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Exergoenvironmental analysis and optimization of a cogeneration plant system using Multimodal Genetic Algorithm (MGA)

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ABSTRACT

In the present work, a combined heat and power plant for cogeneration purposes that produces 50 MW of electricity and 33.3 kg/s of saturated steam at 13 bar is optimized using genetic algorithm. The design parameters of the plant considered are compressor pressure ratio (r_{AC}), compressor isentropic efficiency (η_{comp}), gas turbine isentropic efficiency (η_{GT}), combustion chamber inlet temperature (T_3), and turbine inlet temperature (TIT). In addition, to optimally find the optimum design parameters, an exergoeconomic approach is employed. A new objective function, representing total cost rate of the system product including cost rate of each equipment (sum of the operating cost, related to the fuel consumption) and cost rate of environmental impact (NO_x and CO) is considered. Finally, the optimal values of decision variables are obtained by minimizing the objective function using evolutionary genetic algorithm. Moreover, the influence of changes in the demanded power on various design parameters are parametrically studied for 50, 60, 70 MW of net power output. The results show that for a specific unit cost of fuel, the values of design parameters increase, as the required, with net power output increases. Also, the variations of the optimal decision variables versus unit cost of fuel reveal that by increasing the fuel cost, the pressure ratio, r_{AC}, compressor isentropic efficiency, η_{AC}, turbine isentropic efficiency, η_{GT}, and turbine inlet temperature (TIT) increase.

1. Introduction

Developing techniques for designing efficient and cost-effective energy systems is one of the foremost challenges that energy engineers face. In a world with finite natural resources and increasing energy demand by developing countries, it becomes increasingly important to understand the mechanisms which degrade energy and resources and to develop systematic approaches for improving the design of energy systems and reducing the impact on the environment [1].

The second law of thermodynamics combined with economics represents a very powerful tool for the systematic study and optimization of energy systems. This combination forms the basis of the relatively new field of thermoeconomics or exergoeconomics [2]. Recently exergy and exergoeconomic analyses have been employed for analysis, design, performance improvement and optimization of thermal systems, including CHP (combined heat and power) plants. It is well-known that exergy can be used as a potential too to determine the location, type and true magnitude of exergy loss (or destruction) [3]. Therefore, it can play an important issue in developing strategies and in providing guidelines for more effective use of energy in the existing power plants [4]. Exergoeconomics combines the exergy analysis with the economic principles and incorporates the associated costs of the thermodynamic inefficiencies in the total product cost of an energy system [1,5]. These costs can conduct designers to understand the cost formation process in an energy system and it can be utilized in optimization of thermodynamic systems, in which the task is usually focused on minimizing the unit cost of the system product [6]. Numerous researchers [7–10] have conducted both exergy and exergoeconomic analyses and optimization for thermal systems. The first challenge of exergoeconomic was introduced in a problem called CGAM [11–15]. The CGAM problem refers to a cogeneration plant which delivers 30 MW of electricity and 14 kg/s of saturated steam at 20 bar. The installation consisted of a gas turbine followed by an air preheater that used part of the thermal energy of the gases leaving the turbine, and a heat recovery steam generator in which the required steam was produced. Later, some exergoeconomic analysis studies were performed for CHP plants [8,16–21]. These references clearly reveal the importance of exergy

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and exergoeconomics for design, analysis, performance improvement and optimization of thermal systems.

Therefore; using the optimization procedure with respect to thermodynamics laws as well as exergoeconomics is essential. In fact, the main objectives for design optimization process are as follow [22]: thermodynamically (e.g., maximum efficiency, minimum fuel consumption, minimum irreversibility and so on), economically (e.g., minimum cost per unit of time, maximum profit per unit of production) and environmentally (e.g., limited emissions, minimum environmental impact). Some researchers have carried out the optimization for power plants and CHP systems. Sahoo [8] carried out the exergoeconomic analysis and optimization of a cogeneration system using evolutionary programming. He considered a cogeneration system which produced 50 MW of electricity and 15 kg/s of saturated steam at 2.5 bar. He optimized the CHP unit using exergoeconomic principles and evolutionary programming. The results showed that for the optimum case in the exergoeconomic analysis the cost of electricity and produced cost is 9.9% lower in comparison with the base case. Ameri et al. [10] performed thermodynamic analysis of a tri-generation system based on micro-gas turbine with a steam ejector refrigeration system. In this study, a micro-gas turbine cycle produced 200 kW power, and the exhaust gases of this micro-gas turbine were also recovered in an HRSG (Heat Recovery Steam Generator). The main part of saturated steam in HRSG is used through a steam ejector refrigeration system to produce cooling in summer. They also carried out the exergy analysis of the system to find the exergy efficiency and exergy destruction of each equipment of the MGTC (Micro-Gas Turbine Cycle).

Therefore, the results show the importance of exergoeconomic optimization in thermal systems especially CHP plants. On the other hand, there are some papers in the literature carried out by considering the environmental aspect of thermal systems. Dincer [23] considered the environmental and sustainability aspects of hydrogen and fuel cell systems. He also analyzed the exergetic and environmental aspects of drying systems [24]. In addition to the exergetic and monetary costs of mass and energy streams in the thermal systems, environmental analysis considers the costs related to flows of pollutants [25]. However, by applying the unit damage cost related to NOx and CO emissions [26], this objective function is formulated in the cost terms and it can be considered as an additional economic objective. In this sense, the non-abbreviated term thermoenviroeconomic would be more appropriate, as recognized by Frangopoulos [25]. Ehyaei and Mozafari [27] performed the optimization of micro-gas turbine by exergy, economic and environmental. They performed analysis on various fuels. Their results showed that optimization results are little affected by the type of fuel considered and trends of variations of second law efficiency and cost rate of owning and operating the whole system are independent of the fuels.

In this present work, based on the CGAM problem a new methodology is developed for optimizing the objective function. For the verification of this developed genetic algorithm (GA) code, the results are compared with CGAM problem for verification purposes. After this verification, the GA developed code is used for a CHP plant used in a paper mill company located in Iran. The new objective function including total cost rate of product and cost rate of environmental impact is considered. The design parameters are considered as compressor pressure ratio (r_c), compressor isentropic efficiency (η_{comp}), gas turbine isentropic efficiency (η_{GT}), combustion chamber inlet temperature (T_3), and turbine inlet temperature (TIT).

In summary, the following are the specific contributions of this paper to the subject area:

- A complete thermodynamic modeling of a CHP system used in a paper mill is performed.
- An exergoeconomic modeling and optimization is conducted and compared with a well-known problem named CGAM problem for the accuracy of developed GA code.
- A new objective function, including the cost of environmental impacts (particularly for NO_x and CO) is considered.
- A modified version of evolutionary genetic algorithm is developed for optimization.
- The effect of fuel cost rate and power output of the CHP plant on the selected design parameters is parametrically studied.

2. Energy analysis

As CHP systems are commonly used for many applications, the optimization of such systems is so important in both thermodynamic and economic point of view. In addition, exergoeconomic analysis helps designers to find ways to improve the performance of a system in a cost-effective way. Most of the conventional exergoeconomic optimization methods are iterative in nature and require the interpretation of the designer at each iteration.

To find the optimum physical and thermal design parameters of the system, a simulation program is developed in Matlab software. Thus, the temperature profile in CHP plant, input and output enthalpy and exergy of each line in the plant were estimated to study the optimization of the plant. The energy balance equations for various parts of the CHP plant (Fig. 1) are as follow:

- Air compressor:

$$T_2 = T_1\left\{1+\frac{1}{\eta_{AC}}\left[r_c^{\frac{\gamma_a-1}{\gamma_a}}-1\right]\right\} \tag{1}$$

$$\dot{W}_{AC} = \dot{m}_a C_{pa}(T_2-T_1) \tag{2}$$

where C_{pa} is considered a temperature variable function as follows [28]:

$$C_{pa}(T) = 1.04841-\left(\frac{3.8371T}{10^4}\right)+\left(\frac{9.4537T^2}{10^7}\right)-\left(\frac{5.49031T^3}{10^{10}}\right)+\left(\frac{7.9298T^4}{10^{14}}\right) \tag{3}$$

- Air preheater:

$$\dot{m}_a(h_3-h_2) = \dot{m}_g(h_5-h_6)\eta_{AP} \tag{4}$$

$$\frac{P_3}{P_2} = \left(1-\Delta P_{aph}\right) \tag{5}$$

- Combustion chamber:

$$\dot{m}_a h_3+\dot{m}_f\mathrm{LHV} = \dot{m}_g h_4+(1-\eta_{cc})\dot{m}_f\mathrm{LHV} \tag{6}$$

$$\frac{P_4}{P_3} = (1-\Delta P_{cc}) \tag{7}$$

With the following combustion equation:

$$\lambda C_{x1}H_{y1}+(x_{O_2}O_2+x_{N_2}N_2+x_{H_2O}H_2O+x_{CO_2}CO_2+x_{Ar}Ar)\rightarrow y_{CO_2}CO_2+y_{N_2}N_2+y_{O_2}O_2+y_{H_2O}H_2O+y_{NO}NO+y_{CO}CO+y_{Ar}Ar$$

where

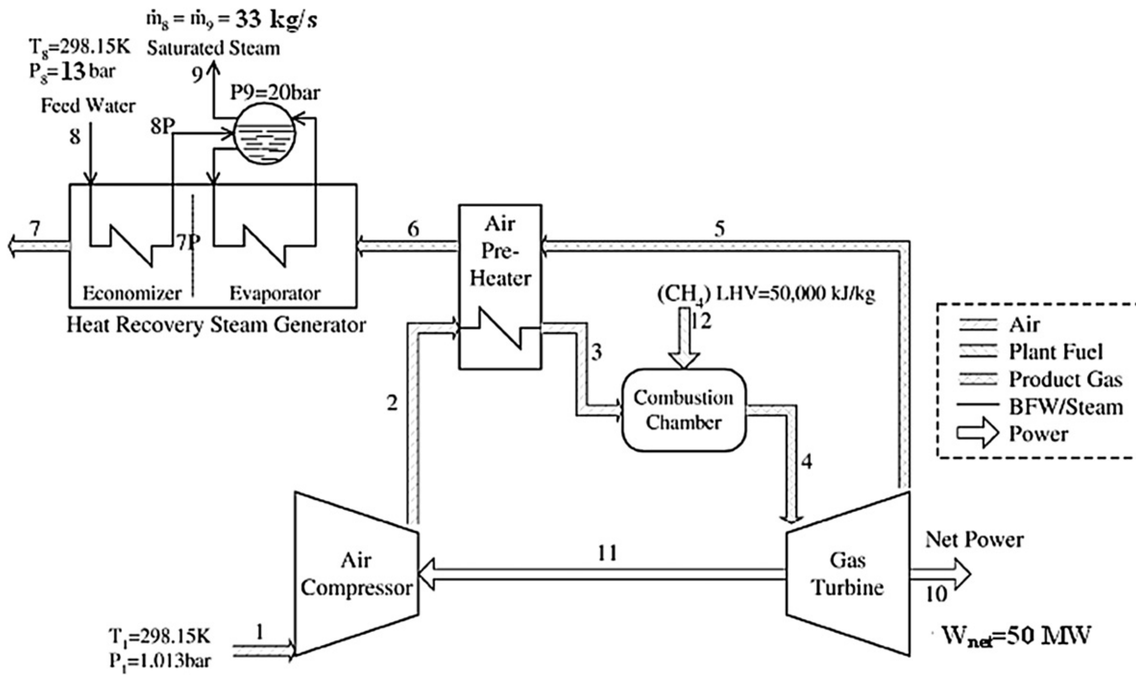

Fig. 1. CHP plant used in the paper mill.

$$
\begin{aligned}
y_{CO_2} &= (\lambda \times x_1 + x_{CO_2} - y_{CO}) \\
y_{N_2} &= x_{N_2} - y_{NO} \\
y_{H_2O} &= x_{H_2O} + \tfrac{\lambda \times y_1}{2} \\
y_{O_2} &= x_{O_2} - \lambda \times x_1 - \frac{\lambda \times y_1}{4} - \frac{y_{CO}}{2} - \frac{y_{NO}}{2} \\
y_{Ar} &= x_{Ar} \\
\lambda &= \frac{n_{fuel}}{n_{air}}
\end{aligned} \tag{8}
$$

- Gas turbine:

$$T_6 = T_5 \left\{ 1 - \eta_{GT} \left[1 - \left(\frac{p_4}{p_5} \right)^{\frac{1-\gamma_g}{\gamma_g}} \right] \right\} \tag{9}$$

$$\dot{W}_{GT} = \dot{m}_g C_{pg} (T_5 - T_6) \tag{10}$$

$$\dot{W}_{Net} = \dot{W}_{GT} - \dot{W}_{AC} \tag{11}$$

$$\dot{m}_g = \dot{m}_f + \dot{m}_a \tag{12}$$

where C_{pg} is considered temperature-dependent as given below [28]:

$$C_{pg}(T) = 0.991615 + \left(\frac{6.99703T}{10^5} \right) + \left(\frac{2.7129T^2}{10^7} \right) - \left(\frac{1.22442T^3}{10^{10}} \right) \tag{13}$$

- Heat recovery steam generator (HRSG):

$$\dot{m}_s (h_9 - h_8) = \dot{m}_g (h_6 - h_7) \tag{14}$$

$$\dot{m}_s (h_9 - h_{8p}) = \dot{m}_g (h_6 - h_{7p}), \quad \frac{P_0}{P_6} = (1 - \Delta P_{HRSG}) \tag{15}$$

These combinations of energy and mass balance equation are numerically solved, and the temperature and enthalpy of each line of the plant are then estimated. In addition, some assumptions are made for analysis as follows [21,29]:

- All processes are of steady-state steady-flow.
- The air and combustion products are treated as ideal gases.
- The fuel injected to the combustion chamber is assumed to be natural gas.
- Heat loss from the combustion chamber is considered to be 3% of the fuel lower heating value. Moreover, all other components are considered adiabatic.
- The dead properties are $P_0 = 1.01$ bar and $T_0 = 293.15$ K.
- In the preheater, a 4% pressure drop is considered. Also, 3% pressure drop is considered in both combustion chamber and HRSG

3. Exergy analysis

Exergy can be divided into four distinct components. The two important ones are the physical exergy and chemical exergy. In this study, the two other components which are kinetic exergy and potential exergy are considered negligible as the elevation and speed have negligible changes [30–34]. The physical exergy is defined as the maximum theoretical useful work obtained as a system interacts with an equilibrium state [35,36]. The chemical exergy is associated with the departure of the chemical composition of a system from its chemical equilibrium. The chemical exergy is an important part of exergy in combustion process. Therefore, the following exergy balance equation is written:

$$\dot{Ex}_Q + \sum_i \dot{m}_i e_i = \sum_e \dot{m}_e e_e + \dot{Ex}_W + \dot{Ex}_D \tag{16}$$

where subscripts e and i are the specific exergy of control volume inlet and outlet flow and Ex_D, is the exergy destruction. Other terms in this equation are:

$$\dot{E}x_Q = \left(1 - \frac{T_0}{T_i}\right)\dot{Q}_i \tag{17}$$

$$\dot{E}x_W = \dot{W} \tag{18}$$

$$ex_{ph} = (h - h_0) - T_0(S - S_0) \tag{19}$$

where $\dot{E}x_Q$ and $\dot{E}x_W$ are the corresponding exergy of heat transfer and work which cross the and boundaries of the control volume, T is the absolute temperature (K) and (0) refer to the ambient conditions respectively. In equation (16), term Ex is defined as follow:

$$\dot{E}x = \dot{E}x_{ph} + \dot{E}x_{ch} \tag{20}$$

where $\dot{E}x = \dot{m}ex$.

The chemical exergy of the mixture is defined as follows [30,35,26,27,36]:

$$ex^{ch}_{mix} = \left[\sum_{i=1}^{n} X_i ex^{ch_i} + RT_0 \sum_{i=1}^{n} X_i \operatorname{Ln} X_i\right] \tag{21}$$

For the evaluation of the fuel exergy, the above equation cannot be used. Thus, the corresponding ratio of simplified exergy is defined as the following [30,36]:

$$\xi^* = ex_f / LHV_f \tag{22}$$

Due to the fact that for the most of usual gaseous fuels, the ratio of chemical exergy to the LHV is usually close to 1, one may write [28]:

$$\begin{aligned} \xi^*_{CH_4} &= 1.06 \\ \xi^*_{H_2} &= 0.985 \end{aligned} \tag{23}$$

For gaseous fuel with C_xH_y, the following relation is used to calculate ξ^* [37,38]:

$$\xi^* = 1.033 + 0.0169\frac{y}{x} - \frac{0.0698}{x} \tag{24}$$

Here, for the exergy analysis of the plant, the exergy of each line is calculated at all states and the changes in the exergy are determined for each major component. The source of exergy destruction (or irreversibility) in combustion chamber is mainly combustion (chemical reaction) and thermal losses in the flow path respectively. However, the exergy destruction in the heat exchanger of the system i.e. air preheater is due to the large temperature difference between the hot and cold fluid. The exergy destruction rate and the exergy efficiency for each component for the whole system in the CHP plant (Fig. 1) are shown in Table 1.

4. Exergoeconomic analysis

4.1. Economic model

In a world with finite natural resources and increasing energy demand by developing countries, it becomes increasingly important to recognize the mechanisms which degrade energy and resources and to develop systematic approaches for improving the design of energy systems and reducing the impact on the environment. The second law of thermodynamics combined with economics represents a very powerful tool for the systematic study and optimization of energy systems. This combination forms the basis of the relatively new field of thermoeconomics (exergoeconomics). Moreover, the economic model takes into account the cost of the components including the amortization and maintenance and the cost of fuel combustion. In order to define a cost function which depends on optimization parameters of interest, component cost should be expressed as function of thermodynamic design parameters [31]. On the other hand, Exergy costing involves cost balance usually formulated for each component separately. A cost balance applied to the k_{th} system components shows that the sum of cost rates associated with all existing exergy stream equals the sum of cost rates of all entering exergy streams plus the appropriate charges due to capital investment and operating and maintenance expenses. The sum of the last two terms is denoted by $\dot{Z}_k$. Accordingly, for a component which receives heat transfer and generates power, one can write [31,36]:

For each flow line in the system, a parameter called flow cost rate C (\$ $s-1$) was defined and the cost balance equation of each component in the following form is used:

$$\sum_e \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} + \sum_i \dot{C}_{i,k} + \dot{Z}_k \tag{25}$$

The cost balances are generally written so that all terms are positive. Using Eq. (25), one can write [31]:

$$\sum (c_e \dot{E}x_e)_k + c_{w,k}\dot{W}_k = c_{q,k}\dot{E}x_{q,k} + \sum (c_i \dot{E}x_i)_k + \dot{Z}_k \tag{26}$$

$$\dot{C}_j = c_j Ex_j \tag{27}$$

The cost balance equations for all components of the system construct a set of non-linear algebraic equations, which were solved for C_j and c_j. In this analysis it is worth mentioning that the fuel and product exergy should be defined. The exergy product is defined according to the components under consideration. The fuel represents the source that is consumed in generating the product.

Table 1
The exergy destruction rate and exergy efficiency equations for plant components.

Components	Exergy destruction	Exergy efficiency
HRSG	$\dot{E}_{D,HRSG} = \sum_{i,HRSG} \dot{E} - \sum_{o,HRSG} \dot{E}$	$\eta_{HRSG} = \frac{E_9 - E_8}{E_6 - E_7}$
Compressor	$E_{D,AC} = E_1 - E_2 - E_{W,AC}$	$\eta_{AC} = \frac{E_2 - E_1}{W_{AC}}$
Combustion chamber	$E_{D,CC} = E_3 + E_{f,CC} - E_4$	$\eta_{CC} = \frac{E_C}{E_3 + E_{f,CC}}$
Gas turbine	$E_{D,GT} = E_4 - E_5 - W_{GT}$	$\eta_{GT} = \frac{W_{GT}}{E_4 - E_5}$
Air preheater (AP)	$E_{D,AP} = \sum_{i,AP} E - \sum_{e,AP} E$	$\eta_{ex,AP} = 1 - \frac{E_{D,AP}}{\sum_{i,AP} E}$

Table 2
Constants for equations (36)–(38) in the text [41,42].

Constants	$0.3 \le \varphi \le 1.0$		$1.0 \le \varphi \le 1.6$	
	$0.92 \le \theta \le 2$	$2 \le \theta \le 3.2$	$0.92 \le \theta \le 2$	$2 \le \theta \le 3.2$
A	2361.7644	2315.752	916.8261	1246.1778
α	0.1157	−0.0493	0.2885	0.3819
β	−0.9489	−1.1141	0.1456	0.3479
λ	−1.0976	−1.1807	−3.2771	−2.0365
a_1	0.0143	0.0106	0.0311	0.0361
b_1	−0.0553	−0.045	−0.078	−0.085
c_1	0.0526	0.0482	0.0497	0.0517
a_2	0.3955	0.5688	0.0254	0.0097
b_2	−0.4417	−0.55	0.2602	0.502
c_2	0.141	0.1319	−0.1318	−0.2471
a_3	0.0052	0.0108	0.0042	0.017
b_3	−0.1289	−0.1291	−0.1781	−0.1894
c_3	0.0827	0.0848	0.098	0.1037

Table 3
The list of constraints.

Constraints	Reason
$T_4 \leq 1600$	Material limitation
$P_2/P_1 \leq 16$	Commercial availability
$\eta_{AC} \leq 0.9$	Commercial availability
$\eta_{GT} \leq 0.93$	Commercial availability
$T_7 \geq 400$ K	To avoid formation of sulfuric acid in exhaust gases
$T_{8p} = T_9 - 15$ K	To avoid evaporation of water in HRSG economizer

Both the product and fuel are expressed in terms of exergy. The cost rates associated with the fuel ($\dot{C}_F$) and product ($\dot{C}_P$) of components are obtained by replacing the exergy rates ($\dot{E}x$). For example, in a turbine, fuel is difference between input and output exergy and product is the generated power of the turbine.

In the cost balance formulation (Eq. (25)), there is no cost term directly associated with exergy destruction of each component. Accordingly, the cost associated with the exergy destruction in a component or process is a hidden cost. Thus, if one combines the exergy balance and exergoeconomics balance together, one can obtain the following equations:

$$\dot{E}x_{F,K} = \dot{E}x_{P,K} + \dot{E}x_{D,K} \tag{28}$$

Accordingly, the expression for the cost of exergy destruction becomes

$$\dot{C}_{D,k} = c_{F,k}\dot{E}x_{D,k} \tag{29}$$

More details of the exergoeconomic analysis, cost balance equations and exergoeconomic factors are extensively discussed in Refs. [1,6,8,10].

$$\dot{C}_{D,k} = c_{F,k}\dot{E}x_{D,k} \tag{30}$$

Further details on exergoeconomic analysis, cost balance equations and exergoeconomic factors are completely discussed in Refs. [4,9,10,21]. In addition, several methods suggest the purchase cost of equipment in terms of design parameters in Eq. (25) [10,31]. However, we have used the cost functions as suggested by Ahmadi et al. [1,39] and Roosen et al. [40]. Nevertheless, some modifications have been made to tailor these results to the regional conditions and taking into account the inflation rate. For converting the capital investment into cost per time unit, one may write:

$$\dot{Z}_k = Z_k \mathrm{CRF}\xi/(N \times 3600) \tag{31}$$

where Z_k is the purchase cost of k_{th} component in dollar. The expression for each component of the gas turbine plant and economic model is presented in Appendix B. The Capital Recovery Factor (CRF) depends on the interest rate as well as estimated equipment life time. CRF is determined using the following relation [31]:

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{32}$$

where i is the interest rate and n is the total operating period of the system in years. N is the annual number of the operation hours of the unit, and ξ (1.06) [1,39] is the maintenance factor. Finally, in order to determine the cost of exergy destruction of each component, the value of exergy destruction, $\mathrm{Ex}_{D,k}$, is computed using exergy balance equation in the previous section.

4.2. Cost balance equations

As we know for estimating the cost of exergy destruction in each component of the plant first we need to solve the cost balance equations for each component. Therefore, in application of the cost balance equation (Eq. (25)), there are usually more than one inlet

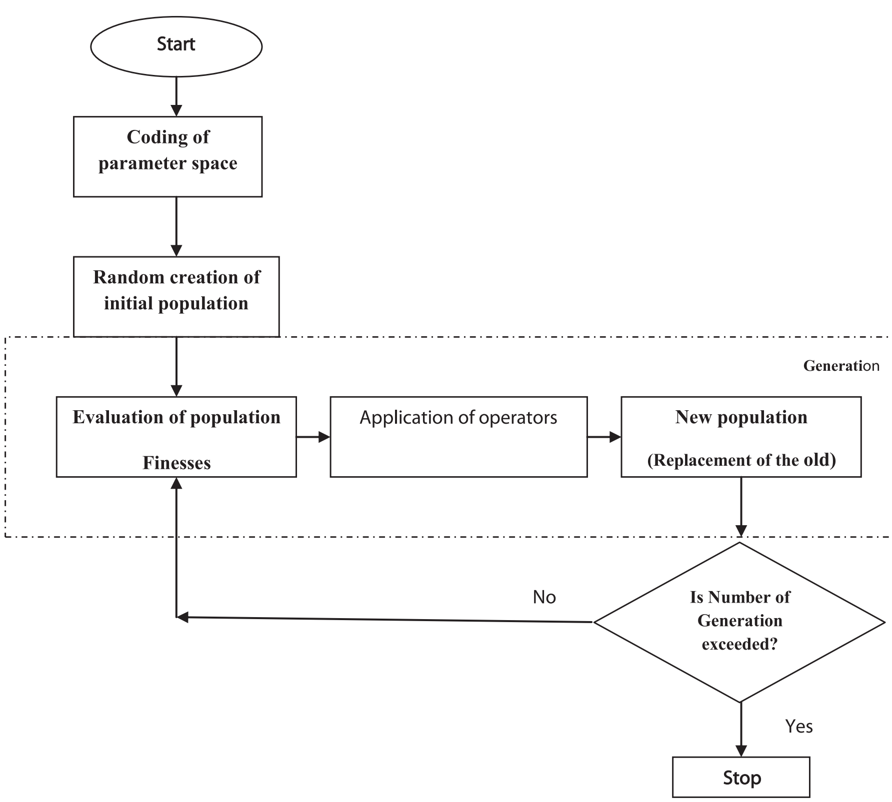

Fig. 2. Genetic algorithm flow chart [43].

outlet streams for some components. In this case the number of unknown cost parameters is higher than the number of cost balance equation for that component. Auxiliary exergoeconomic equations are developed to solve this problem. Implementing Eq. (25) for each component together with the auxiliary equations forms a system of linear equations as follows:

$$[\dot{\mathrm{E}}\mathrm{x}_K] \times [c_k] = [\dot{Z}_k] \tag{33}$$

where $[\dot{\mathrm{E}}\mathrm{x}_K]$, $[c_k]$ and $[\dot{Z}_k]$ are the matrix of exergy rate (obtained in exergy analysis), exergetic cost vector (to be evaluated) and the vector of $\dot{Z}_k$ factors (obtained in economic analysis), respectively.

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & -1 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\mathrm{Ex}_5} & \frac{-1}{\mathrm{Ex}_6} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & -1 & -1 \\ 0 & 0 & 0 & \frac{1}{\mathrm{Ex}_4} & \frac{-1}{\mathrm{Ex}_5} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{\mathrm{Ex}_{11}} & \frac{-1}{\mathrm{Ex}_{12}} \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{\mathrm{Ex}_6} & \frac{-1}{\mathrm{Ex}_7} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} \dot{C}_1 \\ \dot{C}_2 \\ \dot{C}_3 \\ \dot{C}_4 \\ \dot{C}_5 \\ \dot{C}_6 \\ \dot{C}_7 \\ \dot{C}_8 \\ \dot{C}_9 \\ \dot{C}_{10} \\ \dot{C}_{11} \\ \dot{C}_{12} \end{bmatrix} = \begin{bmatrix} 0 \\ -\dot{Z}_{AC} \\ -\dot{Z}_{AP} \\ 0 \\ -\dot{Z}_{CC} \\ C_f \\ -\dot{Z}_{GT} \\ 0 \\ 0 \\ -\dot{Z}_{HRSG} \\ 0 \\ 0 \end{bmatrix} \tag{34}$$

Therefore, by solving these sets of equations one can find the cost rate of each line in Fig. 1. Moreover, they are used to find the cost of exergy destruction in each component of the plant.

5. Exergoenvironmental analysis

In order to minimize the environmental impacts, the objective is to increase the efficiency of energy conversion processes and, thus, decrease the amount of fuel and the related overall environmental impacts, especially the release of carbon dioxide as a major greenhouse gas. Therefore, optimization of thermal systems based on this fact has been an important subject in recent years. Although there are many papers in the literature, dealing with optimization of CHP plants, they consider no environmental impacts. For this reason, one of the major goals of the present work is to consider the environmental impacts as producing the CO and NOx. As it was discussed in Ref. [41], the adiabatic flame temperature in the primary zone of the combustion chamber is derived as follow:

$$T_{pz} = A\sigma^{\alpha}\exp\left(\beta(\sigma+\lambda)^2\right)\pi^{x^*}\theta^{y^*}\psi^{z^*} \tag{35}$$

Here, π is dimensionless pressure (P/P_{ref}), θ is dimensionless temperature (T/T_{ref}), ψ is the H/C atomic ratio, $\sigma = \varphi$ for $\varphi \le 1$ (φ is mass or molar ratio) and $\sigma = \varphi - 0.7$ for $\varphi \ge 1$. Moreover, x, y and z are quadric functions of σ based on following equations:

$$x^* = a_1 + b_1\sigma + c_1\sigma^2 \tag{36}$$

$$y^* = a_2 + b_2\sigma + c_2\sigma^2 \tag{37}$$

$$z^* = a_3 + b_3\sigma + c_3\sigma^2 \tag{38}$$

where parameters A, α, β, λ, a_i, b_i and c_i are constant parameters. More details are presented in [41,42] as listed in Table 2.

As stated in the literature, the amount of CO and NO_x produced in the combustion chamber and combustion reaction change mainly by the adiabatic flame temperature as well. Accordingly, based on Ref. [41] to determine the pollutant emission in grams per kilogram of fuel the proper equations are proposed as follows:

$$\dot{m}_{NO_x} = \frac{0.15\mathrm{E}16\tau^{0.5}\exp(-71,100/T_{pz})}{P_3^{0.05}(\Delta P/P)} \tag{39}$$

$$\dot{m}_{CO} = \frac{0.179\mathrm{E}9\exp(7800/T_{pz})}{P_3^2\tau(\Delta P/P)} \tag{40}$$

where τ is the residence time in the combustion zone (τ is assumed to be 0.002 s); T_{pz} is the primary zone combustion temperature; P is the combustor inlet pressure; $\Delta P/P$ is the non-dimensional pressure drop in the combustion chamber.

6. Optimization

6.1. Definition of the objectives

Here, a new objective function is defined as the sum of four parts; the operational cost rate, which is related to the fuel expense, the rate of capital cost which stands for the capital investment and maintenance expenses, the corresponding cost for the exergy destruction and the cost of environmental impacts (NO_x and CO). Therefore, the objective function represents total cost rate of the plant in terms of dollar per unit of time is defined as:

$$\mathrm{OF} = c_f\dot{m}_f\mathrm{LHV} + \sum\dot{Z}_k + \sum\dot{C}_{D,k} + \dot{C}_{env} \tag{41}$$

where $c_f = 0.003$ $/MJ is the regional cost of fuel per unit of energy [31,39], $\dot{m}_f$ is the fuel mass flow rate, and LHV = 50,000 kJ/kg is the lower heating value of methane. The last part of the objective function (OF) expresses the environmental impact as the total pollution damage ($/s) due to CO and NOx emission by multiplying their respective flow rates by their corresponding unit damage cost (C_{CO}, C_{NOx} are equal to 0.02086 $/kgCO and 6.853 $/kgNOx [36]. In the present work the cost of pollution damage is assumed to be added directly to the expenditures that must be paid. Therefore, the objective function is sum of the exergoeconomic and

Table 4
The comparison of our simulation and optimization numerical output for CGAM problem with results reported in literature [12,14].

Decision variable	Optimum design values reported by [12]	Optimum design values reported by [14]	Optimum design values using (GA), Present Study	Difference	
				With Ref. [12]	With Ref. [12]
r_c	8.597	8.523	6.700	0.22	0.21
η_{AC}	0.8465	0.8468	0.832	0.027	0.0174
η_{GT}	0.8787	0.878	0.865	0.015	0.014
T_3 (K)	913.14	914.28	951.6	0.042	0.040
T_4 (K)	1491.97	1492.63	1475.39	0.011	0.011
Objective function	0.362 ($/s)	0.3617 ($/s)	0.3294 ($/s)	0.09	0.089

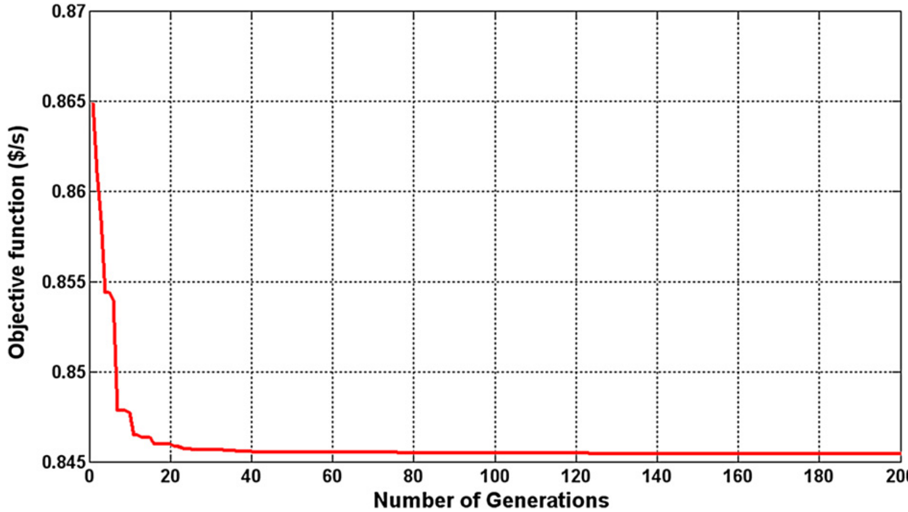

Fig. 3. Variation of objective function of the system with generation ($C_E = .003$/MJ$).

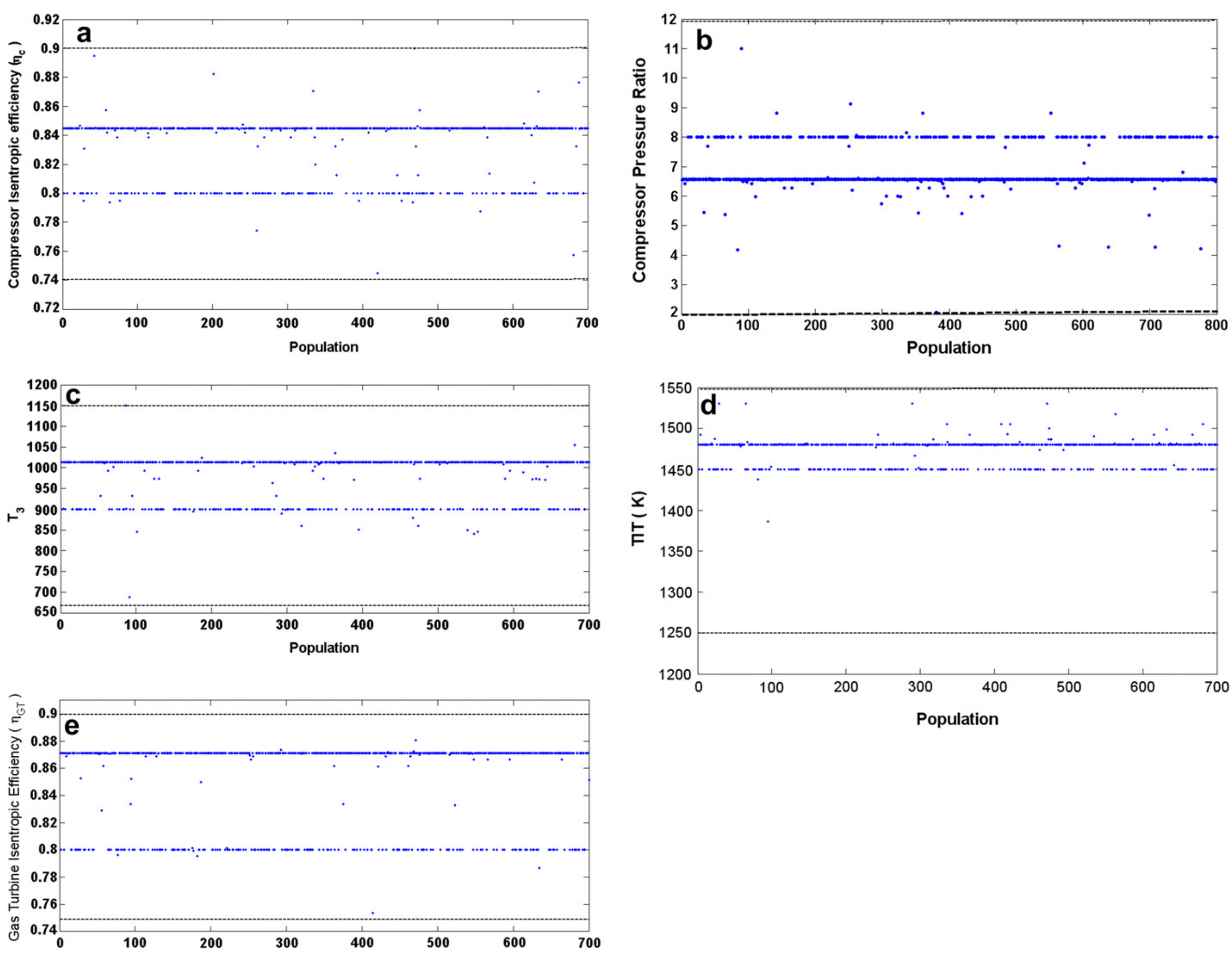

Fig. 4. a. Scattering of compressor isentropic efficiency for the optimal point. b. Scattering of compressor pressure ratio for the optimal point. c. Scattering of T_3 for the optimal point. d. Scattering of TIT for the optimal point. e. Scattering of gas turbine isentropic efficiency for the optimal point.

environmental objectives. Since the amounts of ultimate products (net power and process steam) are fixed, the objective function is to be minimized so that the values of optimal design parameters would be obtained.

$$\dot{C}_{\text{env}} = C_{\text{CO}}\dot{m}_{\text{CO}} + C_{\text{NO}x}\dot{m}_{\text{NO}x} \quad \dot{C}_{\text{F}} = c_{\text{f}}\dot{m}_{\text{f}} \times \text{LHV} \tag{42}$$

where $\dot{Z}_k$, $\dot{C}_{\text{F}}$ and $\dot{C}_{\text{D}}$ are purchase cost of each component, fuel cost and cost of exergy destruction respectively. In addition $\dot{m}_{\text{CO}}$, $\dot{m}_{\text{NO}x}$ are calculated from Eqs. (39) and (40).

6.2. Decision variables

The decision variables (i.e., design parameters) considered in this study are as follows: compressor pressure ratio (r_{AC}), compressor isentropic efficiency (η_{AC}), gas turbine isentropic efficiency (η_{GT}), combustion chamber inlet temperature (T_3), and turbine inlet temperature (TIT). Even though the decision variables may be varied in the optimization procedure, each decision variables is normally required to be within a reasonable range. The list of these constraints and the reasons of their applications are briefed based on Refs. [39,40] and listed in Table 3.

6.3. Constraints

Based on Fig. 1, the following constraints should be satisfied in heat exchangers (air preheater and heat recovery steam generator).

$$T_3 > T_2, \;\; T_5 > T_3, \;\; T_4 > T_3, \;\; T_6 > T_2 \tag{43}$$

$$T_6 > T_9, \;\; T_{7\text{p}} > T_9 + \Delta T_{\text{pinch}} \tag{44}$$

6.4. Evolutionary algorithm

6.4.1. Multimodal Genetic Algorithm

In recent years, optimization algorithms have received increasing attention by the research community as well as the industry. In the area of evolutionary computation (EC), such optimization algorithms simulate an evolutionary process where the goal is to evolve solutions by means of crossover, mutation, and selection based on their quality (fitness) with respect to the optimization problem at hand [43]. Evolutionary algorithms (EAs) are highly relevant for industrial applications, because they are capable of handling problems with non-linear constraints, multiple objectives, and dynamic components properties that frequently appear in real problems [44]. Genetic algorithms (GAs) are an optimization technique based on natural genetics. GAs were developed by Holland [45] in an attempt to simulate growth and decay of living organisms in a natural environment. Even though originally designed as simulators, GAs proved to be a robust optimization technique. The term robust denotes the ability of the GAs for finding the global optimum, or a near-optimal point, for any optimization problem. The basic idea behind GAs could be described in brief as follows. A set of points inside the optimization space is created by random selection of points. Then, this set of points is transformed into a new one. Moreover, this new set will contain more points that are closer to the global optimum. The transformation procedure is based only on the information of how optimal each point is in the set, consists of very simple string manipulations, and is repeated several times. This simplicity in application and the fact that the only information necessary is a measure of how optimal each point is in the optimization space, make GAs attractive as optimizers. Nevertheless, the major advantages of the GAs are the following:

Table 5
Numerical values of selected dependant variables in the optimal design.

Variable	Value in optimal design
$\dot{m}_{\text{f}}$ (kg/s)	2.78
$\dot{m}_{\text{g}}$ (kg/s)	191.58
ΔT_{pinch} (K)	12.83
η_{AC}	0.827
η_{GT}	0.862
r_{AC}	6.72
T_3 (K)	938
TIT (K)	1473
W_{GT} (MW)	98.779
$C_{\text{,env}}$ ($/s)	45.95
C_{D} ($/s)	1116
Total cost ($/h)	3043.8

- Constraints of any type can be easily implemented.
- GAs usually find more than one near-optimal point in the optimization space, thus permitting the use of the most applicable solution for the optimization problem at hand.

The basic steps for the application of a GA for an optimization problem are summarized in Fig. 2 [43]. A set of strings is created randomly. This set, which is transformed continuously in every step of the GA, is called population. This population, which is created randomly at the start, is called initial population. The size of this population may vary from several tens of strings to several thousands. The criterion applied in determining an upper bound for the size of the population is that further increase does not result in improvement of the near-optimal solution. This upper bound for each problem is determined after some test runs. Nevertheless, for most applications the best population size lies within the limits of 10–100 strings .The "optimality" (measure of goodness) of each string in the population is calculated. Then on the basis of this value an objective function value, or fitness, is assigned to each string. This fitness is usually set as the amount of "optimality" of each string in the population divided by the average population "optimality". An effort should be made to see that the fitness value is always a positive number. It is possible that a certain string does not reflect an allowable condition. For such a string there is no "optimality". In this case, the fitness of the string is penalized with a very low value, indicating in such a way to the GA that this is not a good string. Similarly, other constraints may be implemented in the GA. A set of "operators", a kind of population transformation device, is applied to the population. These operators will be discussed. As a result of these operators, a new population is created, that will hopefully consist of more optimal strings. The old population is replaced by the new one. A predefined stopping criterion, usually a maximum number of generations to be performed by the GA, is checked. If this criterion is not satisfied a new generation is started,

Table 6
Values of the temperatures and pressures for the stream in the optimal design of CHP plant.

Flow	T (K)	P (bar)
T_1	298.15	1.013
T_2	556.7	6.65
T_3	935.77	6.36
T_4	1474.17	6.04
T_5	1034.6	1.089
T_6	714.4	1.06
T_7	430.1	1.013
T_8	298.1	13
T_9	464.79	13

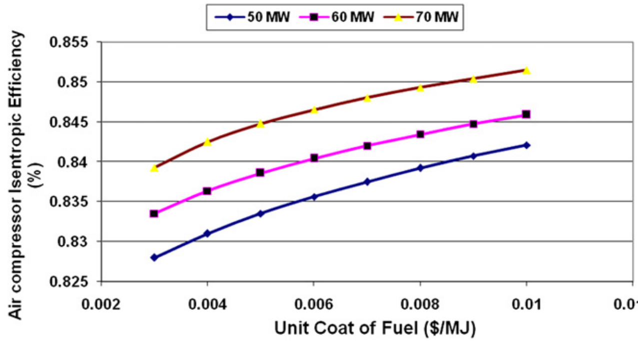

Fig. 5. The effects of fuel unit cost and net power demand on the optimal value of compressor isentropic efficiency η_{comp}.

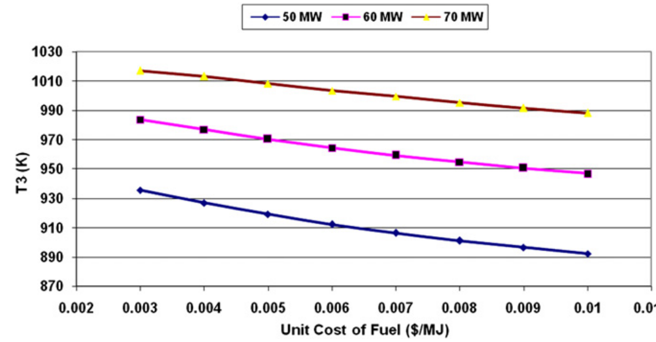

Fig. 7. The effects of fuel unit cost and net power demand on the optimal value of T_3.

otherwise the GA terminates. It is now evident that when the GA terminates, a set of points (final population) has been defined, and in this population more than one equivalently good (optimal) point may exist. As it was discussed, this advantage of the GAs permits the selection of the most appropriate solution for the optimization problem.

7. Results and discussion

7.1. Verification of optimization method

In order to ensure the validity of thermodynamic and economic modeling, as well as the optimization procedure (i.e., developed Genetic Algorithm) first a CHP unit with the same characteristics of classic well-known CGAM problem [11–14] is modeled and optimized by Multimodal Genetic algorithm method. As shown in Table 4 the results of our model are in a good agreement in comparison with other works [12,14] which ensures the correctness of the simulation code as well as GA developed code.

It should be noted that this difference between optimized values is just due to the optimization procedure. As evolutionary algorithm like Particle Swarm and GA is based on random search this difference is reasonable. Moreover, by applying this GA developed code, 9.80% improvement in objective function is achieved which is might be noticeable in thermal systems optimization. Therefore, this verifies the validity of obtained global optimum as well as our simulation code.

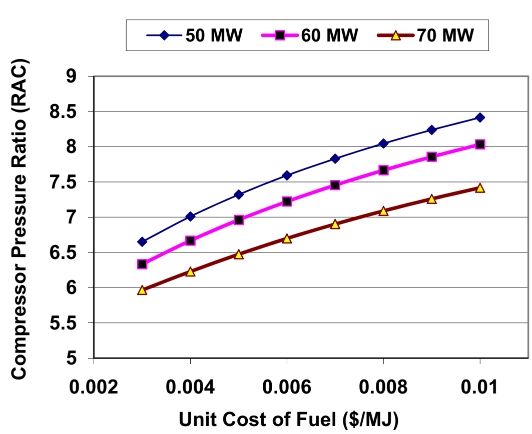

Fig. 6. The effects of fuel unit cost and net power demand on the optimal value of compressor pressure ratio r_{Comp}.

7.2. Optimization of CHP plant using Multimodal Genetic Algorithm

The schematic diagram of a CHP plant is shown in Fig. 1. This figure which shows a CHP plant used in a Paper Mill with need for 50 MW of electric power and 33.3 kg/s of saturated steam at 13 bars is optimized using the GA. The input parameters of the problem are modified to match the conditions and requirements of the paper mill. The fuel unit cost and fuel LHV in this case are 0.003 $/MJ and 50,000 kJ/kg respectively. In addition, considering the values of *i* and *n* to be 14% and 15 years respectively, CRF will be 16.3%. N, the annual number of the operation hours of the unit, and φ, the maintenance factor, are considered 7000 h and 1.1, respectively. Fig. 3 shows the Variation of Objective Function of the system with Generation. As shown in this figure, the genetic algorithm used in this problem has good convergence rate. It shows that after 50 generations the final value of objective function is determined. It has the lower running time of the computer as well as better optimization results. In the present work a new and interesting thing is done. Therefore, for having a good insight into this analysis the distribution of decision variables for the optimal points in Fig. 3 is shown in Fig. 4a–f. The lower and upper bounds of the variables are illustrated by dotted lines. The obtained numerical values of the optimum design parameters for the CHP plant are reported in Table 5. Furthermore, the corresponding numerical values of selected dependent variables are listed in Table 6. In the present work a sensitivity analysis of changes in design parameters via fuel cost and net output power has been carried out. Thus, the simulation and optimization procedures are repeated with the new set of input values. Using the objective function, Figs. 5–11 show the effects of change in power on the numerical values of optimal design parameters (decision variables). Increasing η_{AC} results in decrease in the compressor power consumption and also increasing η_{GT} increases the turbine power

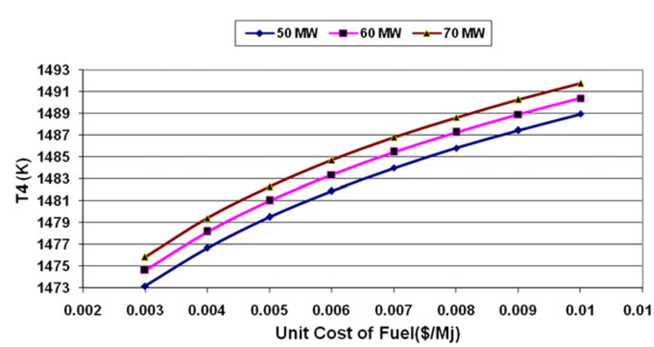

Fig. 8. The effects of fuel unit cost and net power demand on the optimal value of TIT.

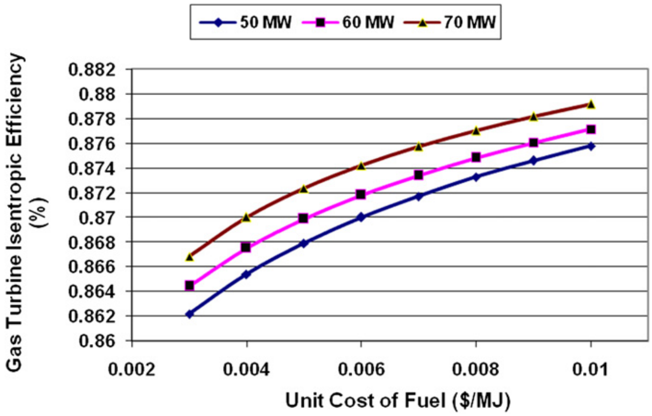

Fig. 9. The effects of fuel unit cost and net power demand on the optimal value of gas turbine isentropic efficiency η_{GT}.

output. Moreover, increasing both r_{Comp} and TIT increases the cycle efficiency and the net power output. When the fuel cost increases, the first term in equation (41) which is associated with fuel cost is increased. Hence, the optimization program goes in a way to decrease of the objective function. It should be noted that equation (41) is sum of the fuel cost, purchase cost, cost of exergy destruction and cost of environmental impact. Hence, by increase in the first term, results should cause in decrease in other terms by selecting the best design parameters. As it is shown in Fig. 5 by increasing the fuel cost, air compressor isentropic efficiency is increased. Because increase in this efficiency results in decreasing the cost of exergy destruction as well as decrease in compressor power. Therefore, the net output of the plant is increased though. On the other hand, at fixed fuel cost, increasing the output power leads to increase in compressor isentropic efficiency because when the net output of the CHP plant increases the mass flow rate injected to the combustion chamber should be increased. Hence by increase in the compressor efficiency one may decrease the cost of exergy destruction as well as the objective function. Fig. 6 shows the variation of compressor pressure ratio versus fuel cost. It is obvious that by increasing the fuel cost; the compressor pressure ratio is increased in order to decrease the objective function. It is worth mentioning that increasing the pressure ratio has two important effects on the plant. It decreases the compressor cost of exergy destruction and also decreasing the fuel injected to the combustion chamber. Fig. 7 shows the variation of combustion chamber inlet temperature with unit cost of fuel. By increase in the unit cost of fuel, the combustion chamber inlet temperature decreases due to the fact that increasing the combustor inlet temperature, T_3, reduces the exergy destruction in the combustion chamber and heat exchangers (air preheater and HRSG), due to the constraint for exhaust gas temperature ($T_7 > 400$ K), T_3

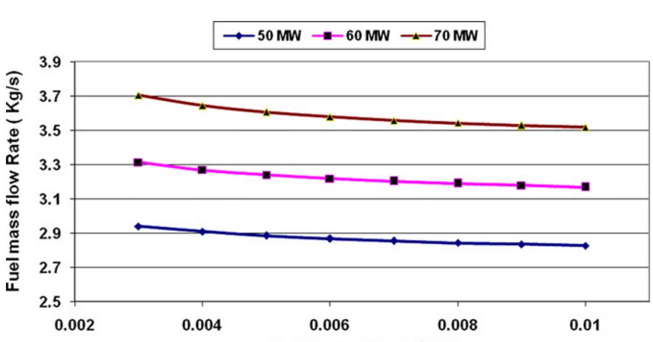

Fig. 10. The effects of fuel unit cost and net power demand on the optimal value of the fuel mass flow rate.

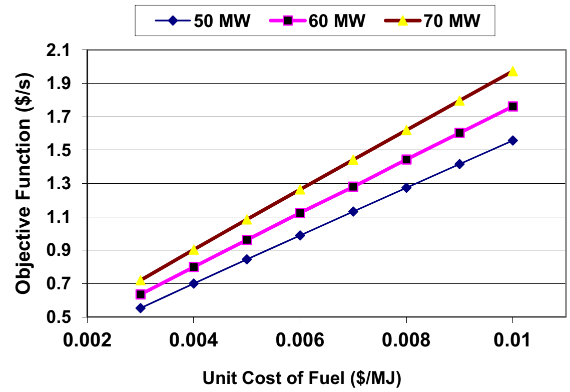

Fig. 11. The effects of fuel unit cost and net power demand on the optimal value of objective function.

decreases with increasing the fuel unit cost. As it was discussed in the literature, combustion chamber is the greatest exergy destructor in CHP system or gas turbine power plants [46]. It is due to the fact that the chemical reaction and the large temperature difference between the burners and working fluid are the main source of irreversibility. Hence any increment in gas turbine inlet temperature results in decrease in the combustion chamber exergy destruction as well as cost of exergy destruction in this part. Fig. 8 shows the variation of TIT with unit cost of fuel. It is shown that increasing the fuel cost results in increasing the TIT. It is due to the fact that by increasing the c_f, the first term in the objective function increases. Thus, the TIT should be chosen in the form that total cost of exergy destruction is decreased. Moreover, from this figure, it can be concluded that at a fixed fuel cost, increasing the net output results in increase in the TIT because the higher output needs both greater TIT and mass flow rate to the combustion chamber. According to equation (41), when the mass flow rate of the plant increases the first term is increased. Therefore, the optimization program proceeds in the way that other terms decrease. The same results are shown in Fig. 9. On the other hand, from Fig. 10 it can be concluded that when the unit cost of fuel increases, the design parameters are selected in the way that the mass flow rate injected to the combustion chamber decreases. It has two significant effects. The first one is that less mass flow rate results in decrease in the environmental impacts and the last one is to decrease in the objective function. Finally, Fig. 11 shows that increase in the unit fuel cost leads to an increase in the objective function. In summary, from these figures it can be concluded that bigger η_{comp} and η_{GT} guarantee less exergy destruction in compressor and turbine as well as less net cycle fuel consumption and operating cost. Moreover, increasing T_4 also decreases the exergy destruction in combustion chamber (and HRSG) and saves fuel consumption as well. However, due to the fact that any increase in T_4 increases the turbine and combustion chamber investment costs, T_4 can only increase within a certain limit. Further, by increasing the above design parameters the capital cost of components (equipment) increases. These costs in summation with the operational cost are minimized using GA optimization technique.

8. Conclusions

In the present paper, the exergoenvironmental analysis and optimization of a typical CHP plant were carried out using multimodal Genetic Algorithm. At the first part of the paper thermodynamic modeling of a CHP plant was done. The results from our developed code for CGAM problem showed that by applying this GA developed code, 9.80% improvement in objective function is achieved.

Moreover, the optimization of CHP plant was performed to find the optimal design parameters of the cycle. The new objective functions including total cost of the plant as well as cost of environmental impacts were considered. Finally, in order to have a good insight into this study, a sensitivity analysis of the variation of both unit cost of fuel and net output power of the CHP plant was performed.

The results from sensitivity analysis showed that increase in η_{AC} results in decrease in the compressor power consumption and also by increasing the fuel cost; the compressor pressure ratio is increased in order to decrease the objective function. In addition, it was concluded that by increase in the unit cost of fuel, the combustion chamber inlet temperature decreases due to the fact that increasing the combustor inlet temperature, reduces the exergy destruction in the combustion chamber. The results showed that by increasing the fuel price the values of decision variables in exergoeconomically optimal design tend to those of thermodynamically optimal design. In addition, by increasing the net electrical power of the unit, more efficient equipment should be chosen.

In summary, from this analysis it was concluded that bigger η_{AC} and η_{GT} guarantee less exergy destruction in compressor and turbine as well as less net cycle fuel consumption and operating cost. Moreover, increasing gas turbine inlet temperature (TIT) also decreases the exergy destruction in combustion chamber (and HRSG) and saves fuel consumption as well.

Nomenclature

c	cost per exergy unit [$/MJ]
c_f	cost of fuel per energy unit [$/MJ]
$\dot{C}$	cost flow rate ($/s)
c_p	specific heat at constant pressure [kJ/kg K]
CRF	capital recovery factor
$\dot{E}x$	exergy flow rate [MW]
$\dot{E}x_D$	exergy destruction rate [MW]
h	enthalpy (kJ/kg)
LHV	lower heating value [kJ/kg]
$\dot{m}$	mass flow rate [kg/s]
r_{AC}	compressor pressure ratio
R	gas constant (kJ/kg K)
S	entropy (kJ/kg K)
$\dot{W}_{Net}$	net power output [MW]
Z	capital cost of a component [$]
$\dot{Z}$	capital cost rate [$/s]
ΔP	pressure loss
η_{AC}	Compressor isentropic efficiency
η_{cc}	combustion chamber first law efficiency
η_{GT}	gas turbine isentropic efficiency
γ	specific heat ratio
X_i	molar fraction
ξ	maintenance factor

Subscripts

a	air
AC	air compressor
aph	air preheater
cc	combustion chamber
ev	evaporator
ec	economizer
e	exit condition
f	fuel
F	fuel for a component
g	combustion gasses
GT	gas turbine
HRSG	heat recovery steam generator
i	inlet condition
j	jth stream
k	kth component
P	product of a component
pinch	pinch point
ξ^*	coefficient of fuel chemical exergy
γ	specific heat ratio
0	reference ambient condition

Appendix A

Cost functions in terms of thermodynamic parameters for the system components [40]

System component	Capital or investment cost functions
AC	$\dot{Z}_{AC} = \left(\frac{c_{11}\dot{m}_a}{c_{12}-\eta_{AC}}\right)\left(\frac{p_2}{p_1}\right)\ln\left(\frac{p_2}{p_1}\right)$
CC	$\dot{Z}_{CC} = \left(\frac{c_{12}\dot{m}_a}{c_{22}-\frac{p_4}{p_3}}\right)\left[1+\mathrm{EXP}\left(C_{23}T_4-C_{24}\right)\right]$
T	$Z_T = \left(\frac{c_{31}\dot{m}_g}{c_{32}-\eta_T}\right)\ln\left(\frac{p_4}{p_5}\right)\left[1+\mathrm{EXP}(c_{33}T_4-c_{34})\right]$
APH	$Z_{aph} = c_{41}\left(\frac{\dot{m}_g(h_5-h_6)}{(U)(\Delta TLM)_{EV}}\right)^{0.6}$
HRSG	$\dot{Z}_{HRSG} = a_{41}\left[\left(\frac{\dot{Q}_{PH}}{(\Delta TLM)_{PH}}\right)^{0.8}+\left(\frac{\dot{Q}_{EV}}{(\Delta TLM)_{EV}}\right)^{0.8}+\left(\frac{\dot{Q}_{SH}}{(\Delta TLM)_{SH}}\right)^{0.8}\right]+a_{42}\dot{m}_s+a_{43}\dot{m}_g^{1.2}$

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