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# PRELIMINARY DESIGN OF OPTIMAL COMBINED CYCLE POWER PLANTS THROUGH EVOLUTIONARY ALGORITHMS.

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**Key words:** Combined Cycle Gas Turbine Power Plant, Optimization, Evolutionary Algorithms.

**Abstract.** *This paper is concerned with the technoeconomic optimization of investments in combined cycle gas turbine (*CCGT*) power plants. Three* CCGT *power plant design problems, with total power output in the range of* $[170, 200]$ $MW$*,* $[360, 400]$ $MW$ *and* $[720, 800]$ $MW$*, are analyzed and discussed. In each one of them, the gas turbine (*GT*) is selected from a list of models which are available in the marketplace and produce, used as a single or multiple units,* $\sim 120MW$*,* $\sim 260MW$ *and* $\sim 520MW$*, respectively.*

*The constrained, multiobjective optimization is carried out through evolutionary algorithms; the design space consists of continuous and integer variables, where the latter correspond to the selection of the* GT *model from a database as well as the type of heat recovery steam generator (*HRSG*). Pareto fronts on the plant efficiency - investment cost plane are plotted and compared with optimal designs based on preselected* GT *models. For each* GT *model, the design of the optimal* HRSG *is of particular importance; one-, two- and three-pressure systems, without or with reheat, are used.*

## 1 DESCRIPTION OF THE POWER PLANTS

As previously stated, this paper is concerned with the design of three *CCGT* power plants (to be referred to as $A$, $B$ and $C$) with different total power output each. Emphasis is put to (a) the selection of the *GT* model from a list of available models and (b) the design of the corresponding *HRSG*. We recall that the designs analyzed below correspond to plants with total power output in the range of:

| Power Plant | Total Power Output (MW) |
|---|---|
| $A$ | [170,200] |
| $B$ | [360,400] |
| $C$ | [720,800] |

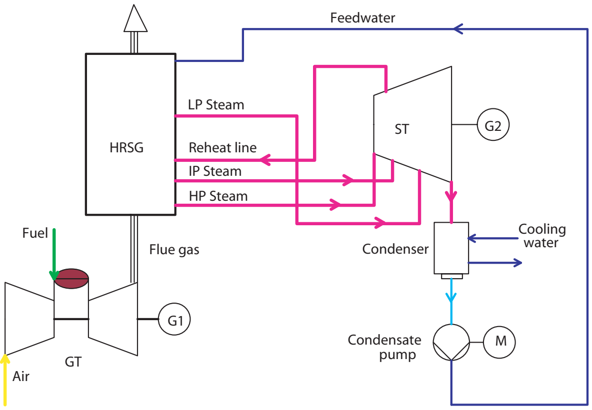

Figure 1: *CCGT* power plant, with a three pressure level *HRSG* and reheat (full configuration).

For each design problem, a pool of candidate *GT* models is formed. Tables 1 (for plant $A$) and 2 (plants $B$ and $C$) summarize the aforementioned *GT* models. Only the first half entries in table 2 can be used for the design of plant $B$. Thus, to summarize, the number of possible *GT* models for plants $A$, $B$ and $C$ are sixteen, four and eight, respectively. Note that this has been computed by considering that the *GT* power output should be approximately equal to two thirds of the total power output. For each *GT* model, the power output, exhaust gas mass flow rate and temperature, efficiency, pressure ratio and cost are tabulated and used. The last column indicates the number of units that should be used in order to achieve the required total power output.

The *CCGT* power plant configuration is schematically given in fig. 1. In this figure, a three-pressure *HRSG* with reheat is shown; any simpler *HRSG* configuration can be derived in a straightforward manner. The *HRSG* should be selected among the following four configurations:

1. one-pressure *HRSG* (*HRSG*-1),

| No. | Power Output | Exh. Gas Mass Flow | Exh. Gas Temper. | Effici-ency | Pressure Ratio | Cost | Number of Units |
|---|---|---|---|---|---|---|---|
| | $(kW)$ | $(kg/s)$ | $(^oC)$ | (%) | | MEuro | Plant $A$ |
| $GT$-1 | 103112 | 213.2 | 410.0 | 43.9 | 41.0 | 39.86 | 1 |
| $GT$-2 | 27520 | 91.8 | 500.0 | 36.2 | 20.8 | 17.53 | 4 |
| $GT$-3 | 56300 | 197.3 | 508.0 | 33.9 | 17.6 | 22.45 | 2 |
| $GT$-4 | 115400 | 400.0 | 531.0 | 33.6 | 15.5 | 32.90 | 1 |
| $GT$-5 | 58000 | 165.9 | 423.3 | 40.9 | 36.0 | 27.26 | 2 |
| $GT$-6 | 29060 | 91.4 | 517.8 | 36.0 | 18.0 | 14.78 | 4 |
| $GT$-7 | 29500 | 95.9 | 493.3 | 37.7 | 21.5 | 17.21 | 4 |
| $GT$-8 | 29921 | 88.7 | 527.8 | 37.1 | 23.1 | 17.29 | 4 |
| $GT$-9 | 30000 | 108.2 | 532.8 | 32.0 | 15.0 | 17.40 | 4 |
| $GT$-10 | 41711 | 127.0 | 447.8 | 40.7 | 29.3 | 17.49 | 3 |
| $GT$-11 | 63000 | 192.2 | 531.0 | 35.2 | 16.1 | 24.67 | 2 |
| $GT$-12 | 126100 | 419.1 | 542.8 | 33.8 | 12.6 | 32.90 | 1 |
| $GT$-13 | 42100 | 141.4 | 547.8 | 32.1 | 12.2 | 18.69 | 3 |
| $GT$-14 | 42519 | 130.2 | 415.6 | 39.8 | 29.2 | 16.72 | 3 |
| $GT$-15 | 32120 | 94.5 | 503.3 | 39.3 | 21.5 | 18.46 | 4 |
| $GT$-16 | 45000 | 130.5 | 538.3 | 37.0 | 19.3 | 19.67 | 3 |

Table 1: Candidate $GT$ models for the design of power plant $A$.

2. two-pressure *HRSG* (*HRSG*-2),
3. three-pressure *HRSG* (*HRSG*-3),
4. three-pressure *HRSG*, with reheat (*HRSG*-4).

The corresponding heat-temperature diagrams are shown in fig. 2.

The efficiency of the steam turbine ($ST$) components and that of generator ($G2$) are fixed. More precisely, the isentropic efficiency of the *HP*, *IP*, *LP ST* components is set to 92%, 90% and 87%, respectively; the mechanical and electrical efficiency is also fixed and equal to $\eta_{mech} = 95\%$ and $\eta_{el}$=98%. The vacuum in the condenser is 51 $mbar$, which ensures minimal waste heat in the condenser for the inlet cooling water temperature of $22^oC$.

The design variables which correspond to the three-pressure level *HRSG*, without or with reheat, are listed below. The lower and upper bounds of these variables, which are common in all cases are also given in brackets. Only real valued variables are listed; over and above, two integer valued design variables are used to determine the $GT$ model and the *HRSG* type (pressure levels, with or without reheat). The real valued design variables are:

- the *HP* steam pressure, $[50, 100\ bar]$,

| No. | Power Output | Exh. Gas Mass Flow | Exh. Gas Temper. | Efficiency | Pressure Ratio | Cost | Number of Units |
|---|---|---|---|---|---|---|---|
| | $(kW)$ | $(kg/s)$ | $(^oC)$ | (%) | | Meuro | Plant $B/C$ |
| $GT$-1 | 255600 | 640.36 | 602.2 | 36.9 | 17.0 | 67.70 | 1/2 |
| $GT$-2 | 263000 | 607.25 | 615.0 | 37.0 | 32.0 | 67.76 | 1/2 |
| $GT$-3 | 265900 | 655.78 | 584.4 | 38.6 | 17.0 | 73.63 | 1/2 |
| $GT$-4 | 126100 | 418.63 | 542.8 | 33.8 | 12.6 | 29.90 | 2/4 |
| $GT$-5 | 270300 | 650.79 | 586.1 | 38.2 | 17.0 | 75.20 | -/2 |
| $GT$-6 | 165100 | 533.18 | 524.0 | 35.7 | 14.6 | 40.56 | -/3 |
| $GT$-7 | 169100 | 509.09 | 556.1 | 34.9 | 14.0 | 42.48 | -/3 |
| $GT$-8 | 159400 | 510.00 | 547.2 | 34.3 | 11.4 | 42.99 | -/3 |

Table 2: Candidate $GT$ models for the design of power plants $B$ and $C$.

- the $IP$ steam pressure, $[20, 40\ bar]$,
- the $LP$ steam pressure, $[1, 15\ bar]$,
- the superheated steam temperature at the exit of the $HP$ branch of the $HRSG$, defined as the difference from the $GT$ exhaust gas temperature, $[30, 50\ K]$,
- the steam temperature at the exit of the reheater or the second $IP$ superheater (for a three-pressure $HRSG$, with or without reheat, respectively), defined as the difference from the $GT$ exhaust gas temperature, $[30, 50\ K]$,
- the superheated steam temperature at the exit of the $LP$ branch of the $HRSG$, defined as the difference from the steam temperature at the exit of the first $IP$ superheater, $[1, 5\ K]$,
- the steam temperature at the exit of the first $IP$ superheater, defined as the difference from the saturated steam temperature at the same pressure, $[10, 40\ K]$,
- the ratio of heat exchanged at the third $HP$ economizer to the total heat exchanged at the second and third $HP$ economizers, $[10\%, 50\%]$,
- the $HP$ pinch point temperature difference $[4, 12\ K]$,
- the $IP$ pinch point temperature difference $[4, 12\ K]$,
- the $LP$ pinch point temperature difference $[4, 12\ K]$,
- the $HRSG$ exhaust gas temperature $[85, 100^oC]$.

It is evident that, for the two- or one- pressure *HRSGs*, some of the above design variables do not apply. For instance, in one-pressure *HRSGs*, the *IP* and *LP* steam

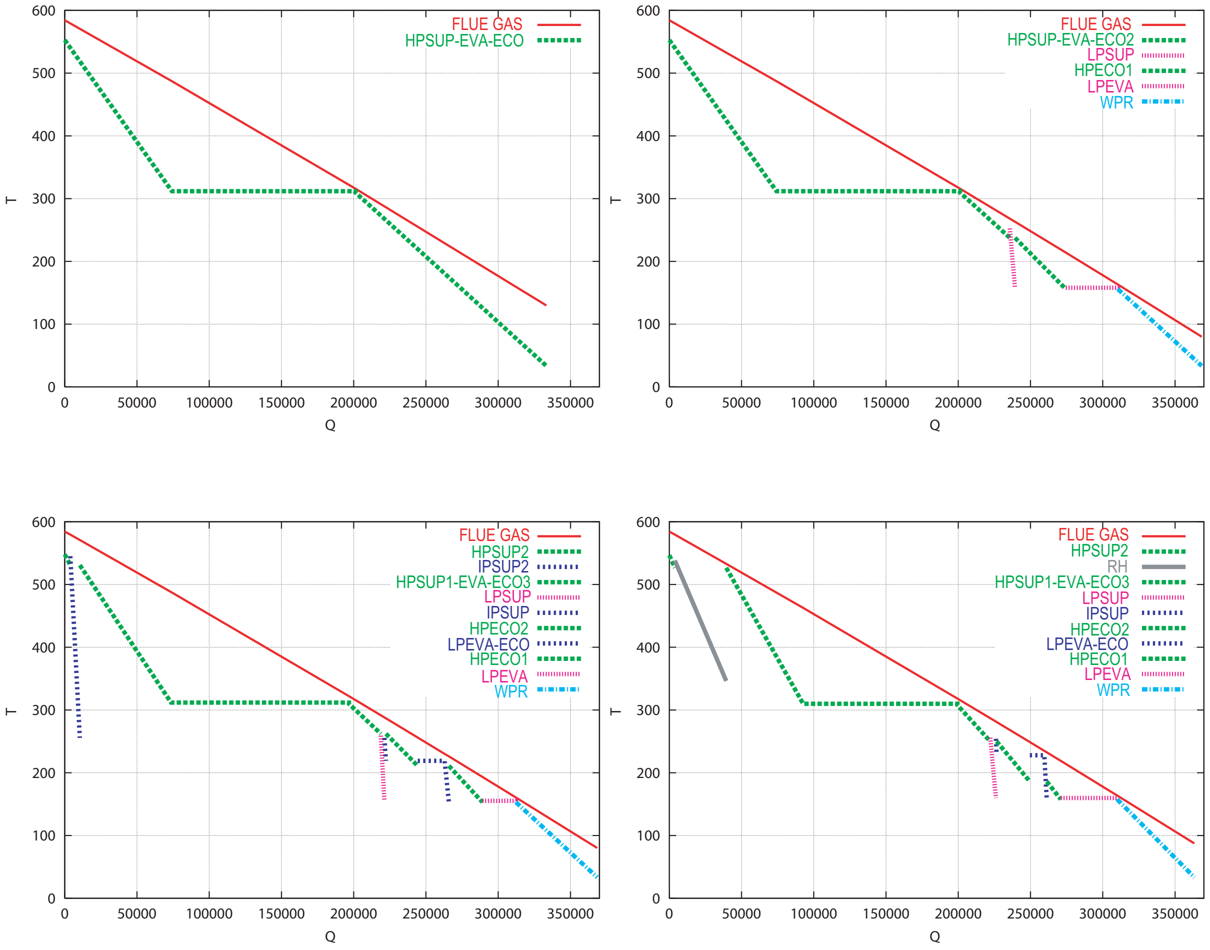

Figure 2: Heat-temperature ($Q-T$) diagrams of: one-pressure $HRSG$ (top-left), two-pressure $HRSG$ (top-right), three-pressure $HRSG$ (bottom-left), three-pressure $HRSG$ with reheat (bottom-right). Notations: $HP$: high pressure, $IP$: intermediate pressure, $LP$: low pressure, $ECO$: economizer, $EVA$: evaporator, $SUP$: superheater, $RH$: reheater, $WPR$: water preheater.

pressure values and pinch point temperature differences become redundant. Apart from the two integer valued design variables which correspond to the $GT$ model and the $HRSG$ type, three (seven) real valued design variables are to be used in the case of a one- (two-) pressure $HRSG$.

The power output of the combined cycle is calculated by solving the energy and mass balance equations at each element of the water/steam cycle. The outcome of the computation is the sum of $GT$ and $ST$ power output (i.e. the total power output) and the plant efficiency; to compute the latter, the $GT$ fuel consumption should be taken into account. The plant investment cost is computed using empirical functions for the $HRSG$ and $ST$ as well as the (known) price of the selected $GT$ model. The cost of the whole plant is directly proportional to the sum of the above costs. More on the evaluation software can be found in previous publications by the authors, [1, 2, 3].

For each candidate configuration, the heat–temperature diagram for the selected type of *HRSG* is calculated. At each point across the *HRSG*, the water/steam temperature should not exceed the flue gas one. Also, the temperature at the inlet to the *ST* should not exceed $565^oC$ and the quality of steam at the exit of the *LP ST* must be higher than 0.80. Thus, we come up with a constrained optimization problem. For each inequality constraint which is violated, the cost value of all the objectives is multiplied by a penalty factor which is an exponential function of the constraint violation percentage.

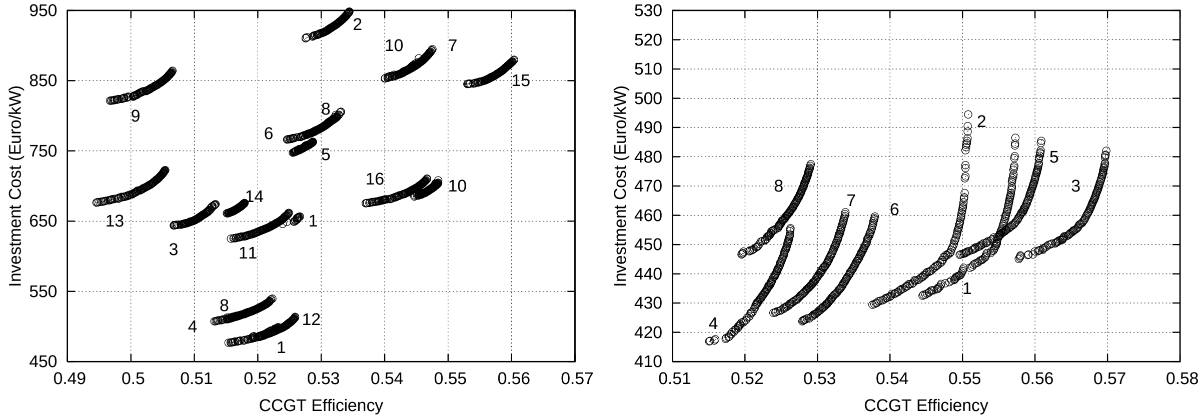

Figure 3: Plant *A* (left) and *C* (right): Separately computed Pareto fronts for each and every *GT* listed in tables 1 (plant *A*) and 2 (plant *B*). In all these cases, a two-pressure *HRSG* (*HRSG*-2) is used.

## 2 THE OPTIMIZATION TOOL

The optimization software used is code *EASY*, developed and brought to market by the National Technical University of Athens. It is based on generalized evolutionary algorithms and handles three populations, namely the parent population with $\mu$ individuals, the offspring population with $\lambda$ individuals and the archival set with $e$ individuals at most. In multi-objective optimization problems, treated through the Pareto front concept, the latter collects the non-dominated solutions in each generation. Should their number exceed $e$, a thinning process is employed. Thinning aims at identifying a subset of non-dominated solutions along the current optimal front; this subset should be spread over the entire front while possessing adequate diversity.

This paper deals with two-objective optimization problems where fitness assignment is carried out through the *SPEA2* technique, [4]. *SPEA2* employs an enhanced fitness assignment strategy along with techniques for archive truncation and density-based selection.

## 3 METHOD APPLICATION

In this section, optimally designed configurations for plants *A*, *B* and *C* are presented and analyzed.

At a first step, a number of preliminary runs is made in order to comparatively investigate the performance of *GTs* listed in tables 1 and 2. For this purpose, for the design objectives of plants *A*, *C* and a two-pressure *HRSG*, sixteen (for plant *A*) and eight (plant *C*) optimizations are carried out, each of which for a different *GT* model. Results, plotted in the form of Pareto fronts of optimal solutions on the efficiency–cost plane are shown in fig. 3. As far as the optimization tool is of concern, it should be stated that, during the computations, all of the design variables are real valued and the redundant ones (such as the *IP* steam pressure) among them are eliminated. For plant *A* (left), *GT*-10, 12, 15, 16 clearly dominate over the remaining twelve *GTs* of table 1. For plant *C*, the dominating *GTs* are: 1, 3, 4, 6. In the last case, more comments can be made for distinguishing the dominating *GTs*; so, *GT*-3 yields higher efficiency with higher investment cost whereas *GT*-4 is the dominant low efficiency–low cost solution.

Fig. 4 presents the optimization results for the design of all three power plants. According to the experience gained from fig. 3, although this governs only the use of a two–pressure *HRSG*, the computed Pareto fronts are expected to consist of distinct parts, each of which corresponds to a different *GT* model and/or *HRSG* type. Note that, for plant *A* (left), the dominant *GT* models in fig. 3 exclusively form the Pareto front of fig. 4; however, each one of these models can be optimally combined with a different *HRSG* (in particular, *HRSG*-2, -3, -4) over different parts of the Pareto front. There is no optimal solution based on one-pressure *HRSGs* since these are filtered out by the constraint governing the steam quality at the exit of the *LP ST*. Also, for the same *GT* model (for instance, *GT*-15), switching from two- to three-pressure *HRSG* yields better plant efficiency with higher investment cost per $kW$. The optimal solutions for plants *B* and *C* (right) almost exclusively consist of configurations with a two-pressure *HRSG*. Only the right-top most part of the front corresponds to a three-pressure *HRSG* with reheat which is an expensive, though well performing solution. For plant *B*, it should also be mentioned that all four candidate *GTs* appear on different parts of the Pareto front.

The optimal solutions can be further scrutinized so as to clearly understand the role of the design parameters. Further insight to rules governing the design of optimal *CCGT* power plants can be gained by examining the *HP* pinch point temperature difference and the pressure value at the *HP* steam circuit (figs. 5 and 6). Regardless of the power plant (*A*, *B* or *C*) under consideration, optimal solutions that maximize cost and efficiency require maximum *HP* steam pressure; from both figures, it is clear that the corresponding major part of the optimal front operates at the upper bound of the *HP* steam pressure defined by the user for the needs of the evolutionary search. At the same time, the highest efficiency and cost, the lower the temperature difference at the *HP* pinch point. On the other hand, cheap optimal solutions with low efficiency operate with the maximum

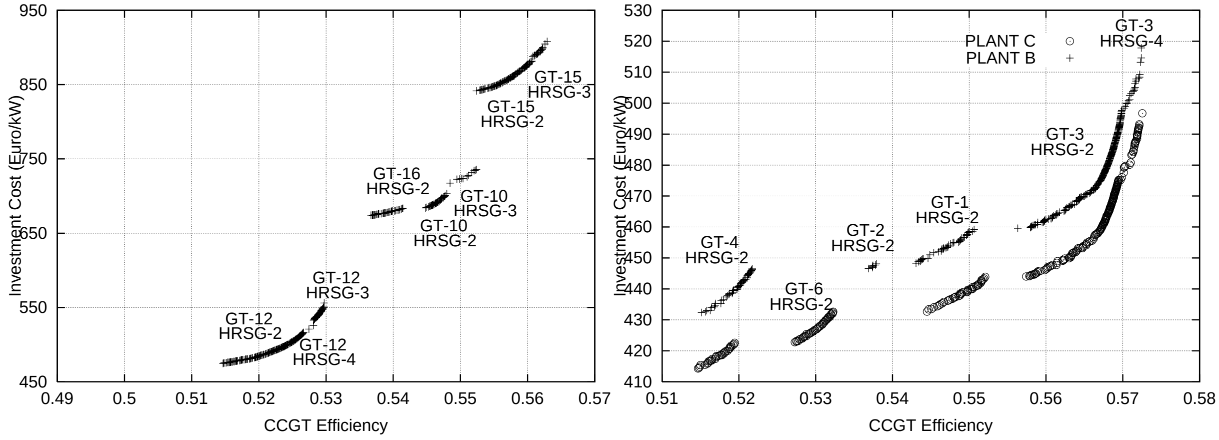

Figure 4: Plant $A$ (left) and $B, C$ (right): Pareto fronts computed using evolutionary algorithms. On each part of the disjoint Pareto front, the $GT$ model and the type of $HRSG$ used are marked.

allowed temperature difference at the $HP$ pinch point.

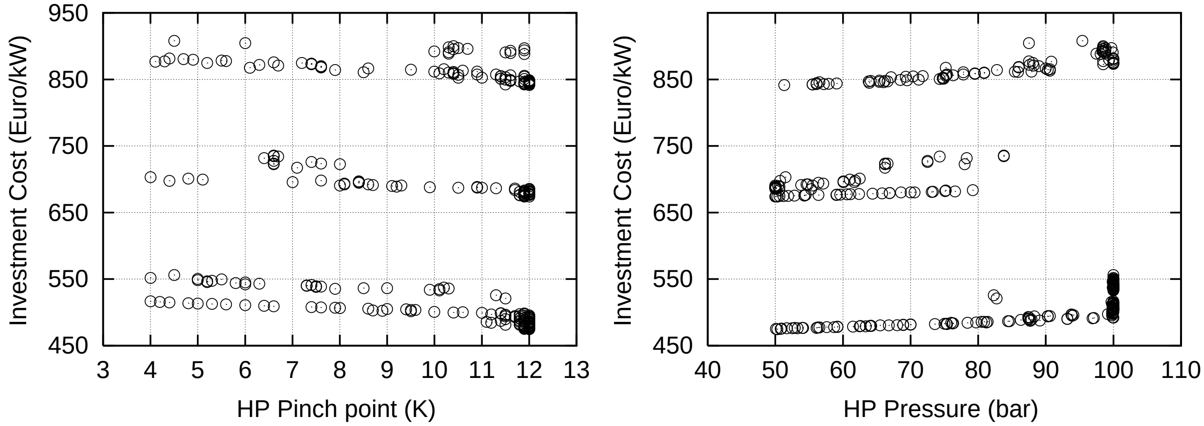

Figure 5: $HP$ pinch point temperature difference (left) and pressure value at the $HP$ steam circuit (right) for the Pareto optimal solutions of fig. 4, for plant $A$.

$LP$ and $IP$ pressure values for the Pareto optimal solutions are shown in fig. 7. Since none of the optimal solutions possesses a single-pressure $HRSG$, the left figure ($LP$ steam pressure) is valid for all optimal solutions and shows that, for the present configurations, the $LP$ steam pressure should stay within 4 and 6 bar, regardless of the final cost and efficiency. The right figure ($IP$ steam pressure) is meaninful only for solutions with a three-pressure $HRSG$ ($HRSG$-3 or 4). For plant $A$, optimal solutions with $[20, 25]$ bar have been found, all of them with a three-pressure $HRSG$ without reheat. For plants $B$ and $C$, the optimal $IP$ pressure values are $[30, 40]$ bar, with a three-pressure $HRSG$, with

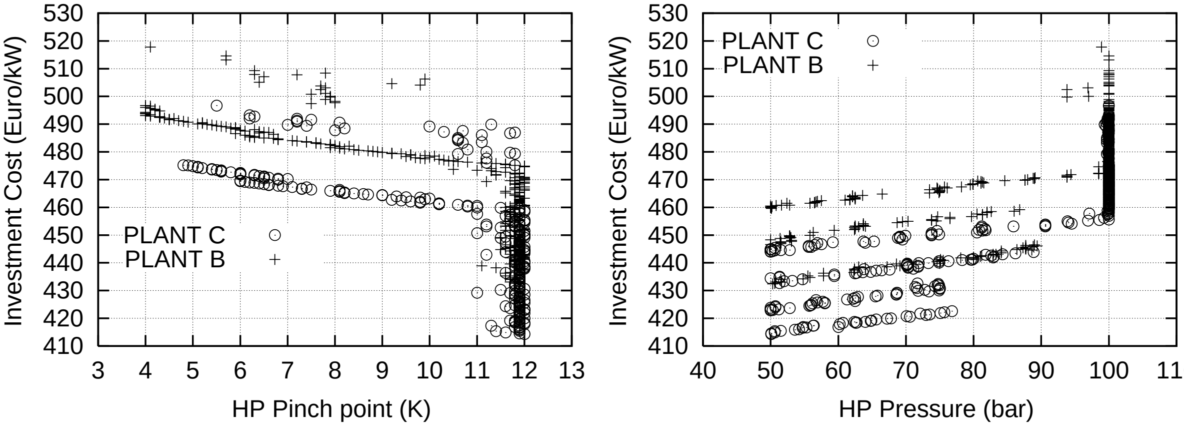

Figure 6: *HP* pinch point temperature difference (left) and *HP* steam pressure (right) for the Pareto optimal solutions of fig. 4, for plants *B* and *C*.

reheat.

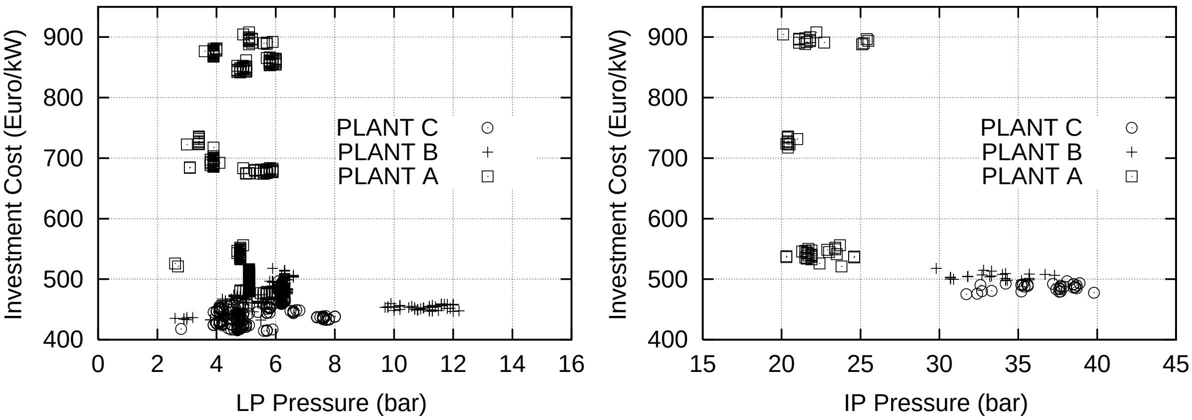

Figure 7: *LP* and *IP* pressure values for the Pareto optimal solutions of fig. 4, for plants *A*, *B* and *C*.

Fig. 8 shows the steam quality at the *ST* outlet. It is obvious that the constraint on steam quality is active and that some otherwise optimal solutions are automatically rejected since the corresponding steam quality is lower than 0.80. As expected, the higher the efficiency, the lower the steam quality. Steam quality values below 0.85 are computed for most of the optimal solutions; however, there are two groups of optimal solutions with steam quality in the range $[0.85, 0.90]$ and these correspond to three-pressure *HRSGs* with reheat.

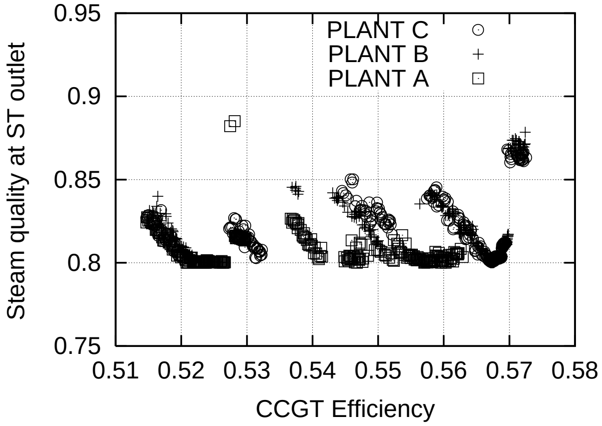

Figure 8: Steam quality at the exit from the *ST* for the Pareto optimal solutions of fig. 4, for plants *A*, *B* and *C*.

## 4 CONCLUSIONS

This paper demonstrated the use of evolutionary algorithms as optimization tool for the design of combined cycle gas turbine power plants, with maximum efficiency and minimum investment cost. For three power plants with given specifications, the evolutionary algorithm takes over the search for the optimal combination of a gas turbine (selected from a database of available models), the type of the heat recovery steam generator (concerning the number of pressure levels and the possible use of reheat) and its major characteristics. A constrained optimization problem was formed and solved without taking particular care of the presence of mixed integer-real valued design variables or the fact that some of the design variables become redundant in some of the steam generator configurations.

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