# Chapter 6
# Optimization of Industrial Process 1

To illustrate the application of the method described in the previous chapter, the multi-objective optimization problem of the regenerative steam power plant with superheat and reheat shown in Fig. 6.1 is taken as an example. It consists of one stage of steam reheat and two closed feed water heaters with drains cascaded backward that operates at different pressure levels. Each feed water heater is a heat exchanger that receives steam bled from the turbine and feed water or high-pressure subcooled liquid water from the condenser. The water stream passes through successive steam-fed preheaters from the turbines and the condensation of which causes the heat to flow to the boiler feed stream to preheat. As the bled steam condenses in each feed water heater, it is passed through a pressure reducing valve to flow to a lower pressure region, such as either the next lower-pressure feed water heater or the condenser. In the condenser, cooling water provided by a wet-cooling tower removes the waste heat from the turbine exhaust steam at the lowest pressure level of the plant, leaving subcooled liquid water or condensate for reuse in the cycle. A pump is placed after the condenser to deliver water through the three-high-pressure closed feed water heaters to the boiler. The boiler generates high-pressure superheated steam from boiler feed water by combusting natural gas. Superheated high-pressure steam from the boiler is used to generate electric power in HP, IP, and LP turbines.

## 6.1 Problem Statement

In this example, it was addressed the simultaneous economic and environmental optimization of regenerative-reheat steam power plants for electric generation as the one illustrated in Fig. 6.1. Given are the plant configuration, temperature, pressure, and flow rate of the boiler output stream and the feed stream to the condenser, hot stream outlet temperature in the condenser, hot stream temperature decrease in



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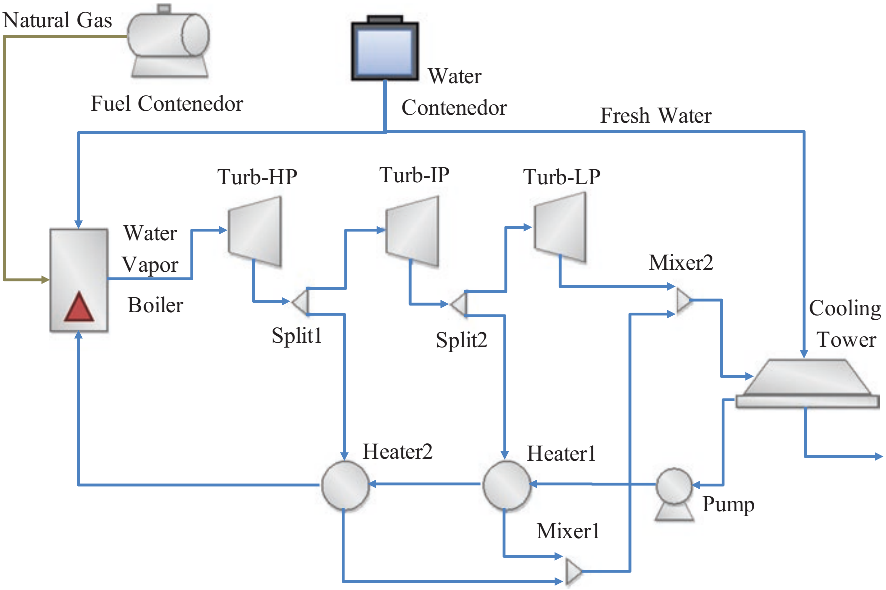


**Fig. 6.1** Generation power plant based on regenerative Rankine cycle

both preheaters, pressure of the pump, temperature and pressure of the boiler, split fraction of both splitters, and pressure decrease in HP, IP, and LP turbines.

The solution of the problem is defined by a set of optimal designs called Pareto optimal set (i.e., the set of the best possible trade-offs between the considered objectives). Each of these solution alternatives achieves a unique combination of profit and environmental impact. For each solution of the Pareto set of the problem, the goal is to determine the optimal values of the temperature and pressure in the boiler, the pressure decrease in HP, IP, and LP turbines, the pressure in the pump, and the split fraction in both splitters as well as the optimal combination of energy sources that simultaneously maximizes the profit and minimizes the environmental impact of the plant (Gutiérrez-Arriaga et al. 2013).

## 6.2 Model Formulation

As can be seen in Fig. 6.1, simple electric power stations have configurations that comprise the following main components: a boiler; HP, IP, and LP turbines; a feed water pump; two feed water preheaters; and a cooling tower as condenser. A variety of steam power plant configurations can result from the different number, type, and connections of these components.

To facilitate the multi-objective optimization of such complex systems characterized by a large number of thermodynamic, economic, and environmental parameters, a simulation framework and a posterior optimization are proposed in this work.

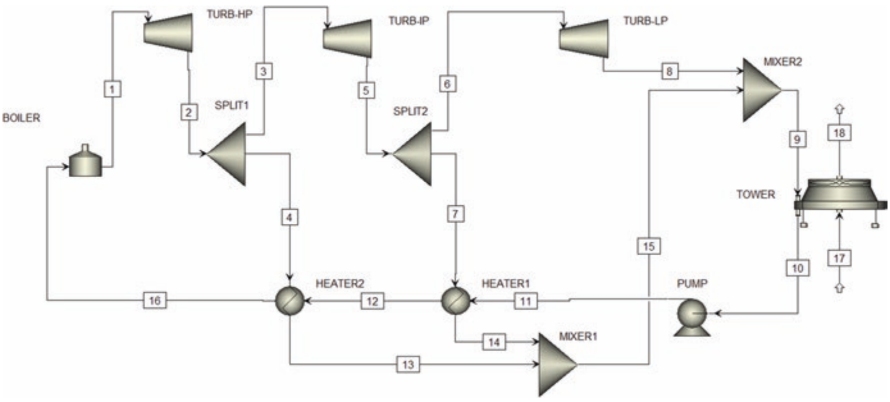


**Fig. 6.2** Process flowsheet in Aspen Plus® for a simple steam power plant for electric generation based on regenerative Rankine cycle

In this section, we present the details of the proposed approach to tackle the problem described above taking as an example the regenerative steam power plant with superheat and reheat shown in Fig. 6.1.

### *6.2.1 Model Simulation Using the Aspen Plus® Software*

The first step corresponds to the simulation of the process, i.e., to set the equipment and connections of streams that relate process units under the specific conditions of each one that allow to offer a representation of the process. For this purpose, Aspen Plus® was used, which is the market-leading chemical process simulation software used by the bulk, specialty, and biochemical industries for the design and operation (aspentech.com). The main advantages of this simulator consist in a large database of specific chemical compounds and unit operations. The process flowsheet in Aspen Plus® for a simple steam power plan for electric generation based on regenerative Rankine cycle is shown in Fig. 6.2.

Economic and environmental objective functions were defined through a mathematical formulation of the problem to be considered. The application of chemical and biochemical engineering simulators was not involved up today in the search of the optimum solutions. Due to this fact, the use of a multi-objective optimization algorithm is necessary which must be stochastic (e.g., genetic algorithm (GA) and differential evolution (DE)). A useful client-server application was developed in order to call Aspen Plus® simulator repetitively for various sets of input variables.

For the first simulation, the following values were used: a temperature of 580 °C, pressure of 38 atm, and total flow of 1000 ton/day for the boiler output stream. The hot stream outlet temperature in the condenser is equal to 100 °C, hot stream temperature decrease of 10 °C in the first preheater and 100 °C in the second one, pressure of the pump of 40 atm, temperature of 600 °C, and pressure of 40 atm in the boiler. The split fraction is 0.8 in both splitters, and the pressure decreases are 20, 10, and 5 atm in the HP, LP, and LP turbines, respectively.

### 6.2.2 Mathematical Formulation

In this step, the multi-objective optimization of steam power plants contains two objective functions including the annual gross profit and the environmental impact that must be satisfied simultaneously. For this purpose, the values of the response variables were used to calculate the performance of the objective functions using the following equations taken from Gutiérrez-Arriaga et al. (2015). The main benefit of using biofuels (i.e., natural gas) as energy sources in steam power plants is the reduction of the net $CO_2$ emissions (i.e., overall environmental impact). However, a lower environmental impact is associated with a lower plant annual gross profit. This poses a challenging multi-objective optimization problem of steam power plants where the overall environmental impact needs to be minimized while maximizing the system annual gross profit. The total income is calculated with the negative of electric energy produced by HP, IP, and LP turbines (WT) in kW and the electric power price of \$0.1039/kWh. The operating time ($t_{OP}$) was set to an average of 24 h for 360 days.

First, it is necessary to calculate the saturation temperature in the boiler ($T_{sb}$), which is calculated in °C using Eq. (6.1) starting with the value of the boiler pressure ($P_b$) expressed in atm:

$$T_{sb} = 13.8 P_b^{0.2264} \tag{6.1}$$

For calculating the bulb temperature of the boiler ($T_{sh}$) in °C, we used Eq. (6.2) introducing the boiler operating temperature ($T_b$) in °C:

$$T_{sh} = T_{sb} + T_b \tag{6.2}$$

Also, two dimensionless factors are necessary for calculating the capital cost of the boiler, the boiler superheat factor ($N_t$), and the cost factor in the boiler pressure ($N_p$), and they are calculated through Eqs. (6.3) and (6.4), respectively:

$$N_t = 1.5 \times 10^{-6} T_{sh}^2 + 1.13 \times 10^{-3} T_{sh} + 1 \tag{6.3}$$

$$N_p = 7 \times 10^{-4} P_b + 1 \tag{6.4}$$

The value of capital cost of the boiler (CB) is obtained by Eq. (6.5) using the dimensionless factors and the net heat required in the boiler operation ($Q_{netboiler}$) in kW:

$$\text{CB} = \frac{3 \cdot N_t \cdot N_p \cdot Q_{\text{netboiler}}^{0.77}}{3412.14} \tag{6.5}$$

while the cost of the pump (CP) is calculated through Eq. (6.6) using the value of the work done on the pump (WP) in kW:

$$\text{CP} = 475.3 + 34.95 \cdot \text{WP} - 0.0301 \cdot \text{WP}^2 \tag{6.6}$$

Another cost is the one associated with the turbine (CT), which is found for the use of Eq. (6.7) starting with the electric energy produced by HP, IP, and LP turbines (WT) in kW:

$$\text{CT} = 2.237 \cdot \text{WT}^{0.41} \tag{6.7}$$

The cost of the cooling tower (CC), given in Eq. (6.8), is calculated using the heat removed from the cooling tower ($Q_c$) in kW:

$$\text{CC} = 43 \cdot Q_c^{0.68} \tag{6.8}$$

The cost for operating the pump (COPP) is the electrical energy consumption in the operation of this equipment in kW, which is calculated by Eq. (6.9) starting with the work done in the pump (WP):

$$\text{COPP} = \frac{\text{WP} \cdot 0.1039 \cdot 8640}{0.6} \tag{6.9}$$

The operating costs of the boiler (COPB) and cooling tower (COPC) are taken from the costs of the utilities used; these are variables that Aspen Plus® provides specifying the type of utility and the unit cost of everyone: for the boiler, it is a natural gas with a unit cost of 0.8552 \$/kg, and for the cooling tower, water was used as a cooling utility with a unit cost of $5.28 \times 10^{-4}$ \$/kg. The capital cost factor (CCF) is taken into account for thermoelectric plants with a value of 0.1.

### 6.2.3 *Definition of the Objective Functions*

The gross annual profit (to be maximized) and the environmental impact (to be minimized) of steam power plants are taken as the two objectives to be simultaneously optimized. Next, we present the equations used to calculate these objective functions.

### 6.2.4 Economic Objective Function

The economic objective function consists in the maximization of the gross annual profit, which represents the difference between the total income and the total annual cost of the steam power plant. The performance of the economic objective function is calculated repetitively using the presented equations starting with the response variables obtained by the simulation software. The economic objective function is expressed in Eq. (6.10):

$$\text{Net Profit} = \left(-\text{WT}\cdot\text{PkWh}\cdot t_{\text{OP}}\right) - \left(\text{CB}+\text{CP}+\text{CT}+\text{CC}\right)\cdot\text{CCF} - \left(\text{COPP}+\text{COPB}+\text{COPC}\right) \tag{6.10}$$

### 6.2.5 Environmental Objective Function

In this study, the environmental objective function is to minimize the entire $CO_2$ emissions associated with electricity generation in power plants that use natural gas as primary energy source.

Aspen Plus® can calculate $CO_2$ emissions using US-EPA-Rule-E9-5711 as $CO_2$ emission factor data source with a value of $2.3e^{-07}$ kg/cal for natural gas. We assume a $CO_2$ energy source efficiency factor of 0.85, and starting with the needed heat in the boiler, which is a response variable calculated by Aspen Plus® after running the simulation of the power plant, we can calculate the total $CO_2$ emission.

## 6.3 Stochastic Optimization Algorithm Used

The multi-objective optimization hybrid method, namely, improved multi-objective differential evolution (I-MODE) developed by Sharma and Rangaiah (2013), is used as stochastic algorithm for the optimization of the process in this example. This improved multi-objective differential evolution algorithm works with a termination criterion using the non-dominated solutions obtained as the search process.

There were selected eight decision variables and introducing a value for the lower and upper boundary. The values of the selected decision variables for the lower and upper bounds, respectively, are 590 and 610 °C for operation temperature in the boiler, 38 and 42 atm for the pressure in the boiler, 18 and 22 atm for the pressure decrease in the HP turbine, 8 and 12 atm for the pressure decrease in the IP turbine, 4 and 6 atm for the pressure decrease in the LP turbine, 38 and 42 atm for the pressure in the pump, and 0.7 and 0.9 for the split fraction in both splitters. All decision variables were selected as continuous variables and the initial value for each was the half between the minimum and the maximum possible value. The

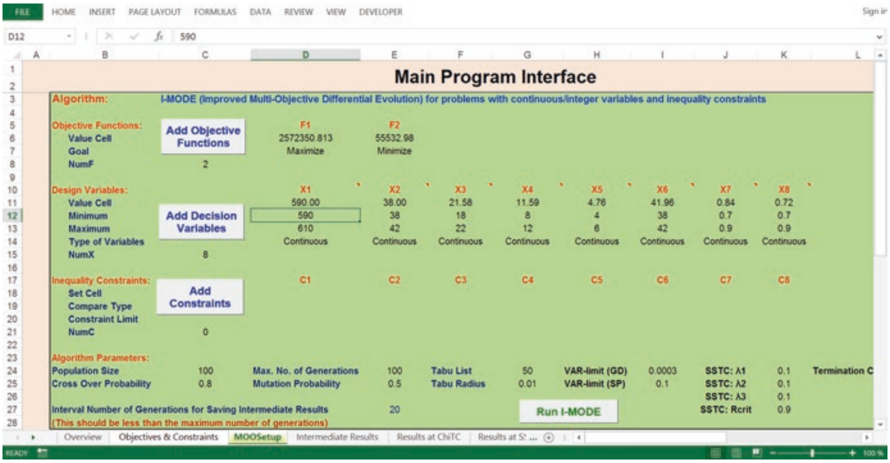


**Fig. 6.3** MS Excel® sheet were main program user interface of the I-MODE (case 1)

optimization was developed without any inequality constraint. These values of the decision variables are introduced into the Main Program User Interface of the I-MODE as shown in Fig. 6.3.

For the optimization process, in this case study, the values for the parameters associated with the used I-MODE algorithm are the following: population size (NP) of 100 individuals, generation number (GenMax) of 100, taboo list size (TLS) of 50 individuals, taboo radius (TR) of 0.01, crossover fractions (Cr) of 0.8, and mutation fractions (F) of 0.5. These values of the parameters associated with the used of the algorithm are also introduced into the main program user interface of the I-MODE as shown in Fig. 6.3.

## 6.4 Link Between the Process Simulator and Optimization Algorithm

For the adequate link between the process simulator software (Aspen Plus for this example) and the stochastic optimization algorithm (the I-MODE in this case), it is necessary to follow the methodology mentioned in previous chapters. It is recommendable to add two more MS Excel® sheets, the first one for the decision variable values that will be sent to the simulator (Fig. 6.4) and the second one for the response variable values that will be received from the simulator (Fig. 6.5).

As can be seen, the additional equations of the mathematical formulation must be introduced in the MS Excel® sheet shown in Fig. 6.5. After that, the appropriated internal link between the decision variables, response variables, and objective functions must be established. Then, run the I-MODE since main program user interface.

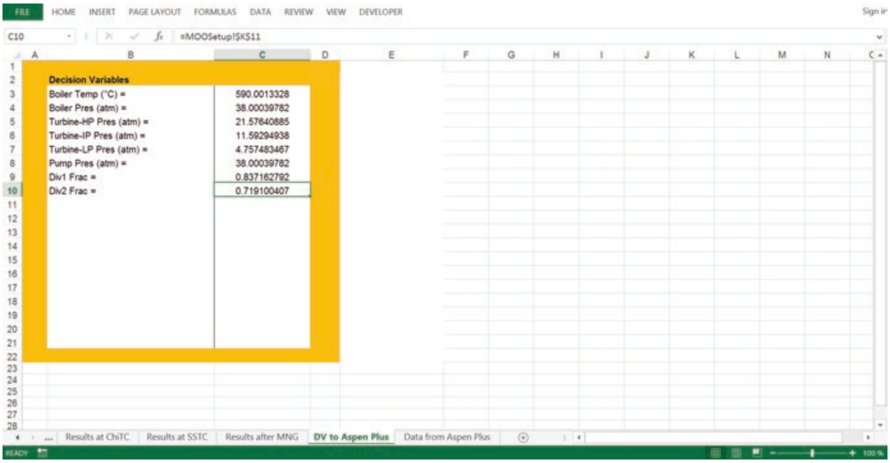


**Fig. 6.4** MS Excel® sheet were decision variable values will be sent to the process simulator (case 1)

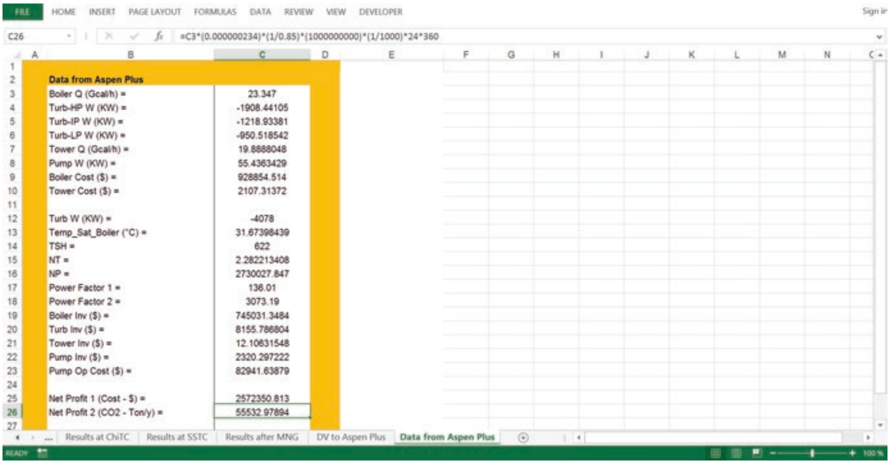


**Fig. 6.5** MS Excel® sheet were response variable values will be received from the simulator (case 1)

## 6.5 Results

This section presents the results of the multi-objective optimization method applied to the case study described in this chapter. All the runs were obtained from an Intel(R) Core TM i7-4700MQ CPU at 2.4 GHz, 32 GB computer; the computing time required to obtain the Pareto optimal solutions varied from 10 to 15 min.

The proposed strategy yields the Pareto sets shown in Figs. 6.6, 6.7, and 6.8, which show the optimal solution generated according to the stochastic procedure of

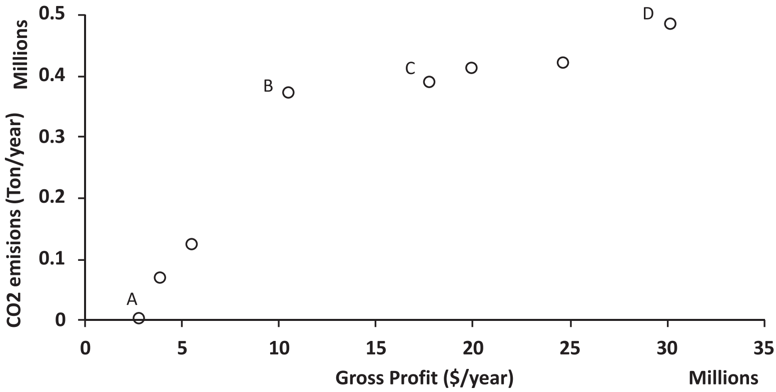


**Fig. 6.6** Graphic of the results at the Chi-squared termination criterion (ChiTC)

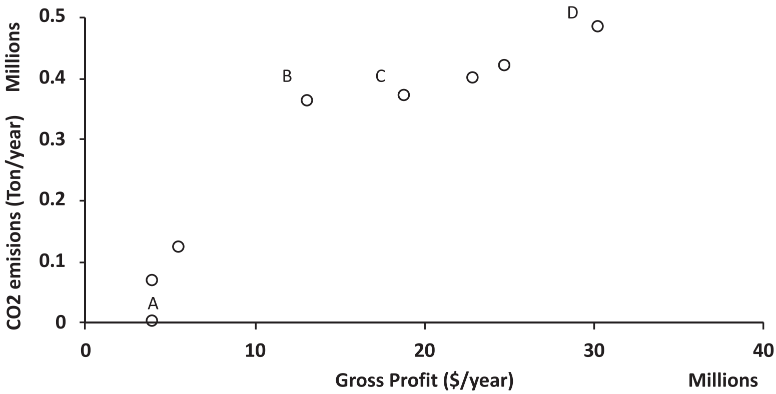


**Fig. 6.7** Graphic of the results at the steady-state termination criterion (SSTC)

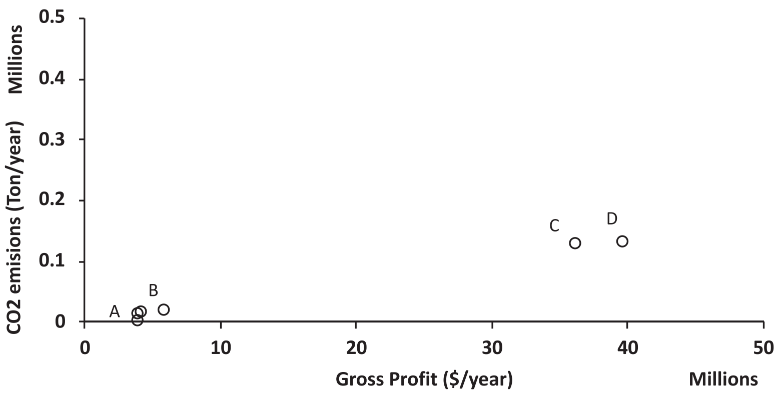


**Fig. 6.8** Graphic of the results of the last generation

this method. The three different presented plots depend on the termination criteria. The shown Pareto plots were obtained starting with the selected decision variables, their values for the lower and upper bounds, and the values for the parameters associated with the used I-MODE algorithm presented in Chap. 3.

The results for the Chi-squared termination criterion (ChiTC) are shown in Fig. 6.6, which converges in 37 generation. In this plot, four important points can be seen (A, B, C, and D). In point A is shown the minimum value for $CO_2$ emissions (0 ton/year), but this point has a gross profit of 2,922,390 \$/year, which is low. In point B and point C, there can be seen acceptable values for both objective functions ($CO_2$ emissions of 369,344 ton/year with a gross profit of 10,624,510 \$/year for point B and $CO_2$ emissions of 385,858 ton/year with a gross profit of 17,891,507 \$/year for point C). And point D shows the maximum value for the gross profit (30,330,600 \$/year), but this point has the maximum value for $CO_2$ emissions too (483,497 ton/year). After the analysis of the graphic shown in Fig. 6.6, it was concluded that the best point is C because it offers a better gross profit than point B with a minimum increment in the $CO_2$ emissions.

The results for the steady-state termination criterion (SSTC) are shown in Fig. 6.7, which converges in 53 generations. In this graphic, four important points can be seen (A, B, C, and D). In point A is shown the minimum value for $CO_2$ emissions (0 ton/year), but this point has a gross profit of 3,975,780 \$/year, which is low. In point B and point C, there can be seen acceptable values for both objective functions ($CO_2$ emissions of 361,757 ton/year with a gross profit of 13,161,987 \$/year for point B and $CO_2$ emissions of 370,516 ton/year with a gross profit of 18,896,151 \$/year for point C). And point D shows the maximum value for the gross profit (30,330,600 \$/year), but this point is the maximum value for $CO_2$ emissions too (483,497 ton/year). After the analysis of the graphic shown in Fig. 6.7, it was concluded that the best point is C because it offers a better gross profit than point B with a minimum increment in the $CO_2$ emissions.

And the results for the last generation are shown in Fig. 6.8. In this graphic, four important points can be seen (A, B, C, and D). In point A is shown the minimum value for $CO_2$ emissions (0 ton/year), but this point (just as in the graphic shown in Fig. 6.7) has a gross profit of 3,975,780 \$/year, which is low. Point B shows values not much different of point A ($CO_2$ emissions of 18,597 ton/year with a gross profit of 5,868,030 \$/year). In point C and point D, there can be seen acceptable values for both objective functions ($CO_2$ emissions of 126,794 ton/year with a gross profit of 30,194,163 \$/year for point C and $CO_2$ emissions of 130,249 ton/year with a gross profit of 39,687,071 \$/year for point D). Point D shows the maximum value for the gross profit and the maximum value for $CO_2$ emissions too, but this point is not much different than point C in the value of $CO_2$ emissions, and it offers a considerable increment in the value of the gross profit. Based on this, it was concluded that the best point is D.

The I-MODE algorithm gives the optimal values for all the decision variables. The optimal values of the selected decision variables after running the optimization are the following: 590 °C for operation temperature in the boiler, 38.00 atm for the pressure in the boiler, 21.58 atm for the pressure decrease in the HP turbine, 11.59 atm for the pressure decrease in the IP turbine, 4.76 atm for the pressure decrease in the LP turbine, 41.96 atm for the pressure in the pump, and 0.84 and 0.72 for the split fraction in the first and second splitters, respectively.

The optimal value of the economic objective function, which consists in the maximization of the annual gross profit, is $2,572,350/year. The optimal value of the environmental objective function, which consists in the minimization of the entire $CO_2$ emissions associated with electricity generation in power plants that use natural gas as primary energy source, is 55,532 ton/year.

## 6.6 Exercises

To download the example of the Generation Power Plant, please click on the following link:

http://extras.springer.com

1. Use the process flowsheet of a regenerative Rankine cycle made in Aspen Plus just as shown in this chapter (Fig. 6.2).
2. Do the following (remember run the simulation after change of any specification):
   (a) Change the operation specification in the boiler, temperature of 590 °C and pressure of 18 atm (the discharge pressure of the pump must be of 18 atm too). What happen with the value of the generated work in the turbines? Why?
   (b) Change the total flow rate of the stream number 1, with a value of 2000 ton/day. What happen with the value of the generated work in the turbines? Why?
3. Use the main program user interface of the I-MODE algorithm shown in Fig. 6.3.
4. Implement the following:
   (a) Change the lower and upper bounds of the decision variables, 580 and 620 °C for the operation temperature in the boiler, 38 and 42 atm for the pressure in the boiler, 16 and 24 atm for the pressure decrease in the HP turbine, 6 and 14 atm for the pressure decrease in the IP turbine, 2 and 8 atm for the pressure decrease in the LP turbine, 36 and 44 atm for the pressure in the pump, and 0.65 and 0.95 for the split fractions in both splitters.
   (b) For the optimization process, in this case study, the values for the parameters associated with the used I-MODE algorithm are the following: population size (NP) of 1000 individuals, generation number (GenMax) of 1000, taboo list size (TLS) of 50 individuals, taboo radius (TR) of 0.01, crossover fractions (Cr) of 0.9, and mutation fractions (F) of 0.6.
   (c) Apply the same methodology to the conventional Rankine cycle, choose four decision variables, and propose different objective functions. Explain the obtained results.

## 6.7 Nomenclature

| | |
|---|---|
| CB | Cost of the boiler |
| CC | Cost of the cooling tower |
| CP | Cost of the pump |
| CT | Cost of the turbine |
| COPB | Cost of operation of the boiler |
| COPC | Operation cost of the cooling tower |
| COPP | Cost of operation of the pump |
| COPT | Turbine operating cost |
| FCC | Capital cost factor |
| Net profit | Net profit |
| $N_p$ | Cost factor in the boiler pressure |
| $N_t$ | Overheating factor in the boiler |
| $P_b$ | Boiler outlet pressure |
| $P_c$ | Pressure of the cooling tower |
| $P_p$ | Discharge pressure of the pump |
| $P_t$ | Turbine output pressure |
| $Q_b$ | Heat produced in the boiler |
| $Q_c$ | Heat removed from the cooling tower |
| $T_b$ | Temperature of the boiler |
| $T_c$ | Temperature of the cooling tower |
| $T_p$ | Temperature in the pump |
| $T_t$ | Turbine output temperature |
| $T_{sb}$ | Saturation temperature in the boiler |
| $T_{sh}$ | Wet bulb temperature |
| $W_n$ | Electric energy produced in the turbine |
| $W_p$ | Work required by the pump |