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# A New Cogeneration Targeting Procedure for Total Site

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Estimation of cogeneration potential prior to the design of the total site utility system is vital to set targets on site fuel demand and steam flowrate as well as heat and power production. This paper introduces a new cogeneration targeting model that has been developed to estimate cogeneration potential of site utility systems. The new procedure has been developed for cogeneration targeting in the total site. The algorithm developed here provides a consistent, general procedure for determining the mass flowrates and the efficiencies of the turbines used. This algorithm utilizes the relationship of the entropy with the enthalpy and the isentropic efficiency. Finally the new model allows targeting shaftwork production, fuel consumption, cooling requirement, degree of superheat at process steam generators and steam boiler with high accuracy. It is superior to previous works in that it does not require cumbersome simulation for initiation, accurate and it can be traced easily which enhance its programmability. A case study is used to illustrate the usefulness of the new cogeneration targeting method for reducing the overall energy consumptions for the site.

## 1. Introduction

The chemical process usually requires steam at different pressure and temperature values for heating and non-heating purposes. In order to provide steam at the required condition, the designer has to decide whether to provide steam at the extreme condition and then let it down to the different levels or produce steams separately at different boilers. Many industrial processes operate within Total Sites (Dhole and Linnhoff, 1993; Raissi, 1994), where they are serviced and linked through a common central utility system. This utility system meets the demands for heat and power of the individual process units by their indirect heat integration. However, greater benefits in terms of energy and capital cost can be obtained by looking at the entire site. Total site integration addresses the task of optimizing each process and the utility system in the context of the overall site (Sorin and Hammache, 2005). One of the important tasks for the utility systems design is targeting d shaftwork production ahead of design. A number of models have been proposed for the early estimation of cogeneration for utility systems using steam turbines. Dhole and Linnhoff (1993) proposed an exergetic model based on the site source-sink profiles. Raissi (1994) proposed the T-H model based on the Salisbury (1942) approximation to assume power be linearly proportional to difference between the inlet and outlet saturation temperatures. Mavromatis and Kokossis (1998) introduced the non-linear model of THM (Turbine Hardware Model) based on the principle of the Willans' line to incorporate the variation of efficiency with turbine size and operating load. Harell (2004) introduced a graphical technique to estimate the cogeneration potential that utilizes the concept of extractable power and header efficiency to establish cogeneration potential. Varbanov et al. (2004) developed the improved turbine hardware

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model. Sorin and Hammache (2005) developed an exergetic model based on thermodynamic insights for the Rankine cycle which shows that power is not linear to saturation temperature differences. Mohan and El-Halwagi (2007) developed a linear algebraic approach based on the concept of extractable power and steam main efficiency. Bandyopadhyay et al. (2010) developed a linear model based on the Salisbury (1942) approximation and energy balance at steam mains. Ghannadzadeh et al. (2011) presented a new shaftwork targeting model, termed the Iterative Bottom-to-Top Model (IBTM). Kapli et al. (2011) introduced a new method to estimate cogeneration potential of site utility systems by a combination of bottom-up and top-down procedures.

## 2. Methodology

In this section, the new model was presented in detail to target the cogeneration potential for site utility systems. The method uses the Site Utility Grand Composite Curve (SUGCC), which represents another form of the site composite curves (Klemeš et al., 1997). The SUGCC was obtained from the site composite curves by being represented on temperature–enthalpy axes of each steam main by its saturation temperature and steam generation and usage loads, respectively, from the source and sinks profiles of the site composites. The differences between steam generation and steam usage set the VHP demand or the supply heat available at each main. The new model calculates the minimum required flow rate from a steam generation unit and the levels of superheat in each steam main based on the heat loads specified by SUGCC.
The isentropic efficiency is a function of the load and, for fixed values of flow rates, it would be better to consider the highest efficiency, assuming to use turbines, for which the calculated flow rate will be the full load (Al_azri, 2008). In the study by Varbanov et al. (2004) thermodynamic model was used to estimate the isentropic efficiency as follows:

$$\eta_{is} = \frac{W_{\max}}{W_{is,\max}} \tag{1}$$

$$W_{\max} = \frac{W_{is,\max} - A}{B} \tag{2}$$

Where A and B are constants that depend on the turbine and are functions of the saturation temperature. A and B are calculated by Eqs. (3) and (4), respectively.

$$A = b_0 + b_1.\Delta T_{sat} \tag{3}$$

$$B = b_2 + b_3.\Delta T_{sat} \tag{4}$$

The values of these constants are given in Table 1. (Varbanov et al., 2004)

*Table 1: The Regression Coefficients Used in the Isentropic Efficiency Equation*

| | Back Pressure Turbines | | Condensing Turbines | |
|---|---|---|---|---|
| | $W_{max}$≤ 2000 kW | $W_{max}$> 2000 kW | $W_{max}$≤ 2000 kW | $W_{max}$> 2000 kW |
| $a_0$(kW) | 0 | 0 | 0 | -463 |
| $a_1$(kW/°C) | 1.08 | 4.23 | 0.662 | 3.53 |
| $a_2$ | 1.097 | 1.155 | 1.191 | 1.22 |
| $a_3$(°C$^{-1}$) | 0.00172 | 0.000538 | 0.000759 | 0.000148 |

At the boiler exit, for a given pressure and steam temperature, the enthalpy can be obtained with the aid of steam tables. The actual input enthalpy of steam mains are usually provided from the calculations of the previous steam mains. The input isentropic enthalpy of steam main can be obtained in the superheated region. Then, the efficiency is calculated. The actual enthalpy which will serve as the input enthalpy for the next zone is then calculated using the isentropic enthalpies and efficiency by Eq. (5).

$h_{i,actual} = h_{i\text{-}1,isentropic} - \eta(h_{i\text{-}1,isentropic} - h_{i,isentropic})$ (5)

In this study, the calculation of superheat temperature at each steam level was done using the iterative procedure based on a certain desirable amount of superheat in the LP steam main. If the degree of superheat in the resulting LP steam main was less than the required level, then, operating conditions of VHP would be updated and iterated until the acceptable superheated conditions would be met for the LP steam main.

The mass flow rate of steam expanding through the Z-th turbine ($\dot{m}_z$) can be calculated by the mass balance for i-th by Eq. (6), as shown in Figure 1:

$m_{z} = m_{z\text{-}1} + m_i^{DEM} - m_i^{GEN}$ (6)

Where, $\dot{m}_i^{GEN}$ is the flow rate of steam generated by the process and $\dot{m}_i^{DEM}$ is the flow rate of steam demanded by the process.

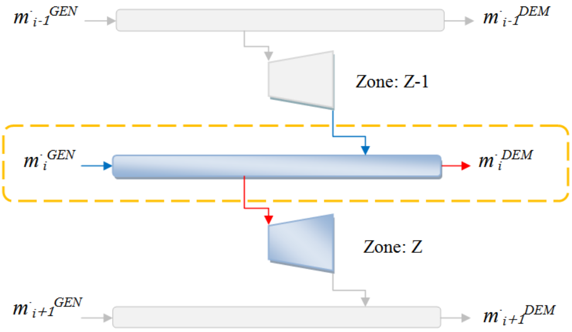


*Figure 1: Mass load balance for i-th steam main*

The procedure of cogeneration targeting for a given site utility system (Figure 2) is presented as follows:

Step 1: Preparation of a model in SUGCC

Step 2: Initial estimates of boiler superheat temperature

Step 3: Finding initial estimates of mass flow rates passing by each zone, assuming isentropic expansions throughout the levels by Eq. (7)

$$m_{z,initial} = \frac{\dot{Q}_{net,i}}{h_i - h_{f,i}} \quad (7)$$

Where, $\dot{Q}_{net,i}$ =Net load at the given level (MW)

$h_i$=Steam main isentropic enthalpy at the given level (kJ/kg)

$h_f$=Saturated liquid enthalpy at the given level (kJ/kg)

Step 4: Correcting efficiency by Eq.(1)

Step 5: Correcting $h_i$ and $\dot{m}_i^{NET}$ for the given steam level

Step6: Repeating the steps from the second iteration through convergence in a manner until they meet the stopping criterion (Eq. (8))

$$\sqrt{\sum_{i=1}^{z} (m_z - m_{z,new})^2} \leq \varepsilon \quad (8)$$

Step 7:Checking the superheat temperature when the first loop of algorithm terminates(if it falls below the allowed minimum, the superheat temperature of the boiler is increased and repeats the steps until meeting the desirable amount of superheat in the LP steam main.)

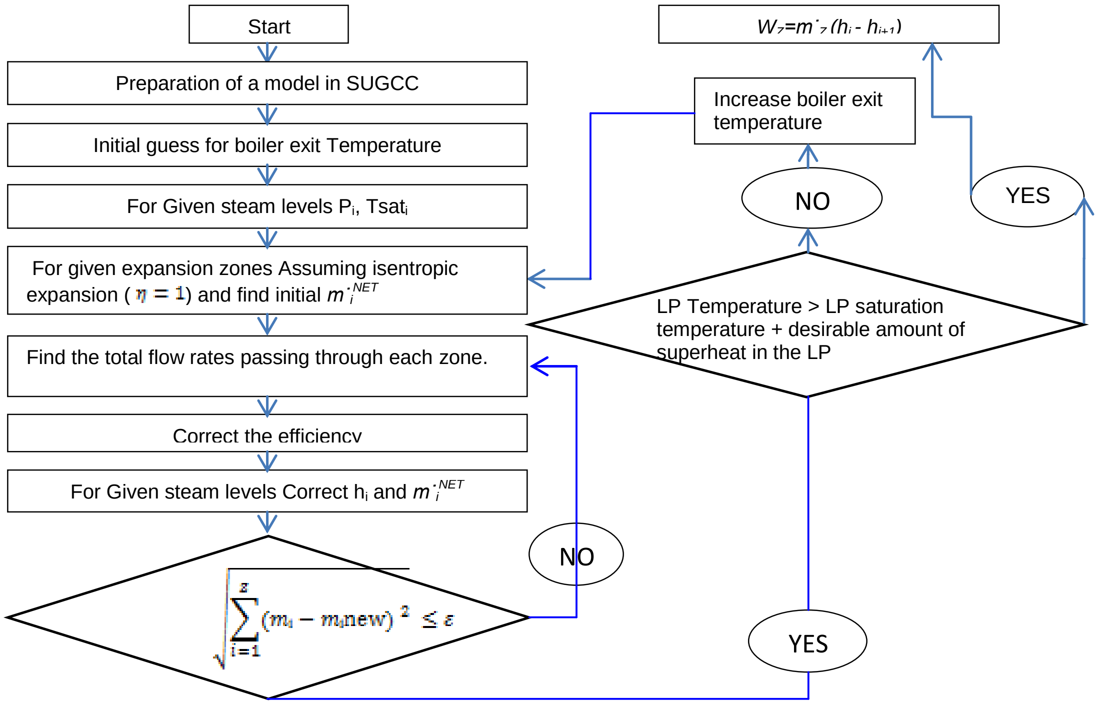


*Figure 2: Flow diagram of the algorithm for the new method*

## 3. Case Study

To show the applicability of the new method in the total site analysis, 2 case studies were considered. In the first case study (Ghannadzadeh et al., 2011), the four considered steam levels were very high pressure (VHP), high pressure (HP), medium pressure (MP) and low pressure (LP) at 120, 50, 14 and 3 bar(a), respectively. The net heat demand at HP, MP and LP steam levels was 50, 40 and 85 MW respectively. In this case, the water supplied to the boiler was assumed to be at the temperature of 105 °C and the degree of superheat in LP was assumed to be 40 °C.
In the second case study (Ghannadzadeh et al., 2011), the four considered steam levels were very high pressure (VHP), high pressure (HP), medium pressure (MP) and low pressure (LP) at 90, 46, 15.5 and 2.7 bar(a), respectively. The heat demand at MP and LP steam levels was 6.88 and 16.25 MW, respectively, and, in this case, the process steam generation at HP level was higher than the process steam demand and heat surplus at HP steam levels was10.63 MW. It was assumed that the water supplied to the boiler was at the temperature of 105 °C and the degree of superheat in LP was assumed to be 20 °C.

## 4. Results

A schematic of the shaft power target in the second case study obtained from the new method is demonstrated in Figure 3. Table 2 indicates the shaft power targeting results from the main shaft work targeting models and the new method.
As shown in Table 2, the total power target of 34.100 MW from IBTM methodology was significantly different from the detailed design procedure of 38.104 MW with an error of 10.50 %. The shaft work target obtained from the THM model of 14.100 MW was 63.00 % different from the shaft work obtained from the detailed design procedure. Similarly, SHM model target was 8.73 % different from the actual shaft work from the detailed design procedure. These discrepancies in the shaft work targets were due to the assumptions used in these models. The shaft work target obtained from the new method of

37.970 MW was only 0.35 % different from the detailed design procedure in THERMOFLOW and was only 0.0079 % different from the STAR Software.

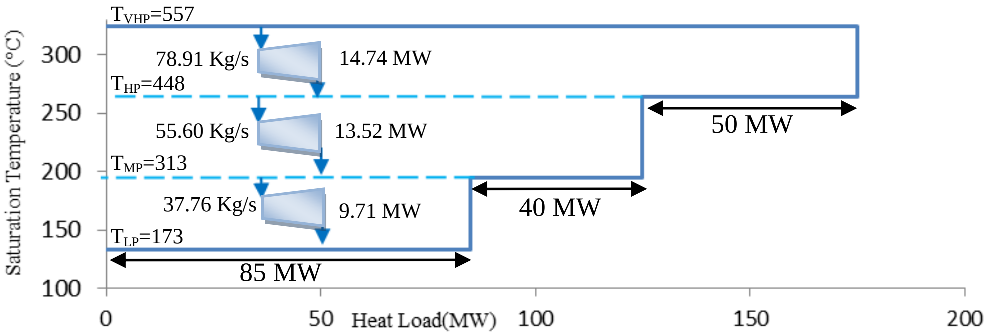


*Figure 3: Cogeneration potential obtained from the new method (Case study 1)*

*Table 2: Shaft power targeting results for case study 1*

| Methodology | Error % | Total (MW) | 'VHP-HP' (MW) | 'HP-MP' (MW) | 'MP-LP' (MW) |
|---|---|---|---|---|---|
| IBTM | -10.50 | 34.100 | 13.490 | 12.28 | 8.330 |
| THM -Model in STAR | -63.00 | 14.100 | 9.400 | 4.700 | 0 |
| SHM | +8.99 | 41.430 | 18.200 | 14.460 | 8.770 |
| New method | -0.352 | 37.970 | 14.740 | 13.520 | 9.710 |
| STAR Simulation | -0.344 | 37.973 | 14.740 | 13.520 | 9.710 |
| Thermoflow Simulation | - | 38.104 | 14.797 | 13.558 | 9.749 |

Figure 4 presents a schematic of the shaft power target in the second case study obtained from the new method. In addition, Table 4 presents the shaft power targeting results from the main shaft work targeting models and the new method.

As shown in Table 3, the total power target of 4.4 MW from the IBTM methodology was significantly different from the detailed design procedure of 4.524 MW with an error of 2.74 %. The shaft work target obtained from the THM model of 4.200 MW was7.16 % different from the shaft work obtained from the detailed design procedure. Similarly, SHM model target was19.36 % different from the actual shaft work from the detailed design procedure. These discrepancies in the shaft work targets were due to the assumptions used in these models. The shaft work target obtained from the new method of 4.520 MW was only 0.088 % different from the detailed design procedure in THERMOFLOW and was only 0.022% different from the STAR Software.

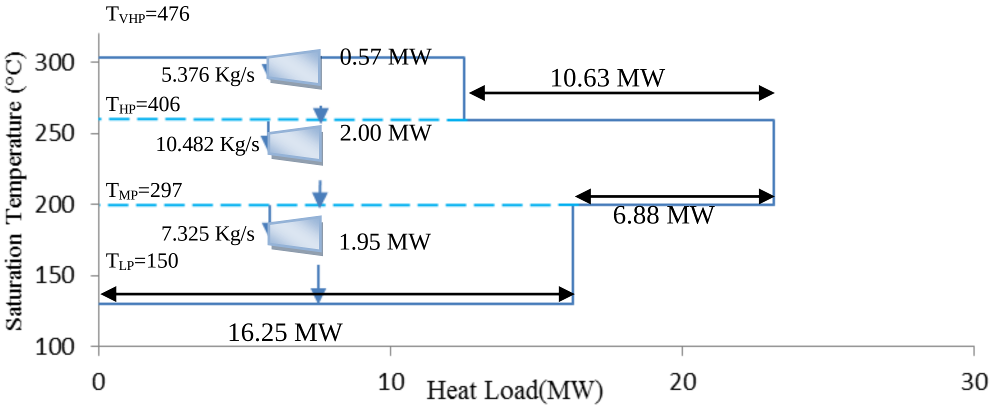


*Figure 4: Cogeneration potential obtained from the new method (Case study 2)*

*Table 3: Shaft power targeting results for case study 2*

| Methodology | Error % | Total (MW) | 'VHP-HP' (MW) | 'HP-MP' (MW) | 'MP-LP' (MW) |
|---|---|---|---|---|---|
| IBTM | -2.91 | 4.520 | 0.80 | 1.9 | 1.70 |
| THM [Model in STAR] | -7.33 | 4.400 | 0.50 | 1.9 | 1.80 |
| SHM | 19.15 | 4.200 | 1.80 | 1.9 | 1.70 |
| New method | -0.26 | 5.400 | 0.57 | 2.0 | 1.95 |
| STAR Simulation | -0.22 | 4.521 | 0.57 | 2.0 | 1.951 |
| Thermoflow Simulation | - | 4.524 | 0.571 | 2.001 | 1.952 |

## 5. Conclusion

A new cogeneration targeting model was developed in this work sincethe existing models have been shown to give misleading results compared with thedetailed design procedure. A new model for targeting different steam consumption, steam generation and shaft work production was developed using an original thermodynamic insight in cogeneration. The new model which was proposed here provideda consistent, general procedure for determining the mass flowrates and the efficiencies of the used turbines. In adition, the new model allowed for targeting shaftwork production and degree of superheat in the steam boiler with a high level of accuracy. It was superior to previous works in that it was accurate, didnot require cumbersome simulation for initiation and could be traced easily, which enhance its programmability. The developed methodology is required to be further extended to accommodate theintegration of renewable energy sources, such as solar, wind, etc. for thetotal site with high accuracy. Another work which could be considered in future is to optimizesteam levels for reducing theoverall energy consumptions for the site.

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