APPLICATION OF SUPERSTRUCTURES TO THE OPTIMIZATION OF COGENERATION SYSTEMS

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Abstract. *This work presents a new approach, based on the application of superstructures, to the structural and parametric optimization of energy systems. Emphasis is placed on cogeneration systems. The basic strategy consists in the replacement of the original integrated optimization problem with a multilevel problem. In the first-level problem, the superstructure for the energy system is decomposed into several smaller thermoeconomically isolated subsystems, each with its own goals and constraints. Specific exergoeconomic costs of the outputs (products) of these subsystems are independently minimized. The conceived superstructure, modeled here within the environment of a professional process simulator, inserts the major design options suitable to the case under study. In the second-level problem, the optimal configuration of the energy system is determined, limited to the configuration options embedded in the modeled superstructure. The first-level optimization routines are based on the flexible polyhedron method, whereas the second-level optimization routine combine the latter with principles from exergoeconomic analysis. To evaluate the new approach, the optimization of a cogeneration system with fixed process energy demands is carried out, allowing for variable configurations within a superstructure.*

Keywords. *superstructures, optimization, cogeneration systems, exergoeconomic analysis*

1. Introduction

Nowadays, due to issues such as environmental preservation, economical competitiveness and even the survival of the human race, the optimal utilization of natural energy resources, particularly the unrenewable ones, becomes necessary in order to rationally maintain the activities on the planet. Cogeneration systems, which are known to operate more efficiently than systems yielding heat and power separately, should therefore be installed whenever possible.

Cogeneration systems (Balestieri, 2002; Horlock, 1997) are essential to industrial and commercial facilities dealing with electrical and thermal energy demands. The efficient design, operation and maintenance of cogeneration plants, as well as their installation, are factors that contribute to a better economic performance and an increase in the competitiveness of cogeneration enterprises. Moreover, because cogeneration system design costs and complexity are increasing, it becomes necessary to understand and to additionally improve the design procedures for cogeneration systems. In recent times, in Brazil, this necessity is further motivated by the expectation of installation of many cogeneration plants, due to changes in the regulations of the electrical energy sector.

After computers became a reality in the 60's and 70's, the design and optimization of thermal systems, especially cogeneration plants, have been evolving together with the development and large scale application of suitable techniques and methods of analysis. Examples of these techniques and methods are: exergoeconomic analysis and optimization (Vieira et al., 2000; Donatelli et al., 2000; Tsatsaronis, 1993), improvement of estimation procedures for thermodynamic properties of substances, development and application of process simulators, and, more recently, programs based on artificial intelligence (Sciubba and Melli, 1998), which aim at the conception of suitable configurations for thermal systems.

In view of the above scenario, it is thus academically and practically significant to carry on research towards a general method that can provide the optimal thermal system (optimized configuration and operation of system's components) with few initial data. In this paper, we present a new approach, based on the application of superstructures, to the structural and parametric optimization of energy systems. The approach is largely computational, and simultaneously combines the technique of superstructures with a professional thermodynamic process simulator, exergoeconomic analysis and methods of mathematical optimization.

2. The optimization procedure

The basic stages of the optimization procedure employed here, detailed in Donatelli (2002), are shown schematically in Fig. (1). A task of vital importance is the conception of the superstructure suitable to the cogeneration system design. To appropriately execute this task, the following premises are considered in this study: (*i*) known average process electrical and thermal demands; (*ii*) natural gas is the fuel, and its average price is assumed available; (*iii*) the electrical energy which is traded with the local utility company has fixed price, but no bound on the physical quantity traded; (*iv*) a list of components that can be used in the superstructure for the cogeneration system is supplied; (*v*) component models are either supplied by a library of components of the process simulator or developed separately and incorporated into the library; (*vi*) a suitable economic model is available; and (*vii*) average environmental parameters (temperature, altitude and relative humidity) are prescribed.

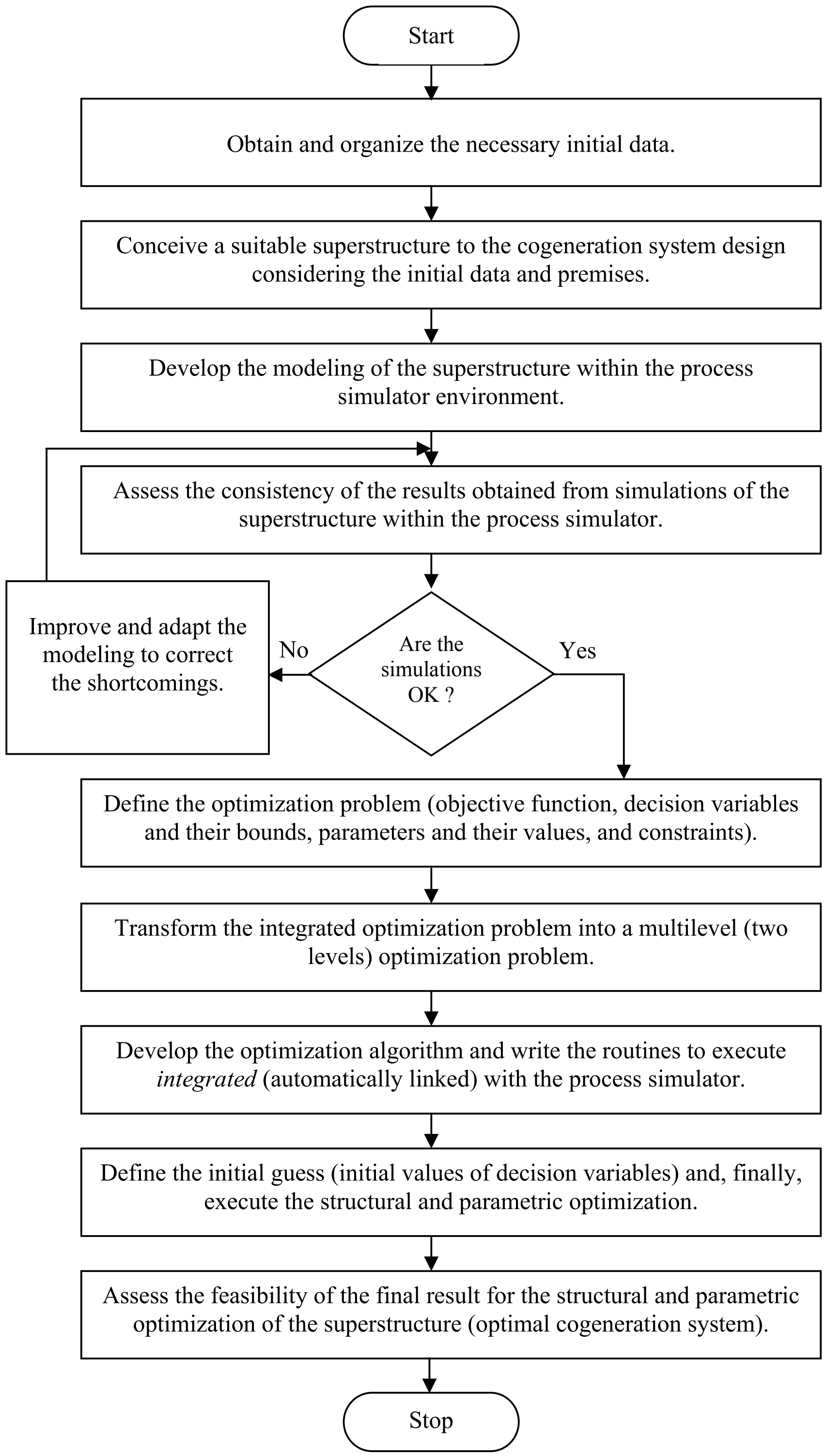

Figure 1. Basic stages of the optimization procedure.

The basic steps of the optimization procedure are: modeling of the superstructure within the environment of a process simulator; definition of the optimization problem (objective function, decision variables, constraints and economic model); transformation of the integrated optimization problem into a two-level optimization problem; establishment of automatic links to interconnect the optimization routines with the process simulator; development of the first-level parametric optimization routines based only on the flexible polyhedron method and effecting optimization by parts due to subsystems components and/or decision variables with small influence on the objective function; and development of the second-level structural optimization routines based on the flexible polyhedron method combined with principles from exergoeconomic analysis. The multilevel optimization problem is solved iteratively according to the flow diagram shown in Fig. (3), presented in section 4.2.

3. The conception and modeling of the superstructure

A superstructure for structural and parametric optimization of cogeneration systems can be defined as a comprehensive thermal system, whose modeling takes into account the existence of several different basic options, each able to supply, individually or combined with other options, the electrical and thermal energy demands of the process. The basic purposes of the superstructure are, therefore, to embed configuration flexibility to the search for the optimal cogeneration system, and to provide, without any shortcomings and for all points generated in the optimization process, the mass and energy balances. Artificial devices are created in the superstructure model to always ensure that a solution to the mass and energy balances exists, even when physically unfeasible points are 'visited' throughout the optimization process.

The thermodynamic process simulator to be used in the optimization of the cogeneration system using a superstructure model must have some fundamental features. First, the simulator must permit integration with the optimization program (routines) through suitable automatic links. Second, it is also necessary that the simulator contains a programmable library of models, since the modeling of the superstructure normally requires the inclusion of specific features over the existing models and/or the development of new models. Third, the simulator must execute efficiently on a personal computer, and have a user-friendly interface. Given these requirements, we have chosen the professional software IPSEpro (Simtech, 2000) to be used as the process simulator in this work. The superstructure shown in Fig. (2) has been modeled to carry out the structural and parametric optimization of a cogeneration system conforming to the premises given in section 2.

The components used in the superstructure shown in Fig. (2) are: artificial MP (21) and LP (24) steam demand, artificial steam supplier (20), process MP (22) and LP (25) steam demand, MP (23) and LP (26) steam header, reduction valve and dessuperheating (32), artificial cold water supplier (28) and demand (29), process cold water demand (27), electrical energy utility (30) and process demand (31). See Tab. (1) to identify the other components.

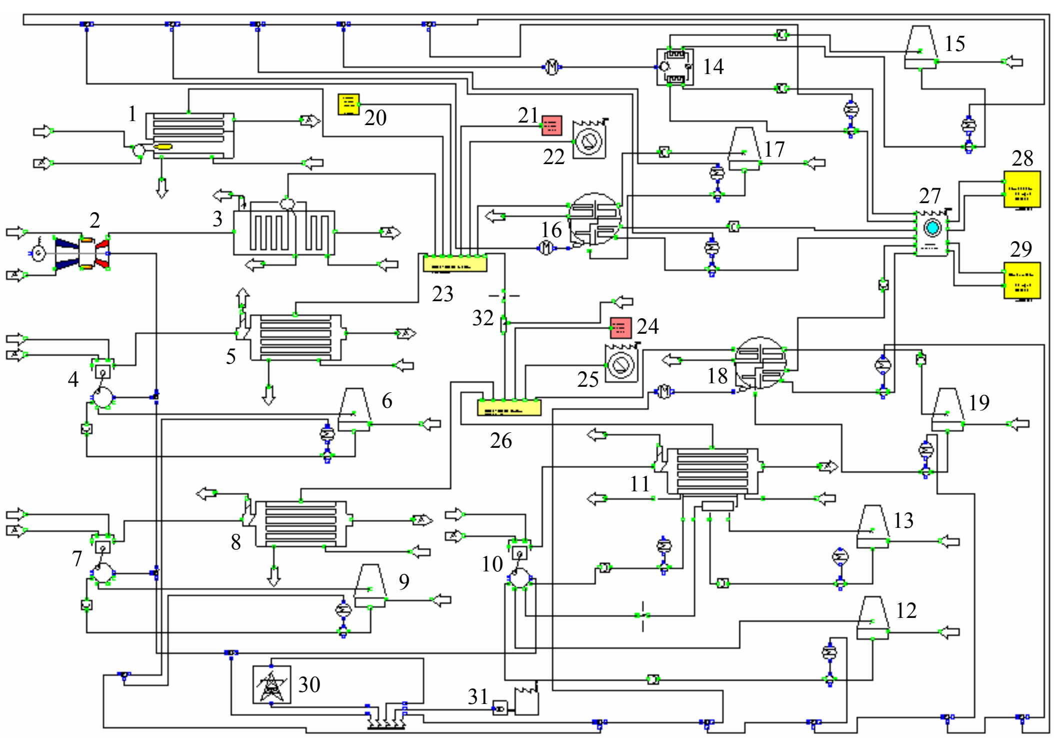

Figure 2. Configuration of the superstructure used in the structural and parametric optimization of a cogeneration system.

4. The integrated optimization problem

The integrated optimization problem consists of the minimization of the complete expenditures per unit time (objective function) with respect to 57 decision variables, including expenditures related to the purchase of fuel, purchase of electrical energy provided by the local utility company, amortization of capital invested in purchasing equipment, plus the operation and maintenance costs. The total number of variables involved in the problem and treated in the process simulator is 1855. This set of variables can be divided into 1593 dependent variables, which are determined in each simulation of the superstructure by the process simulator, and other 262 independent variables, of which 57 are decision variables and 205 are parameters. The major parameters, held constant throughout the optimization process, are: electrical energy cost, average demands of process steam and cold water, average environmental parameters (temperature, altitude and relative humidity), pressure levels of the medium- and low-pressure steam, average specific prices of fuel and electrical energy, and interest rates.

4.1. Mathematical formulation of the optimization problem

In this section, the mathematical formulation of the integrated problem of optimization of cogeneration systems is presented. The equations are solved by optimization routines automatically linked to the professional process simulator IPSEpro. A single evaluation period for the objective function is assumed. The process electrical and thermal energy demands, the environmental parameters and the fuel and electrical energy prices are average values, held constant throughout the optimization process.

$$\begin{aligned}
&\textit{Minimize } \hat{F}\left(x, y^{+}(x,p), p\right) = F\left(x, y(x,p), p\right) + \gamma\left(y_{art}(x,p)\right)^{2} + \theta\left(g\left(x, y(x,p), p\right)\right)^{2} \\
&\textit{Subject to}: \\
&y^{+}(x,p) = 0 \\
&x \in [\min, \max] \\
&x \in \Re^{n},\ y \in \Re^{m},\ p \in \Re^{k},\ y^{+} \in \Re^{(m+d)},\ y_{art} \in \Re^{d},\ \hat{F}, F, \gamma, \theta \in \Re
\end{aligned} \qquad (1)$$

where:
- $\hat{F}$ – objective function including appropriate penalty terms;
- F – objective function;
- x – set of decision variables;
- p – set of independent variables treated as parameters;
- g – inequality constraints ($g(x, y(x, p), p) \leq 0$);
- y – set of dependent variables;
- y_{art} – set of dependent variables related to artificial devices;
- y^{+} – set of dependent variables including variables related to artificial devices, which are determined by the process simulator ($\left\{y^{+}(x,p)\right\} = \left\{y(x,p)\right\} \cup \left\{y_{art}(x,p)\right\}$);
- d – number of variables related to artificial devices;
- n – number of decision variables;
- m – number of dependent variables;
- k – number of independent variables treated as parameters;
- γ – weighting factor of the penalty terms related to the use of artificial devices inserted in the modeling of the superstructure to avoid simulation shortcomings ($y_{art}(x,p) > 0 \Rightarrow \gamma\left(y_{art}(x,p)\right)^{2} >> \hat{F}$);
- θ – weighting factor of the penalty terms related to the infringement of the inequality constraints ($g(x, y(x,p), p) \leq 0 \Rightarrow \theta = 0$, $g\left(x, y(x,p), p\right) > 0 \Rightarrow \theta\left(g\left(x, y(x,p), p\right)\right)^{2} >> \hat{F}$);
- *min, max* – minimum and maximum values of decision variables, which bound the search region.

4.2. Transformation of the integrated optimization problem into a multilevel problem

The technique of transformation of an integrated optimization problem into a multilevel problem (Schoeffler, 1971) is employed here to transform the problem (1) into a two-level problem. In the first-level problem, the global system, i.e. the superstructure, is decomposed into eight subsystems. Each of these subsystems is parametrically optimized with respect to a specific subset of decision variables, related to equipment specification parameters. For each subsystem, the specific cost per unit of exergy associated with the product is regarded as the objective function. The 57 decision variables are then divided into two sets of 45 and 12 variables, respectively, to the first- and second-level optimization problems, according to Tab. (1). The meaning of each decision variable is described in Tab. (2). The integrated optimization problem (1) is solved by an iterative process, as shown in Fig. (3).

If, in the last two iterations, a change less than 0.5% in the decision variables and in the objective function is verified, that is, if the test

$$\left|\frac{x_k^i - x_k^{i-2}}{x_k^i}\right| < 0.005 \ , \ k = 1,\ 2,\ ...,\ n, \ \text{and} \quad \left|\frac{\hat{F}^i - \hat{F}^{i-2}}{\hat{F}^i}\right| < 0.005 \qquad (2)$$

is satisfied, then the optimization process is considered to have converged. In Eq. (2), x_k^i is the value of the *k-th* decision variable at the *i-th* iteration, n is the number of decision variables, and $\hat{F}^i$ is the value of the objective function at the *i-th* iteration.

Table 1. Eight subsystems resulting from the decomposition of the superstructure of Fig. (2).

Subsystems		**Decision variables**		**Product(s)**
Acronym	**Description of components**	**1st-level optimization problem**	**2nd-level optimization problem**	
Cald-Conv	Conventional boiler (1)#	dt_pinch [ºC] load [-]	m_vapor [kg/s]	Medium-pressure (11 bar) saturated water steam
TG&HRSG	Gas turbine (2) and associated heat recovery steam generator (3)	eta_0 [-] load [-] dt_pinch [ºC] load [-]	m_vapor [kg/s] power [kW]	Electrical energy and medium-pressure (11 bar) saturated water steam
MCI&HRSG&TR-MP	Internal combustion engine (4) and associated heat recovery steam generator (5), cooling tower and pumps (6)	eta_0 [-] load [-] dt_pinch [ºC] load [-] q_ct_0 [kW] range_0 [ºC] ap_0 [ºC]	m_vapor [kg/s] power [kW]	Electrical energy and medium-pressure (11 bar) saturated water steam
MCI&HRSG&TR-BP	Internal combustion engine (7) and associated heat recovery steam generator (8), cooling tower and pumps (9)	eta_0 [-] load [-] dt_pinch [ºC] load [-] q_ct_0 [kW] range_0 [ºC] ap_0 [ºC]	m_vapor [kg/s] power [kW]	Electrical energy and low-pressure (1.85 bar) saturated water steam
MCI&HRSG&TR&TRstby-BP	Internal combustion engine (10) and associated heat recovery steam generator (11), cooling tower and pumps (12), stand-by cooling tower and pumps (13)	eta_0 [-] load [-] dt_pinch [ºC] load [-] q_ct_0 [kW] range_0 [ºC] ap_0 [ºC] q_ct_0 [kW] range_0 [ºC] ap_0 [ºC]	m_vapor [kg/s] power [kW]	Electrical energy and low-pressure (1.85 bar) saturated water steam
Chiller-C	Compression chiller (14) and associated cooling tower and pumps (15)	COP_0 [-] carga [-] q_ct_0 [kW] range_0 [ºC] ap_0 [ºC]	q_evap [kW]	Cold water
Chiller-A2	Double effect absorption chiller (16) and associated cooling tower and pumps (17)	COP_0 [-] carga [-] q_ct_0 [kW] range_0 [ºC] ap_0 [ºC]	q_evap [kW]	Cold water
Chiller-A1	Single effect absorption chiller (18) and associated cooling tower and pumps (19)	COP_0 [-] carga [-] q_ct_0 [kW] range_0 [ºC] ap_0 [ºC]	q_evap [kW]	Cold water

identify number of the components used in the superstructure shown in Fig. (2).

Table 2. Meaning of the decision variables.

Decision variables		Description of meaning
1^{st}-level optimization problem	dt_pinch [°C]	Temperature difference between the gas and water at the pinch point of the conventional boilers and heat recovery steam generators.
	load [-]	The same as the variable "carga."
	eta_0 [-]	Thermal efficiency of the gas turbines and internal combustion engines at nominal operational conditions.
	q_ct_0 [kW]	Heat load of the cooling towers at nominal operational conditions.
	range_0 [°C]	Difference between the circulating hot and cold water temperatures at nominal operational conditions of the cooling towers.
	ap_0 [°C]	Difference between the circulating cold water temperature and wet bulb temperature at nominal operational conditions of the cooling towers.
	COP_0 [-]	Coefficient of Performance of the compression and absorption chillers at nominal operational conditions.
	carga [-]	Ratio between output rate and nominal capacity corrected with respect to operational conditions.
2^{nd}-level optimization problem	m_vapor [kg/s]	Steam output rate of the conventional boilers and heat recovery steam generators.
	power [kW]	Electrical energy output rate of the prime movers (gas turbines and internal combustion engines).
	q_evap [kW]	Cold water output rate of the compression and absorption chillers.

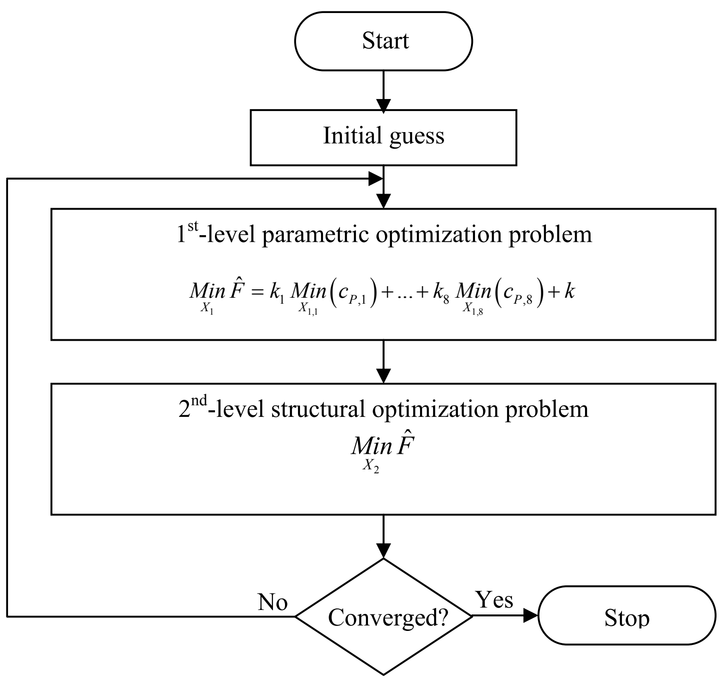

Figure 3. Iterative process for the multilevel optimization problem.

5. The mathematical optimization method aided by exergoeconomic analysis

The structural optimization of the cogeneration system is carried out mainly in the second-level problem, using an optimization routine that combines the flexible polyhedron method, a direct mathematical optimization method proposed originally by Nelder and Mead (Edgar and Himmelblau, 1988), with a logic based on an exergoeconomic analysis of the system. In this work, this logic is divided into two ones, to assess the cogeneration subsystem, whose basic stages are shown in Fig. (4), and to assess the subsystems that yield cold water. The fundamental purpose of this logic is to suggest additional sets of values for the decision variables to the mathematical optimization method, which can accept these sets to replace the worst points of the polyhedron. A complete flow diagram showing the flexible polyhedron method combined with a logic based on exergoeconomic analysis can be found in Donatelli (2002).

The logic based on an exergoeconomic analysis applied to assess the subsystems that simultaneously yield electrical energy and steam (cogenerator subsystems - COGS) regard the conventional boiler and utility (the conventional system for supplying steam and electrical energy, respectively, for the process). A similar logic is applied to assess the subsystems that yield cold water. In this last case, the cogenerator subsystems and the conventional energy supply system have to undergo adjustments in their output rates to compensate, in the best possible way, for changes in the electrical energy and steam demands of the subsystems that yield cold water. A more comprehensive discussion on this use of exergoeconomic analysis to optimize cogeneration systems can be found in Donatelli (2002).

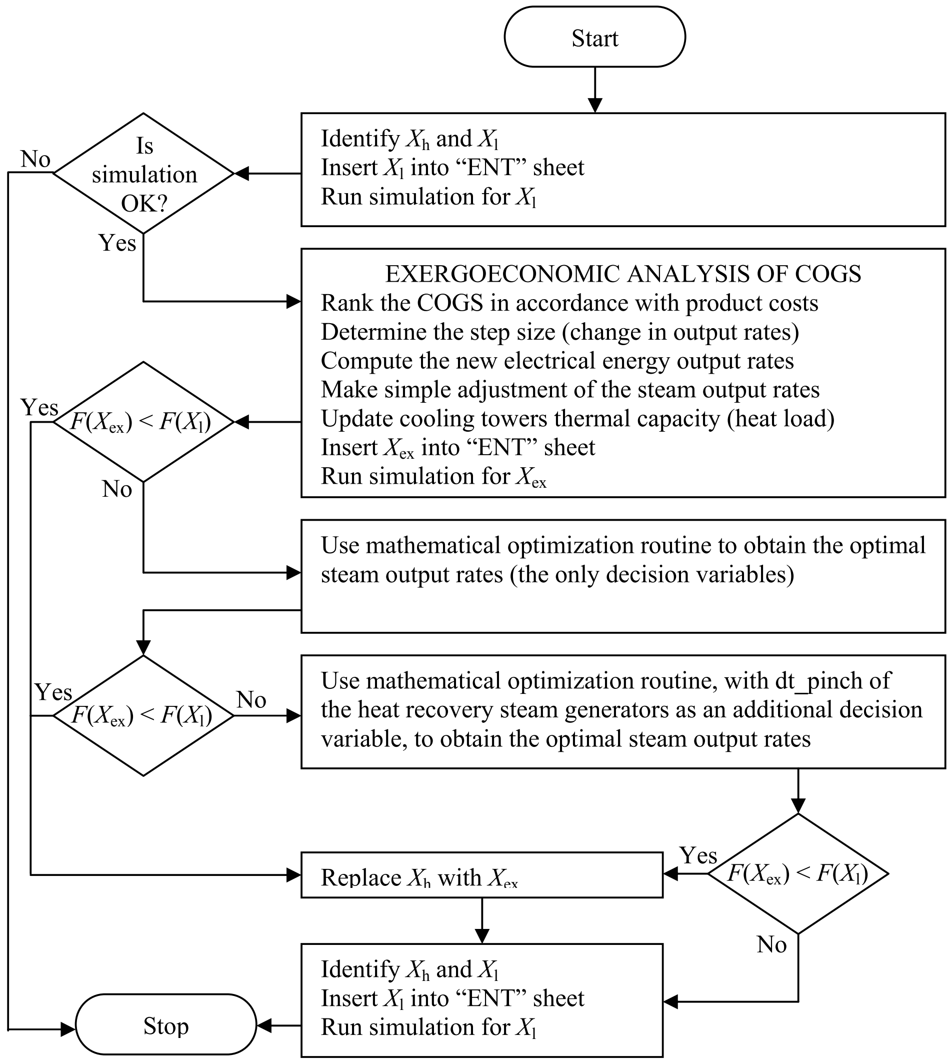

Figure 4. Logic based on an exergoeconomic analysis to assess the cogenerator subsystems (COGS).

6. Results and discussion

The results obtained in the structural and parametric optimization of the superstructure shown in Fig. (2) are now presented, for fixed process demands for electrical and thermal energy. As described in section 4, the technique for the transformation of an integrated optimization problem into a multilevel problem is applied to optimize the superstructure. In Tab. (3), the results are organized considering two cases: Case 1- application of the mathematical method of optimization, and Case 2- application of the mathematical method of optimization combined with a logic based on an exergoeconomic analysis to improve the structural optimization carried out mainly in the second-level problem (in the first-level problem, as previously mentioned, only the parametric optimization is carried out by mathematical method of optimization).

It is observed from the curves in Fig. (5), for both Cases 1 and 2, that the value of the objective function decreases as the number of superstructure simulations increases throughout the optimization process. In particular, the final value of the objective function for Case 2 is considerably lower. The evolution of the configuration of the cogeneration system throughout the optimization process of the superstructure is presented in Figs. (6) and (7) for Cases 1 and 2, respectively. In Case 2, the combined strategy permits further reduction of the objective function with the removal of some components of the cogeneration system (see Table 3), leading to a clear definition of the final optimal configuration. This evolution is not foreseen in Case 1, because there was premature convergence and the optimization process stopped.

The optimization routine based on the mathematical method of optimization simultaneously changes all decision variables involved in the structural optimization problem. On the other hand, the use of a strategy based on exergoeconomic analysis promotes changes solely in the decision variables related to one or two subsystems at a time. This allows one to achieve a better performance in the optimization process. The Case-2 results show a tendency towards fewer components in the final configurations.

7. Conclusions

The approach based on the application of superstructures to structurally and parametrically optimize cogeneration systems reveals itself able to lead to the optimal configuration and operational point of the designed system. To be efficient, the superstructure must be modeled within the environment of a professional process simulator. A combination of a mathematical method of optimization with a logic based on an exergoeconomic analysis reveals itself to be an effective strategy to solve the structural optimization problem. Such combination represents an original contribution related to the field of exergoeconomic structural optimization.

A literature review of recent work indicates that exergoeconomic analysis is usually applied to thermal systems with fixed configurations. As a consequence, the exergoeconomic figures-of-merit defined and applied up to now are not suitable for structural optimization. In this work, to achieve structural optimization, we have developed new criteria to compare the exergoeconomic performance among competing subsystems/equipments within the superstructure.

Table 3. Results of the structural and parametric optimization of the superstructure shown in Fig. (2).

Decision variables	Initial point	Optimal point Case 1	Optimal point Case 2	Decision variables	Initial point	Optimal point Case 1	Optimal point Case 2
CaldConv-dt_pinch [ºC]	100	53.53	56.72	*MCI&HRSG&TR_BP-dt_pinch [ºC]	100	198.02	178.40
CaldConv-load [-]	1	1	1	*MCI&HRSG&TR_BP-load [-]	1	1	1
CaldConv-m_vapor [kg/s]	3.5	3.09	2.00	*MCI&HRSG&TR_BP-q_ct_0 [kW]	150	104.17	334.628
TG&HRSG-eta_0 [-]	0.23	0.207	0.088	*MCI&HRSG&TR_BP-range_0 [ºC]	6	8.591	7.851
TG&HRSG-load [-]	1	1	1	*MCI&HRSG&TR_BP-ap_0 [ºC]	6	7.917	10.808
TG&HRSG-dt_pinch [ºC]	100	195.8	200	*MCI&HRSG&TR_BP-q_ct_0 [kW]	900	930.46	3075.17
TG&HRSG-load [-]	1	1	0.97	*MCI&HRSG&TR_BP-range_0 [ºC]	6	15	13.8
TG&HRSG-m_vapor [kg/s]	0.5	0.38	0.0001	*MCI&HRSG&TR_BP-ap_0 [ºC]	6	15	13.3
TG&HRSG-power [kW]	1000	531.2	1.5	*MCI&HRSG&TR_BP-m_vapor [kg/s]	0.5	0.7370	2.5006
MCI&HRSG&TR_MP-eta_0 [-]	0.35	0.369	0.223	*MCI&HRSG&TR_BP-power [kW]	1000	1860.93	6150.34
MCI&HRSG&TR_MP-load [-]	1	1	0.921	Chiller_C&TR-COP_0 [-]	3.9	4.041	4.075
MCI&HRSG&TR_MP-dt_pinch [ºC]	100	182.69	193.2	Chiller_C&TR-carga [-]	1	1	1
MCI&HRSG&TR_MP-load [-]	1	0.99	0.984	Chiller_C&TR-q_ct_0 [kW]	250	415.536	1201.43
MCI&HRSG&TR_MP-q_ct_0 [kW]	1000	1123.97	1.322	Chiller_C&TR-range_0 [ºC]	6	7.426	6.540
MCI&HRSG&TR_MP-range_0 [ºC]	6	7.636	7.788	Chiller_C&TR-ap_0 [ºC]	6	6.408	8.973
MCI&HRSG&TR_MP-ap_0 [ºC]	6	8.334	6.82	Chiller_C&TR-q_evap [kW]	205	207.781	600.775
MCI&HRSG&TR_MP-m_vapor [kg/s]	0.15	0.227	0.0001	Chiller_A2&TR-COP_0 [-]	1.075	1.058	1.000
MCI&HRSG&TR_MP-power [kW]	1000	2247.95	1.5	Chiller_A2&TR-carga [-]	1	1	1
MCI&HRSG&TR_BP-eta_0 [-]	0.35	0.3571	0.213	Chiller_A2&TR-q_ct_0 [kW]	450	370.286	3.887
MCI&HRSG&TR_BP-load [-]	1	1	0.902	Chiller_A2&TR-range_0 [ºC]	6	5.083	9.295
MCI&HRSG&TR_BP-dt_pinch [ºC]	100	198	199.99	Chiller_A2&TR-ap_0 [ºC]	6	3	4.539
MCI&HRSG&TR_BP-load [-]	1	0.99	0.937	Chiller_A2&TR-q_evap [kW]	200	209.671	1
MCI&HRSG&TR_BP-q_ct_0 [kW]	1000	698.84	1.461	Chiller_A1&TR-COP_0 [-]	0.625	0.6297	0.58
MCI&HRSG&TR_BP-range_0 [ºC]	6	8.025	8.369	Chiller_A1&TR-carga [-]	1	1	1
MCI&HRSG&TR_BP-ap_0 [ºC]	6	7.351	6.88	Chiller_A1&TR-q_ct_0 [kW]	600	434.76	4.5
MCI&HRSG&TR_BP-m_vapor [kg/s]	0.15	0.1903	0.0001	Chiller_A1&TR-range_0 [ºC]	6	8.321	11.40
MCI&HRSG&TR_BP-power [kW]	1000	1397.7	1.5	Chiller_A1&TR-ap_0 [ºC]	6	3.000	4.5
*MCI&HRSG&TR_BP-eta_0 [-]	0.35	0.3626	0.3939	Chiller_A1&TR-q_evap [kW]	200	186.993	1
*MCI&HRSG&TR_BP-load [-]	1	1	1				
EEcons [kW] {dependent variable}	2084.68	---	0				
Objective function value [US$/h]	723.50	661.75	546.58				
Number of IPSEpro use (simulations)		12026	13229				
Fuel cost [US$/GJ]		4	4				
Cost of electrical energy from utility [US$/kWh]		0.08	0.08				
Process electrical energy demand [kW]		6000	6000				
Process MP$^{\#}$ steam demand [kg/s]		2.0	2.0				
Process LP$^{\#\#}$ steam demand [kg/s]		2.5	2.5				
Process cold water demand [kW]		600	600				
Pressure of the MP$^{\#}$ steam [bar]		11	11				
Pressure of the LP$^{\#\#}$ steam [bar]		1.85	1.85				

$^{\#}$ medium-pressure; $^{\#\#}$ low-pressure

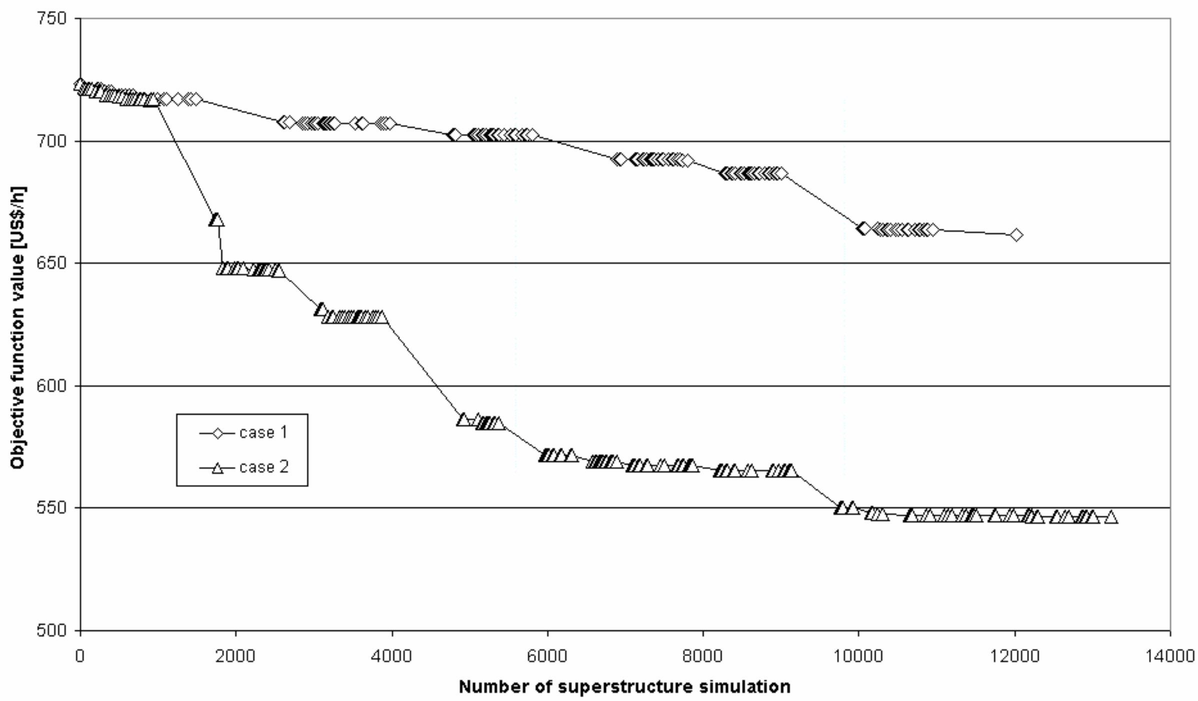

Figure 5. Objective function variation for Cases 1 and 2 throughout the optimization process of the superstructure shown in Fig. (2).

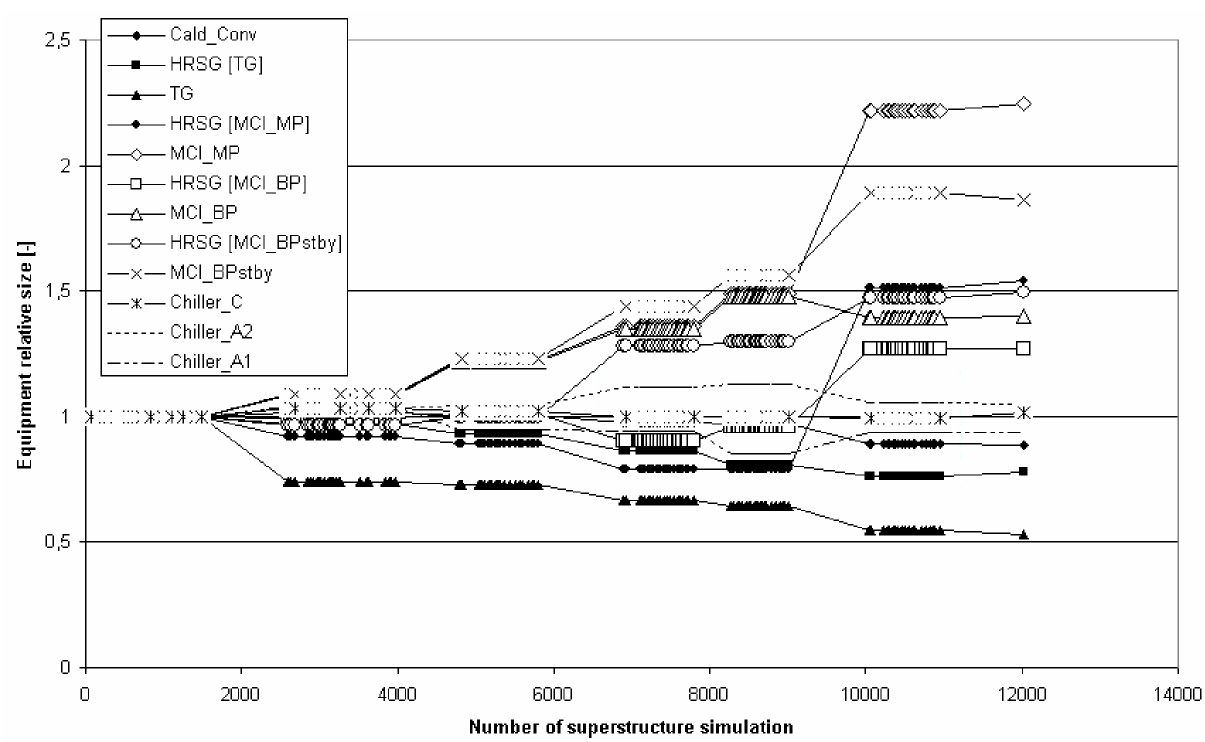

Figure 6. Evolution of the configuration of the cogeneration system for Case 1 throughout the optimization process of the superstructure shown in Fig. (2).

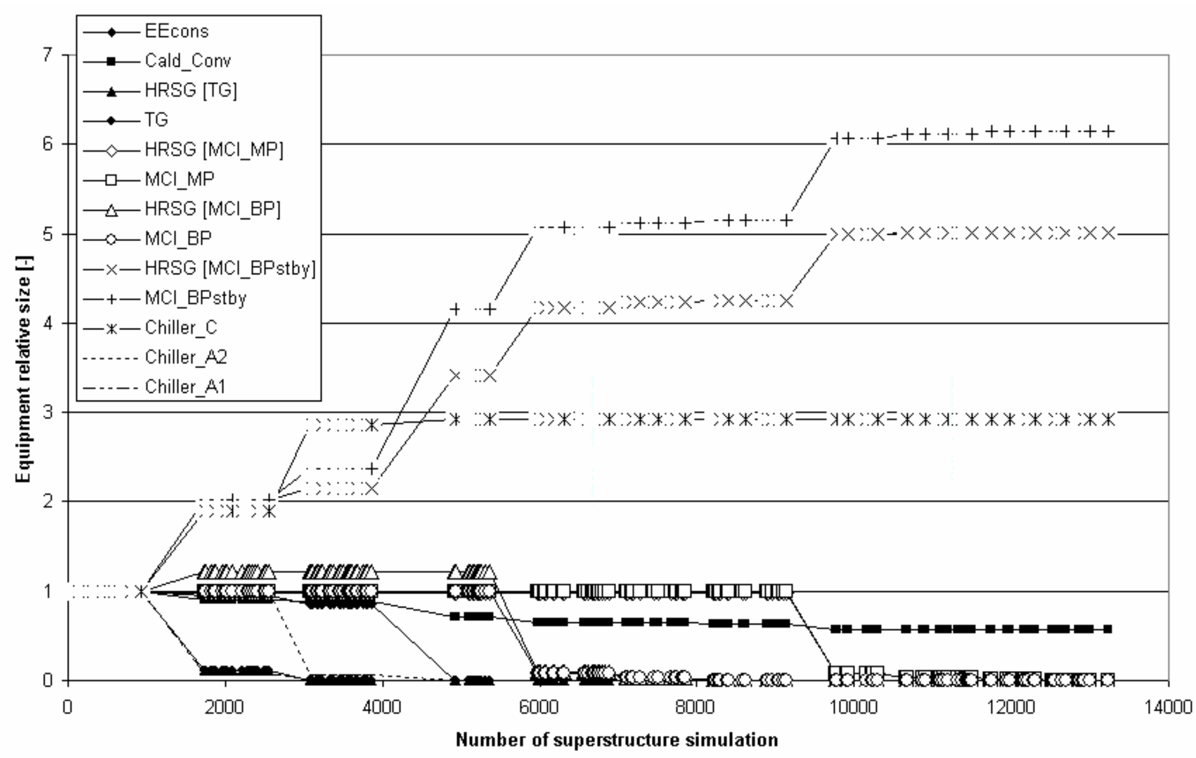

Figure 6. Evolution of the configuration of the cogeneration system for Case 2 throughout the optimization process of the superstructure shown in Fig. (2).

8. Acknowledgements

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