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Thermoeconomic and environmental Optimization of a 160 MW Combined Cycle Power Plant by MOEA

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Abstract

In this paper, Multi-Objective Optimization of a 160 MW combined cycle power plant has been performed from Exergetic, Economic, Environmental aspects simultaneously. In this regard, thermodynamic, exergetic and thermoeconomic modeling and simulation for this case have been done. The Multi Objective Evolutionary Algorithms (MOEAs) are used and evaluated by MINLP approach to find optimum design in view of exergetic, exergoeconomic and environmental impacts. In order to facilitate selecting optimum sets, the environmental impact objective function has been defined and expressed in cost terms and added to the economic objective. Furthermore, extended combined pinch and exergy analysis has been performed to demonstrate the system graphically for each case in the base case and the optimum case. So, the performance of a different component of the system can be demonstrated better. In addition, the feasible region for optimization problem has been indicated by extended combined pinch and exergy method. Results show overall exergetic efficiency increases about 7.5% through MOEA method. Finally, the exergetic product cost of electricity reduces to 0.0183 \$/MJ consecutively.

Keywords

Pinch-Exergy; Multi-Objective; Thermoeconomic; Genetic Algorithm; Combined Cycle

1. Introduction

Exergy, thermoeconomic and pinch approaches can be used for evaluation of process plant. Exergy analysis usually estimates the thermodynamic performance. Entropy generation is calculated by the entropy balance, and exergy balance calculates irreversibility. Also, thermoeconomic analysis predicts the unit cost of products such as power, steam and calculates monetary loss (Sanjay, Singh, & Prasad, 2007; Zhang, Wang, Zheng, & Lou, 2006). Furthermore, it supplies a tool for the optimum design and operation optimization of thermal systems. Nowadays, such analysis is vital because accurate prediction of the production costs is necessary for companies to work profitably(Modesto & Nebra, 2006).

Furthermore, combined pinch and exergy analysis guide us to the better understanding of the system by graphical representation as Feng introduced in 1997(Feng & Zhu, 1997). The power of pinch analysis is that the system can be represented by simple diagrams. So, targets are easily achieved prior to the design phase. The strength of exergy analysis is that it can demonstrate the major inefficiency of the plant. In this regard, promising modifications can be indicated easily. For better improvement of base design, by applying the advantages of these analyses, the whole system can be shown in one diagram which guides to find the efficient modifications quickly.

Heuristic rules are often applied in the design and improvement of energy systems to simplify the problem. Also, combined pinch and exergy analysis as a graphical tool can guide us to an indication of best modification and constraints for optimization(Kotas, 2013). Rules taken from the fields of artificial intelligence (Frank Cziesla, 2000) and computational intelligence fuzzy systems (F. Cziesla & Tsatsaronis, 2002)

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and evolutionary algorithms can help the designer to achieve an optimum cost-effective case.

Generally, the electricity cost is more sensitive to modifies in the configuration of the process structure than to modified values of the variables. The objective of this research is to optimization with an evolutionary algorithm ("Matlab 7.1 Tutorial ").

Uhlenbruck and Lucas (Uhlenbruck & Lucas, 2004) applied an exergoeconomic approach (Bejan, Tsatsaronis, Moran, Moran, & Moran, 1996) with an evolution concept to speed up the search for an optimum economic design of simple power plant concepts. By the evolution approach, only process variables are modified. Emmerich et al integrate a knowledge-based system based on an evolutionary algorithm which produces feasible design configurations (M. Emmerich, Gr, tzner, Sch, & tz, 2001; Michael Emmerich, Grötzner, Groß, & Schütz, 2000). So, the requirement for superstructure model can be removed.

Sepelling et al proposed a thermoeconomc optimization for a combined cycle with a solar tower power plant. A dynamic model of a solar combined-cycle power plant has been proposed. Two objectives namely minimal investment costs and minimal electricity costs will be considered (Spelling, Favrat, Martin, & Augsburger, 2012).

Bracco et al proposed a MILP optimization model for a combined heat and power plant based on economic and environmental objectives. The multi-objective optimization of operation and capital costs and carbon dioxide emissions have been considered (Bracco, Dentici, & Siri, 2013).

Multi-objective exergoeconomic optimization of a CGAM solar-hybrid cogeneration cycle using genetic algorithm has been performed by Soltani et al (Soltani et al., 2014). Solar power tower plant has been considered.

Mahmoudi et al focused on thermoeconomic modeling, evaluation and optimization of a novel combined supercritical carbon dioxide recompression based on Brayton/Kalina cycle (Mahmoudi, Delkhah Akbari, & Rosen, 2016).

Energy recovery and overall energy efficiency improvement in the gas transmission networks has been studied by Safarian & Mousavai. In this regard, they extended a model with detailed characteristics of compressor and pressure reduction stations. Furthermore, they determined three different scenarios with gas turbine including an organic Rankine cycle, air bottoming cycle, and air bottoming cycle along with steam injection (Safarian & Mousavi, 2015).

Multi-objective thermoeconomic optimization for combined-cycle power plant using particle swarm optimization has been performed by Abdalisousan et al (Abdalisousan, Fani, Farhanieh, & Abbaspour, 2015). Thermoeconomic optimization and parametric investigation and of a combined cycle for recovering the waste heat from nuclear-closed Brayton cycle have been performed by Luo et al (Luo, Gao, Liu, & Xu, 2016).

The energetic, exergetic and exergoeconomic evaluation of using different inlet air cooling systems in warm dry and wet climate stations have been performed by Khoshgoftar Manesh et al (Khoshgoftarmanesh, Vazini Modabber, & Mazhari, 2016).

Khoshgoftar Manesh and Ameryan used Cuckoo Search algorithm to optimal synthesis of a hybrid solar CHP cycle (M. H. Khoshgoftar Manesh & Ameryan, 2016).

Memon et al investigated on thermo-environmental and economic evaluation of a combined cycle power plants based on regression modeling and optimization. In this regard, a relationship between optimal efficiency and the total cost is defined. In addition, multiple polynomials based on regression models are developed (Memon, Memon, & Qureshi, 2017).

The scope of this work is to find optimal configuration and process condition of a 160 MW gas-fired combined cycle based on thermoeconomic and environmental objectives. In this regard, the optimum structure and main process variables have been achieved by MOEA. Furthermore, extended combined pinch and exergy approach has been employed to show the performance of cycle before and after optimization. In addition, the extended combined pinch and exergy method help us to determine the limits of the optimization problem to reduce the superstructure of an optimization problem.

In this paper, three configurations for HRSG have been considered. In addition, multi-objective optimization of a 160 MW combined based on the minimization of the cost of electricity using GA as well as maximizing exergy efficiency and minimization of environmental pollutions has been performed.

2. Case Study: A 160 MW Combined Cycle

A 160-MW combined cycle power plant was studied here. As demonstrated in the schematic diagram (Fig.1), this power plant has one gas turbine, one compressor, one HRSG, one deaerator, one steam turbine and a cooling system. The exhaust flue gas at 546^{0}C enters the HRSG. The rated output power of the steam turbine is 49.638 MW (at 100% Load) at the design condition i.e. the ambient temperature of 25^{0}C. The stream data of a 160 MW combined cycle power plant is shown in Table 1.

3. Thermodynamic Modeling

Thermodynamic modeling has been performed as indicated in (Bejan et al., 1996; Dincer, Rosen, & Ahmadi, 2017; Koch, Cziesla, & Tsatsaronis, 2007; Tsatsaronis, 1993). The equations of the thermodynamic model can be found in Appendix A. Furthermore, exergy equations have been illustrated in Appendix B. The assumptions of thermodynamic modeling are as follows (Dincer et al., 2017):

- The plant operates at steady state.
- Ideal-gas mixture assumption is applied to the combustion products and air.

So, we will have slight differences in simulation results rather than plant data.

4. Combined Pinch and Exergy Evaluation

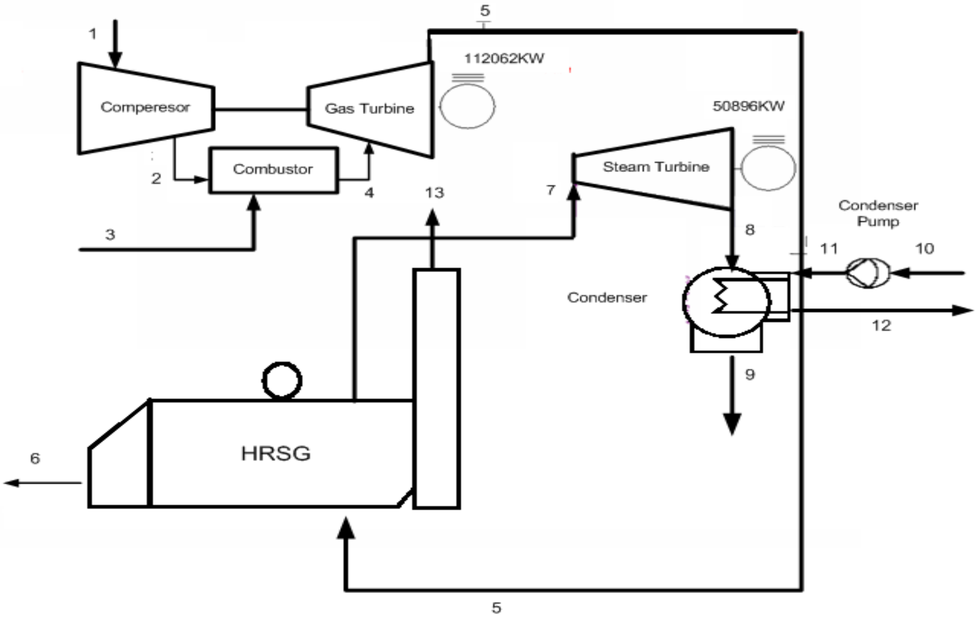

Figure 1. PFD of a 160 MW combined cycle power plant

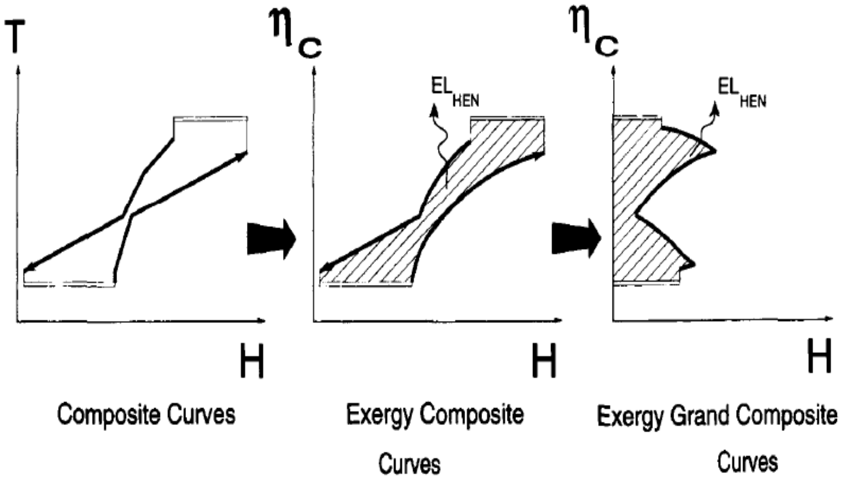

Figure 2. Exergy transformation from CC to ECC and EGCC (Feng & Zhu, 1997)

Table 1. Stream Data at 100% Load for 160MW Combined Cycle

	Stream	**T (◌°C)**	**P(bar)**	**m (kg/s)**
1	Air in	25	1.013	363.8
2	Air out	396	13.68	331.32
3	Fuel	25	25.18	6.622
4	GT inlet	1176.8	13.13	337.9
5	GT Out	546	1.04	370.5
6	Stack gas	177.7	1.04	317.2
7	ST in	509.3	53.78	42.94
8	ST out	38.7	0.069	45.727
9	Condenser out	38.74	0.4279	45.74
10	Pump in	15	1.013	2349.76
11	CW in	15	1.013	2349.76
12	CW out	25	1.013	2349.76
13	Condenser in	38.9	1.221	45.738

Pinch technology has become a general approach for targeting and design of process plants and power stations (Feng & Zhu, 1997). The composite curves (CC) and the grand composite curve (GCC) are two main graphical curves, which are indicated by temperature versus enthalpy axes (Feng & Zhu, 1997; Mohammad Hasan Khoshgoftar Manesh & Amidpour, 2008; M. H. Khoshgoftar Manesh & Amidpour, 2009; Manesh & Rosen, 2018). The CC and GCC supply the targets set. The CC and GCC have been developed for use in the heat and power systems. Therefore, based on the Carnot factor (η) versus enthalpy, the exergy composite curves (ECC) and the exergy grand composite curve (EGCC) were proposed (Feng & Zhu, 1997; M. H. Khoshgoftar Manesh & Amidpour, 2009; Manesh & Rosen, 2018).

The CCs for the thermal system can be converted into the ECCs and the GCC. The shaded areas determine the exergy destruction related to the heat transfer. By a combination of pinch analysis and exergy analysis, it is possible to estimate the power demand or production for both power systems and refrigeration (Feng & Zhu, 1997). The combined pinch and exergy analysis was extended for targeting of shaft work. Particularly, only processes associated with heat transfer can be demonstrated on the η_c-H diagram but not the processes related to composition and pressure modifications. Therefore, the curve is constructed associated with temperatures:

$$\eta = 1 - \frac{T_0}{T} \tag{1}$$

The turbines and heat transfer systems are major parts of a thermal power plant. The chemical energy in the natural gas supplies the total exergy for the plant, as an exergy source. Part of the exergy from the fuel is lost in the heat transfer system, including the combustion chamber, heat recovery steam generator, and the condenser. The rest of the exergy enters into the turbine and compressor as the exergy input for power production. Some of the exergy destruction is associated with the driver such as turbines, compressors, and pumps which are related to by their machine efficiency. In addition, the exhausted gas lost the evident amount of input exergy. The remaining exergy gives the shaft work which is received by electrical generators, which becomes the final exergy sink (Feng & Zhu, 1997; Mohammad Hasan Khoshgoftar Manesh & Amidpour, 2008).

Based on pinch and exergy analysis, the Energy Level Curves (ELC) draws on the earlier strategies of the thermodynamic method to process integration, namely the concept of CCs and the combined pinch and exergy approach (Manesh & Rosen, 2018). Figure 2 shows the exergy transformation from CC to ECC and EGCC.

In this regard, the graphical representation as energy level (Ω) defined as (Feng & Zhu, 1997; Mohammad Hasan Khoshgoftar Manesh & Amidpour, 2008; Manesh & Rosen, 2018):

$$\Omega = \frac{Exergy}{Energy} \tag{2}$$

Thus, for work

$$\Omega = 1 \tag{3}$$

and for heat

$$\Omega = 1 - \frac{T_0}{T} \tag{4}$$

and for a steady-state-flow system

$$\Omega = \frac{\Delta E}{\Delta H} \tag{5}$$

5. Economic Analysis

The cost of the components has been taken into account in the economic model, including amortization, maintenance, and the cost of fuel demand. In order to introduce a function of cost which related to optimization parameters, the cost of components has to be defined as functions of thermodynamic parameters (Sanjay et al., 2007). These relationships can be constructed by statistical correlations between costs and the main thermodynamic. In this paper, cost equations have been considered based on (Dincer et al., 2017).

In this paper, to predict each equipment capital cost the Moran method was applied to calculate the total annualized cost (Bejan et al., 1996; Sanjay et al., 2007). The cost of amortization cost for equipment can be estimated as follows:

$$PW = C_i - S_n PWF(i,n) \tag{6}$$

$$\dot{C}(\$/year) = PW \times CRF(i,n) \tag{7}$$

The annualized cost is calculated from the present worth of each component by applying the capital recovery factor CRF (i,n) (Sanjay et al., 2007). The capital cost for the kth component of the plant for 8000 operating hours per year is calculated as:

$$Z_k = \Phi_k \dot{C}_k/(3600 \times 8000) \tag{8}$$

By assumption of 30 years of plant life, the maintenance and operating cost factor $\Phi_k = 1.06$ are for each plant component (Sanjay et al., 2007).

6. Exergoeconomic Modeling and Analysis

The results of exergy analysis are used for exergoeconomic modeling and analysis (Bejan et al., 1996; Dincer et al., 2017). For the whole system an exergoeconomic balance as (Bejan et al., 1996; Dincer et al., 2017):

$$C_{P,k} = C_{F,k} - C_{L,k} + Z_k \tag{9}$$

So, for a component receiving a heat transfer and generating power, we would write (Bejan et al., 1996; Dincer et al., 2017):

$$\sum_e \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} + \sum_i \dot{C}_{i,k} + Z_k \tag{10}$$

To solve for the unknown variables, it is necessary to develop a system of equations by applying Eq. (10) to each component, and in some cases we need to apply some additional equations, to fit the number of unknown variables with the number of equations (Bejan et al., 1996; Dincer et al., 2017). The general equations applied to each component are the following, according to Fig.1. The cost balance equations for these components are as follows:

Air compressor

$$c_1 E_1 + c_{w,cp} W_{cp} = c_2 E_2 \tag{11}$$

Combustor

$$c_2 E_2 + c_3 E_3 = c_4 E_4 \tag{12}$$

Gas turbine

$$c_4 E_4 = c_5 E_5 + c_{w,GT} W_{GT} \tag{13}$$

$$c_4 = c_5 \tag{14}$$

$$\begin{bmatrix} -E_2 & 0 & 0 & 0 & 0 & 0 & 0 & W_{Comp} \\ E_2 & -E_4 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & E_4 - E_5 & 0 & 0 & 0 & 0 & 0 & W_{GT} - W_{Comp} \\ 0 & 0 & E_7 - E_8 & 0 & 0 & 0 & W_{ST} & 0 \\ 0 & E_5 - E_6 & -E_7 & 0 & 0 & E_{13} & 0 & 0 \\ 0 & 0 & E_8 & -E_9 & E_{11} - E_{12} & 0 & 0 & 0 \\ 0 & 0 & 0 & E_9 & 0 & -E_{13} & 0 & W_{FP} \\ 0 & 0 & 0 & 0 & -E_{11} & 0 & 0 & W_{CP} \end{bmatrix} \bullet \begin{bmatrix} c_2 \\ c_4 \\ c_7 \\ c_9 \\ c_{11} \\ c_{13} \\ c_{ST} \\ c_{GT} \end{bmatrix} = \begin{bmatrix} -c_1 E_1 - Z_1 \\ -c_3 E_3 - Z_2 \\ -Z_3 \\ -Z_4 \\ -Z_5 \\ -Z_6 \\ -Z_7 \\ -c_{10} E_{10} - Z_8 \end{bmatrix}$$

Output Unit Cost Input Cost

Figure 3. Cost structure of a 160 MW gas combined cycle power plant

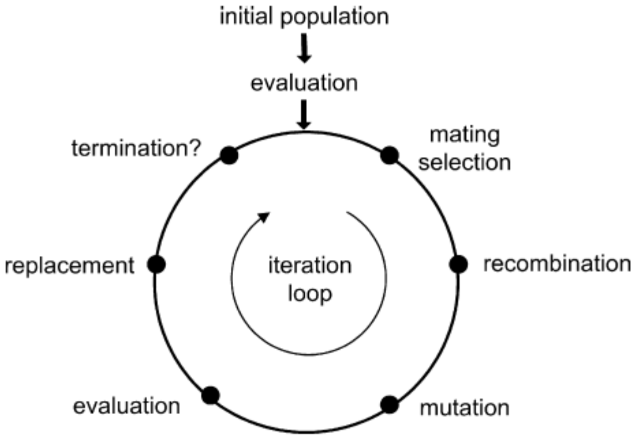

Figure 4. Basic concept of an evolutionary algorithm (Coello et al., 2002)

Steam turbine

$$c_7E_7 = c_8E_8 + c_{w,ST}W_{ST} \tag{15}$$

$$c_7 = c_8 \tag{16}$$

Heat recovery steam generator

$$c_5E_5 + c_{13}E_{13} = c_6E_6 + c_7E_7 \tag{17}$$

$$c_5 = c_6 \tag{18}$$

Condenser

$$c_8E_8 + c_{11}E_{11} = c_9E_9 + c_{12}E_{12} \tag{19}$$

$$c_{11} = c_{12} \tag{20}$$

Feed water pump

$$c_9E_9 + c_{w,FP}W_{FP} = c_{13}E_{13} \tag{21}$$

$$c_{w,FP} = c_{w,GT} \tag{22}$$

Condenser pump

$$c_{10}E_{10} + c_{w,CP}W_{CP} = c_{11}E_{11} \tag{23}$$

$$c_{w,CP} = c_{w,GT} \tag{24}$$

The cost balance equation for each component has been done. The exergoeconomic model of the case study is shown in Fig.3.

7. Optimization Strategy

7.1. Mathematical Programming

The equations have been integrated into an optimization framework developed to analysis the exergoeconomic optimization of the problem. The product cost of power generation is defined as an objective function. The optimization framework can modify process conditions to minimize exergetic production cost. In addition, three configurations for HRSG have been proposed. In addition, LINGO software as mathematical optimization program has been linked to Matlab environment by Excel. The iteration continues until solution convergence has been achieved.

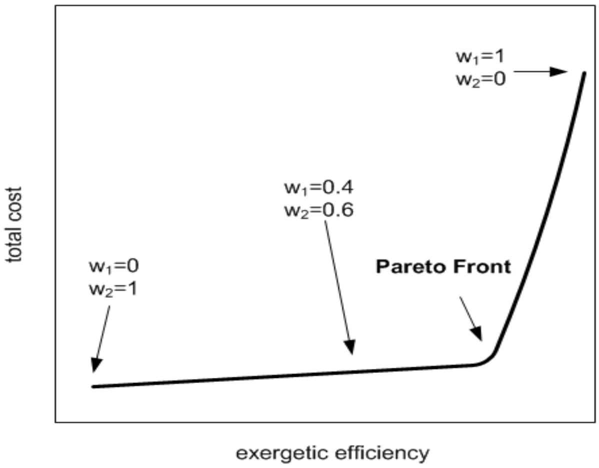

Figure 5. Comparison between the single and the multi-objective approaches to the energetic and economic design optimization of energy systems (Coello et al., 2002)

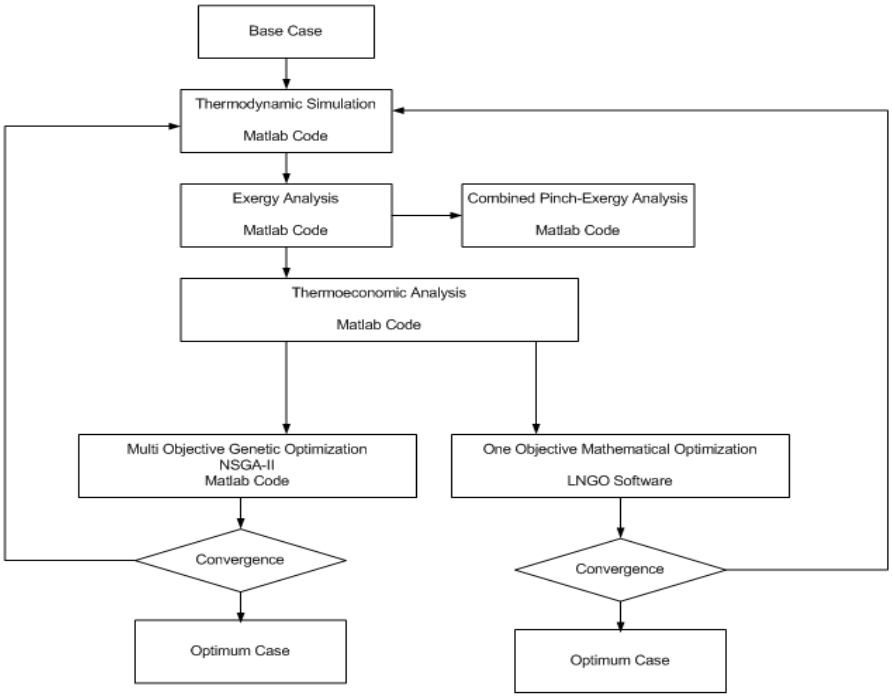

Figure 6. Integration of different techniques and optimization procedure

7.2. Evolutionary Algorithms

7.2.1. Introduction

An iterative, stochastic search strategy as an evolutionary algorithm was applied to find the optimum structure and condition (Fig. 4) (Coello, Van Veldhuizen, & Lamont, 2002). For the plant, a black box model and one objective were applied to evaluate individual fitness. Pairs of individuals are selected to create new individuals based on their performance to optimize the objective function .

Each individual is evaluated to calculate its fitness. The thermodynamic simulation, estimation of equipment costs, and an economic analysis have been evaluated (Deb, 2001).

If an individual violates any, additional penalty terms are added to the fitness value. After a fitness value has been assigned to each individual in the initial population, some of the individuals are selected for the mating pool. Selected individuals have more chances to produce in the next generation. In the next step, recombination and mutation operators are performed by the individuals in the mating pool, generating the off springs. These operators integrate randomly and change slightly the decision parameters of different individuals in the mating pool so that an offspring might get a better fitness than its parents. As shown in Fig.4, the iteration loop is repeated until the maximum number of generations is achieved. Optimization of evolutionary procedures includes evolution strategies and genetic algorithms. A detailed description of evolutionary computation and introduction is presented in (Abdalisousan et al., 2015; Coello et al., 2002; Deb, 2001; Michael Emmerich et al., 2000; M. H. Khoshgoftar Manesh & Amidpour, 2009; Lazzaretto & Toffolo, 2004).

Selection of appropriate variable settings for the evolutionary algorithm is a time-consuming task. An individual with a new process structure, even the optimal one, might need a few generations to improve the values of its process variables and to be competitive with the best individuals in the population. Regardless, the best existing individual produces some good performance off springs. The individual with the new process structure is often inferior to these solutions and is quickly removed from the population. Niching approaches within a population are capable to find and maintaining multiple solutions.

In each generation, 95% of the individuals are replaced by offspring. Since the initial population is generated randomly, all optimization runs were repeated several times with a different initial population. The optimal solutions for all cases differed only slightly. In the search for an optimal solution, an evolutionary algorithm only makes use of the value of the objective function. No gradient information is required (Coello et al., 2002; Deb, 2001).

7.2.2. Multi-Objective Optimization

The MOEA method applied as demonstrated in Fig. 5. In the first step, with each individual having the same probability of being parent selection has been done. In the next step, parents enter the reproduction step, producing μ offspring with a crossover approach. So, the values of the decision variable of the offspring convert a range defined by the decision variable values of the parents. Some decision variable values of the offspring are also randomly mutated with a probability $Pmut_t$. Then, checking of the whole population of μ+μ individuals is performed for possible clones. Then, to encourage the finding of the search space, the clones are crashed and replaced with new randomly produced individuals. In the next step, the values of an objective function of the μ offspring are evaluated. According to the scheme of Goldberg, a Pareto ranking of the $\mu+\mu$ individuals is done in multi-objective optimization (Coello et al., 2002; Deb, 2001; Lazzaretto & Toffolo, 2004).

Lastly, the number of generations go away is evaluated to create maximum number of generations; otherwise, the population for the next generation is begun. The thermo-economic objective function to be minimized expresses the total cost rate as the sum of fuel and investment (equipment/maintenance) cost rates(Deb, 2001; Dincer et al., 2017; M. H. Khoshgoftar Manesh & Amidpour, 2009; Lazzaretto & Toffolo, 2004):

$$C_{total} = C_{fuel}\,(\varepsilon\,(X)) + C_{inv}\,(X) \qquad (25)$$

Where ε is the exergetic efficiency, and X is a vector containing the design variables. C_{total} includes information in the fuel cost rate ($C_{fuel} = c_{fuel} . E_{fuel}$) through E_{fuel} (fuel exergy flow rate).This dependence does not change the nature of the objective function, which still accounts for the total money to be spent. Thus, the two terms of the function, that in principle are associated with two different objectives, merge into a single objective C_{total}. If C_{total} is minimized for a particular unit cost of fuel, only the extremum of the Pareto front corresponding to the economic minimum is found. On the other hand, in a single-objective approach considering both the thermodynamic and economic objectives (ε and C_{total}), the overall single-objective function (to be maximized) would be constructed by combining the two functions through appropriate weights, as follows (Lazzaretto & Toffolo, 2004):

$$F\,(X) = w1 \cdot \varepsilon\,(X) - w2 \cdot C_{total}\,(X, \varepsilon\,(X)) = w1 \cdot \varepsilon\,(X) - w2 \cdot C_{total}\,(X) \qquad (26)$$

With w1 ≥ 0, w2 ≤ 1 and w1 + w2 = 1.

By modification of w1 and w2, the optimal conditions regarding the Pareto front of the multi-objective method are achieved as shown in Fig 5.

For multi-objective optimization, the Pareto approach is the type of multi-objective evolutionary algorithms (MOEAs). This method has been extended over the past decade (Lazzaretto & Toffolo, 2004); difficult tests on complex problems and on real engineering problems have determined that MOEAs can remove difficulties of classical approaches.

Due to MOEAs apply a population of solutions during explore; a single run will obtain multiple Pareto optimal solutions.

7.3. Environmental Objective

The minimization of environmental pollution regarding the operating of the combined cycle was considered. So, the other objective function was introduced based on environmental emissions as environmental impact [23, 24]

Gülder proposed that the adiabatic flame temperature in the primary zone of the combustion chamber is derived as follows (Dincer et al., 2017; Gülder, 1986):

$$T_{pz} = A\,\sigma\,\alpha\,exp(\,\beta\,(\sigma + \lambda\,)\,2\,)\,\pi\,x\,\theta\,y\,\psi\,z \qquad (27)$$

where π is a dimensionless pressure p/pref. In this regard, p is related to the combustion pressure p_3 and pref is equal to 101.325 kPa. In addition, θ is T/Tref as a dimensionless temperature and T is related to the inlet temperature T3 and Tref is equal to 300 K. Furthermore, ψ is the H/C atomic ratio ψ = 4, the fuel is assumed to be pure methane; Also, σ = φ for φ ≤ 1 which φ related to the fuel to air equivalence ratio and σ = φ − 0.7 for φ > 1 (It is assumed that φ = 0.64); x, y, and z are quadratic functions of σ related to the following equations:

$$0.3 \le \varphi \le 1.0 \quad \text{and} \quad 0.92 \le \theta < 2.0 \qquad (28)$$

$$0.3 \le \varphi \le 1.0 \quad \text{and} \quad 2.0 \le \theta \le 3.2 \qquad (29)$$

$$1.0 < \varphi \le 1.6 \quad \text{and} \quad 0.92 \le \theta < 2.0 \qquad (30)$$

$$1.0 < \varphi \le 1.6 \quad \text{and} \quad 2.0 \le \theta \le 3.2 \qquad (31)$$

As Rizk and Mongia were proposed, the pollutant emissions in grams per kilogram of fuel were calculated as (Rizk & Mongia, 1993):

$$NOx = \frac{0.15E16\tau^{0.5}\exp\left(-71100/T_{pz}\right)}{P_3^{0.05}\left(\Delta p_3/p_3\right)^{0.5}} \qquad (32)$$

$$CO = \frac{0.179E9\exp\left(7800/T_{pz}\right)}{p_3^{\,2}\tau\left(\Delta p_3/p_3\right)^{0.5}} \qquad (33)$$

The minimization of the total product cost of a plant as the main objective function has been considered.

In addition, another objective function is an environmental impact to be minimized. The environmental objective has been formulated in cost terms by multiplying the respective flow rates of pollutions damage cost (Lazzaretto & Toffolo, 2004)(cCO and cNOx are levelized back to 1994 to keep all cost values homogeneous and they are equal to 0.02086 \$/kgCO and 6.853 \$/kg NOx, respectively and then combined with economic objective. Therefore, in this research, the pollution damage cost has been considered in conjunction with economic objective and the optimization problem, named as environmental optimization, is a single-objective as follows:

$$C_P = C_F + \sum Z_k + C_{envtot,k} \tag{34}$$

7.4. Decision Variables

In the optimization problem, the decision variables may be varied. All other variables are dependent variables. Their values are calculated from independent variables using a thermodynamic model. In this paper, decision variables have been selected as follows:

- Gas turbine inlet; (*T*)
- High-pressure steam (*m* ; *T*)
- Low-pressure steam (*m* ; *T*)
- Hot reheat steam (*m* ; *T*)
- HRSG exhaust (*T*)
- η_{AC} (efficiency)
- η_{GT} (efficiency)
- Compressor pressure ratio (p_2/p_1)
- HRSG configuration topology (one, two or triple pressure)

The range of the decision variable is as follow:

$$6 \le p_2 / p_1 \le 16 \tag{35}$$

$$0.6 \le \eta_{GT} \le 0.92 \tag{36}$$

$$0.6 \le \eta_{st} \le 0.92 \tag{37}$$

$$700 \le T_3 \le 1000\text{ K} \tag{38}$$

$$1200 \le T_4 \le 1550\text{ K} \tag{39}$$

The heat exchange between hot and cold streams in the HRSG must satisfy the following feasibility constraint:

$$\Delta T_{PINCH} > 0 \tag{40}$$

8. Computer Program

Integration of different techniques and optimization procedures has been shown in Fig.6. As shown, in the first step thermodynamic simulation that is necessary for another analysis has been performed in Matlab code. In the next step, exergy and thermoeconomic analysis have been applied for the demonstration of irreversibility of equipment and estimation of electricity exergetic cost that is produced in steam and gas turbines. Objective function has been achieved by calculation of exergetic cost of electricityon and environmental pollution. After iteration best solution has been found. Iteration started from base case and it has been finished in optimum case. Three structures for HRSG have been proposed. Three configurations for HRSG and different process condition have been examined by evolutionary algorithms and best configuration and process condition have been selected as an optimal solution. Moreover, combined pinch-exergy representation demonstrates thermal performance of the system in base and optimum case. Also, it can be used for analysis and evaluation of the system.

Table 2. Main Data at Full Load for 160-MW combined cycle (Plant Data and Simulation Result)

Parameter (Unit)	Plant data	Simulation Result
Ambient Temperature (°C)	25	25
Atmospheric pressure (bar)	1.01	1.013
Relative humidity (%)	60	60.01
Fuel :Natural gas, LHV (kJ/kg)	50046.71	50045.32
Combustion efficiency (%)	92.122	92.121
Gas turbine efficiency (%)	33.81	33.80
HRSG efficiency (%)	70.44	70.41
Net heat rate (kJ/kWh)	7506.8	7504.9
Gross heat rate	7379	7378.45
Gross electric efficiency (%)	48.79	48.78
Steam turbine shaft work (MW)	49.638	49.632
Gas turbine shaft work (MW)	112.062	112.013
Net total electric power (MW)	158.964	158.897
Net plant efficiency (%)	47.96	47.853

Table 3. Exergy and exergoeconomic parametes in each component in Base Case

Component	E_D(MW)	C_F(\$/MW)	C_P(\$/MW)	E_F (MW)	E_P (MW)	Efficiency
Air Compressor	22.1107553	0.0047	0.005585	139.474	117.3632	84.147
Combustor	86.76001663	0.004915	0.0061	460.9134	374.1534	81.1765
Gas Turbine	22.41635759	0.001906	0.0047	276.2924	112.062	91.0881
Steam Turbine	3.89953351	0.017927	0.0193	54.79553	50.896	92.8835
Condenser	5.473911779	2.12E-05	3.08E-05	86.00833	59.12407	-
HRSG	26.88425748	0.006941	0.010097	86.00833	59.12407	68.7423
CW Pump	0.2795	0.0047	0.005483	1.957876	1.678376	85.7243
FW Pump	0.035422686	0.0047	0.006285	0.081479	0.060934	77.47846

By using stream data, the extended combined pinch and exergy representations have been constructed.

A computer program for thermodynamic, economic, exergy, thermoeconomic and combined pinch and exergy analyses of the 162-MW combined power plant has been developed in Matlab environment. The data inputs of this program as:

(a) Standard pressure (P_0) and Standard temperature (T_0);

(b) Compositions of fuel and fuel costs

(c) The composition of air and air relative humidity;

(d) Load conditions

(d) Gross shaft power of steam turbine and gas turbine;

(e) Required power for compressor and pumps;

(f) For streams at the inlet and outlet of each component pressure (MPa), mass flow rate (kg/s) and temperature (°C);

(g) Economic inputs such as capital cost, interest rate, and salvage value factor;

By applying these input data; composition of combustion products and adiabatic flame temperature can be calculated. Also, enthalpy and entropy for each fluid streams at various conditions can be computed. Also, computer code has been written for thermodynamic simulation and evaluation of plant. The enthalpy and entropy of non-interacting gas species were calculated by using appropriated polynomials fitted to the JANAF thermochemical tables ("JANAF thermochemical tables, 1975 supplement," 1975). Furthermore, by the International Association for the Properties of Water and Steam, enthalpy and entropy of water and steam were calculated (Wagner & Kretzschmar, 2007). Using the values of these properties, the thermodynamic simulation and exergy analysis of plant‘s components have been performed. In addition, exergy balances for the plant boundary and components were created. Then, the unit cost of products was calculated by solving the cost balance equations simultaneously. Furthermore, this program can generate improved combined pinch and exergy representation. To perform the optimization of the 160-MW case study, the evolutionary algorithms of Multi-Objective Evolutionary through NSGA-II are interfaced with a MATLAB m-file model in which the thermodynamic, economic and environmental equations of the case problem are implemented and solved and then returning the values of the objectives for a given set of decision variables. In addition, the thermoeconomic and environment MATLAB m-file model have been exported to LINGO to find optimal solution by MINLP.

9. Result

Exergy and thermoeconomic analysis have been performed for a 160-MW combined cycle power plant. Matlab code has been developed for the simulation of this power plant. Main data of 160-MW combined cycle in plant data and simulation case are shown in Table 2. The slight differences existing between the two columns show the accuracy of simulation results and due to some assumptions that have been used for thermodynamic modeling and simulation. Exergy and exergoeconomic parameters such as exergy destruction, the cost rate of fuel, cost rate of the product, exergy of fuel, exergy of product and efficiency of each component are shown in Table 3.

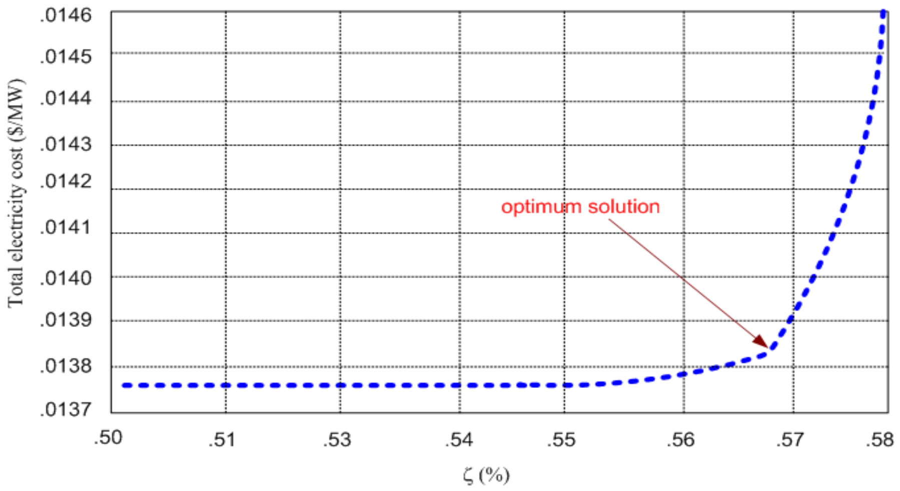

Figure 7. Optimum solution through multi-objective function

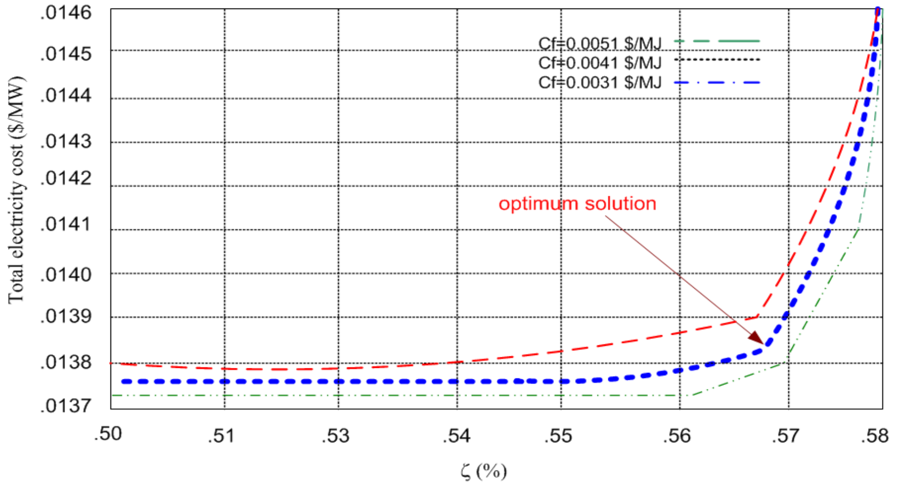

Figure 8. Sensitivity analysis of multi-objective optimization by modification of specific fuel cost corresponding to Pareto optimal sets

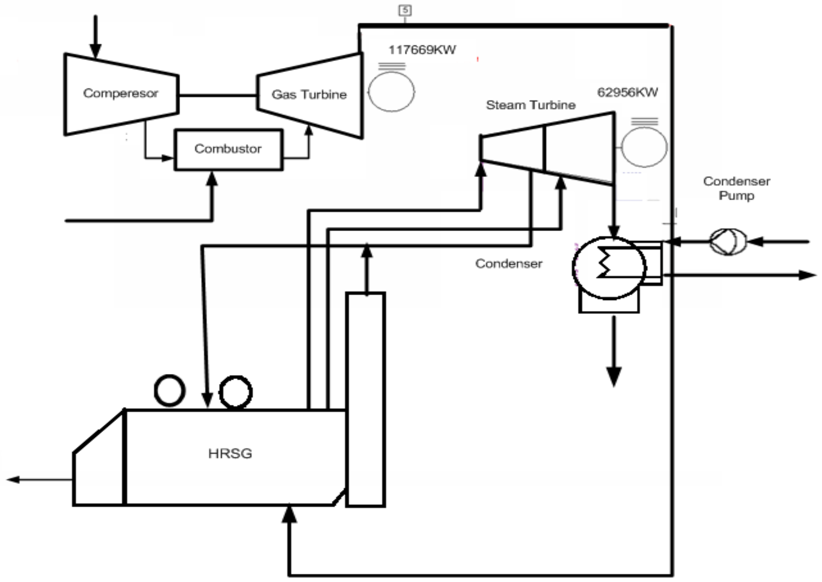

Figure 9. PFD of power plant-after optimisation

Multi-Objective Thermoeconmic optimization through Evolutionary Algorithm (NSGA-II) has been applied for 160- MW combined cycle power plant to minimization of generated electricity cost. In this research, three methods have been used for finding optimum configuration and process condition of combined cycle plants. The combined pinch exergy approach has been employed to demonstrate the limitation of problem. It helps us to reduce the superstructure of problem. Also, different analysis has been applied for better showing thermal behavior and the evaluation of the system in the base and optimum case by best optimization method.

In this case, the setting of the evolutionary algorithm is as follows:

Population size: 500
No. of Generations: 900
Pc (Probability of crossover): 0.7
No. of crossover points: 2
Pm (Probability of mutation): 0.01
Selection process: Tournament
Tournament Size: 2

The Pareto Front for this multi-objective optimization problem, which shows the best trade-off values of two objective functions, has been presented in Fig.7.

As shown in this figure, while the total exergetic efficiency of the plant increased to about 55%, the total cost rate of the products increases very slightly. Increasing of total exergetic efficiency from 55% to 57.3% is corresponding to a moderate increase of cost rate of the product. Eventually, from 57.3% to a higher value of ε_{tot}, the total cost rate increases sharply. It should be noted that the selection of the optimum solution is depending on preferences and criterions of each decision maker. Therefore, another person may select a different point as the optimum solution which better suits his desires. Therefore, in the optimum solution exergetic efficiency is about 56.8% and cost of electricity is 0.01384 $/MJ.

Also, mathematical optimization has been applied by LINGO software. Table 4 shows the comparison of mathematical programming and one objective GA and MOEA methods. As shown in this table, MOEA gives us a better solution rather than other methods.

Sensitivity analysis of multi-objective optimization by modification of specific fuel cost corresponding to Pareto optimal sets has been shown in Fig.8. As shown in these figures, by increasing specific fuel cost or interest rate, specific production cost has been increased.

The value of characteristic process variables after the calculation has been determined in Table 5.

The best structure of HRSG after optimization has been shown in Fig.9. In this study, the configuration of HRSG has been modified through the Evolutionary algorithm. The profiles of HRSG temperature in the base case and the optimum case has been illustrated in Fig.10 and Fig.11.

In addition, for better evaluation of component's performance in the base case and optimum case, extended combined pinch and exergy approach has been applied to demonstrate the thermal behavior of the plant. The energy level curve helps us to a better understanding of the thermal behavior of the power plant's components in the base and optimal case as shown in Fig.12 and Fig.13 consequently.

Table 4. Results Comparison of Different Methods (MINLP, GA-One Objective and MOEA)

Parameter(Unit)	MINLP	GA One Objective	MOEA
Net total electric power (MW)	189.20	185.20	191.63
Net plant efficiency (%)	55.0	52.0	56.8
CP steam turbine($/MJ)	0.0193	0.021	0.0183

Table 5. Values of characteristic process variables after 60 generation

Stream	Parameters	Values
Gas turbine inlet	m ; T	372.51 kg/s ; 597.49 °C
High pressure steam	m ; T	38.01 kg/s ; 319.31 °C
Low pressure steam	m ; T	2.102 kg/s ; 107.34 °C
Hot reheat steam	m ; T	47,94 kg/s ; 539.18 °C
HRSG exhaust	T	160.12 °C
η_{AC}	efficiency	84.17 %
η_{GT}	efficiency	92.16 %
Compressor pressure ratio	p_2/p_1	7.44

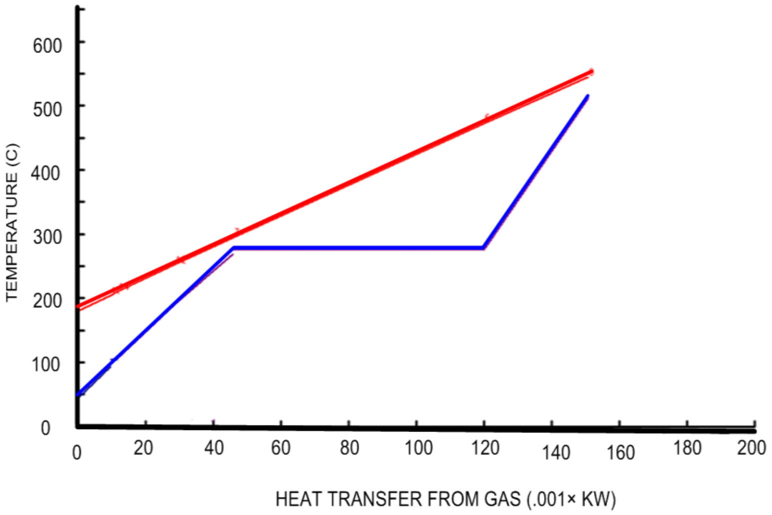

Figure 10. HRSG temperature profile-base case

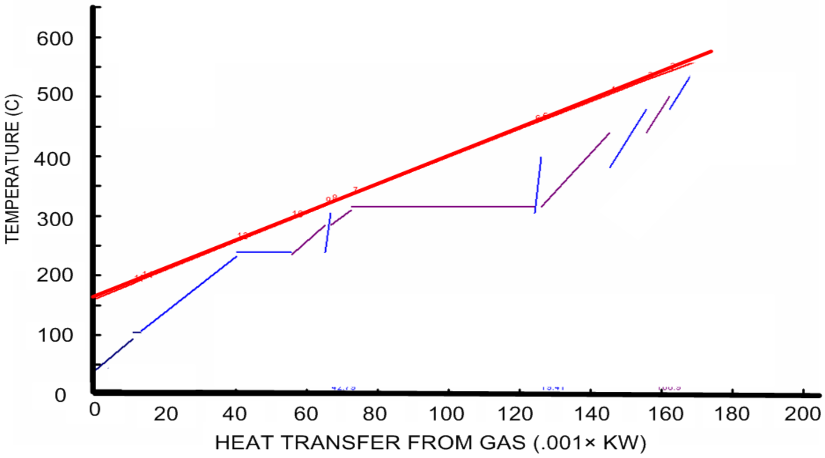

Figure 11. HRSG temperature profile-optimal case

Energy level curve that is generated by Matlab code shows the effects of this improvement in different component and thermal interaction in whole plant graphically.

In addition, comparison of exergy destruction in the base and optimum case after thermo economic optimization with evolutionary algorithm are shown in Fig.14. Also, figure 15 compares the cost of exergy destruction in the base and optimum case.

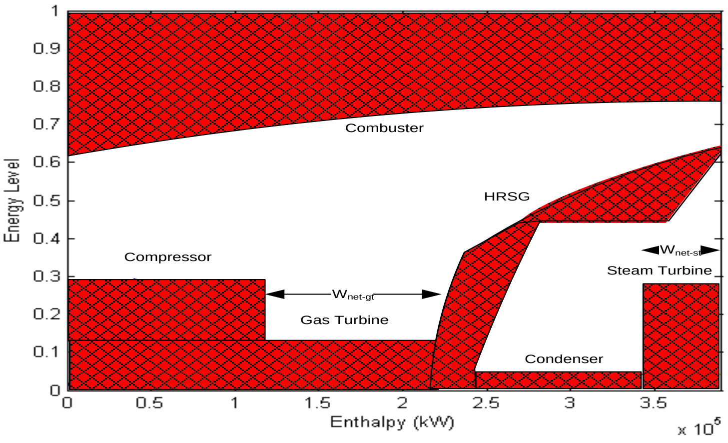

Figure 12. Energy level representation- base case

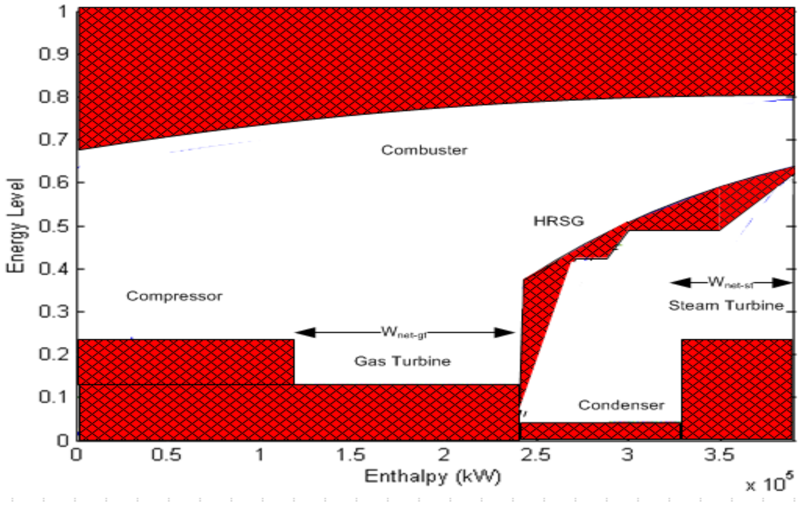

Figure 13. Energy level representation- optimal case

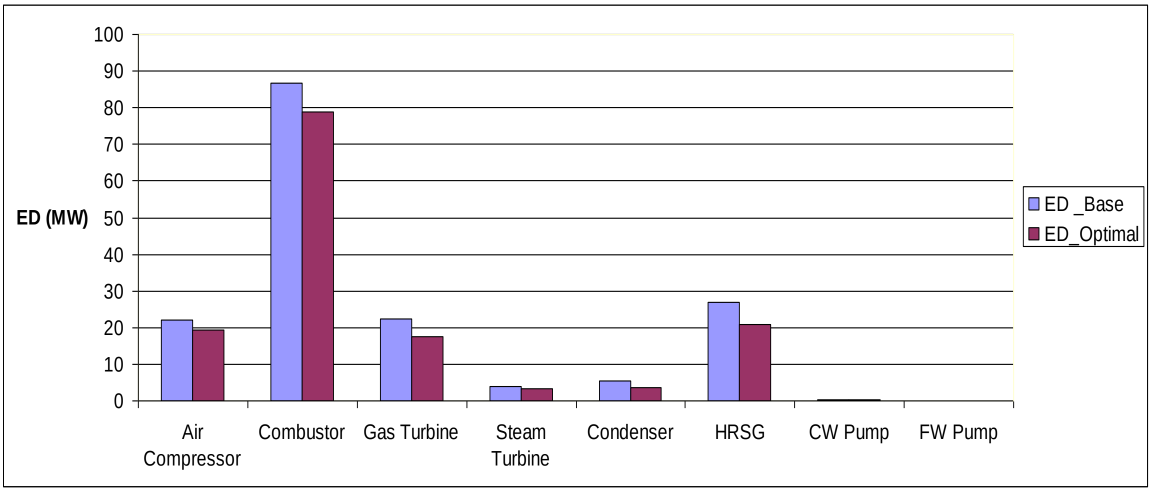

Figure 14. Comparison of exergy destruction in base and optimal case

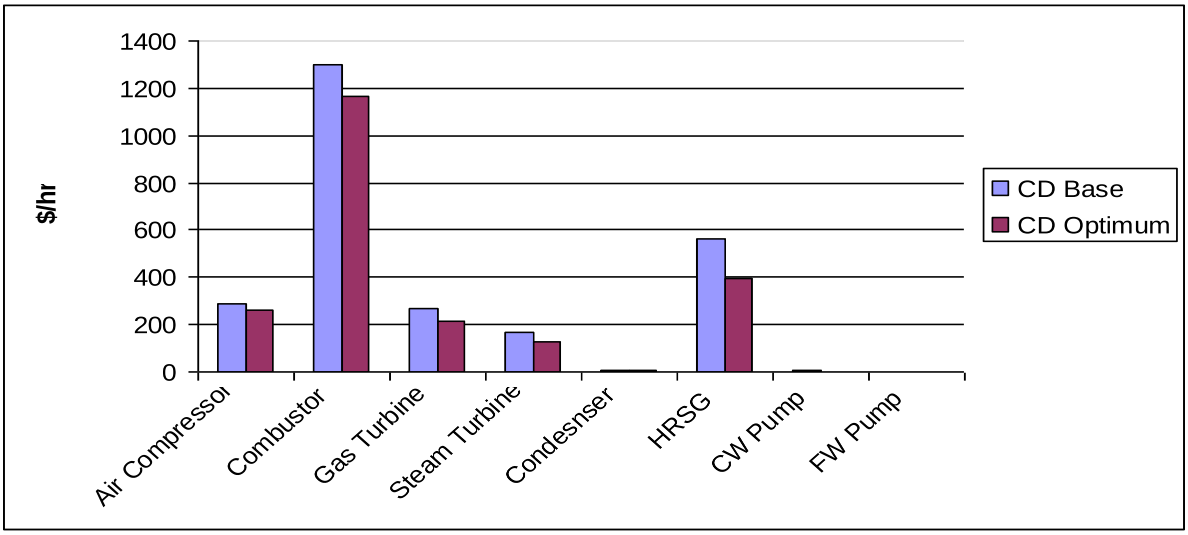

Figure 15. Comparison of exergy cost destruction in base and optimal case

10. Conclusion

In this paper, Matlab m-file program has been developed for the thermodynamic simulation of 160-MW combined cycle power plant. An exergoecomic has been applied to this plant to predict the unit costs of power produced from gas and steam turbines.

Also, this program that has been developed which shows that the exergy, thermo economic, combined pinch-exergy analysis and thermo economic optimization of configurations in HRSG and process variables via NSGA-II. This algorithm presented here can be applied to combined cycle power plant systematically.

In addition, extended combined pinch and exergy approach have the strength for promising modifications and feasible region for optimization. It can help us to identify major improvement. Also, it can be applied for evaluation and comparison of the base and optimum case. As shown in the results, overall exergetic efficiency increases about 7.5% by MOEA approach. In addition, the exergetic product cost of electricity reduces to 0.0183 $/MJ consecutively. As sensitivity analysis has been shown, by increasing specific fuel cost or interest rate, specific production cost has been increased.

The proposed evolutionary algorithm has been shown to be a powerful and effective tool in finding the set of the optimal solutions rather than multi-objective mathematical programming and GA one objective optimization for finding optimum design variables in this plant. In this study, the combined pinch exergy analysis has been performed to determine the optimization potentials and limitations. Therefore, this evolutionary-based procedure will be very useful for the optimization of complex thermal systems.

Nomenclature

A	constant coefficient
e	exergy rate per mass
E	time rate of exergy
T	temperature
P	pressure
m	mass flow rate
W	shaft work
C	cost rate
Z	cost rate of capital investment and O&M
x	quadratic functions
y	quadratic functions
z	quadratic functions
Greek letters	
η	carnot factor
Ω	energy level
π	dimensionless pressure
θ	dimensionless temperature
ψ	H/C atomic ratio
φ	the fuel to air equivalence ratio
ε	exergetic efficiency
σ	constant related to fuel to air equivalence ratio
τ	time constant
α	constant coefficient
β	constant coefficient
γ	constant coefficient
Superscript	
CI	capital investment
OM	operating and maintenance cost
Subscript	
p	product
f	fuel
D	destruction
L	loss
pz	the adiabatic flame temperature in the primary zone of the combustion chamber

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Appendix A (Thermodynamic model)

The enthalpy and entropy of gas species were calculated by using polynomials fitted to the thermo physical data in the JANAF Tables [29]. In addition, the values of as enthalpy and entropy for water and steam were evaluated by using by the International Association for the Properties of Water and Steam (IAPWS-IF97) [30].

Governing Equations

A set of governing equations can be developed as follows [10]:

Combustion Chamber

Denoting the fuel-air ratio on molar basis on a molar basis as λ, the molar flow rates of the fuel, air, and combustion products are related by [10]:

$$\frac{n_F}{n_a} = \bar{\lambda}, \frac{n_p}{n_a} = 1 + \bar{\lambda} \qquad (41)$$

where the subscripts *F, P* and *a* denote, respectively, fuel, combustion products and air. For complete combustion of methane, the chemical equation takes the form [10]:

$$\bar{\lambda} CH_4 + \left[0.7748N_2 + 0.2059O_2 + 0.0003CO_2 + 0.019H_2O\right] \rightarrow \left[1+\bar{\lambda}\right]\begin{bmatrix} x_{N_2} N_2 + x_{O2}O_2 + \\ x_{CO2}CO_2 + x_{H2O}H_2O \end{bmatrix} \qquad (42)$$

The molar analysis of the combustion products is fixed once the fuel-air ratio λ has been determined. The fuel air ratio can be obtained from an energy rate balance as follows [10]:

$$Q_{CV} - W_{CV} + n_F\, h_F + n_a h_a - n_p h_p = 0 \qquad (43)$$

As the heat loss is assumed to be 2% of the lower heating value, we have [10]:

$$Q_{CV} = -0.02 n_F h_F LHV = n_a \left(-0.02\, \bar{\lambda}\, LHV \right) \qquad (44)$$

Turbine and Compressor

For this control volume the energy rate balance takes the form [10]:

$$0 = Q_{CV} - W_{CV} + n_a\left(h_1 - h_2\right) + n_p\left(h_4 - h_5\right) \qquad (45)$$

The term ($h1 - h2$) of Eq. (45) is evaluated using the compressor isentropic efficiency [10]:

$$\eta_{comp} = \frac{h_{2s} - h_1}{h_2 - h_1} \qquad (46)$$

where h_{2s} denotes the specific enthalpy for an isentropic compression from inlet state *1* to the specified exit pressure p_2. The state *2s* fixed using $s_{2s} - s_1 = 0$.

The value of h_2 determined from Eq. (45) is used to calculate the value of T_2 by solving an equation derived from Eq. (46). The term ($h_7 - h_8$) of Eq. (47) is evaluated using the turbine isentropic efficiency [10]:

$$\eta_{st} = \frac{h_7 - h_8}{h_7 - h_{8s}} \qquad (47)$$

Heat Recovery Steam Generator

For this control volume the energy rate balance takes the form [10]:

$$m_5\left(h_5 - h_6\right) + m_{12}\left(h_{12} - h_7\right) = 0 \qquad (48)$$

Appendix B (Exergy Analysis)

Combustor

The exergy destruction in the combustor is calculated as [10]:

$$\dot{I}_{Combuster} = \sum(\dot{m}e)_{in} - \sum(\dot{m}e)_{out} \qquad (49)$$

E_{in} is sum of fuel exergy and air exergy that input to the combustion chamber. E_{out} is exergy of combustion that produces in combustor [6].

Turbines

In this cycle we have one gas and steam turbine. Exergy destruction for turbines is defined as:

$$\dot{I}_{Turbine}=\sum(\dot{m}e)_{in}-\sum(\dot{m}e)_{out}-W_{out} \tag{50}$$

W_{out} is the shaft work. The exergetic efficiency of the turbines introduced as the ratio of the minimum work input to the actual work input [6, 7] as follows:

$$\varepsilon_{Turbine}=\frac{\dot{W}_{out}}{\sum(\dot{m}e)_{out}-\sum(\dot{m}e)_{in}} \tag{51}$$

Heat Exchanger

Heat recovery steam generator and condensers are essentially heat exchangers designed to perform different tasks. The exergy model is defined as follows:

$$\dot{I}_{Heat\ Exchanger}=\dot{E}_{in}-\dot{E}_{out}=[\sum\dot{m}e]_{in}-[\sum\dot{m}e]_{out} \tag{52}$$

The exergetic efficiency of a heat exchanger is defined as follows [6]:

$$\varepsilon_{Heat\ Exchanger}=\frac{\sum[\dot{m}e_{out}-\dot{m}e_{in}]_{Cold\ Stream}}{\sum[\dot{m}e_{in}-\dot{m}e_{out}]_{Hot\ Stream}} \tag{53}$$

Compressor or Pump

The exergy destruction in compressor or pump can be defined as:

$$\dot{I}_{Compressor,Pump}=\dot{E}_{in}-\dot{E}_{out}=\sum(\dot{m}e)_{in}+\dot{W}_{in}-\sum(\dot{m}e)_{out} \tag{54}$$

The exergetic efficiency of the compressor or pump can be defined as:

$$\varepsilon_{Compressor}=\frac{\sum(\dot{m}e)_{out}-\sum(\dot{m}e)_{in}}{\dot{W}_{in}} \tag{55}$$

3.5. Cycle

The overall exergetic efficiency of the cycle can be defined as:

$$\varepsilon_{Cycle}=\frac{\dot{W}_{net}}{E_{fuel}} \tag{56}$$