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Research Paper

A New Approach for Exergoeconomics Evaluation by Considering Uncertainty with Monte Carlo Method

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Abstract. The exergoeconomics analysis combines thermodynamic assessments based on exergy analysis with economic concepts. this article suggests a new method for exergoeconomics analysis and evaluation of energy systems by considering uncertainty in economic parameters. As the first step, the future values of economic parameters that influence the operating cost of the energy system are forecasted by the Monte Carlo Method. Then, as a novel approach, principles of exergoeconomics analysis method are coupled with the Monte Carlo Method for exergoeconomics evaluation of energy systems. Also, three new parameters, i.e. Risk Factor (RF), Risk Factor Sensitivity (RFS), and Product Cost Sensitivity (PCS), are proposed. Two different approaches are considered in the evaluation process to improve the system: a) decreasing the total cost of products and b) reducing the risk of the cost of products. Also, the proposed method is applied to the CGAM system as a benchmark. Eventually, the results of the first and second approaches show that the total cost of products can be reduced 4.1% (from 22.270 $/GJ to 21.358 $/GJ) and also the risk of the cost of the products can be reduced 5.8% (from 25.8% to 24.3%).

Keywords: Exergoeconomics Analysis; Exergoeconomics Evaluation; Monte Carlo Method; CGAM System

1. Introduction

The applications of energy have a wide range and contain energy systems to produce electricity, engines to run automobiles, and so forth. Industry uses more than 40% of worldwide energy [1] and more effective use of energy resources and also the development of renewable energy is essential for tackling climate change and for improving competitiveness [2]. Energy analysis and exergy analysis are applied to analyze energy systems for improving efficiency [3]. Energy analysis reports the amount of energy only based on the first law of thermodynamics but exergy analysis works by the combination of the first and second laws of thermodynamics which includes the irreversibility.

Exergy analysis recognizes all details of the system inefficiencies and prepares insight about the difference with the ideal system [4]. Two different types of exergy analysis are available for analyzing energy systems: a) Overall exergy analysis, which indicates the entire exergy efficiency of the energy system, and b) Detailed exergy analysis, which identifies exergy efficiency and exergy destruction of all parts individually [3]. Owing to the advantages of exergy analysis, researchers focused on this analyzing method for improving the efficiency of a wide variety of energy systems in recent years [5-6].

Since the vital goal of energy systems is profitability, detailed analysis of energy systems in the economic aspect is very essential. As a result, the exergoeconomics analysis is proposed, which combines thermodynamic assessments based on exergy analysis with economic concepts. The first time, idea of linking exergy streams to cost streams was introduced by Benedict in 1948 [7]. Then, Tribus and Evans highlighted the interest to formulate the interaction between cost and efficiency and proposed the term "Thermoeconomics" [8]. In 1985, Tsatsaronis and Winhold proposed a new approach for the exergoeconomic analysis of energy-conversion processes and introduced the key concepts of Fuel and Product for the first time [9]. After that, Lozano and Valero presented theoretical basis of the theory of exergetic cost in the field of thermoeconomics. Then, they presented several applications, e.g. operation optimization, cost allocation, and energy audits and assessment of fuel impact of malfunctions, for this methodology [10]. Later, for exergoeconomics analysis of complex energy systems, Kim et al. proposed an exergy-costing method which can be applied to each section of the system and to each connection [11].

Similar to the exergy analysis, exergoeconomics analysis can assess an energy system in two different ways: a) Overall exergoeconomics evaluation. This approach is usually used by applying the optimization method which is developed based on the exergoeconomics principle to minimize the product cost. b) Detail exergoeconomics analysis. equations are solved simultaneously to estimate the cost per unit of exergy for all streams. This approach is used in multi-product systems such as cogeneration systems to estimate each product cost separately. Furthermore, it is used in exergoeconomics evaluation. In exergoecomic evaluation, the components with high influence on the final cost of the products are recognized to find effective scenarios to improve the final product cost. There are different algorithms in this regards, in which the algorithm proposed by

Bejan and Tsatsaronis is the most famous one. They proposed two parameters and a methodology to improve energy systems [2,12]. There have been several studies on exergoeconomics evaluation of energy systems [13-15].

In a basic analysis of energy systems, risks and uncertainties are not considered during the analysis period. However, most of the effective parameters in energy systems performance are subject to a significant level of uncertainty [16]. These uncertain parameters in energy systems can be classified by two different categories: a) technical factors and b) economic factors [17]. Parameters such as failure of the components, the system, and the network are the main technical parameters with uncertainty. On the other hand, parameters like uncertainty in costs of energy and production, environmental policies, and interest rates are considered as economic parameters. Many studies addressed these uncertainties in the field of energy systems. Posen et al. considered the uncertainty in the GHG emission of the U.S. plastics industry with the help of Monte Carlo method [18]. Pereira et al. introduced a risk analysis procedure for renewable energy generation which uses Monte Carlo method to evaluate trends of economic parameters such as interest rate and each cost of the system [19]. Momen et al. proposed a novel layout to notice economic uncertainties in the optimization of energy systems. Instead of mere numbers, the results of this method are NPV of the optimized design in the probability function form [20]. Also recently, Hofmann and Tsatsaronis, showed the impact of uncertain economic parameters, on the levelized cost of electricity in the comparative exergoeconomics evaluation of power plants [21].

In this study, a novel method for exergoeconomics evaluation and improvement of energy systems under economic uncertainty is proposed. As the first step, the future values of economic parameters that influence the operating cost of the energy system are forecasted by the Monte Carlo Method. Then, Bejan's exergoeconomics improvement procedure [3] is coupled with the Monte Carlo method for exergoeconomics evaluation of energy systems. The Bejan methodology is modified by a set of variables computed for each part of the system based on uncertainties in input parameters. Given that some of the inputs of the problem are generated by iterating with help of the Monte Carlo Method, all the parameters are calculated as a probability distribution function. Unlike previous efforts, the probability function of the results of the exergoeconomics analysis creates a detailed understanding of the profit sustainability of the system. Eventually, as a novel approach, three new parameters, i.e. Risk Factor (RF), Risk Factor Sensitivity (RFS), and Product Cost Sensitivity (PCS), are proposed for exergoeconomics evaluation of energy systems under economic uncertainty. Two distinct procedures are considered in the evaluation process: a) lessening the final product cost and b) reducing the risk and the uncertainties in the system. The proposed method is applied to a benchmark cogeneration system, i.e. CGAM.

2. Methodology

2.1 Exergoeconomics Analysis

Exergoeconomics is based on cost balance. The cost balance for a structure (or even for each component) is formulated as follows in steady state condition [3]:

$$\dot{C}_P = \dot{C}_F + \dot{Z}^{cl} + \dot{Z}^{OM} \tag{1}$$

The cost balance represents that the *cost rate* of the final product ($\dot{C}_P$) equals the total rate of fund consumptions for product generation, the fuel cost rate ($\dot{C}_F$), the capital investment cost rate ($\dot{Z}^{cl}$) and operating and maintenance cost rate ($\dot{Z}^{OM}$).

The exergy rates exiting and entering the kth element have been computed in an exergy analysis and based on existing streams, fuel and product have been described. The term $\dot{Z}_k$ is obtained by first calculating the capital investment, operating and maintenance costs associated with the kth element and then calculating the levelized quantities of these costs per unit of time (second, day, or month) of system operation [3]:

$$(c_P \dot{E}_P)_k = (c_F \dot{E}_F)_k + \dot{Z}_k \tag{2}$$

Now the *average costs per exergy unit of fuel and product* can be defined for a component. The average unit cost of the fuel ($c_{F,k}$) the kth component is defined by Equation 3.

$$c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{E}_{F,k}} \tag{3}$$

Similarly, average unit cost of the product ($c_{P,k}$) for the kth component is defined by Equation 4.

$$c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{E}_{P,k}} \tag{4}$$

2.2 Economic Model and Uncertainty

Reliable results can be achieved if the economic parameters and the risk of their changes are considered carefully in real problems. Also, uncertainties of the results can be assessed from the amount of input uncertainties in engineering and economic evaluations.

Figure 1 shows the values of electric and fuel inflation and discount rate which are calculated from the past 20 years data by using the Monte Carlo Method [20]. Economics parameter which was described in previous part would forecast as probability distribution function by using this method on the past 20 years. Fuel inflation would be obtained as a probability distribution function by using probability distribution function of discount rate. The annual money effective discount rate is predicted as a probability distribution function for each operating year during the system life cycle. So, the capital recovery factor (CRF) also describes probability distribution function which leads the annual income requirement to a probability distribution. As a result, the capital recovery factor (CRF) is given by [3]:

$$CRF = \frac{i_{eff} \prod_{m=1}^{n} (1 + i_m)}{\prod_{m=1}^{n} (1 + i_m) - 1} \tag{5}$$

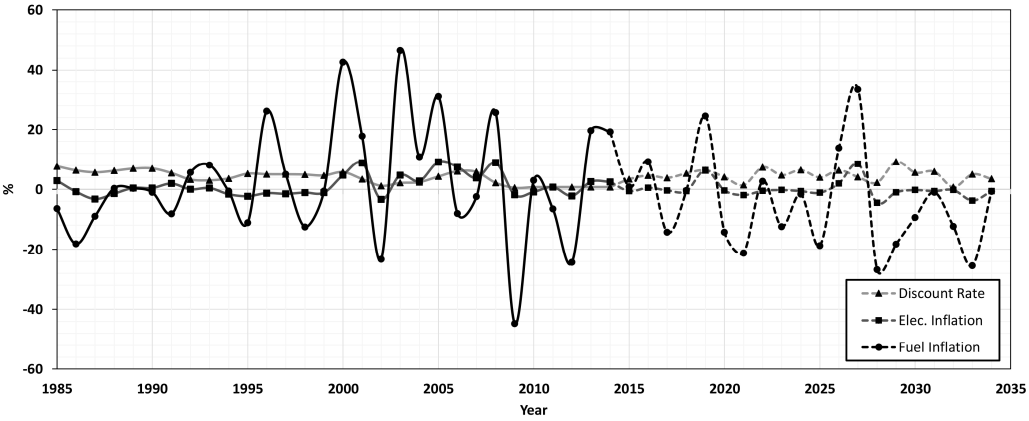


Fig. 1. One of the predictions made by the Mont Carlo method [20]

i_m is the annual effective discount rate in the mth year of the system operation which is computed by applying Monte-Carlo on the recent years behavior discount rate, also i_{eff} refers to the average annual effective discount rate and n denotes the economic life cycle of the system expressed in years.

The levelized fuel cost of the series can be calculated by Equation 6, if the annual fuel cost series (FC_j) is uniform over time except for a constant growth rate r_{FC} (Fig. 2) [3]:

$$FC_L = FC_0 \times \frac{k_{FC}\left(1-k_{FC}^{n}\right)\times CRF}{\left(1-k_{FC}\right)} \tag{6}$$

with

$$k_{FC} = \frac{1+r_{FC}}{1+i_{eff}} \tag{7}$$

The terms FC_L, r_{FC} and CRF show the levelized uniform annual cost of fuel in the system life cycle, the average annual escalation rate for the cost of fuel and the capital recovery factor respectively. Bejan et al. defined the levelized cost rate for the fuel $\dot{C}_F$ supplied to the overall system [3]:

$$\dot{C}_F = \frac{FC_L}{\tau} \tag{8}$$

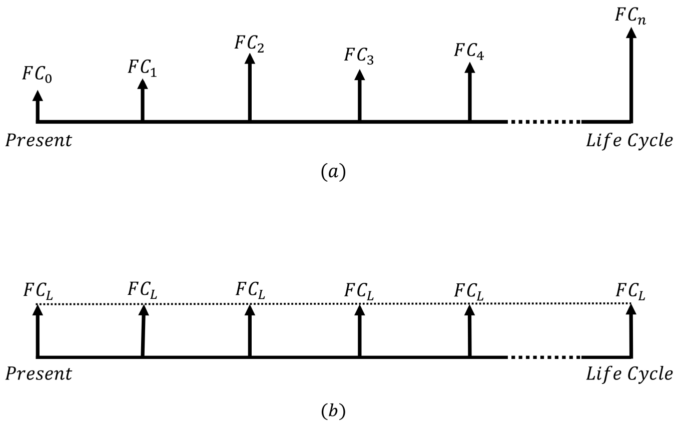
τ is the operational time of the system in hours and $\dot{C}_F$ is levelized cost of the plant which is used as input data. Therefore, product cost of each component would be calculated by using exergoeconomics analysis as a distribution function.

2.3 Evaluation

2.3.1 Modified Bejan analysis procedure

According to Bejan's method [3] two parameters are presented, i.e. relative cost difference and exergoeconomics factor. The relative cost difference (r_k) demonstrates the relative growth in the average cost per exergy unit between fuel and product of the component [3]:

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \tag{9}$$



(a)

(b)

Fig. 2. (a) Annual predicted fuel cost (b) Levelized uniform annual fuel cost

The cost sources in a component may group into two categories. a) non-exergy-related costs b) exergy destruction and exergy loss. each category can be important in evaluating the efficiency of different elements. This provided by the exergoeconomic factor (f_k), defined for component k by [3]:

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{F,k}\dot{E}_{D,k}} \tag{10}$$

The *exergoeconomic factor* (f_k) represents as the proportion of the non-exergy-related cost to the total cost increase.

Given that some of the inputs of the problem are generated by iterating with help of the Monte Carlo Method, all the parameters, such as r_k and f_k , are calculated as a probability distribution function and by using the mean value of this function the next steps can be done.

After that, to improve the cost-effectiveness of a thermal system, the bellow actions are done by the mean value of each variable:

1. Rank the components in descending order of cost significance using the value of $\dot{C}_D + \dot{Z}$
2. Notice structure and layout transitions initially for the components which high value for this sum.
3. Consider components with greater relative cost difference r_k, especially when the amount of $\dot{C}_D$ and $\dot{Z}$ are significant.
4. Use the exergoeconomic factor f_k to recognize the main cost source,
    a. If the quantity of f_k is high, check whether it is cost effective to diminish the capital investment for the kth component at the expense of the component efficiency.
    b. If the quantity of f_k is low, attempt to modify the component performance by more capital investment.
5. Remove any subprocesses which rise the exergy destruction or exergy loss without contributing to the diminution of capital investment or other components fuel cost.
6. Consider enhancing the exergetic efficiency of a component if it has a relatively low exergetic efficiency or relatively high exergy destruction ratio or the exergy loss ratio.

It is common in the design of energy systems to have states with more than one purpose. The two objective functions that have been investigated in this study are the “cost of products” and the “risk of investment”.

2.3.2 Sensitivity Analysis Procedure

Consider a power plant, which is set up in an unstable area has significant oscillation in discount rate, fuel inflation rate, and electricity inflation rate, so decreasing risk parameter has same importance with decreasing the cost of products. For this purpose, three new parameters are introduced in this study, in order to make the accurate improvement in the system.

- Risk Factor (RF)

One of the parameters has been defined in this study as ‘Risk Factor’ in order to find the dependence of the distribution of product cost around average value and it represents the amount of uncertainty.

$$RF = \frac{\sigma_{C_p}}{\mu_{C_p}} \tag{11}$$

That μ_{C_p} is the average amount of product costs in iterative solution by Monte Carlo method and σ_{C_p} is the standard deviation of product costs.

- Product Cost Sensitivity (PCS)

The other parameter is PCS which indicates the sensitivity of product cost (μ_{C_p}) to each decision parameter (*x*).

$$\mathrm{PCS} = x \times \frac{d\left(\mu_{C_p}\right)}{dx} \tag{12}$$

- Risk Factor Sensitivity (RFS)

Similarly, RFS is defined as the sensitivity of risk factor (RF) to each decision parameter (x).

$$RFS = x \times \frac{d(RF)}{dx} \tag{13}$$

Two approaches of evaluation have described in this study; the first one is to minimize the cost of products, which is utilizable for power plant set up in a stable area (regions with high economic stability). Otherwise, for the unstable areas (regions with low economic stability), the second optimizing approach minimizing the risk as an objective is suitable.

It should be noticed that the main application of the proposed method is to help owners (investors) of an already completely designed system. With this method, they can improve the system on economic aspect by changing only one or two components. This method selects the target component which it should be changed but it does not suggest the exact features of the alternative component (only the less or greater value of the decision parameter is specified). The alternative component is selected through the available components in the market.

Figure 3 shows the general algorithm which is used to evaluate and to improve the CGAM system performance as a benchmark by considering economic parameters uncertainties.

The created code contains the below sections:

- Thermodynamic simulation
- Economic parameters forecasting by performing the Monte Carlo method
- Economic assessment to calculate the cost of products
- Evaluation and improvement algorithm

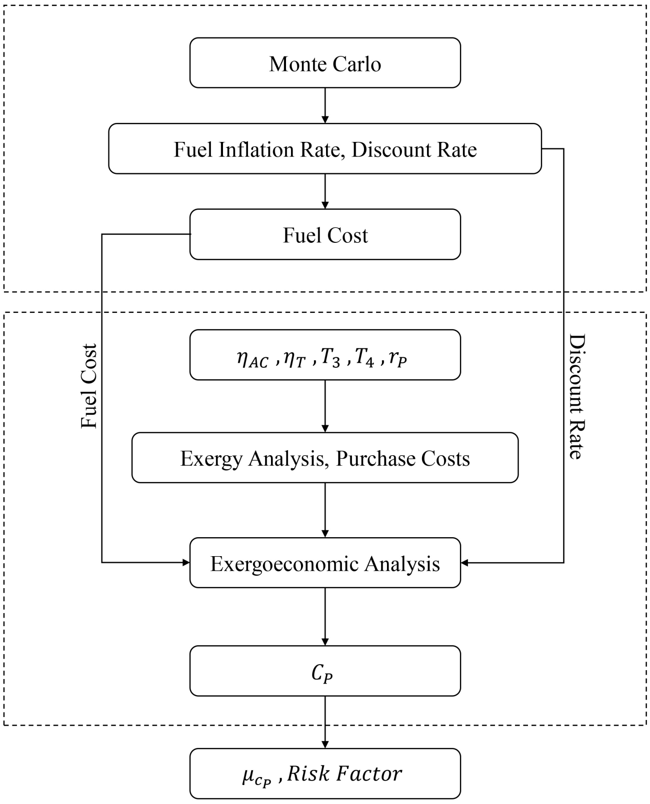


Fig. 3. The flowchart of the exergoeconomics analysis by considering uncertainty

3. Case Study

3.1 CGAM

A well-known cogeneration system (CGAM) [22] has used to demonstrate the procedure of exergoeconomics methods for complex cases assessment. There are many studies of exergoeconomics analysis that have applied to this problem by foremost researchers. It assumes ideal gas behavior and constant heat capacities. The CGAM system as a cogeneration power plant have two type of products (30 MW of electricity and 14 kg/s of saturated steam at 20 bars). The main components of installation are a gas turbine (GT), air compressor (AC), air preheater (APH), combustion chamber (CC), and HRSG The schematic form of the CGAM system can be seen in Fig.4

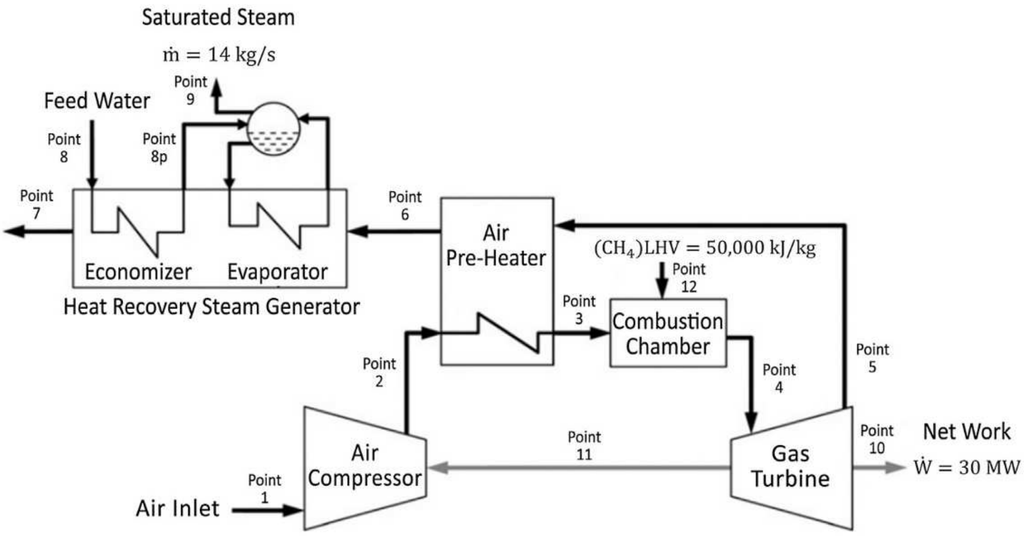


Fig. 4. Schematic of CGAM system [22]

Table 1. Thermodynamic Properties and Operating Conditions for CGAM system

Decision Variables	Quantity
Air Compressor Pressure Ratio	10
Gas Turbine Isentropic Efficiency	86.4%
Air Compressor Isentropic Efficiency	88.3%
Inlet Temperature of Combustion Chamber	900 K
Inlet Temperature of Gas Turbine	1505 K
Parameters	**Quantity**
Air Compressor Inlet Conditions	25 °C, 1.013 bars
Air Preheater Pressure Drops	3% on the gas side 5% on the air side
Condensate Return Conditions	25 °C, 20 bars
Stack Pressure	1.013 bars
HRSG Pressure Drop	5% on the gas side
Fuel (Natural Gas) Conditions	25 °C, 12 bars
Pressure Drop in Combustion Chamber	5%
Process Steam Conditions	20 bars, 14 kg/s
Net Power Generated by the System	30 MW

Table 2. Initial conditions for CGAM system and Total cost of products

Parameter	Initial Value
r_P	8.46
η_{AC}	0.883
η_{GT}	0.864
T_3	900 K
T_4	1505 K
$C_{P_{Total}}(\mu,\sigma)$	22.270, 5.739 ($/GJ)
RF	0.258

Table 3. The exergoeconimc variables calculated for each component of the CGAM system

Component	ε (%)	$\dot{E}_D(MW)$	$c_F(\frac{\$}{GJ})$		$c_P(\frac{\$}{GJ})$		$\dot{C}_D+\dot{Z}(\frac{\$}{hr})$		r (%)		f (%)		RF
			μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	
CC	79.68	24.78	6.38	1.80	8.16	2.27	1017	225.22	27.91	7.34	7.02	1.70	0.278
GT	97.8	2.61	8.16	2.27	8.35	2.22	156	20.97	2.28	0.55	47.61	6.46	0.266
AC	93.7	1.70	10.94	2.52	11.94	2.25	204	15.47	31.10	3.62	68.75	3.62	0.231
HRSG	70.17	5.84	8.16	2.27	14.03	3.54	231	47.67	71.98	15.60	9.76	2.27	0.252
APH	81.57	2.62	8.16	2.27	12.35	2.95	170	27.85	51.42	8.40	42.11	8.40	0.239

3.2 Results

Solving the linear system including exergy balance equations of each component, the amount of the cost flow rates of each stream are obtained. Note that the maximum internal exergy unit cost reached by stream exiting from the air compressor where all exergy available at the exit supplied by mechanical power, which is the most valuable exergy stream in the system. The parameters which were defined in this paper would be calculated by the initial values. The total cost of products and also the RF are shown in table 2.

The key exergoeconomics parameters of CGAM system components are presented in Table 3. These parameters are the exergy destruction variables ($\dot{E}_D$ & $\dot{C}_D$), fuel and product average costs per unit of exergy ($\dot{C}_P$ & $\dot{C}_F$) investment and operating and maintenance cost rate (Z), relative cost difference (r), exergoeconomic factor (f), and risk factor (RF).

3.2.1 Modified Bejan Methodology Results

As the initial step, a modified version of Bejan method is applied to the CGAM system. Since the uncertainties are considered in this evaluation, unlike the Bejan's method, the results include the mean value and variance of each parameter.

The bellow variations in the design variables are applied to improve the efficiency and performance of the system:

- Increase the value of T_4 (by combustion chamber and HRSG assessment)
- Decrease r_P, η_{AC} and η_{GT} (by gas turbine and air compressor assessment)

Table 4. Changes made after executing the Bejan instructions without considering uncertainty parameters (PCS and RFS)

Parameter	Initial Values	Final values after applying Modified Bejan Evaluation
r_P	↓ 8.46	8
η_{AC}	↓ 0.883	0.875
η_{GT}	↓ 0.864	0.855
T_3	900 K	900 K
T_4	↑ 1505 K	1515 K
$C_{P_{Total}}(\mu,\sigma)$	22.270, 5.739 ($/GJ)	21.337, 5.688 ($/GJ)
RF	0.258	0.267

Table 5. Comparison between PCS and RFS of components at the initial state

Parameter	Value	PCS	RFS
r_P	8.46	90.81	-0.984
η_{AC}	0.883	188.05	-2.312
η_{GT}	0.864	158.80	-0.076
T_3	900 K	149.34	-1.247
T_4	1505 K	-141.12	-1.576
$C_{P_{Total}}(\mu,\sigma)$	22.270, 5.739 ($/GJ)		
RF	0.258		

Table 6. Exergoeconomics evaluation by the Product Cost Sensitivity (PCS)

	Operating Point		1st Iteration		2nd Iteration	
Parameters	Value	RFS	Value	Parameters	Value	RFS
r_P	8.46	90.81	8.46	73.28	8.46	22.41
η_{AC}	↓ 0.883	188.05	0.874	85.25	0.874	70.87
η_{GT}	0.864	158.80	↓ 0.864	109.65	0.855	78.82
T_3	900 K	149.34	900 K	96.58	900 K	77.55
T_4	1505 K	-141.12	1505 K	-75.24	1505 K	-17.12
$C_{P_{Total}}(\mu,\sigma)$	22.270, 5.739 ($/GJ)		21.757, 5.717 ($/GJ)		21.358, 5.620 ($/GJ)	
RF	0.258		0.263		0.263	

3.2.2 Product Cost Sensitivity and Risk Factor Sensitivity Evaluation

In this study, $x \times d(\mu_{C_P})/dx$ is defined as Product Cost Sensitivity (PCS) and $x \times d(RF)/dx$ is defined as risk factor sensitivity (RFS) which indicates the sensitivity of C_P and RF in terms of describing parameters x including r_P, η_{AC}, η_{GT}, T_3 and T_4. Table 5 compares the sensitivity of components.

- **Cost of Product Evaluation**

One approach is minimizing the cost of products containing power and steam. So, at initial values, the component with the most sensitivity to the cost of products as described in table 6 is air compressor and also at first iteration is the gas turbine.

Table 6 presents the results of 2 iterations for reducing the cost of products. As it can be seen, in the operating point the mean value of the product cost is 22.270 $/GJ which is reduced to 21.757 $/GJ and 21.358 $/GJ in the first and second iteration respectively. By continuing these iterations the cost of products will reach the smaller values. In addition, the risk factor values in the operating point and the first two iterations are presented in Table 6. This parameter can be used as a constraint when reducing the cost of products.

As it has shown in table 6, air compressor efficiency has been changed in the first iteration and by listing components in order of descending the value of the parameter of sensitivity to cost of products, for the second iteration the gas turbine should be changed. The mean value of total Cost of products which indicated in table 6 demonstrate the downtrend its value.

This analysis demonstrated that the cost of product can be reduced from 22.270 $/GJ to 21.757 $/GJ only by replacing the current air compressor (η_{AC}= 89.1%) with another air compressor (η_{AC}= 87.4%). It reduces the cost of products in term of cost of investment. If this reduction is not sufficient, changing the gas turbine simultaneously can bring the lower cost of product.

- **Risk Factor Evaluation**

Another approach is minimizing the risk of investment by minimizing the amount of uncertainty. In each iteration, the component with the most effective on the risk factor of products cost chosen as the decision parameter.

Table 7 indicates two iterations of the evaluation procedure in terms of risk parameter. The last row demonstrates the downtrend of the cost of product uncertainty. This analysis showed that the risk factor can be decreased from 25.8% to 24.5% only by replacing the current air compressor (η_{AC}= 88.3%) with another air compressor (η_{AC}= 89.1%). It reduces the cost of products in term of exergy destruction. If this reduction is not sufficient, changing the combustion chamber simultaneously can bring the lower cost of product.

Table 7. Exergoeconomics evaluation by risk factor sensitivity (RFS)

	Operating Point		1st Iteration		2nd Iteration	
Parameters	Value	RFS	Value	RFS	Value	RFS
r_P	8.46	-0.984	8.46	-1.123	8.46	-0.998
η_{AC}	↑ 0.883	-2.312	0.891	-1.105	0.891	-1.187
η_{GT}	0.864	-0.076	0.864	-0.733	0.864	-1.367
T_3	900 K	-1.247	900 K	-0.817	900 K	-0.207
T_4	1505 K	-1.576	↑ 1505 K	-1.522	1520 K	-1.096
$C_{P_{Total}}(\mu,\sigma)$	22.270, 5.739 ($/GJ)		23.459, 5.759 ($/GJ)		22.249, 5.640 ($/GJ)	
RF	0.258		0.245		0.243	

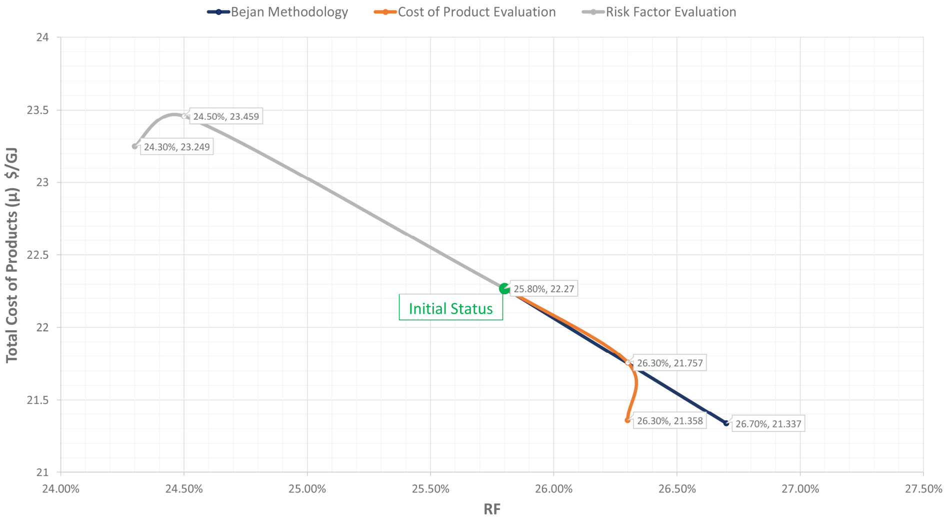


Fig. 5. Comparison between Bejan methodology result [3] vs. Proposed approaches result

3.2.3 Comparison Between The Results

Based on the final results it is clear that "cost of product evaluation" like Bejan's methodology is focused on minimizing the cost of the products. But there is a significant difference that notices to risk factor by second priority. In the other hand, "risk factor evaluation" unlike Bejan's methodology is focused on minimizing the economic risk of production and decreasing the cost of the products is the second target. Figure 5 shows the difference and similarity of these approaches performance.

4. Conclusion

This paper was a study to deal with economic uncertainty in design and evaluation of energy systems by using the exergoeconomics analysis. The Monte Carlo Method was used to forecast future variations in economic inflation and discount factors based on historical data. A new parameter, i.e. risk factor, was introduced which determines the uncertainty of the product cost. Exergoeconomics evaluation was used in order to assess the probabilistic cost of products and all other parameters. After that, a modified Bejan method [3] was proposed for evaluating energy system by including the uncertainties and using the mean values of the calculated parameters. Result shows the total cost of products was reduced but there are two obstacles. First, some changes were made at the same time and it makes that impractical to evaluate the effect of changing each parameter individually. Second, there is no control on the risk of the total cost of products. Also, after introducing two new parameters, which consider the sensitivity of product cost and risk factor (RF) to each decision parameter, a new approach was proposed for improving the performance of energy systems. The region economic condition imposes to select “cost of products” as an evaluation parameter or “risk factor”. Then this method selects the target component which it should be changed and the alternative component is selected through the available components in the market. As demonstrated in the case study, by using the sensitivities analysis, if the total cost of products is the target, it can be reduced from 22.270 $/GJ to 21.358 $/GJ by two iterations. And also if the risk of the cost of products is the target, it can be reduced from 25.8% to 24.3% by two iterations. It should be noticed, presented method may be used to improve simultaneously “cost of products” and “risk factor”.

Author Contributions

The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed, and approved the final version of the manuscript.

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Conflict of Interest

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Data Availability Statements

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Appendix

Part of the code from the Monte Carlo section is added in the appendix:

```
function [Elec_inf_MC_generated , NG_inf_MC_generated ,Disc_MC_generated] = Monte_Carlo(N)
Elec_inf=[2.898550725,-0.804828974,-3.245436105,-1.467505241,0.425531915,0.423728814,1.898734177,0,0.414078675,-1.649484536,-2.306079665,-
1.287553648,-1.52173913,-1.103752759,-1.116071429,4.740406321,8.836206897,-
3.366336634,4.713114754,2.739726027,9.142857143,7.504363002,3.733766234,8.920187793,-1.867816092,-0.878477306,0.738552437,-
2.19941349,2.548725637,2.485380117] ; % Industrial cost base
NG_inf=[0.340136054,0.338983051,-1.013513514,-8.19112628,5.576208178,8.098591549,-0.651465798,-11.14754098,26.19926199,4.970760234,-
12.53481894,-0.636942675,42.62820513,17.75280899,-23.28244275,46.51741294,10.86587436,31.08728943,-8.060747664,-2.414231258,25.65104167,-
44.76683938,3.001876173,-6.557377049,-24.36647173,19.58762887,21.12068966,-30.07117438,-10.6870229,16.80911681] ;
Disc=[6.19,6.92,6.98,5.44,3.25,3,3.59,5.21,5.02,5,4.91,4.62,5.73,3.41,1.17,2.1,2.39,4.25,6.02,5.79,2.16,0.5,0.73,0.75,0.75,0.75,0.75,0.75,1,1.25] ;

for x=1:1000
NG_price(x,1) = 4.10 ; % $/Thousand Cubic Feet (2017)
Elec_inf_ND = fitdist(Elec_inf','Normal') ;
Elec_inf_mu = Elec_inf_ND.mu ;
Elec_inf_sigma = Elec_inf_ND.sigma ;
NG_inf_ND = fitdist(NG_inf','Normal') ;
NG_inf_mu = NG_inf_ND.mu ;
NG_inf_sigma = NG_inf_ND.sigma ;
Disc_ND = fitdist(Disc','Normal') ;
Disc_ND_mu = Disc_ND.mu ;
Disc_ND_sigma = Disc_ND.sigma ;

for j = 1:20
    NG_inf_MC_generated(x,j) = normrnd(NG_inf_mu,NG_inf_sigma) ;
    Elec_inf_MC_generated(j) = 4.299e-9 * NG_inf_MC_generated(j)^6 -2.031e-7 * NG_inf_MC_generated(j)^5 -1.302e-5 * NG_inf_MC_generated(j)^4
    + 0.0004416 * NG_inf_MC_generated(j)^3 + 0.009927 * NG_inf_MC_generated(j)^2 + 0.007005 * NG_inf_MC_generated(j) - 0.6122 ;
    Elec_inf_MC_generated(j) = Elec_inf_MC_generated(j)/100 ;
    NG_inf_MC_generated(x,j) = NG_inf_MC_generated(x,j)/100 ;
```

```
        Disc_MC_generated(x,j) = normrnd(Disc_ND_mu,Disc_ND_sigma)/100 ;
        NG_price(x,j+1) = NG_price(x,j) * (1+NG_inf_MC_generated(x,j));

    end
    end
    i_eff= mean(Disc_MC_generated,2);

    for y=1:1000
        CRF(y)=i_eff(y,1)*prod(1+Disc_MC_generated(y,:))/(prod(1+Disc_MC_generated(y,:))-1);
        nn=mean(NG_inf_MC_generated(y,:));
        mm=i_eff(y,1);
        K_FC(y)=(1+nn)/(1+mm);
        NG_price_L(y)=NG_price(1,1)*(K_FC(y)*(1-(K_FC(y)^20))*CRF(y))/(1-K_FC(y));
    end
```

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