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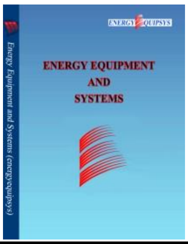

Thermo-economic analysis and optimization of cogeneration systems by considering economic parameters fluctuations

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ABSTRACT

A successful cogeneration system design project needs an estimation of the economical parameters of the project, including capital investment, costs of fuel, expenses in maintenance and operating, and the proper cost for the products. This study describes the economic consideration of the benchmark cogeneration systems, called CGAM system located in the United States. To evaluate the profitability of alternative investments, cost estimation of the capital investment, calculation of the main product cost under the realistic assumption of fuel inflation, electricity inflation, and discount rate are required. Probabilistic analysis of lifetime discounted costs, including fuel and electricity cost changes, are defined by using the Monte-Carlo method for the next 20 years. Also, the total Revenue Requirement (TRR) method is selected as the main evaluation method for the economic model. As the result of calculations, the range of optimized value for inlet and outlet temperature of the combustion chamber, the efficiency of the gas turbine, efficiency and pressure ratio of air compressor in which the plant is economically and functionally in the best operation for the minimum cost of products of the cycle are achieved.

Keywords: Cantilever Beam, Piezoelectric, Surrogate Model, Deep Neural Network, Energy Optimization.

1. Introduction

Regarding the simultaneous increase in world energy demand and running out of finite resources, applying novel techniques and policies for energy consumption are turned to be the priority of mechanical and financial experts. Therefore, problematic issues confront designers that generally deal with the aspect of combined heat and power energy production systems (CHP) in the economy, environment, and energy. To overcome technical matters, two approaches are introduced; the first refers to utilizing sources of renewable energy, including wind or solar energy systems, and the other is cogeneration systems. In comparison with conventional methods, cogeneration systems gained more attention due to the elimination of losses in power distribution and an increase in energy efficiency [1]. Furthermore, Gas turbine cogeneration systems due to simple cycle and low capital cost are indeed common among CHP systems. Using a heat recovery steam generator (HRSG), the CGAM system, as a

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cogeneration benchmark, recovers gas turbine exhaust's waste heat [2].

For the first time, Frangopoulos et al. introduced their methodologies, and to compare their method with other methods; they defined a simple optimization problem named CGAM problem [3]. CGAM benchmark is a way to improve the heat recovery ability of CHP systems. There is much research that has been done to analyze the financial [4-6] and technical [7-14] impacts. Valero et al. investigated the thermo-economic optimization of cogeneration systems for a simplified model employing five thermodynamic decision variables [15]. Sayadi and Aminian developed a multi-objective optimization in which the purchased cost for recuperators, cost rate of the output power, and the efficiency of exergy analysis for the gas cycle are considered simultaneously [16]. Soltani et al. investigated an exergoeconomic multi-objective optimization for the cycle of solar-hybrid cogeneration [17]. To reduce the environmental effects of the energy system, Hwang and Chang employed mixed-integer non-linear programming (MINLP) for an energy system [18]. Roosen et al. studied the balance of costs, including operating and investment, using multi-objective optimization [19]. In a recent study, Momen et al. carried out an economic optimization for cogeneration systems with a probability distribution function of the net present value method of the maximum profit [20].

Owing to the fuel supply crisis and the high energy prices, the main goal of energy management methods is to reach the optimum utilization of energy; hence, thermo-economic analysis is highly important. Thermo-economic, as a combination of thermodynamic analysis and economic rules, provides a great interpretation in which the associated inefficiencies of the cogeneration system are demonstrated in the total cost using distinct economic methods. Designers utilize thermo-economic analysis as an applicable criterion to provide a sensitive balance between economic principles and technical requirements. There are conventional methods for economic evaluations such as net present value (NPV), internal rate of return (IRR), and payback period (PP), total revenue requirement (TRR). Biezma and Cristobal conducted a study to evaluate the criteria for the investment of a CHP unit using various methods, including NPV, IRR and PP [21]. Hanafizadeh et al. checked different operating conditions to verify his results [22-23]. Momen et al. applied the Monte Carlo approach several times to consider uncertainties in various economic parameters. Thus, results are provided for the probability distribution function of NPV [20]. In the open literature, many researchers used the revenue requirement method (TRR) to estimate the cost of the final products for cogeneration systems [2, 16, and 24]. Despite the numerous efforts available and the results these criteria provide, there is still a lack of uncertainty consideration in economic parameters. According to the reference [20], employing probability distribution function offers a profound insight into the profitability of the cogeneration system, which considers the uncertainties in key parameters.

In this article, a CGAM system has opted for a case study to be investigated in the thermo-economic analysis. As the first step, for prediction of main economic parameters such as fuel inflation rate, discount rate, and electricity inflation rate, the Monte Carlo approach is used. Then, by using the comprehensive economic model based on the total revenue requirement (TRR) approach, the thermodynamic parameters of the CGAM system are optimized. The provided results are the probability function of TRR in the optimum design.

Nomenclature

$CGAM$	benchmark cogeneration system
IRR	internal rate of return
TRR [\$]	total revenue requirement
NPV [\$]	net present value
PP [$year$]	payback period
$HRSG$	heat recovery steam generator
GT	gas turbine
i	ith year of operation
CRF	capital recovery factor
OMC [\$]	operating and maintenance costs
FC [\$]	fuel cost
ITX [\$]	income taxes
$OTXI$ [\$]	other taxes and insurance
r	annual escalation rate; pressure ratio
T [K]	Temperature
ROI [\$]	return on investments
CC [\$]	carrying charges

$\dot{Z}$ [$/year]	annual charges and costs of the maintenance and operating
PEC [$]	purchase equipment cost
τ [$year$]	operational time
$\dot{C}$ [$/s]	The levelized cost rate
CHP	combined heat and power energy production systems
TCR [$]	total capital recovery
Subscript	
FC	fuel cost
OMC	operating and maintenance costs
L	levelized
F	Fuel
OM	operating and maintenance
CI	Capital investment
P	product
GT	gas turbine
AC	air compressor
d	debt
ps	preferred stocks
ce	common equity
0	At the beginning of the first year of procedure
3	Combustion chamber inlet
4	Combustion chamber outlet
Greek symbols	
μ	mean value
σ	variance
η	isentropic efficiency

2. CGAM; A benchmark for cogeneration systems

This study refers to the CGAM problem generates 30 MW of electricity and 14 kg/s saturated steam flow at 20 bar. To provide 50000Kj/kg specific energy, natural gas (Methane) is taken as the fuel of gas turbine. Fig.1 depicts the schematic of the CGAM model that is realistic but incomplete from an economic point of view, and this article tends to present more applicable economic analysis. In the definition of thermodynamic equations, the following simplifications are implemented which do not cause loss of methodical generality:

- Steady-state operations
- Ideal gas with constant specific heats assumption for air and combustion gases

Adiabatic condition for all components except combustion chamber.

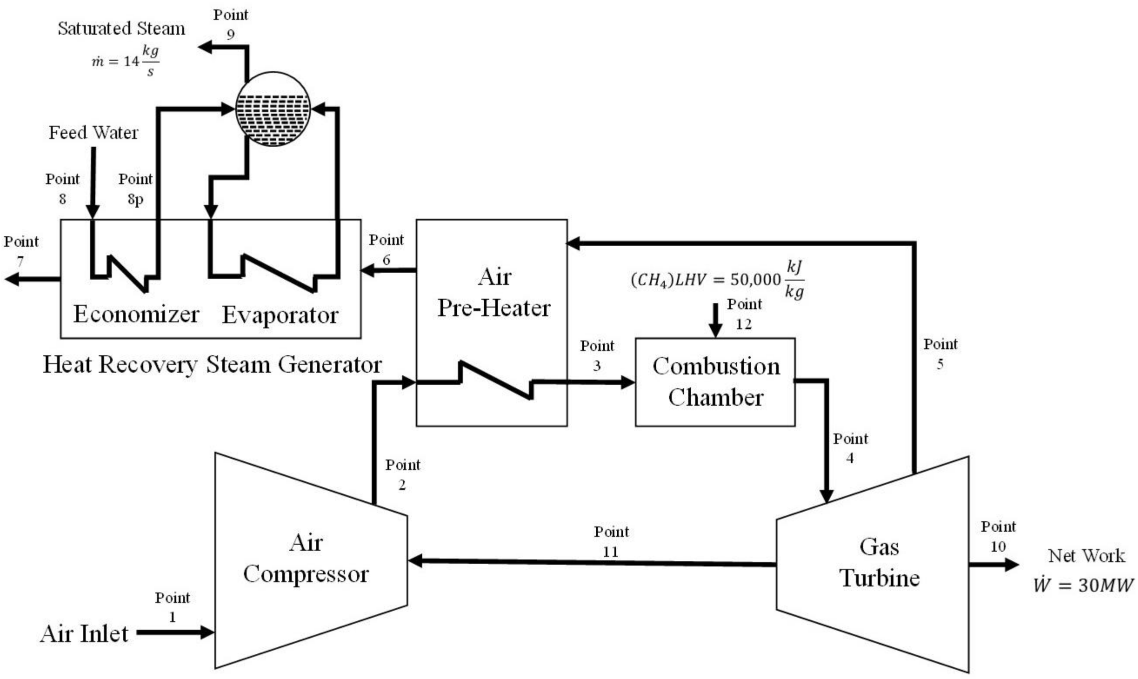

Fig.1. The schematic of the CGAM model

To optimize thermal systems, it is highly essential to identify variables for decision making. In this thermodynamic model, selected variables are as follow [11]:

- Pressure ratio of air outlet over air inlet of air compressor
- Isentropic efficiency of the compressor
- Isentropic efficiency of gas turbine
- Air temperature at point 3
- Air temperature at point 4

3. Economic model

The cost of components consists of capital, maintenance, and fuel consumption costs. Thermodynamic variables can be used to define a cost function for components costs. [20]. Furthermore, to optimize the economic model, thermodynamic variables and costs have been correlated statistically based on data series such as carrying charges and fuel costs. Therefore, to optimize the levelized annual cost, the TRR method is selected as the main evaluation method for the economic model.

This section illustrates the TRR that is adopted from the Electric Power Research Institute [3]. To consider the effects and uncertainties of inflations, including debt inflation, electricity price inflation and fuel price inflation, Momen et al. used the Monte Carlo method several times to get an applicable estimation of inflations for the next 20 years which this method is applied in this study [20]. By calculating capital investment based on the Monte-Carlo method and the following considerations for financial, economic, operational, and commercial parameters, TRR is calculated annually, and finally, calculated annual capital costs, operating and maintenance costs, and fuel costs are levelized.

To be sure that the plant operation of a company is economically profitable in a year, it is required to know the revenue obtain from the sale to compensate for the expenses. That is what the TRR defines [24]. The carrying charge is a kind of expense that is related to capital investment, whereas other expenses like taxes, capital recovery, debt, insurance, stocks, and common equity are costs that are paid in operational hours of the system. It includes total [25].

The annual costs such as cost of fuel and operating maintenance (respectively FC and OMC) are dividing into expenses and charges which are specified for each year of operation and are not uniform. Applying a discount and recovery factor to the TRR for each year leads to a levelized amount of annual TRR_L, as given by

$$TRR_L = CRF \sum_{j=1}^{n} \frac{TRR_j}{\prod_{m=1}^{j}(1+i_m)}, \tag{1}$$

where Total Revenue Requirement of the j^{th} year of operation, rate of discount for the mth year of operation are respectively represented as TRR_j and i_m. Monte-Carlo method is applied to discount rates in recent years to calculate the i_m. The operating years of the system are shown by n.

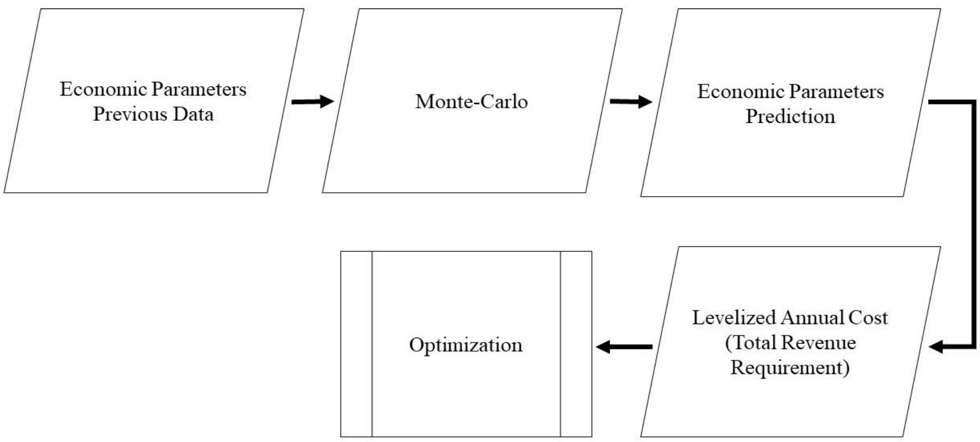

Fig.2. Proposed algorithm for economic analysis.

The annual TRR can be calculated by summing the annual amounts of the following parameters: TCR, FC, OMC, ITX, $OTXI$, ROI of debt and preferred stocks and common equity [1]. Thus

$$TRR_j = TCR_j + ROI_{j,ce} + ROI_{J,d} + ROI_{j,ps} + ITX_j + OTXI_j + FC_j + OMC_j. \quad (2)$$

Detailed definition of calculation for components of TRR_j is provided in reference [25].

Equation 1 is based on the assumption that all money transactions are occurred by the end of the year. The annual rate of money discount is predicted as a probability distribution function for each operating year during the book life; therefore, the capital recovery factor (CRF) also describes the probability distribution function, which leads the annual total revenue requirement to the probability distribution. Therefore, CRF is calculated using

$$CRF = \frac{i_{eff} \prod_{m=1}^{n}(1+i_m)}{\prod_{m=1}^{n}(1+i_m) - 1}. \quad (3)$$

The cost of fuel for each year represented by FC_j is assumed to be uniform over the expected time with a constant rate represented by r_{FC}. Therefore, the levelized cost of fuel is given by

$$FC_L = FC_0 \times \frac{k_{FC}(1-k_{FC}^n) \times CRF}{(1-k_{FC})}, \quad (4a)$$

along with

$$k_{FC} = \frac{1+r_{FC}}{1+i_{eff}}, \quad (4b)$$

where, i_{eff} refers to the rate of discount for each year. Accordingly, the levelized OMC for each year is given by

$$OMC_L = OMC_0 \frac{k_{OMC}(1-k_{OMC}^n)}{(1-k_{OMC})}, \quad (5a)$$

where

$$k_{OMC} = \frac{1+r_{OMC}}{1+i_{eff}}, \quad (5b)$$

and the nominal cost rate of operation and maintenance is shown by r_{OMC}. Finally, the carrying charges will be levelized by

$$CC_L = TRR_L - FC_L - OMC_L, \quad (6)$$

apportioned values for components.

Equation (7) shows the annual CC_L and OMC_L of the plant which apportioned on components of the system based on the contribution of the k^{th} component to the purchased equipment cost for the entire system. Thus,

$$\dot{Z}_k^{CI} = \frac{CC_L}{\tau} \frac{PEC_k}{\sum_k PEC_k} \quad and \quad (7)$$

$$\dot{Z}_k^{OM} = \frac{OMC_L}{\tau} \frac{PEC_k}{\sum_k PEC_k} \quad (8)$$

The equipment cost of the k^{th} component and the time that the system is operating are represented by PEC_k and τ, respectively. $\dot{C}_F$ denotes the rate of the fuel cost, which is levelized and is presented by Bejan et al. [25] using

$$\dot{C}_F = \frac{FC_L}{\tau}. \quad (9)$$

The $\dot{Z}_k^{OM}$, $\dot{Z}_k^{CI}$ and $\dot{C}_F$ are levelized costs of the plant, which are used as input data for the thermodynamic analyses. Finally, the total cost for all of the products can be calculated by using

$$\dot{C}_{P,tot} = \dot{C}_F + \dot{Z}_k^{OM} + \dot{Z}_k^{CI}. \quad (10)$$

As it includes all thermodynamic and economic parameters, Eq. (10) is opted as the objective function for the optimization procedure.

4. Optimization method

In this section, the main goal is to choose the best criterion for the optimization process. The most important point in the flowchart depicted in Fig. 3 is the designation of the fitness function in which the computed results are compared with. To compare the probability chart of product costs, the fitness function of $\mu - 3\sigma$ based on the efforts of Momen et al. [20] is chosen. Which μ and σ are average and standard deviation of spent cost, respectively.

The genetic algorithm was applied for thousands of futures anticipated by Monte

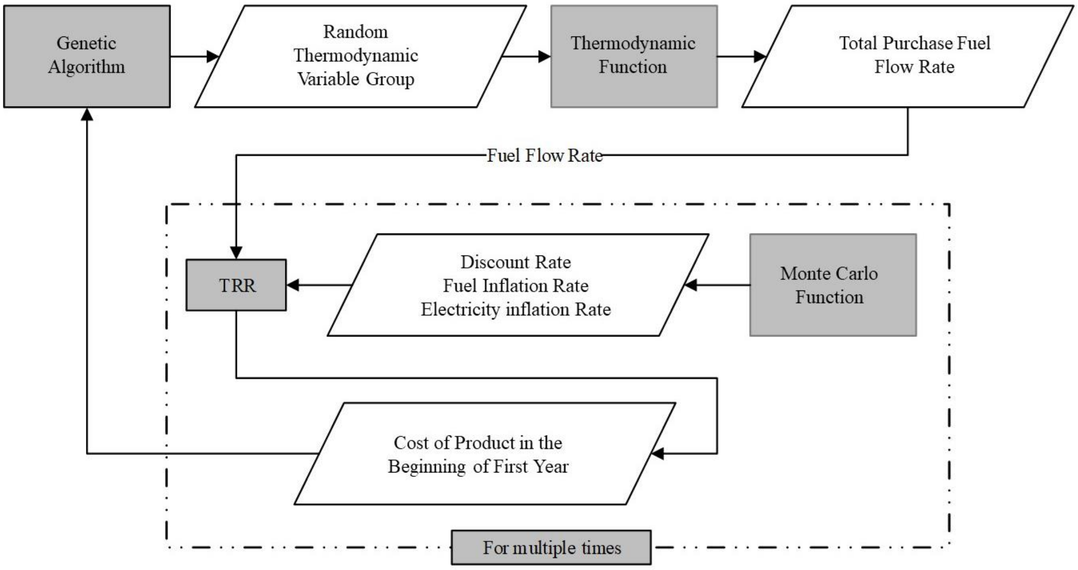

Fig.3 The flowchart of the optimization algorithm

Carlo, so the results indicate a limited range for each parameter. The achieved optimized range for parameters which lead to the optimum point of the plant considering the uncertainty of future condition fig.4-8, were applied as constraints on thermoeconomic optimization procedure for T_3, T_4, η_{gt}, η_{ac} and r_P which represent the inlet and outlet temperature of the chamber, gas turbine efficiency, pressure ratio, and air compressor efficiency, respectively. These constraints significantly reduced the processing time, so the computational costs decrease by up to 78%.

5. Results

The main optimization process was applied considering the domain of five parameters and was repeated for one thousand times, and results are shown in Fig.4-8. These plots demonstrate the probability distribution of $T_3, T_4, \eta_{gt}, \eta_{ac}$ and r_P. Figure 4 is the optimized temperature value for the entrance

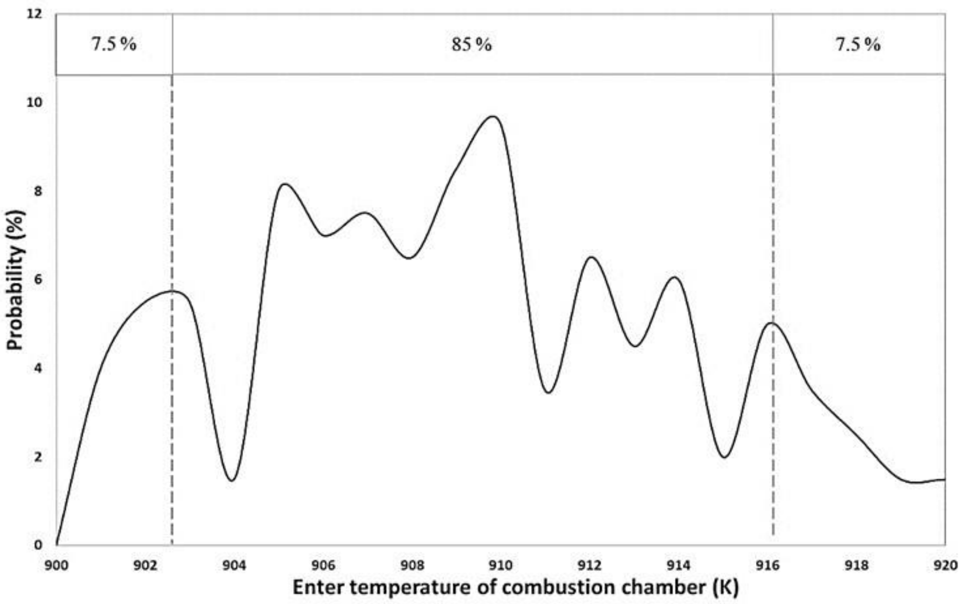

Fig.4. Probability distribution of $\boldsymbol{T_3}$

combustion chamber. Therefore, this is expectable that the maximum probability for the operating cycle at the optimal temperature point will be achieved by choosing 902 to 916 $[K]$ for the entrance temperature of the combustion chamber.

Figure 5 is the probability distribution for the optimized departure temperature of the combustion chamber. If T_4 varies within the range of 1492 to 1510 K, the cycle will be at the optimal working point with a probability of 85%.

Figure 6 shows the probability of the optimized efficiency of the gas turbine. The cycle would be in optimum operation when this efficiency varies between 0.85 and 0.9. Also, more than 90% of data are in the range of 0.852 to 0.887.

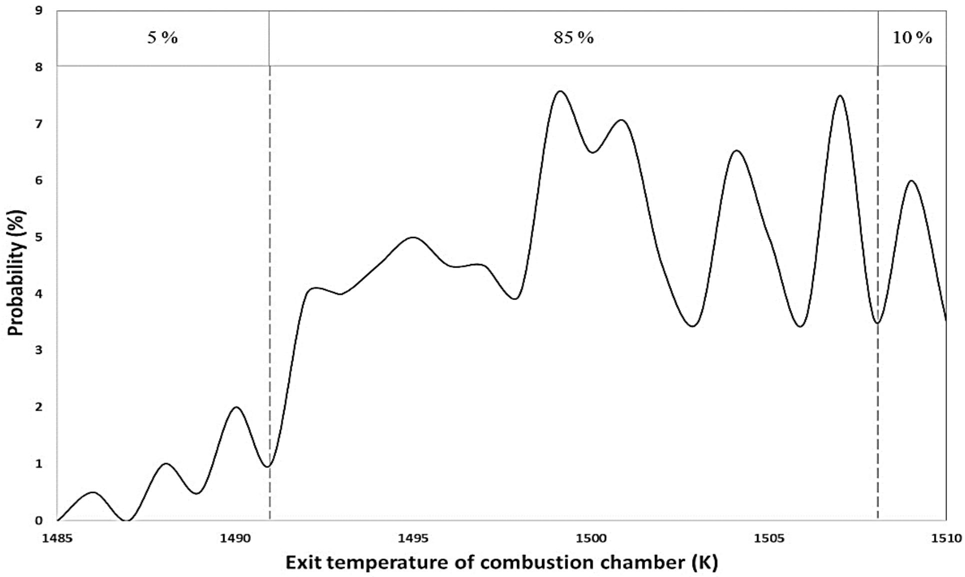

Fig.5. Probability distribution of T_4

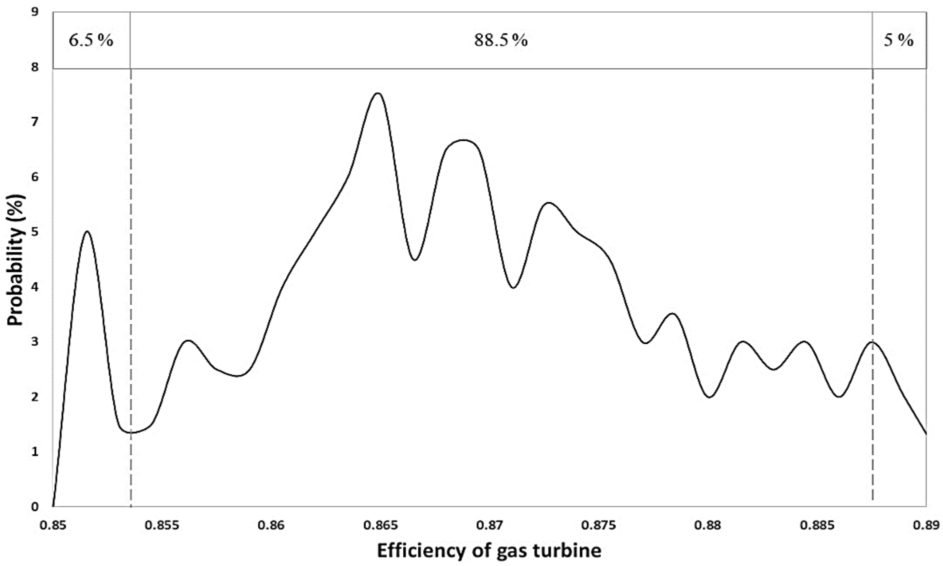

Fig.6. The probability distribution of optimum η_{gt}

Figure 7 shows the optimum efficiency of the air compressor that results in the minimum cost is within the range of 82 to 88 percent.

Figure 8 shows the probability of pressure ratio. Range of 8 to 9 is the optimal ration that cycle will be at the optimal working point with the maximum probability.

Table 1 shows the optimized value of parameters that are derived from the Genetic algorithm. That is, utilizing the Genetic algorithm, the predicted values are updated iteratively until the optimized values in which the maximum benefit of investment has maximum probability are achieved.

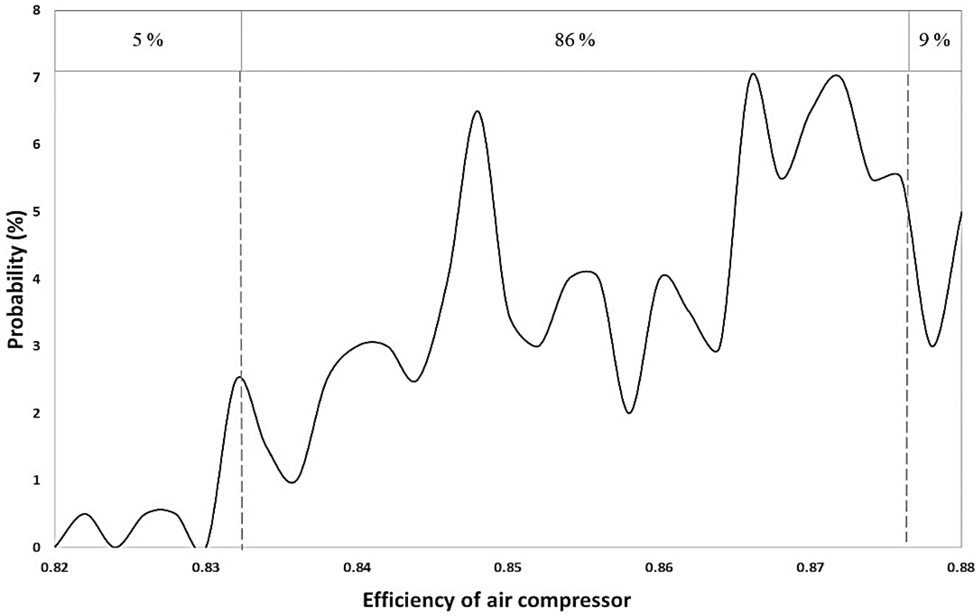

Fig.7. The probability distribution of optimum η_{ac}

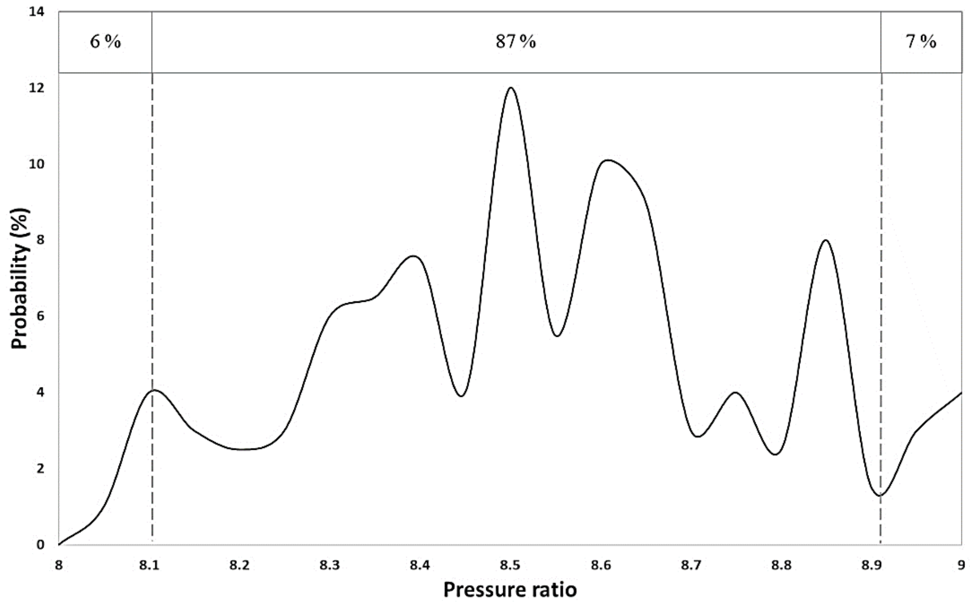

Fig.8. The probability distribution of optimum pressure ratio

Table 1. Thermoeconomic optimized parameters

r_p	η_{ac}	η_{gt}	$T_3\ (K)$	$T_4\ (K)$
8.56	0.87	0.87	910.8	1495.0

Figure 9 depicts the capital recovery factor for the optimum point, by the variation of predicted inflation, is varying 0.065 to 0.08. Also, 70% of distribution has concentrated in the range of 0.07 to 0.075.

Based on the optimized procedure, the product cost and total revenue requirement achieved. Figure10 shows the distribution of product cost; the range of product cost is 18 to 30 $[\frac{\$}{min}]$ and its distribution centralized in range of 19.8 to 24 $[\frac{\$}{min}]$ that is 80% of results among 1000 different considered future circumstances.

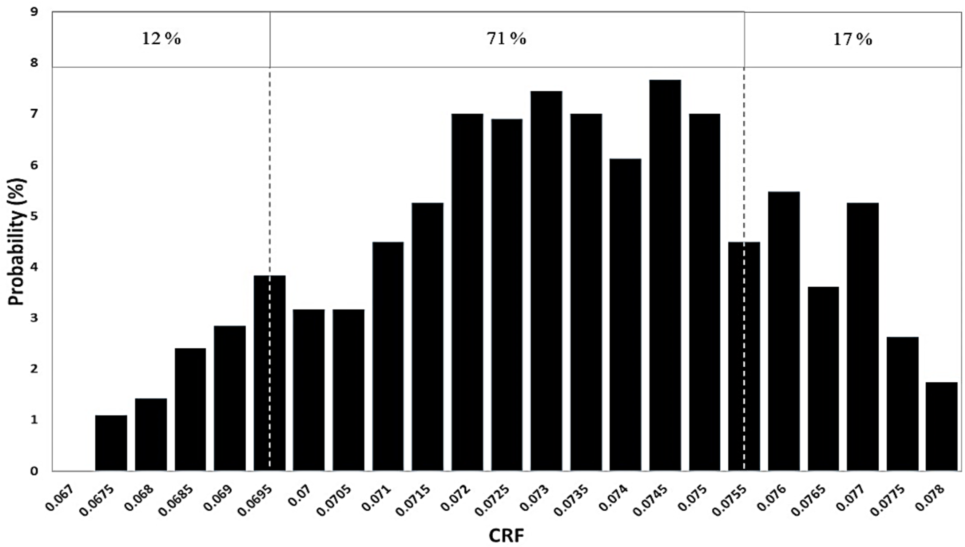

Fig. 9. The probability distribution of CRF

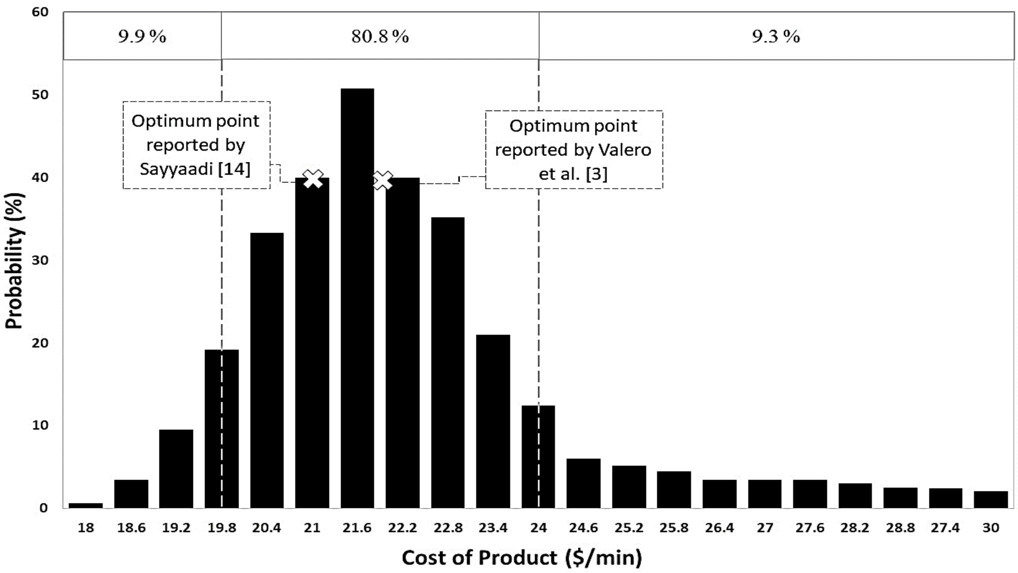

Fig.10. Distribution of product cost

Figure 11 shows the probability distribution of TRR_L for the optimized value of parameters.

Figure 11 represents that the annually required cost mainly varies in the range of 7 to 20 M$.

Table 2 is showing that using the presented method, 1296.35 $\$/h$ is the optimal value obtained. However, reference [2] obtained 1283.41 $\$/h$ using the MOEA optimization program, and reference [3] obtained 1303.23 $\$/h$ using the mathematical approach.

6. Conclusion

This study efforts to deal with uncertainties in economic and in the optimization of cogeneration systems by using exergoeconomic analysis, which has applied to conventional cogeneration plant called CGAM. As initially intended by the developers of this plant, exergoeconomic analysis lead to the optimized working point, which has the most profit for the investment, due to considering the irreversibility of

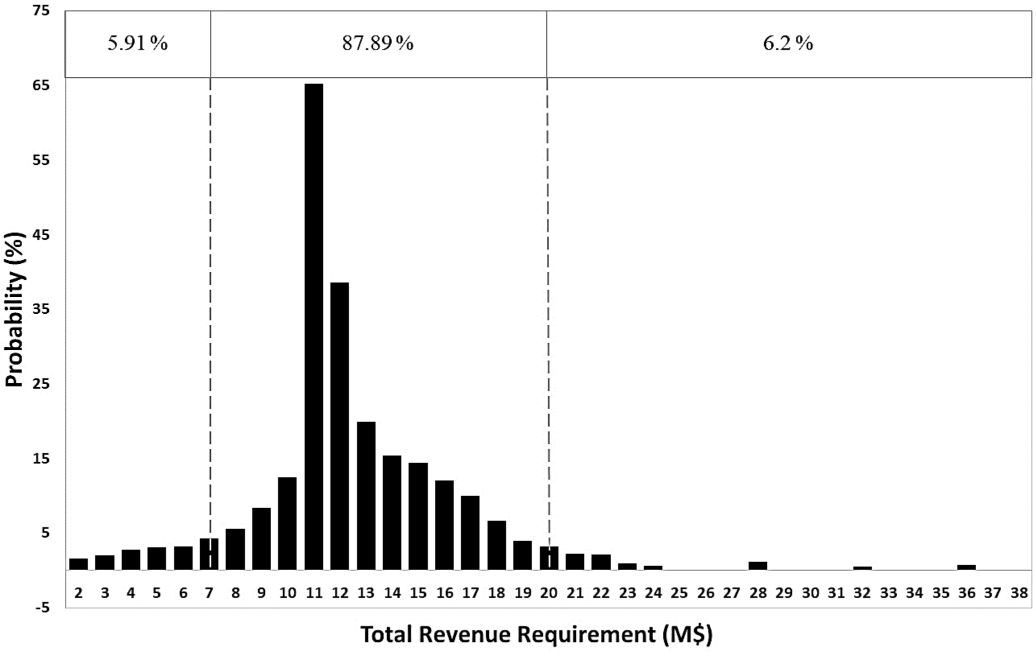

Fig. 11. The probability distribution of TRR_L

Table 2. Comparing the results of the optimization of the present work with those obtained by the others [3], [14]

Results		Optimization method presented in [3]	Optimization algorithms presented in [2]	Optimization method developed in this work
Rate of product cost ($/h)		1303.23	1283.41	1296.35
Rate of fuel Cost ($/h)		1171.76	1175.4	1147.1
Decision Variables	$T_3(K)$	914.28	920.19	918.04
	$T_4\ (K)$	1492.63	1492.47	1487.53
	η_{ac}	0.8468	0.8306	0.8743
	η_{gt}	0.8786	0.8456	0.8518
	r	8.52	7.70	8.16

process and economic considerations together. Additionally, it should be noted that unexpected events, like a sudden change in electricity inflation, fuel inflation and debt, which had not considered in the design phase, can change the optimal operation point. Therefore, it seems logical to regard the uncertainty in the design phase. The proposed uncertainty method was shown that can be a reliable tool in optimizing the set of the operation point, which has the most probability to bring the most profit; this solution may indicate the lower benefit of investment in comparison with optimization method presented in previous studies ([2]), but this approach is more confident and reliable. Also, by employing the optimization approach, the range of changes for five primary variables is identified and then easily by simplifying computations using bonds for primary variables, the final optimization was applied which this simplification significantly led to increasing the processing speed up to 78%.

Managing the risk of investment and saving the cost of calculations in the disruption occurred cases are the main benefits of this method. Achievements of this study help the decision-maker to select the optimum solution in order to achieve their objective effectively.

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