesn't consider the exit pressure variation of turbine in case of extraction turbine and it is based on assumption of constant internal losses.

This paper introduces the Detailed Shaft-work Targeting Model (DSTM) based on the efficiency data of steam turbines at different conditions as reported by Fink and Beaty (1978). This model considers exit pressure variation to remove the drawback of THM to predict more accurate turbine efficiency. Maximum possible cogeneration potential is addressed through mathematical optimisation using superstructure of steam turbines satisfying required process heat load. It may be noted that in the proposed methodology, heat demand or supply from different processes are assumed to be constant. The same may be obtained either from the design package of the individual process or through applying pinch analysis procedure. Cogeneration potential of the entire site is then maximised subject to fulfilment of these given thermal loads. Therefore, in the proposed procedure, generation of power is going to reduce the electricity bill of the overall process plant and it is not going to influence the performance of the individual process. The proposed methodology is illustrated through an example.

## 2. Detailed Shaft-work Targeting Model (DSTM)

Basic methodology and approach for this model are discussed in the following sub-sections.

### *2.1. Turbine Efficiency*

The actual work output of a turbine is less than the isentropic work output due to several losses. Isentropic efficiency of a steam turbine may be expressed as product of base efficiency and different correction factors. Typical data for efficiency and efficiency correction factors for steam turbines is given by Fink and Beaty (1978). Turbine efficiency may be expressed as

$$\eta = f_1 \times f_2 \times f_3 \tag{1}$$

Base efficiency is denoted by $f_1$ and it is a function of inlet pressure and power generation capacity. Correction for exit pressure is denoted by $f_2$ and $f_3$ denotes the correction for degree of superheat of the inlet steam. Analytical expressions for these function has been obtained applying multiple regression analysis of the data provided by Fink and Beaty (1978). Detailed expressions for condensing and non-condensing steam turbines are tabulate in Table 1. Correlation are expressed in terms of inlet pressure $(P_{in})$, rated power output $(E)$, degree of superheat $(\Delta t)$, pressure ratio $P_{in} / P_{out} = p_r$ and exhaust pressure ($P_{out}$). In these correlations, pressure is in bars, temperature difference is in °C and power is in MW.

Table 1. Correlations to calculate steam turbine efficiency.

| | Correlations |
|---|---|
| Condensing turbine | $\ln(f_1) = -0.0229\ln(P_{in}) + 0.0414\ln(E) - 0.304$ |
| | $f_2 = 0.0357\ln(P_{out}) + 1.1011$ |
| | $f_3 = 0.0003\times(\Delta t) + 0.956$ |
| Non-condensing turbine | $\ln(f_1) = -0.04\ln(P_{in}) + 0.06\ln(E) - 0.241$ |
| | $f_2 = -0.0005(p_r)^2 + 0.0127(p_r) + 0.932$ |
| | $f_3 = -0.000005(\Delta t)^2 + 0.001(\Delta t) + 0.95$ |

### *2.2. Superstructure of Turbine Network*

Using the above model, it is possible to calculate exact efficiency of a steam turbine and the total power produced. Once steam levels are selected, a large number of turbine arrangement are possible and each alternative arrangement of turbine result in different shaftwork power. It is necessary to develop a generalized optimisation procedure to select the optimum turbine arrangement. This is obtained through a mixed integer non-linear programming (MINLP) approach considering a superstructure of turbine networks. The superstructure encompasses all possible turbine arrangements. A part of the superstructure is shown in Figure 1. The optimization problem is formulated to maximize the power output after satisfying process heat loads, mass and energy balance of each steam level. In this formulation, however, it is assumed that all steam turbines are simple turbines.

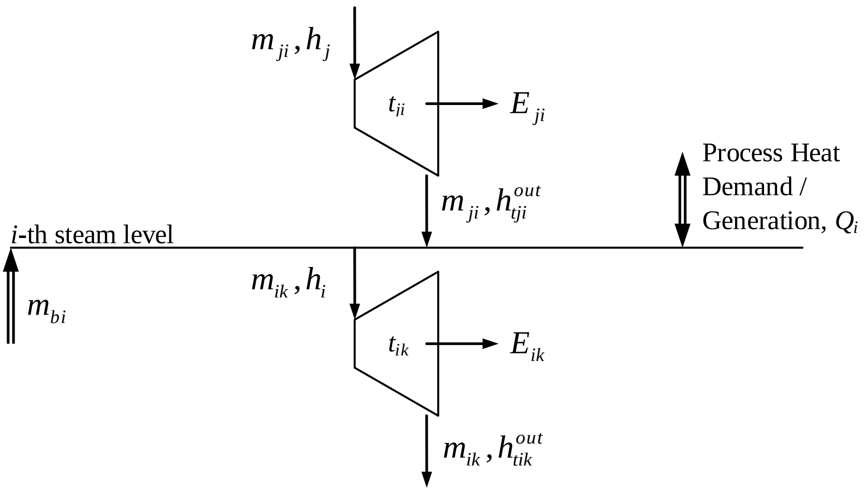


Figure 1: Supersturecture of turbine arrangement.

### *2.3. Problem Formulation*

In the problem formulation steam levels are denoted by $i$ where $i$ varies from 1 to $N$, total number of stream levels. Turbine $t_{ij}$ is connected between $i$-th and the $j$-th steam level. Mass flow rate of steam through the turbine $t_{ij}$ is denoted as $m_{ij}$. At steam level $i$, process required $Q_i$ amount of heat ($Q_i$ is negative if steam is generated by the process) and $m_{bi}$ amount of steam from the boiler house is supplies at the *i*-th steam level. Typically, steam from the boiler house will be supplied only at the top most level.

Mass balance for the *i*-th steam level (see Figure 1) may be written as

$$m_{bi} + \sum_{j=1}^{i-1} m_{ji} = \sum_{k=i+1}^{N} m_{ik} + m_{pi} \tag{2}$$

Energy balance for the *i*-th steam level (see Figure 1) may be written as

$$m_{bi}h_{bi} + \sum_{j=1}^{i-1} m_{ji}h_{ji}^{out} = \sum_{k=i+1}^{N} m_{ik}h_{i} + m_{pi}h_{pi} \tag{3}$$

Heat demand or supply form a process may be expressed as follows

$$Q_i^{demand} = m_{pi}(h_{pi} - h_p^{sat}) \tag{4}$$

$$Q_i^{supply} = m_{pi}h_{pi} \tag{5}$$

The total power output of superstructure has to be maximise:

$$\max\ E = \sum E_{ij} = \sum m_{ij}(h_i - h_{tij}^{out})\eta_{ij} \tag{6}$$

The optimization problem is formulated and solved using Excel solver. Properties of steam are calculated using TPX add-in (Goodwin, 1998). The methodology is applied on the following example.

## 3. Example

This example is taken from Mavromatis and Kokossis (1998). The steam system comprises of four steam levels along with cooling water utility. The very high pressure steam (VHP) is produced in the boiler house at 500°C and 90 bar $(T_{sat} = 302°C)$. The high (HP), medium (MP) and low pressure (LP) steam correspond to 46 bar $(T_{sat} = 260°C)$, 15.5 bar $(T_{sat} = 200°C)$ and 2.7 bar $(T_{sat} = 130°C)$, respectively. In the site, overall it generates 10.63 MW of HP steam, requires 6.88 MW of MP steam and 16.25 MW of LP steam.

Solution of the model shows that there are three simple steam turbines arrangement produces maximum power of 3.95 MW. Detailed results are tabulated in Table 2. It may be noted that unlike any existing method, the proposed procedure is independent of any pre-determined turbine arrangement. In THM, it has been assumed that there exists one turbine between every alternate steam levels. However, this arrangement need not always gives maximum power generation potential. In this problem, maximum power generation corresponds to a turbine between VHP and HP level, a turbine between HP and MP level and a turbine between HP and LP level. Unlike THM, there is no turbine between MP and LP at maximum power generation.

Table 2 . Shaftwork targets using the DSTM

| Sr. No. | Turbine | hin (kJ/kg) | hout (kJ/kg) | m (t/h) | $\eta$ | E (MW) |
|---|---|---|---|---|---|---|
| 1 | t (VHP-HP) | 3386.06 | 3293.19 | 17.47 | 0.59 | 0.45 |
| 2 | t (HP-MP) | 3012.39 | 2867.63 | 12.29 | 0.67 | 0.49 |
| 3 | t (HP-LP) | 3012.39 | 2627.46 | 28.10 | 0.70 | 3.00 |
| Total | | | | | | **3.95** |

## 4. Conclusion

The detailed shaft-work targeting model (DSTM), proposed in this paper, considers the variation in capacity, inlet pressure, exit pressure and degree of superheat while predicting the efficiency of a simple steam turbine. In comparison to other existing model, the proposed method does not take any assumption about turbine arrangement. Superstructure based MINLP formulation helps in finding best possible network arrangement of simple steam turbines while evaluating maximum cogeneration potential for a site. Detailed evaluation and evolution of turbine network may be addressed based on the preliminary network obtained by applying the proposed procedure.

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