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A New Shaftwork Targeting Model for Total Sites

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Estimation of cogeneration potential prior to the design of the central utility system for Total Sites, is vital to set targets on site fuel demand as well as heat and power production. This paper introduces a new shaftwork targeting model, termed the Iterative Bottom-to-Top Model (IBTM), in order to facilitate the targeting stage and also eliminate the need for simulation of the steam turbine networks. The advantages of the IBTM are presented through a comparative study of the main shaftwork targeting models on different configurations of steam turbine network. Finally, a refinery plant has been briefly analyzed to highlight the importance of a reliable shaftwork targeting model to identify the areas in which heat recovery projects should be focused.

1. Introduction

Most processes operate within Total Sites where they are integrated 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. Indirect heat integration is often achieved by a steam turbine network in which steam is generated by waste heat from some processes and will be used as a heat source in other processes. Prior to the design of steam turbine network, estimation of cogeneration potential is vital to set targets on boiler fuel consumption and flowrate of steam through steam mains as well as heat and power production.

There are several models for cogeneration targeting. Dhole and Linnhoff (1993) introduced an exergetic model based on the site source-sink profiles. Raissi (1994) proposed the T-H model relied on the Salisbury (1942) approximation to assume power be linearly proportional to difference between saturation temperatures. Mavromatis and Kokossis (1998) introduced the non-linear model of THM based on the Willans' Line to incorporate the variation of efficiency with turbine size and operating load. Varbanov et al. (2004) developed the improved turbine hardware model. Sorin and Hammache (2005) developed an exergetic model 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. Medina-Flores and Picon-Nunez (2010) presented a modified thermodynamic model by taking advantages of the THM. Bandyopadhyay et al. (2010) developed a linear model based on the Salisbury (1942) approximation and energy balance at steam mains.

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Besides these targeting models, Kundra (2005) presented an application of STAR (2008) for cogeneration targeting by a stepwise procedure which starts with bringing steam turbines in action from bottom to top. Unlike the existing shaftwork targeting models, this methodology takes into account the degree of superheat (DSH). While this detailed procedure is considerably more accurate than the existing shaftwork targeting models, it needs several parameters which are not often available at the targeting stage.

2. The Iterative Bottom-to-Top Model (IBTM)

The new shaftwork targeting model (IBTM) employs the same thermodynamic working equations as the STAR simulation in Kundra (2005). However, its iterative procedure eliminates the need for simulation.

Before calculation, preparation of the Site Utility Grand Composite Curve (SUGCC) is required as follows:

1. The steam mains are indexed by i from lowest pressure steam main. This means i is equal to 1, 2, 3 and 4 for low pressure (LP), medium pressure (MP), high pressure (HP) and very high pressure (VHP) steam mains, respectively.
2. The SUGCC is divided into several domains characterized by temperature intervals.
3. Temperature intervals are indexed by j starting from bottom, i.e. j=1 is for MP-LP.
4. One single steam turbine is placed at each interval and is also indexed by j.
5. The actual temperature (T^{ACTUAL}) of the first steam main (i=1) is specified by adding an assumed DSH (e.g. 30°C) to the saturation temperature (T^{SAT}).

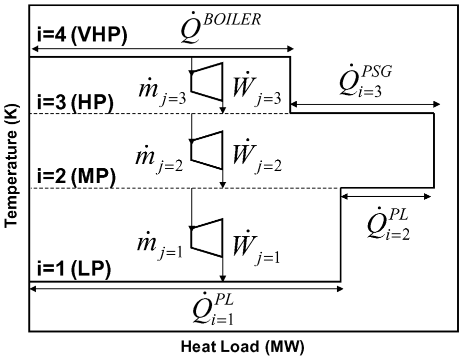

Figure 1: SUGCC preparation for IBTM

At the end of the preparatory stage, a SUGCC is produced as shown in Figure 1.

The shaftpower calculation procedure for the j-th steam turbine operating between i+1 and i-th steam mains in the given SUGCC with the known actual pressure of the steam mains (P^{ACTUAL}) is as follows, starting from bottom (j=1) where heat loads are known:

Step 1: The inlet temperature of the j-th turbine (T_{i+1}^{ACTUAL}) is determined by an iterative procedure as shown in Figure 2. Isentropic efficiency η^{IS} is used to relate actual enthalpy h^{ACTUAL} and entropy s^{ACTUAL} to the isentropic enthalpy h^{IS} and entropy s^{IS}. The outlet temperature of j-th turbine (T_i^{ACTUAL}) is given by the inlet of (j-1)-th turbine as turbines are placed in series, except for first turbine (j=1) which is specified by DSH.

Step 2: The enthalpy of (i+1)-th level (h_{i+1}^{ACTUAL}) is calculated as a function T_{i+1}^{ACTUAL}.

Step 3: The heat load of process load $\dot{Q}_i^{PL}$ and process steam generator (PSG) $\dot{Q}_i^{PSG}$ at the outlet of j-th turbine is converted into mass load by Eqs. (1) and (2), respectively.

$$\dot{m}_i^{PL} = \frac{\dot{Q}_i^{PL}}{h_i^{ACTUAL} - h_{\mathrm{Ref}}} \qquad (1)$$

$$\dot{m}_i^{PSG} = \frac{\dot{Q}_i^{PSG}}{h_i^{ACTUAL} - h_{\text{Ref}}} \tag{2}$$

where h_{Ref} is enthalpy of the condensate return (CR) at the pressure of i-th steam main and temperature of boiler feed water (BFW) by assuming that heat of steam is exploitable down to the BFW temperature.

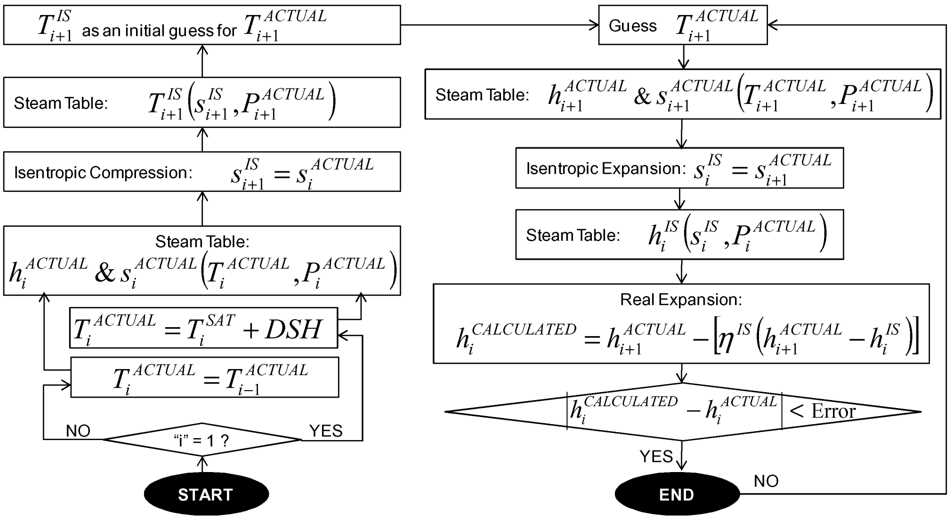

Figure 2: Algorithm for the calculation of the inlet temperature of j-th turbine (T_{i+1}^{ACTUAL}*)*

Step 4: The mass flowrate of steam expanding through the j-th steam turbine is calculated by mass balance for i-th steam main at the outlet of j-th steam turbine:

$$\dot{m}_j^{TURBINE} = \dot{m}_{j-1}^{TURBINE} + \dot{m}_i^{PL} - \dot{m}_i^{PSG} \tag{3}$$

Step 5: The shaftpower generated by j-th steam turbine is calculated by Eq. (4).

$$\dot{W}_j = \dot{m}_j^{TURBINE}\left(h_{i+1}^{ACTUAL} - h_i^{ACTUAL}\right) \tag{4}$$

Note that flowrate of steam generated by the boiler is equal to the flowrate of steam expanding in the last steam turbine. Clearly, total shaftpower is the sum of all the shaftpower of steam turbines placed in all intervals.

3. A Comparative Study of the Shaftwork Targeting Models

Three SUGCCs are taken to examine the targeting models as shown in Figure 3. In these three cases it is assumed that the temperature of both BFW and CR is 105°C and isentropic efficiency η^{IS} is 70%. The temperatures of the boiler and PSG shown in Figure 3 are given by the IBTM and used as input data for simulation.

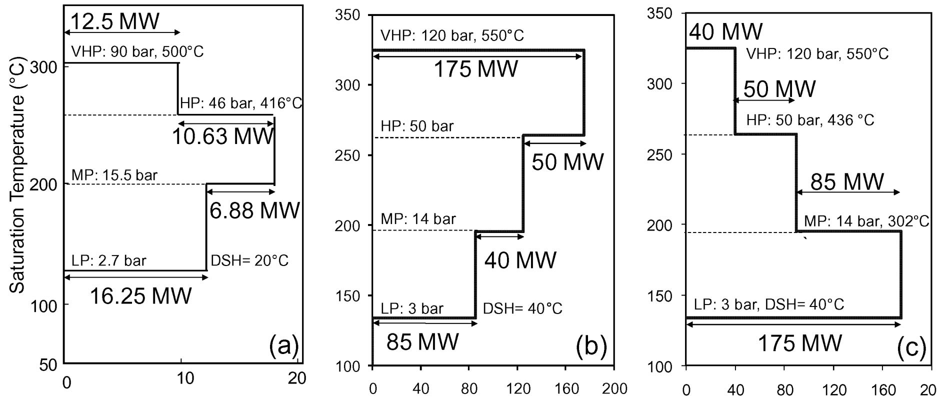

Figure 3: Input data: (a) 1st SUGCC, (b) 2nd SUGCC, (c) 3rd SUGCC

Tables 1, 2 and 3 present the shaftpower targeting results from the main shaftwork targeting models and the IBTM as well as the results of simulation in STAR (2008).

The exact match between the results of the IBTM and simulation is due to using the same thermodynamic working equations as it has already been indicated.

Table 1: Shaftpower (MW) for 1st SUGCC

Method	VHP-HP	HP-MP	MP-LP
TH	0.8	2.1	1.7
THM	0.5	1.9	1.8
SHM	1.8	1.9	0.8
IBTM	0.8	1.9	1.7
Simulation	0.8	1.9	1.7

As Sorin and Hammache (2005) Model (SHM) is based on both energy and exergy balance, therefore total power output cannot be deviated from its real one. However, the use of the average temperature results in overestimating the total power output. In addition, the use of the transiting heat in calculations allows deviation for some intervals in which PSG are placed. Power generated by PSG is being modeled as the exhaust of steam turbine expanding the steam originating from the boiler. Hence, it cannot account for the PSG specifications. For example, in the 1st SUGCC although total power is slightly different from simulation, but VHP-HP and MP-LP intervals have more than 100% error, due to the abovementioned assumptions.

Unlike SHM, overall deviation of T-H is evenly distributed in the all pressure intervals. Besides, approximation of Salisbury (1942) makes T-H valid for pressure less than 100 bar. For example, 120 bar steam from the boiler in the 2nd and the 3rd SUGCC causes a higher deviation compared to the 1st SUGCC with 90 bar steam. In addition, Table 2 and 3 show how T-H does not work for turbines in series.

Table 2: Shaftpower (MW) for 2nd SUGCC

Method	VHP-HP	HP-MP	MP-LP
TH (SAT)	14.35	11.62	7.06
TH (SC-SH)	12.24	9.39	5.53
THM (SAT)	9.4	4.7	0
THM (SC-SH)	9.1	4.4	0
SHM	18.2	14.46	8.77
IBTM	13.49	12.28	8.33
Simulation	13.47	12.27	8.33

Table 3: Shaftpower (MW) for 3rd SUGCC

Method	VHP-HP	HP-MP	MP-LP
TH (SC-SH) DCF	4.4	9.2	13.7
TH (SC-SH) BCF	4.6	9.6	14. 3
TH (SAT) DCF	3.2	8.3	14.5
TH (SAT) BCF	3.4	8.6	15.0
THM	0	6.3	16.0
SHM	6.4	11.6	18.0
IBTM	4.6	9.8	17.1
Simulation	4.6	9.8	17.1

All the assumptions in T-H result in deviation from simulation. However, there are three possible improvements as follows: The first is to use particular conversion factor (CF) for each SUGCC. For example, specifying boiler-dependent CF (BCF) for the 3rd SUGCC reduces the deviation compared with default CF (DCF) defined by STAR (2008). The second possible improvement is a better presentation of steam profile by including subcooling (SC) and superheating (SH) sections. However, the working equation of T-H model is based on the T^{SAT} (SAT). Thus, including the complete steam profile (SC-SH) causes more deviation especially for the cases in which all of the steam originates from only one steam generator (e.g. the 2nd SUGCC). In the case of several PSG (e.g. the 3rd SUGCC), it cannot make a big difference due to the shape of the SUGCC. The third possible improvement is to define a particular CF for each enthalpy interval to account for the PSG rather than only the boiler. To evaluate the feasibility of this improvement, two turbine layouts need to be examined: turbines in series and in parallel under fixed load conditions. Having a same shaftpower in both layouts means parallel placement of turbines is a feasible way to define different CFs for a SUGCC.

Concerning THM, the surprising zero power in the 2nd and the 3rd SUGCC (see Tables 2 and 3) might be due to non-linear nature of THM and its basis on mass flowrate rather than heat load. The constant load is assumed to obtain a first estimate of the mass flowrate. If iterative procedure fails in the flowrate calculation, it will not be surprising to obtain zero. Comparing the 2nd with the 3rd SUGCC, the inverse SUGCC leads to reversing the interval with zero power. Besides, steams from PSG is assumed to be raised at T^{SAT} of the given steam main. Thus, the specific heat will be equal to the latent heat of steam at the given pressure. This explains why THM does not estimate power well when steam originates from the several sources rather than only the boiler.

4. The Importance of Targeting Models in Scoping and Screening

Table 4: Shaftpower Target vs Fuel Demand

Unit	Shaftpower (kW)			Site Fuel Demand (kW)		
	White	Grey	Black	White	Grey	Black
1	1777	1783	1782	13799	13848	13860
2		1796	1848		14054	14469
5		1958	1958		14520	14521
6		1938	2117		15193	16343
7		1759	1972		13782	15151

To highlight the importance of a reliable shaftwork targeting model in the scoping phase of Total Site Analysis, a refinery plant (Fraser and Gillespie, 1992) is briefly analyzed. Generally, the more heat that is recovered, the less power will be generated and the less fuel will be demanded. To determine a focus where it is likely to yield the greatest benefits, the most sensitive unit to the cogeneration potential needs to be found. To do so, different sets of data are prepared by categorization of all units as black-, grey- or white-box (Linnhoff March, 2000). Application of this approach using the T-H model in STAR (2008) is summarized in Table 4. As all units do not show the same trend, they do not have the same potential for retrofitting. For units 2, 6 and 7 including more heat exchangers in retrofit design leads to an increase of cogeneration potential, while for unit 1 and 5 it is not worthwhile to retrofit process-utility heat exchangers at the expense of total site fuel demand.

5. Conclusion

The new model (IBTM) presented in this paper will not only facilitate the targeting stage, but it will also eliminate the need for simulation as all the key parameters (e.g. user-defined degree of superheat) have been taken into account. This feature makes the IBTM preferable for its implementation in flexible targeting tools to set realistic targets on site fuel demand and cogeneration at the early stages of design.

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