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Steam Turbine Network Synthesis Using Total Site Analysis and Exergoeconomic Optimization

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This paper presents a systematic methodology for synthesis of steam turbine network in the site utility of process plant. The optimization problem involves the selection of the steam turbines. Exergoeconomic modelling techniques are well known techniques to optimize thermal systems. These methods are usually based on the definition of a superstructure that includes the major options of the design. It reveals some weaknesses when dealing with particularly complex systems where total site analysis leads to a lot of possible configuration. In this regard, a new procedure has been developed to be used in the context of a multi-objective optimization framework and heat integration techniques. The application of the proposed optimization approach is illustrated through a case study.

1. Introduction

A steam network is considered as a unit that consumes energy greatly. The main objective of the network is to produce the steam, which must satisfy the energy requirements of the site, mainly electricity, steam, mechanical power, and cooling water. The design and optimization of site utility systems is one of the most challenging topics in process industries, as the complexity of equipment networks and choice of operating conditions present significant challenges to optimize utility systems in practice. The simulation and optimization of the utility systems require an accurate estimation of the cogeneration potential for the total site analysis as it aids the evaluation of performance and profitability of the energy systems (Kapil et al. 2011). Cogeneration targeting in utility systems is used to determine fuel consumption, shaft power production and cooling requirements before the actual design of the utility systems (Sorin and Hammache, 2005). To estimate cogeneration potential of the site utility system, its overall picture has to be represented in form of the site utility grand composite curve (SUGCC) (Raissi, 1994) starting with construction of the total site profiles (TSP) (Dhole and Linnhoff, 1993, Klemeš et al. 1997). On the basis of the Steam Composite Curves, cogeneration targeting and exergoeconomic optimization can be set. Exergoeconomic optimization aims at minimizing the total levelized cost of the system product (eg. heat and power), which implicitly includes fuel cost and the cost of inefficiencies. The principles and methodologies of exergoeconomic are well established by Bejan et al. (1996).
This paper suggests how to perform a multi-objective optimization in order to find solutions that simultaneously satisfy exergetic and economic objectives. This corresponds to a search for the set of Pareto optimal solutions with respect to the two competing objectives. The integrated approach has

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been developed for design and optimization of utility system through process integration techniques and exergoeconomic analysis.

2. Method and materials

2.1 Targeting

In this study, IBTM method was used to estimate the cogeneration potential of the system prior to the detailed design. As the iterative procedure of this model calculates shaft power from bottom to top, it is called the Iterative Bottom-to-Top Model (IBTM). Its methodology is based on a simple steam turbine expansion model with a constant isentropic efficiency to calculate the shaft power of the steam turbines presented in the SUGCC (Ghannadzadeh et al. 2011). Based on the heat loads of different steam mains which are initially specified by the process, steam boiler heat load and fuel flow rate are obtained.

2.2 Exergy analysis

The purpose of an exergy analysis is generally to identify the location, the source, and the magnitude of true thermodynamic inefficiencies in energy systems. All parts of systems were modeled and simulated and exergy equations were developed and applied to evaluate performance of combined system (Bejan et al. 1996).

2.3 Economic model

All costs due to owning and operating a plant depend on the type of financing, the required capital, the expected life of a component, and so on. The annualized (levelized) cost method (Bejan et al. 1996) were used to estimate the capital cost of system components in this study.

2.4 Exergoeconomic analysis

Exergoeconomic analysis is applied to calculate the expenditure cost and the unit product cost and also to point out the unit that needs more improvement. Exergoeconomic analysis requires solving energy, exergy and cost balance equations of the considered different components. The governing equation of exergoeconomic model for the cost balancing of an energy system is written as:

$$\mathrm{C_F} + \mathrm{Z} = \mathrm{C_P} \quad (1)$$

By defining exergy cost of each stream, c, Eq. (1) could be changed to

$$\mathrm{c_F} E_F + \mathrm{Z} = \mathrm{c_P} E_P \quad (2)$$

The above relations are global cost balance equation, which should be applied for different component. Here, for each component of combined system, cost balance equation is taken into account.

2.5 Optimization approach

The multi objective exergoeconomic optimization approach has been applied to find optimum solution. The two issues in multi-objective optimization are: (1) find solutions close to the true Pareto optimal set and; (2) find solutions that are widely different from each other, in order to cover the entire Pareto optimal set as well as not introduce bias towards any particular objective. The class of search algorithms that implement the Pareto approach for multi-objective optimization in the most straightforward way is the class of multi-objective evolutionary algorithms (MOEAs). MOEAs have been developed over the past decade (Emmerich et al. 2001). Since MOEAs use a population of solutions during the search, a single run will find multiple Pareto-optimal (Khoshgoftar Manesh et al. 2009).

2.6 Objective functions

The goal of the optimization is to synthesis of optimal steam network. The objective functions of the optimization problem are to minimize the total exergy destruction cost and to minimize the total cost of products as follows:

Objective function 1=min (Cptot) $=\Sigma Cp_{,w}+\Sigma Cp_{,st}$ (3)

Objective function 2=min (C_D) $=\Sigma\ (C_{F,k}-C_{p,k})$ (4)

Figure 1 illustrates the algorithm of new procedure.

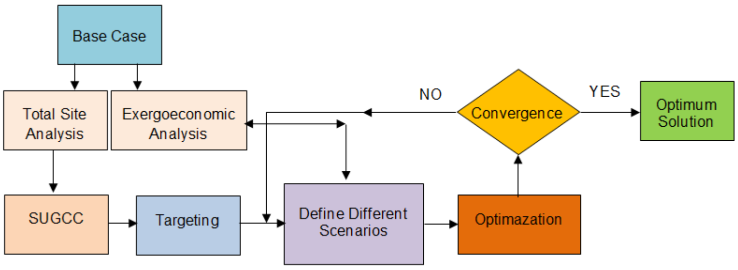


Figure 1: Algorithm of new procedure for synthesis of site utility

3. Case Studies

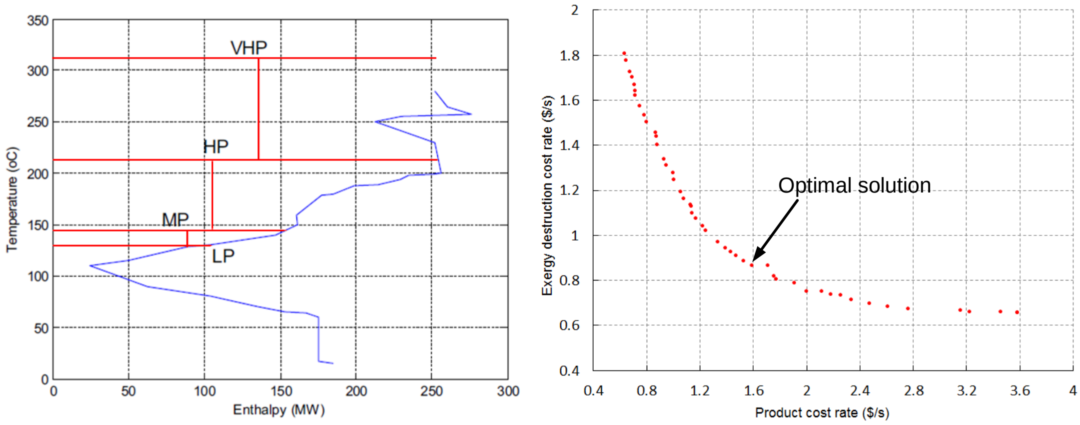
The proposed optimization model is applied to a site utility which was presented by Aguillar (2005), which consists of four boilers, four back-pressure turbines between VHP and HP levels, and one back-pressure turbine between HP and LP steam levels. Two multi-stage turbines are available for the expansion of steam between HP-MP and MP-LP respectively, while there are four mechanical pumps to be driven by either steam turbines or electric motors, and an electric motor is used for the supply of the feed water to the boiler. It is assumed that the temperatures of both BFW and CR are 105 °C, isentropic efficiency η_{IS} is 70 % and degree of superheat is 40 °C.

4. Results and discussions

4.1 Grassroot design

The grand composite curves (GCC) of the individual process are modified by removing the pockets corresponding to additional heat recovery within the process. These modified process GCC are then combined together to form the total site sink and source profile. The SUGCC represents the horizontal separation between the source and the sink. Steam demand at VHP, HP, MP and LP levels are 110.8, 21.4, 9.3 and 73.6 MW respectively. Power generation potential is represented as areas in the SUGCC with VHP-HP, HP-MP and MP-LP cogeneration potential of 79.8, 58.4 and 49.1 MW respectively (figure 2a) when a full steam recovery is made within the site utility systems.

The Pareto frontier solution obtained via multi-objective optimization with the objective functions in Eqs. 3 and 4 are shown in figure 2b. It can be seen in this figure that the exergy destruction cost rate of site utility system decreases slightly as the overall product cost rate of the cycle increases.



(a) (b)

Figure 2: (a) Site utility grand composite curve (SUGCC), (b) The Pareto frontier for exergy destruction cost rate versus overall product cost rate for grassroot design

Figure 3 demonstrates the optimum configuration of steam network achieved by optimal Pareto frontier solution as shown in Figure 2b. Also, the shaft work targets, steam flow rates, steam boiler loads and fuel flow rates has been shown in Figure 3. Also, Table 1 shows product cost, exergy destruction cost and capital cost rate of each components.

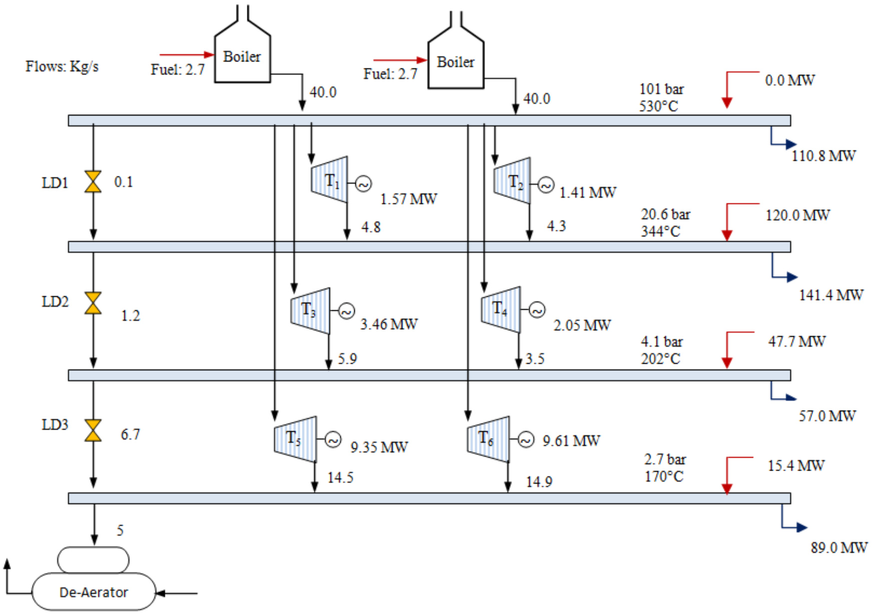


Figure 3: Optimum arrangement of steam network

Table 1: Exergoeconomic parameters for components of the optimal case

	C_D ($/h)	c_p ($/MJ)	C_P ($/h)	z($/h)	ε (%)
Boiler1	1423.901	0.0117	2487.6	23.86	43.25
Boiler2	1423.901	0.0117	2487.6	23.86	43.25
Turbine 1	8.840	0.0111	62.45	9.798	82.6
Turbine 2	8.521	0.0111	56.34	8.68	82.0
Turbine 3	12.254	0.0115	84.87	29.64	80.5
Turbine 4	7.437	0.0119	87.82	17.58	80.4
Turbine 5	47.425	0.0106	553.32	23.10	80.0
Turbine 6	48.231	0.0102	547.13	22.48	80.0
Letdown 1	1.202	0.0	0.0	-	0.0
Letdown 2	8.508	0.0	0.0	-	0.0
Letdown 3	13.5	0.0	0.0	-	0.0
Deaerator	34.8	-	-	18.37	97.81

4.2 Retrofit design

Base on algorithm (Figure 1), the results of optimization of existing case on base season taken from Aguillar (2005) are shown in Figure 4 achieved by optimal Pareto frontier solution as shown in Figure 5. The cost and annualized cost comparison between the existing case and optimum case are determined in Table 2 and Table 3 consequently. Furthermore, the fuel consumption and exergy product cost and total operating cost are decreased significantly.

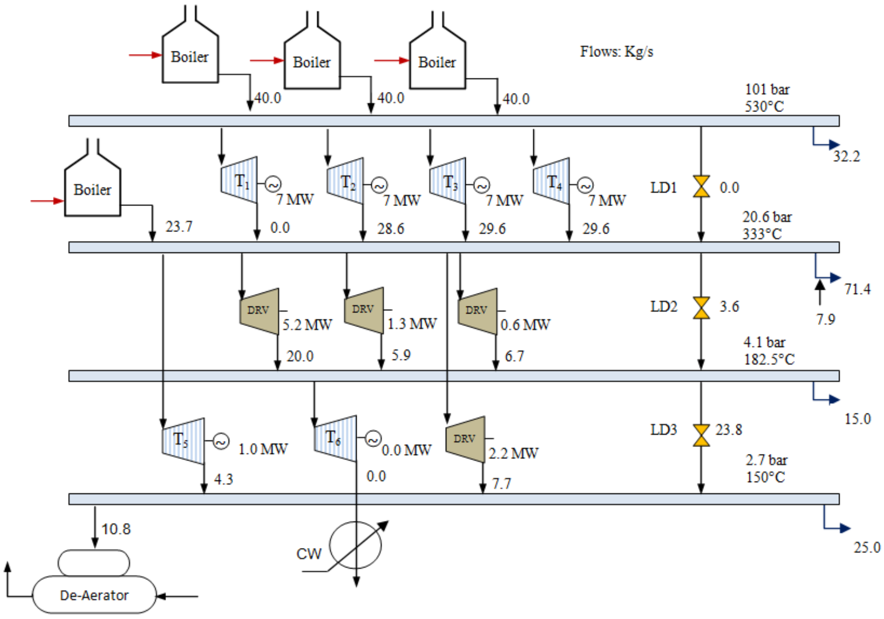


Figure 4: The operational flow sheets of the optimum case.

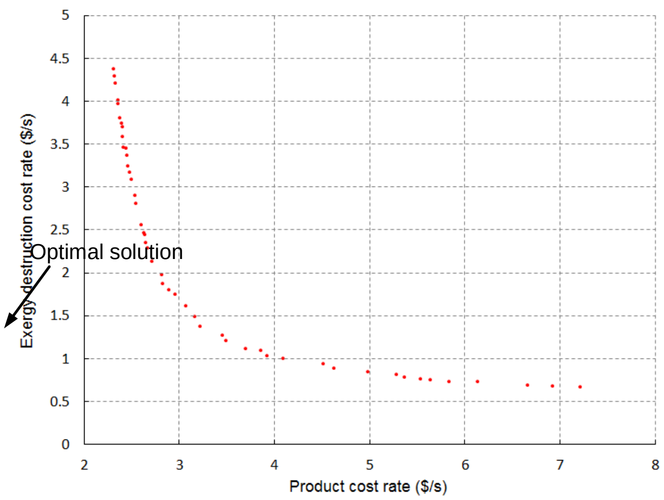


Figure 5: The Pareto frontier for exergy destruction cost rate versus overall product cost rate for retrofit design

Table 3: Cost comparison between the existing case and optimum operation.

	Base case	Optimum case Proposed Methods
$C_{p,total}$ ($/MW)	3.26	3
Fuel consumption (kg/s)	10	9.5
Power production (MW)	39.9	40.3

Table 4: Annualized cost comparison between the existing case and optimum operation.

	base case (M$/y)	optimum proposed method (M$/y)
Overall fuel cost	68.11	64.70
Overall water cost	0.39	0.35
Overall electricity cost	18.20	18.06
Overall operation cost	86.70	83.11

5. Conclusion

In this paper, the integrated approach has been developed for design and optimization of existing utility system through process integration techniques and exergoeconomic analysis. The exergoeconomic model, which represented the productive structure of the system considered, was used to visualize the cost formation process and the productive interaction between components. Also, site utility grand composite curve was applied to demonstrate the potential of energy saving, cogeneration targets and promising modification in the retrofit cases. The computer code has been provided based on new procedure for geassroot design and retrofit of steam network. The exergoeconomic optimization through genetic algorithm based on hybrid techniques was performed for a central utility of chemical plant as a case study.

There are three significant advantages of knowing the practical maximum potential and limit for improvement. First, the performance of a process and equipment can be evaluated based on the maximum potential which is achievable in current technical and economical conditions. The practical maximum potential for improvement defined as such distinguishes itself from the theoretical maximum potential, which cannot be realized either technically or economically. Therefore, the practical maximum potential indicates what can be done and what cannot be done in current conditions. Secondly, by knowing the practical maximum potential for improvement, a designer sets the target for improvement by making modifications. Different modifications can then be compared in terms of how much benefit can be achieved and what is the capital cost involved. Thirdly, any processes or units with very small potential for improvement can be immediately ruled out from consideration.

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