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Thermoeconomic optimization of a dual-purpose power and desalination plant

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Abstract

The thermoeconomic optimization of an actual steam power plant coupled with a MSF desalination unit is reported. A global optimization of the whole system is performed based on separated local optimizations of different plant units. The local optimization procedure described herein requires fewer computing resources and deals with simpler mathematical problems than conventional optimization methods. On the other hand, the local optimization method requires a thermoeconomic model providing the exergy and economic costs of all mass and energy flows of a plant, including those corresponding to fresh water and electricity produced. This application can be very useful, either for the plant management in order to achieve a cost-effective operation, and for a better plant design. In the example given, approximately 11% of the total cost was saved according to the optimization results in the nominal operating conditions of the plant.

Keywords: Thermoeconomic optimization; Local optimization; Thermoeconomic analysis

1. Introduction

Desalination is one of the most important processes to provide water to population in water scarcity areas, especially in the Gulf Area. But desalination processes consume a lot of energy, unfortunately the majority of the energy currently used for desalination is obtained from oil or natural gas. Co-generation plants providing freshwater but also electricity are installed in the arid areas; the combination of steam turbine plants and multi-stage flash (MSF) units is one of the most common schemes for the water and energy requirements.

If desalination is powered almost entirely by the combustion of fossil fuels, these fuels are

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rapidly being depleted because of their finite supply, but also they pollute the air and contribute to global climate change [1]. Development of renewable-driven desalination is still severely impeded, if not buried, by the pressure of contemporary economic factors and political inertia. The whole industry, including desalination, needs to gear itself towards enhanced efficiency, minimization of waste and minimization of environmental impact. Therefore, a more sustainable operation of existing dual-purpose plants must be oriented to the improvement of the plant behavior. Note that the operation of dual-coupled plants, i.e., a power plant and desalination unit, is usually managed by two different companies, and as a result, the entire system frequently does not operate at optimum conditions.

Thermoeconomic analysis (a Second Law discipline) techniques are very suitable tools to be applied in the analysis of highly complex energy conversion systems, as a dual plant is, helping to achieve better production management with a more cost-effective and energy-efficient operation and gain a better understanding of the plant's performance. Thermoeconomic analysis techniques in a plant are used to:

- calculate the physical costs of their flows and products
- assess the alternatives for energy savings
- optimize the operation and design, and
- diagnose the operation.

Fundamentals and examples of these applications explained in detail can be found in [2,3].

Regarding thermoeconomic optimization, it can be envisaged from two different points of view: design and operation. This paper presents the thermoeconomic optimization of an actual dual plant consisting of a steam power plant and a MSF desalination unit. Global optimization of the whole system, based on separated local optimizations of different plant units below some operating conditions (maximum production of water and electricity), is performed applying the local optimization procedure proposed in [4].

2. Thermoeconomic optimization

Many thermal systems are very complex, with numerous and often strongly interdependent subsystems. A good example is a dual-purpose power and desalination plant. Its thermoeconomic optimization involves exploiting the information from the thermoeconomic costs of internal flows [4–11]. Monetary savings in energy resources are calculated as the cost of local resources consumed by subsystems. The key aspect of the optimization process is to find the minimum product cost of each subsystem [4,9,10]. Local and global optimization of seawater desalting systems has also been developed by other authors [11] based on Second Law decomposition strategies and Lagrange multipliers. The Second-Law decomposition strategy is very similar to the process proposed in [4] and described in this paper but uses the exergy destruction term. We applied strategies to optimize complex systems based on the sequential optimization of sub-systems for the main process units of the dual plant [4]. We also demonstrated the simplicity of this methodology with respect to global optimi-zation, which considers a global objective function and all the constraints, derived from the complexity of the physical model of the whole plant.

Normally plant process units can be sequentially optimized since they are interdependent, but the process units of the MSF plant are too strongly interdependent, and it is not convenient to optimize them in this way. For this reason the whole MSF unit is considered as another component and the dual plant as a co-generation plant with two products (electricity and water).

As seen below, the proposed procedure minimized the total cost of water and electricity in this very complex installation, considering the dual plant as a whole system. This example was used to validate the method in a very complex and actual plant and not to obtain optimum realistic results for each component. The capital costs of most components were adjusted from the literature to obtain a reliable set of optimum parameters.

2.1. Thermoeconomic isolation

Local optimization requires the Thermoeconomic Isolation Principle [12] to be upheld. Basically this principle states that the modification of the operating conditions of a plant unit do not vary from the cost of the internal flowstreams of the plant, i.e., do not affect the behavior of the rest of the plant units. This is not always the case in a complex system since the component product and cost may vary with changes in the design variables of other components. Lozano et al. proposed a sensitivity analysis to identify the local and global free variables [4,9]. Local variables are only sensitive to their process units, i.e., their modification does not significantly affect the rest of the plant units' behavior, and they can be locally optimized. The thermoeconomic diagnosis of the dual plant [2] provides the same information as the sensitivity analysis.

Regarding the power plant, process units could be considered isolated from other power plant devices. A design-free variable chosen for each device would be a local variable to be optimized, around which the whole system would be optimized. However, the thermoeconomic isolation principle is not upheld in the MSF unit (see [2,3] for details). Since changes in a device's behavior strongly affected other MSF process units, the thermoeconomic isolation could not be applied, and local thermoeconomic sequential optimization was not possible.

The most important MSF design variables affect the whole plant: top brine temperature (*TBT*), distillate production (*D*) etc. Design-free variables can minimize final product cost of the whole MSF unit (freshwater). As a result, the MSF is considered as a process unit in the power plant system. If a design variable that only affects the distiller behavior is taken for the optimization, the MSF global variable is independent of other local variables of the power plant. It can be considered a local variable in the dual-purpose plant and is included in the local optimization sequence of the whole system.

2.2. Physical and thermoeconomic models

The physical model of the analyzed plant is shown in Fig. 1. The dual plant is a power co-generation plant combined with a MSF desalination plant. The power generation plant provides both electrical power and the steam required for the seawater desalination plant (MSF plant). The turbojet at the co-generation design point will produce 122 MW of electricity and 198 MJ/s of process heat to produce 57,600 m^3/d of drinking water. In pure condensing mode, i.e., MSF unit is off, a maximum of 147 MW of electricity can be delivered in generator terminals. In the power plant extraction/ condensing turbines are operated in fixed pressure mode, i.e, pressure at the high- pressure turbine inlet (HPT1) remains constant. The steam turbine has two sections (high and low pressure), and steam extraction outlets for the seawater desalination plant and the feedwater heaters are available in both sections.

The MSF plant is a brine recirculation flow, high-temperature (HT), anti-scale treatment and cross-tube configuration — the most typical of MSF plant types. The plant has a single-effect MSF evaporator with recycled brine containing three main sections: the "heat input" section (or brine heater), the "heat recovery section" and the "reject section". The recovery and reject sections both have made a series of stages (17 and 3, respectively), consisting of a flash chamber and a heat exchanger/condenser where the vapor, flashed off in the flash chamber, is condensed.

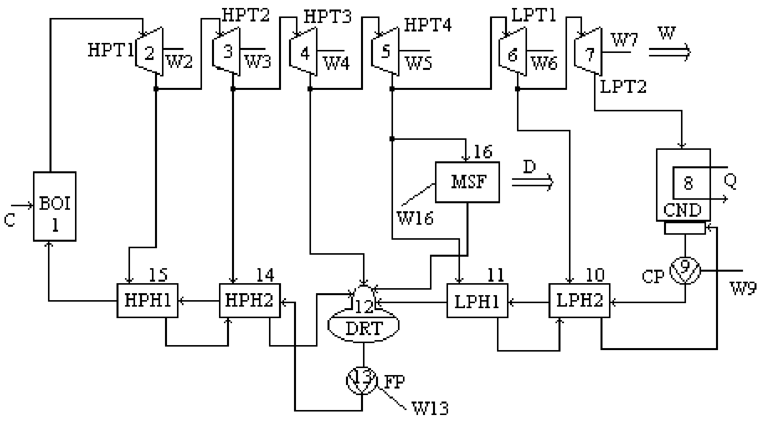

Fig. 1. Physical model of the dual-purpose power and desalination plant.

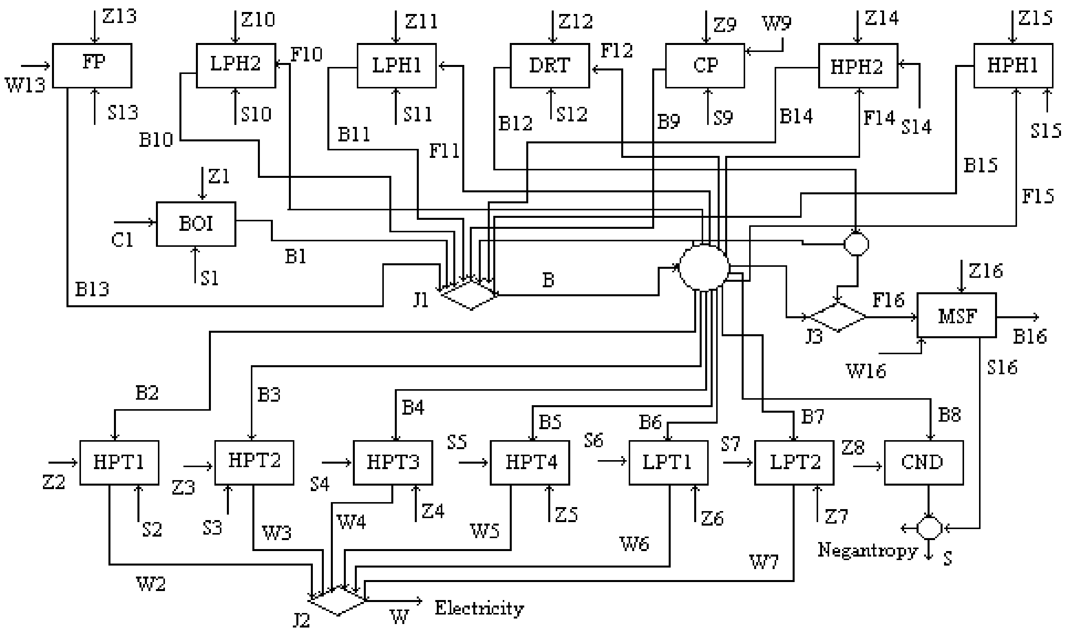

Fig. 2. Fuel/product diagram (Productive Structure) of the thermoeconomic model applied to the dual-purpose plant.

When applying a thermoeconomic optimization, or whatever thermoeconomic analysis, it is necessary to define a thermoeconomic model for the analyzed system, which is depicted with the fuel-product diagram, also called productive structure (see Fig. 2).

The thermoeconomic model encompasses the definition of a productive function (product) for each component and the resources that each one needs to consume (fuel) in order to achieve the production objective (see [2,3] for details).

The productive structure (Fig. 2) represents

Table 1
Equations of the thermoeconomic model applied in the optimization process

Device	Equation	kBi	kSi	kZi
1 BOI	c1=kB1*cf+kS1*cs+kZ1	kB1=C1/B1	kS1=S1/B1	kZ1=φ*Z1/B1
2 HPT1	c2=kB2*ca+kS2*cs+kZ2	kB2=B2/W2	kS2=S2/W2	kZ2=φ*Z2/W2
3 HPT2	c3=kB3*ca+kS3*cs+kZ3	kB3=B3/W3	kS3=S3/W3	kZ3=φ*Z3/W3
4 HPT3	c4=kB4*ca+kS4*cs+kZ4	kB4=B4/W4	kS4=S4/W4	kZ4=φ*Z4/W4
5 HPT4	c5=kB5*ca+kS5*cs+kZ5	kB5=B5/W5	kS5=S5/W5	kZ5=φ*Z5/W5
6 LPT1	c6=kB6*ca+kS6*cs+kZ6	kB6=B6/W6	kS6=S6/W6	kZ6=φ*Z6/W6
7 LPT2	c7=kB7*ca+kS7*cs+kZ7	kB7=B7/W7	kS7=S7/W7	kZ7=φ*Z7/W7
8 CND	c8=cs=kB8*ca+kZ8	kB8=B8/S		kZ8=φ*Z8/S
9 CP	c9=kW9*cb+kS9*cs+kZ9	kW9=W9/B9	kS9=S9/B9	kZ9=φ*Z9/B9
10 LPH2	c10=kB10*ca+kS10*cs+kZ10	kB10=F10/B10	kS10=S10/B10	kZ10=φ*Z10/B10
11 LPH1	c11=kB11*ca+kS11*cs+kZ11	kB11=F11/B11	kS11=S11/B11	kZ11=φ*Z11/B11
12 DRT	c12=kB12*ca+kS12*cs+kZ12	kB12=F12/B12	kS12=S12/B12	kZ12=φ*Z12/B12
13 FP	c13=kW13*cb+kS13*cs+kZ13	kW13=W13/B13	kS13=S13/B13	kZ13=φ*Z13/B13
14 HPH2	c14=kB14*ca+kS14*cs+kZ14	kB14=F14/B14	kS14=S14/B14	kZ14=φ*Z14/B14
15 HPH1	c15=kB15*ca+kS15*cs+kZ15	kB15=F15/B15	kS15=S15/B15	kZ15=φ*Z15/B15
16 MSF	c16=kB16*cc+kW16*cb+kS16*cs+kZ16	kB16=F16/B16 kW16=W16/B16	kS16=S16/B16	kZ16=φ*Z16/B16
17 J1	ca=(1/B)*(B9*c9+B10*c10+B11*c11+ B12*c12+B13*c13+B14*c14+B15*c15)			
18 J2	cb=(1/W)*(W1*c1+W2*c2+W3*c3+W4*c4+W5*c5+W6*c6+W7*c7)			
19 J3	cc= (1/F16)*(ca*FJ3b+c12*FJ3a)			

the productive interactions among the different components of the plant, and it is a tool that helps to calculate the costs of the internal flows of the plant. The inlet arrows to the components represent the resources consumed in the component, i.e., the fuel; the outlet arrows correspond to the products. The squares represent the productive components in the plant. Bifurcations, also called branches (ellipses) and junctions (rhombus) are fictitious devices that represent how the fuel and products, i.e., the resources, are distributed among the different plant components. The fuels or resources were classified according to flow type entering the unit: natural gas (*C*), exergy flow (*B*), negentropy flow (*S*) or electricity (*W*). Capital costs (*Z*) of each device are also introduced in the productive structure of the dual plant. Once the productive structure is built, the thermoeconomic model provides the costs of the main flowstreams of the plant by solving the set of equations presented in Table 1. Costs ci (expressed in \$/kJ) of each device product were calculated using a fuel cost cf of 2×10^{-6} \$/kJ, and an amortization factor φ of 6.7×10^{-9} s^{-1} [4].

2.3. Choosing local variables

The first step in whatever optimization process is to select a set of free variables, which represent the design and operation of the system equipment. Local optimization involves choosing a set of local variables for each device and minimizing their product cost as a function of the selected variables. The whole plant can be optimized by separately minimizing the product cost of system process units (boiler, turbine sections, heaters, pumps, etc.).

The temperature of steam leaving the boiler (or set point) is a global variable for the power plant + MSF system. The complexity of our physical model implies that the set point affects the behavior of basically all system devices. Therefore, a very complex cost function including all devices has to be minimized to optimize this set point (it is like applying a global optimization). This methodology is only valid for local design free variables (we did not consider the optimization of global design free variables in this paper).

Design local free variables must appear in the equations that model the physical subsystems (a local variable does not need to appear in the thermoeconomic model [4]). The thermoeconomic isolation principle assures that the local variable does not significantly change the behavior of the rest of components. The local variable should directly or indirectly appear in the equations modeling the capital cost of the components (the convergence in the local optimization process is easier). The proposed free variables for each device in the power plant and the MSF unit were:

1. Boiler: First Law efficiency, defined as the heat transmitted to the water cycle divided by the energy (or exergy) of consumed fuel.

2. Turbine sections: isoentropic efficiency, i.e, the enthalpy drop ratio of steam between the real and ideal adiabatic expansion in a turbine section.

3. Pumps: Isoentropic efficiency defined as the enthalpy increase ratio of water between the ideal and real adiabatic pumping process.

4. Heaters: Terminal temperature difference (TTD), defined as the temperature difference between saturated steam from the extraction and feedwater leaving the heater.

5. As explained above, the MSF unit was dealt with as a separate component in the cogeneration system. Its design-free variable is global one in the MSF subsystem. A free variable related with the power plant is the TTD of the MSF unit, i.e., the temperature difference between the saturated steam extracted from the turbine, which is condensed in the brine heater, and the TBT of the distiller. This variable is intimately related with the capital cost of the MSF distiller.

The local optimization involves 14 design-free variables. The optimization of an actual complex system with 14 design-free variables is obviously complex.

2.4. Local optimization of subsystems

The objective function of the local optimization (the minimum product cost) of each plant component is shown in Table 2. Capital cost equations of each device included in these functions are also included in this table.

2.5. Local optimization results

Thermodynamic values (including energy and entropy) of the main flow streams of the plant are calculated by using a specific simulator [2], which models the physical behavior of the whole system with a high accuracy. Average error of pressures, temperatures and mass flow rates of the most significant flow streams of the plant is lower than the 0.5% [2,3]. The input conditions of the maximum continuous rating (MCR) performance case were used to develop the local optimization process of the real plant in this paper:

- 122.731 MW gross output power
- 89.68 kg/s steam to MSF unit
- 0.069 bar condenser pressure

Table 2
Objective function and capital cost in the local optimization of the dual plant

Device	Comp.	F.d.v.*	Objective function ($/kJ)	Devices capital cost ($) and source
Boiler	1	$\eta 1$	*kB1*co+kS1*cs+kZ1*	$Z1=20.1552224*exp(0.0014110546*P_1)*$ $*exp(0.7718795*ln(M_1))*FAR*FAN*FAT)$ [13] $FAR=1.0+((1-\Delta P_r)/(1-\Delta P))^8$ $FAN=1.0+((1-\eta 1_r)/(1-\eta 1))^{7.0}$ $FAT=1.0+5*exp((T_1-T_{1r})/18.75$
Turbine sections	2-7	$\eta 2$	*kB2*ca+kS2*cs+kZ2*	$Z2=3000*(1+5*exp((T_1-866)/10.42))*$ $*(1+((1-\eta 2_r)/(1-\eta 2))^3)*W^{0.782}$ [4] $\eta 2_r=0.97$(high-pressure), 0.85 (low-pressure)
Condenser	8			$Z8=(1/(T_o*e))*217*(0.247+1/(3.24*v^{0.8}))*$ $*ln(1/1-e))+138)*(1/(1-\eta 8))*S*50$ [4]
Pumps	9,13	$\eta 9$	*kW9*cb+kS9*cs+kZ9*	$Z9=378*(1+((1-\eta 9_r)/(1-\eta 9)^3)*B9^{0.71}$ [4] $\eta 9_r=0.85.$
Heaters	10,11 14,15	TTD10	*kB10*ca+kS10*cs+kZ10*	$Z10=0.02*3.3*Q*abs(1/(TTD10-a))^{-0.1}*$ $*\Delta P_t^{-0.08}*\Delta P_s^{-0.04}*1000$ [11] *a* (ºC)=1 (HP heaters), 2 (LPH1), 5(LPH2)
MSF	16	TTD	*KB16*ca+KB16*cb+kZ16*	$Z16=0.01*80*Q_{msf}*\Delta T^{-0.75}*TTD^{0.024}*\Delta Pt^{-0.1}$ [11]

*In case of several components the objective function and capital cost equation are only related to the variable included here.

Table 3
Results of the local variables in the optimization process

	Variable	Iteration 0	Iteration 1	Iteration 2	Iteration 3
1 BOI	$\eta 1$	0.8	0.8605	0.8608	0.8608
2 HPT1	$\eta 2$	0.945	0.925	0.924	0.924
3 HPT2	$\eta 3$	0.95	0.929	0.928	0.929
4 HPT3	$\eta 4$	0.938	0.932	0.931	0.931
5 HPT4	$\eta 5$	0.847	0.934	0.932	0.932
6 LPT1	$\eta 6$	0.755	0.803	0.803	0.801
7 LPT2	$\eta 7$	0.733	0.808	0.805	0.805
9 CP	$\eta 9$	0.773	0.842	0.838	0.838
10 LPH2	TTD10	1.5	1.111	1.111	1.111
11 LPH1	TTD11	1.5	2.778	2.778	2.778
13 FP	$\eta 13$	0.861	0.864	0.863	0.863
14 HPH2	TTD14	-1.7	0.556	0.556	0.556
15 HPH1	TTD15	0.9	0.556	0.556	0.556
16 MSF	TTD16	2.73	1.667	1.667	1.667
Total cost ($/s)		**1.8158**	**1.6220**	**1.6220**	**1.6219**

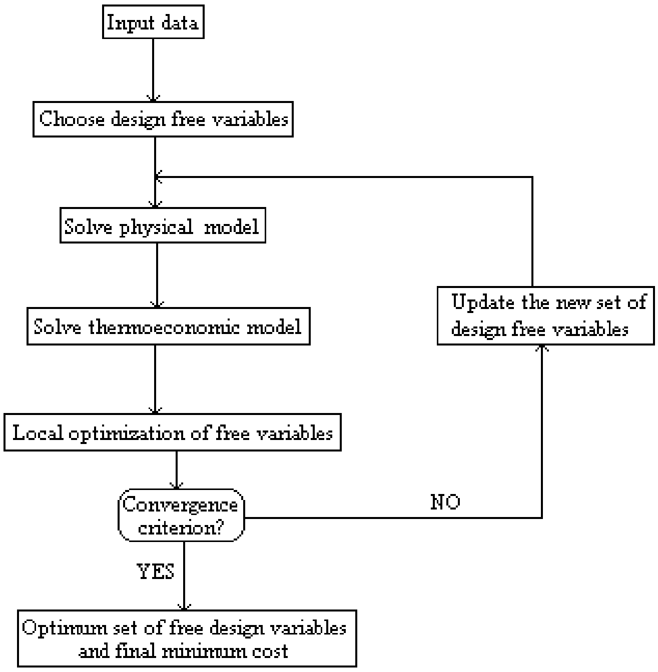

Fig. 3. Local optimization algorithm.

Table 4
Main physical variables after the optimization process

	Initial	Optimum
Live steam mass flow rate (kg/s)	156.0	154.0
Exhaust vapor to condenser temperature (°C)	39.17	38.83
Quality of exhaust vapor to condenser	0.882	0.868
Condensate from the condenser (kg/s)	29.2	28.4
Feedwater temperature to deaerator (°C)	128.2	128.5
Feedwater temperature leaving deaerator (°C)	161.9	161.8
Feedwater temperature to boiler (°C)	229.8	227.5

- 2.76 bar steam extracted to MSF unit
- live steam conditions (fixed pressure control in turbine): 535°C and 93 bar.

Once the physical model is solved for the sample operating conditions, then the cost of the product of each device was obtained by solving the thermoeconomic model. The local optimum value of each free variable was calculated, minimizing the production cost of the component represented by that variable. After obtaining the new values of the local variables corresponding

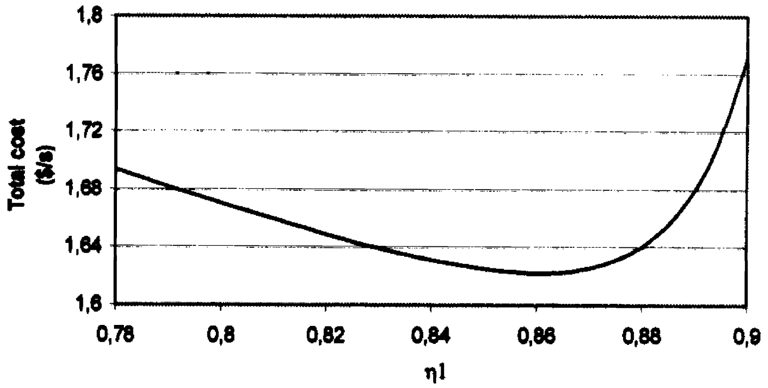

Fig. 4. Sensitivity analysis of the energetic efficiency of the boiler around the optimum point (h1 = 0.8608).

to the local optimal design of the productive units, the procedure was repeated until the desired convergence. Fig. 3 shows the strategy for finding the optimum set of design free variables in the power and MSF desalination plant.

As we can see in Table 3, one iteration is almost enough to reach the convergence criterion or global optimal design.

Tables 4 (thermodynamic values) and 5 (thermoeconomic values) show some of the most significant flowstreams in design and optimum conditions using the thermoeconomic optimization process. Approximately 11% of the total installation cost was saved according to the optimization results in the nominal operating conditions (MCR performance case). Note that not all of the design variables of the optimal set had to improve their values (see the isoentropic efficiency of the high-pressure turbine sections, Table 3). The compromise between thermodynamic efficiency and economy (device capital cost increases with efficiency) is reached at the optimum value of the design free variables.

The optimum product costs of all the components in the dual-purpose plant decreased with respect to the initial values, although the capital cost of some components increased (Table 5).

A sensitivity analysis of the global cost using the optimum selected free variables assured that the optimum was a global minimum. The whole set of variables was analyzed individually. Fig. 4 shows the sensitivity analysis for the energetic efficiency of the boiler. Similar analysis was performed for the rest of the design free variables. In all cases the local optimum satisfied the minimum global cost of the dual-purpose plant. If the thermoeconomic isolation principle were not fulfilled, the minimum global cost would not be obtained for the whole optimum set of design free variables.

3. Conclusions

A complex plant can be optimized by applying local optimization based on thermoeconomic techniques when the devices are isolated enough (i.e., the perturbations in a component only affect its behavior). The most important advantages of the local optimization approach follow:

1. Improvements and optimal design of individual units in highly complex systems are greatly facilitated, as well as of whole systems.

2. The designers can be specialized and their efforts concentrated on designing the variables of single units, while resting assured that these

Table 5
Results for the optimization of the dual-purpose plant in the MCR performance case (main exergy flows are described in Fig. 2)

Flow	Initial			Optimum		
	MW	c (10^{-6} \$/kJ)	Z (10^6 \$)	MW	c (10^{-6} \$/kJ)	Z (10^6 \$)
C1	**481.720**	2.000	—	**443.798**	2.000	—
S1	177.721	—	—	176.308	—	—
B1	208.782	6.927	31.810	206.825	6.642	34.340
B2	53.010	—	—	51.913	—	—
S2	1.992	—	—	2.435	—	—
W2	49.731	9.632	13.780	48.213	9.156	12.160
B3	24.175	—	—	23.785	—	—
S3	0.619	—	—	0.867	—	—
W3	23.360	9.464	6.744	22.726	8.953	5.810
B4	21.308	—	—	21.267	—	—
S4	0.796	—	—	0.874	—	—
W4	20.331	9.414	5.370	20.211	9.010	5.200
B5	21.704	—	—	22.253	—	—
S5	2.357	—	—	1.047	—	—
W5	19.161	9.989	4.590	21.001	9.076	5.421
B6	8.595	—	—	8.507	—	—
S6	1.880	—	—	1.617	—	—
W6	6.449	12.040	1.833	6.609	11.470	2.244
B7	7.295	—	—	7.040	—	—
S7	1.761	—	—	1.231	—	—
W7	5.507	11.950	1.542	5.780	10.990	2.000
B8	7.822	—	—	7.422	—	—
S	54.310	1.517	3.849	51.970	1.453	3.662
W9	0.055	—	—	0.049	—	—
S9	0.010	—	—	0.006	—	—
B9	0.043	14.420	0.072	0.041	13.200	0.095
F10	1.250	—	—	1.154	—	—
S10	0.076	—	—	0.071	—	—
B10	0.994	11.750	0.375	0.912	9.878	0.147
F11	2.442	—	—	2.487	—	—
S11	0.158	—	—	0.166	—	—
B11	2.005	10.450	0.452	2.029	9.206	0.203
F12	9.087	—	—	9.108	—	—
S12	1.179	—	—	1.174	—	—
B12	7.997	9.781	1.593	8.023	9.339	1.596
W13	2.270	—	—	2.240	—	—

Flow	Initial			Optimum		
	MW	c (10^{-6} \$/kJ)	Z (10^{6} \$)	MW	c (10^{-6} \$/kJ)	Z (10^{6} \$)
S13	0.196	—	—	0.190	—	—
B13	2.072	11.720	0.193	2.047	11.090	0.196
F14	8.765	—	—	8.596	—	—
S14	0.467	—	—	0.454	—	—
B14	8.298	8.733	1.243	8.141	7.739	0.497
F15	11.776	—	—	10.777	—	—
S15	0.735	—	—	0.704	—	—
B15	11.162	8.834	1.830	10.190	7.734	0.566
F16	63.664	7.485	—	63.452	7.109	—
S16	−133.421	—	—	−132.977	—	—
W16	8.000	—	—	8.000	—	—
B16	**3.889**	89.500	51.950	**3.889**	61.220	35.542
W	**122.731**	9.993	—	**122.731**	9.427	—
B	238.862	7.237	—	235.756	6.865	—
ΣZ	—	—	127.200	—	—	109.500

efforts yield optimum design and/or improve the overall system.

3. The convergence of the solution is faster.

The design variables selected for the optimization process must influence the physical behavior of the plant and the capital cost of the corresponding component. The two terms composing the product cost of each device must be optimized. This optimum value can be used to readapt the design of the existing components.

In some cases the optimum set of variables does not correspond to any thermodynamic state of the plant, i.e., the obtained state corresponding to the optimum values of the design-free variables does not correspond with feasible operating conditions of the whole plant. In general, when the number of variables exceeds a limit (>5 variables), conventional global optimization methods have serious convergence problems that can be avoided with the optimization method presented in this paper. On the other hand, the local optimization methods suffer also from the feasibility of the optimum solution.

Local optimization is a very powerful tool to design plant components of a complex system such as a power plant coupled with a desalination plant. The optimum design point of each component, under the most usual operating conditions and plant loads, can be obtained by locally optimizing. These components should be designed for best efficiency under all operating conditions. The experience of the designers in calculating the capital cost of the components as a function of their capacity and efficiency is essential to find an optimum that coincides with the optimum of the real system.

4. Symbols

B	—	Exergy flow, kW
c	—	Economic cost, S/kJ
C	—	Fuel, kW
cf	—	Fuel cost, \$/kJ

e	—	Condenser efficiency
k^*	—	Exergy unit cost
M	—	Mass flow rate
P	—	Pressure
Q	—	Heat supplied, kW
S	—	Negentropy flow, kW
T	—	Temperature
v	—	Tube velocity
W	—	Work, kW
Z	—	Capital cost, $

Greek

φ	—	Amortization factor, s^{-1}
Δ	—	Difference
η	—	Efficiency

Subscripts

es	—	Exhaust steam
i	—	Inlet
msf	—	MSF unit
o	—	Ambient or outlet
r	—	Reference
s	—	Shell
t	—	Tubes
w	—	Cooling water (condenser)
1	—	Live steam conditions

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