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Thermoeconomic Optimization for A Co-Generation Plant Based on Productive Structure Technique

By

A. H.Gomaa[*] A. F. El-Dib[**] I. H.Afefy[***]

Abstract:

In this paper, thermoeconomic optimization method based on productive structure technique is applied to a co-generation plant**.** The co-generation plant consists of a water-tube boiler, steam turbine, feed-water pump, deaerator, condenser, process-heaters and condensate tank**.** Global optimization of the whole plant is carried out based on separated local optimizations of different main components. The local optimization technique requires thermoeconomic and mathematical models. The results show that the boiler efficiency increases from 81% for the initial (normal) operating conditions to 90.48% for the optimum ones. On the other hand, the process-air heater efficiency increases from 63 % to 64.5% for the optimum operating conditions. Moreover, as a global result, about 11.53 % of the total product cost for all components of the plant is reduced when using optimum operating conditions other than normal ones.

Keywords:

Thermoeconomic Optimization; Productive Structure; Product Cost

* Professor of Industrial Engineering - Faculty of Engineering -Benha University
** Professor of Mechanical Power Engineering- Faculty of Engineering – Cairo University
*** Lecture of Industrial Engineering - Faculty of Engineering- Fayoum University

1. Introduction:

The present study has been performed for a practical co-generation plant. The plant provides electrical and thermal energies to Egyptian Minerals and Salts Company (EMISAL), EL-Fayoum, Egypt. The main product of the company is sodium sulphate unhydrous. Thermoeconomic optimization technique of specific process unit variables is the suitable tool to minimize final product costs and save resource energy [1]. Moreover, the optimization process is based on analytic methodologies that determine optimal or near-optimal solutions by calculating exergy losses and entropy production cost in different system components [2]. The following aspects show the necessity of applying optimization procedures in the design and operation of the steam system[3, 4]:-

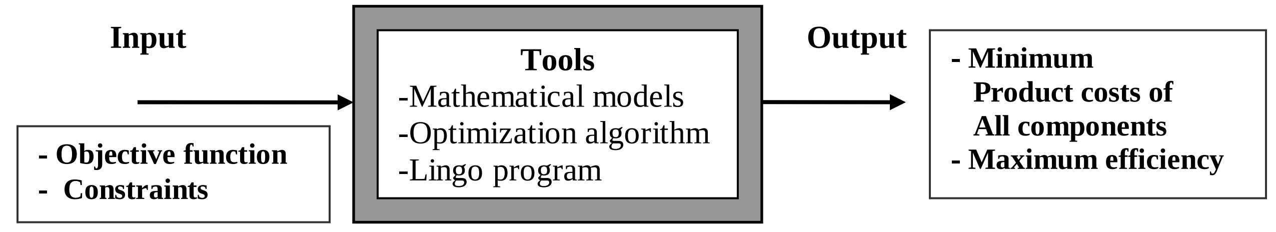
- Increasing the quality and capacity of the system while reducing cost in order to be competitive
- Saving energy and material resources.
- Best operating point at each instant time such as temperature, pressure and mass flow rate.

A thermoeconomic model represents mathematically the productive structure of a plant, which is a graphical representation of resource distribution. The flows in the productive structure describe the productive relations between all the components based on physical structure. The thermoeconomic model can be logically defined by the following procedures [5]:

i. A physical model of the plant is built first
ii. Productive structure is applied

Flow streams entering the system components are usually its fuel, and the flow stream leaving the system components is its product [4, 6, 7, 8].

The block diagram describes the relation between the input to the optimization mathematical model (objective function and constraints) and output from the model (minimum product costs of all components and maximum efficiency). To optimize the steam systems, mathematical model, optimization algorithm and Lingo program are chosen as the suitable tools. The block diagram for the optimization mathematical model is shown in Fig.1.



Figure(1): Block diagram for optimization mathematical.

The physical model of the analyzed co-generation plant is shown in Fig.2. The co-generation plant provides electrical energy and heat to electric grid and process-heaters in installation. Steam generated in the boiler is used for both operating the steam turbine to produce the electric power output and supplying the process steam to heat process brine and process air. Condensate leaving both process-brine and process-air heaters is collected in the condensate tank, and then supplied to the deaerator through two condensate pumps. Feed water is fed to the boiler through the feed-water pump. Some steam is taken directly from the boiler where its pressure is reduced through a throttling valve (Thv7) and its temperature is controlled through a desuperheater (Desup8) to heat air in the process–air heater. The process-brine heater uses steam extracted from the low-pressure section of the turbine, whose temperature is controlled in another desuperheater (Desup10). Dearator (DRT5) is very important to remove the non-condensable gases via the deaeration process.

2. Productive Structure Technique:

The productive structure (Fig. 3) represents the productive interaction among the different components of the plant, and it is a tool that helps to calculate the cost of the internal flows of the system. The inlet arrows to the components represent the resources consumed in the component and the outlet arrows correspond to the products. Bifurcations, also called branches (b1), and junctions (J1) are fictitious devices that represent the fuel and products.

2.1 Thermoeconomic Analysis:

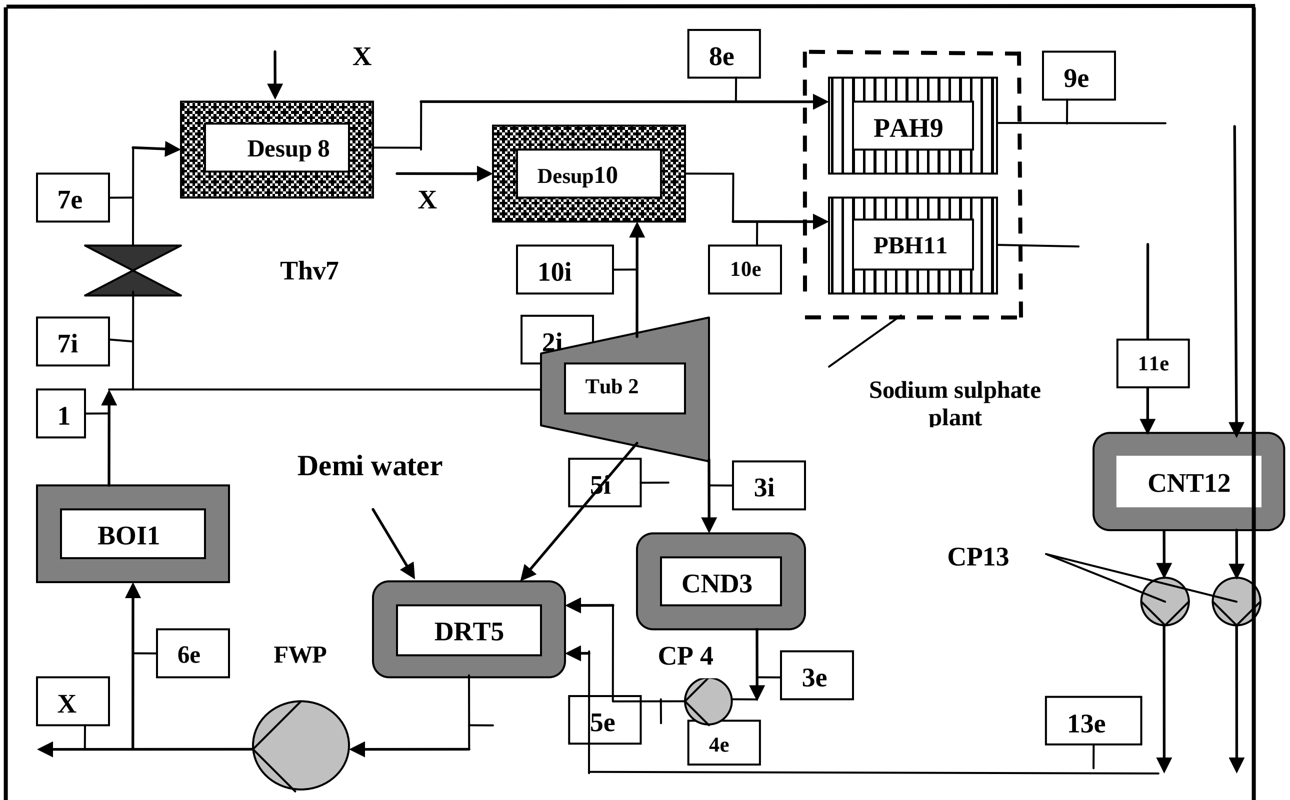
Thermoeconomic analysis is used in technical and economic evaluation of the plant. Also, it is used to perform a diagnostic of the steam systems. The thermeconomic model encompasses the definition of a productive structure function (product) for each component and resource that each one needs to consume (fuel) in order to achieve the production objective. The product cost equations and the costs of the main flow streams of the plant are presented in Table 1. Equations of the capital cost for the plant are presented in Table 2 .

$$\dot{Z}=Z*\varphi \qquad (1)$$

And,

$$\varphi = (FCR*\Phi)/(3.6*10^{5}*n) \qquad (2)$$

where, Φ is the maintenance factor; FCR is the annual fixed charge rate percent; n is the number of operating hours per year, and Z is the capital cost. The following standard values have been considered: FCR=18.2 %; Φ=1.06; n=8000 h/y [11].



BOI	Boiler	Desup	Desuperheater	T	Throttling valve
CND	Condenser	e	Exit	Tub2	Turbine
CNT	Condensate tank	PBH	Process-brine heater	i	Inlet
CP	Condensate pump	PAH	Process-air heater	X	Water of all desuperheaters
DRT	Deaerator	1,2.13	Thermodynamic states		

Figure(2): physical model of co-generation plant.

Table (1): Product cost equations applied in the productive structure [1]

Device No.	Device symbol	Product cost equations
1	Boiler (BOI1)	$c_1= (C_1*c_f+N_1*cs+Z_1*\varphi)/ B_1$
2	Turbine (Tub2)	$c_2= (B_2*ca+N_2*cs+Z_2* \varphi)/W_2$
3	Condenser (CND3)	$c_3 = (B_3*ca+ Z_3*\varphi)/N_3$
4	Condensate Pump (CP4)	$c_4 = (W_4*cb+N_4*cs+Z_4*\varphi)/B_4$
5	Dearator (DRT5)	$c_5= (F_5*ca+N_5*cs+Z_5*\varphi)/B_5$
6	Feed-Water Pump (FWP6)	$c_6= (W_6*cb+N_6*cs+Z_6*\varphi)/B_6$
7	Throttling Valve (Thv7)	$c_7= (F_7*ca+N_7*cs+Z_7*\varphi)/B_7$
8	Desuperheater (Desup8)	$c_8= (F_8*ca+N_8*cs+Z_8*\varphi)/B_8$
8	Process-Air Heater (PAH9)	$c_9= (F_9*ca+N_9*cs+Z_9*\varphi)/B_9$
10	Desuperheater (Desup10)	$c_{10}= (F_{10}*ca+N_{10}*cs+Z_{10}*\varphi) /B_{10}$
11	Process-Brine Heater(PBH11)	$c_{11}= (F_{11}*ca+N_{11}*cs+Z_{11}*\varphi) /B_{11}$

12	Condensate Tank (CNT12)	$c_{12}= (F_{12}*ca+N_{12}*cs+Z_{12}*\varphi)/B_{12}$
13	Condensate Pump (CP13)	$c_{13}= (W_{13}*cb+N_{13}*cs+Z_{13}*\varphi)/B_{13}$
14	Junction (J1)	$ca= [B_1*c_1+ B_4*c_4+ B_5*c_5+ B_6*c_6+ B_{13}*c_{13}] /B$

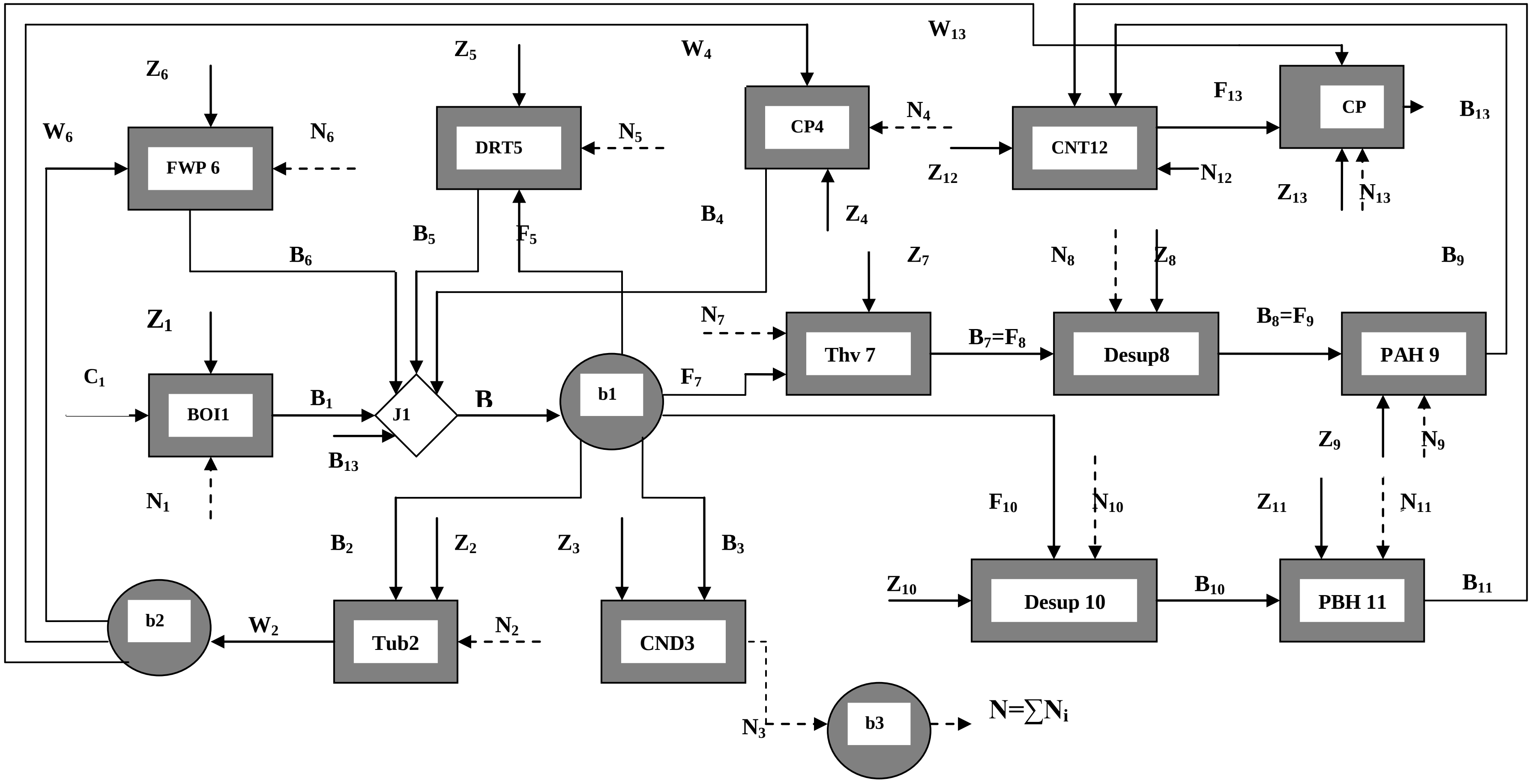


Figure (3): Productive structure of the thermoeconomic model applied to co-generation plant

Table (2): Equations of the capital cost for the plant

Device No.	**Device symbol**	**Capital cost equations**		**Ref.**
1	BOI1	$\dot{Z}_1=(a_{11})\ (g_{1\eta})(g_{1T})\ (g_{1p})\ (\acute{Y}_1)^{0.8}$ $g_{1\eta}= 1+ [(1- \eta_r)/(1-\eta_1)]^7$ $g_{1T}= 1 +5\exp[(T_1- 866)/10.42]$	$a_{11} = 360$ \$/kW $g_{1p} = \exp[(P_1-28)/150]$ $\acute{Y}_1 = M_{st}\ [h_{in} -h_{out}]$	[10]
2	Tub2	$Z_2 = 3000*[1+5\exp((T_2-866)/10.42)*[1+((1-\eta_r)/(1-\eta_2))^3]*W_2)^{0.782}$ $W_2 = M_2h_2\ )_i - M_3h_3\ )_i - M_{10}h_{10}\ )_i- M_5h_5\ )_i$ $\eta_2\ = (h_{2i} - h_{5i})/\ (h_{2i} - h_{5i})_s$		[1]
3	CND3	$Z_3 = [1/(T_o-e_3)] * 217 * [0.247 + 1/(3.24 *(V_3)^{0.8})] * \ln[1/(1-e_3) + 138] +[1/(1- \eta_3)] * N_3 * 50$		[1]
4, 6,13	CP	$Z = 378* B^{0.71}* [1+ ((1 -\eta_r)/(1 - \eta))^3]$		[1]
5	DRT5	$Z_5 = 10.4\ \acute{Y}5$	$\acute{Y}5= \Sigma\ M\ h)_{in} - \Sigma M\ h)_{out}$	[10]
9, 11	PAH 9, PBH11	$Z = 0.02 * 3.3* Q * (\Delta P_s)^{-0.04} *\mathrm{abs}(1/(TTD-1))^{-0.1}* (\Delta P_t)^{-0.08} *1000$		[1]
12	CNT12	$Z_{12} = 10.4\ \acute{Y}_{12}$	$\acute{Y}_{12} = \Sigma\ M\ h)_{in} - \Sigma M\ h)_{out}$	[10]

3. Optimization Mathematical Model:

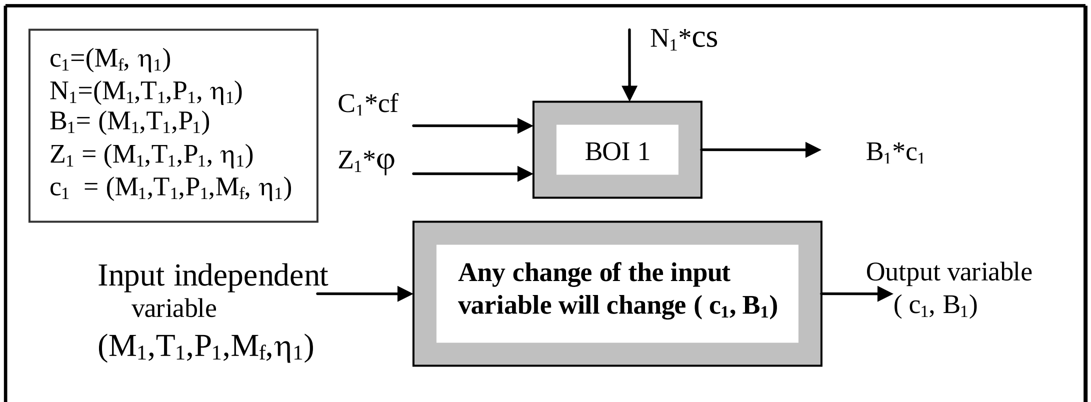
The mathematical model is a set of non-linear algebraic equations and can be logically defined by the following procedures:

- Objective function equation
- Constraints equation

The purpose of the mathematical model is to use generated simplified performance equations to describe the impact of the operating conditions and cost parameters on the steam systems performance. Also, these models describe the economic framework of the production facility. An optimization problem is called a problem of quadratic programming, if it consists of a quadratic objective function and inequality constraints.

3.1 Boiler:

The modeling system for boiler is presented in Fig. 4. The steam product cost depends on operating and economic parameters (P_1, T_1, M_1, M_f and cs). Minimization of the cost rate (c_1) of the steam generation from boiler is selected as the optimization objective function:-



Figure(4): Water-tube boiler modeling

Objective function

$$\text{Min } c_1= [C_1*cf +N_1*cs +6.7 *10^{-9}*Z_1]/B_1 \quad (1)$$

$$B_1=M_1[(h_1 – 104.9) – 298*(s_1 – 0.3987)] \quad (2)$$

$$Z_1=360 (Y_1)^{0.8} (g_{1\eta}) (g_{1t})(g_{1p}) \quad (3)$$

$$Y_1= M_1(h_1-572.4) \quad (4)$$

$$g_{1\eta}= 1+ [(1- \eta_r)/(1-\eta)]^7 \quad (5)$$

$$g_{1T} = 1 +5\exp[(T-866)/10.42] \quad (6)$$

$$g_p = \exp[(P-28)/150] \quad (7)$$

$$N_1=M_1 *T_o (s_1 – s_6) \quad (8)$$

$$h_1= 2587.67*\exp (0.00060054T_1)*\exp ((-0.003724 + 0.0000123T_1- 1.09T*10^{-8} (T1)^2)*P_1) \quad (9)$$

$$s_1= 6.24757*\exp (0.0003692T_1)*\exp ((-0.0053377+0.000014654T_1- 1.383*10^{-8} *T1^2)*P_1) \quad (10)$$

$$s_6= 6.24757*\exp (0.0003692T_6)*\exp ((-0.0053377+0.000014654T_6- 1.383*10^{-8}*T_6^2)*P_6) \quad (11)$$

$$cs= (1.3354*10^{-6})*\exp (-0.000414*T_1)*\exp((0.0861-0.0003824*T_1 +4.22*10^{-7} *T_1^2)*P_1) \quad (12)$$

Subject to

$$55 \le P_1 \le 65 \text{ bar}, \quad 400 \le T_1 \le 470\ ^oC, \quad 32 \le M_1 \le 35 \text{ t/h}, \quad 0.45 \le M_f \le 0.55 \text{ kg/s and } 81 \le \eta_1 \le 100\ \% \quad (13)$$

3. 2 Turbine:

The modeling system for the studied steam turbine is presented in Fig. 5. This model shows the cost rate of the electric energy product (c_2) depends on physical and economic parameters (T_{10i}, M_{2i}, M_{10i}, η_2, ca and cs). Moreover, minimization of the cost rate of the electric energy product from turbine is selected as the optimization objective function:-

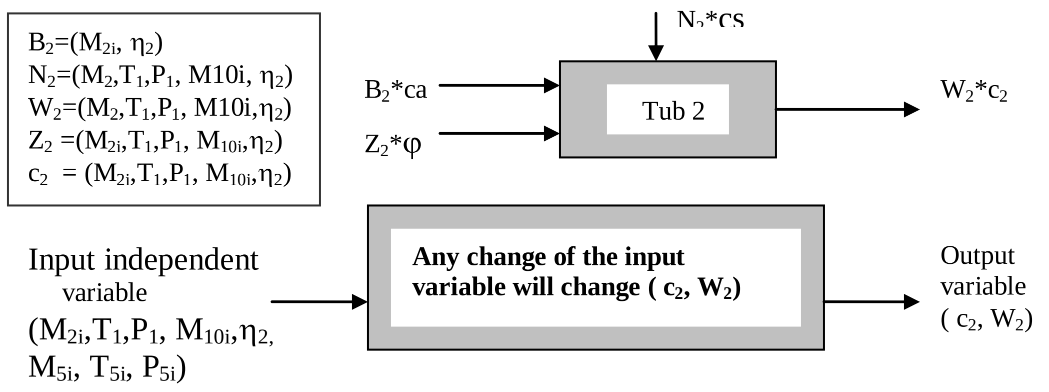


Figure (5): Steam turbine modeling

Objective function

Min $c_2=[B_2*ca + 0.733*10^{-6}* N_2 +6.7 *10^{-9}*Z_2]/W_2$ (14)

$B_2=M_2[(h_2– 104.9) – 298*(s_2 – 0.3987)]$ (15)

$N_2= T_0*(M_3*s_{3i}+ M_{10i}*s_{10i}+ M_{5i}*s_{5i}-M_{2i}*s_{2i})$ (16)

$Z_2 = 3000*[1+5\exp((T_2-866)/10.42))*[1+((1-\eta_r)/(1-\eta_2))^3]*W_2)^{0.782}$ (17)

$h_2= 2587.67*\exp (0.00060054T_{2i})*\exp ((-0.003724 + 0.0000123T_{2i}- 1.09T*10^{-8} T_{2i}^2)*P_{2i})$ (18)

$s_2= 6.24757*\exp (0.0003692T_{2i})*\exp ((-0.0053377+0.000014654T_{2i}- 1.383*10^{-8} *T_{2i}^2)*P_{2i})$ (19)

$h_{5i}=2456.32*\exp(0.0007579*T_{5i})$ (20)

$s_{5i}=6.2462*(0.00065717*T_{5i})$ (21)

$W_2 = M_2h_2)_i – M_3h_3)_i – M_{10}h_{10})i- M_5h_5)_i$ (22)

$\eta_2 = (h_{2i} – h_{3i})/ (h_{2i} – h_{3i})_s$ (23)

$ca=(9.56193*10^{-6})* \exp(-0.004906*T_{10i})$ (24)

Subject to

$180 \le T_{10i} \le 200\ ^oC$, $29 \le M_{2i} \le 31$ t/h , $75.58 \le \eta_2 \le 100$ % and
$11 \le M_{10i} \le 14$ t/h, $180 \le T_{5i} \le 200\ ^oC$, M_{5i} & P_{5i} = constant (25)

3.3 Process-Air Heater (PAH9):

The modeling system for process-air heater (PAH9) is presented in Fig. 6. This model shows the product cost of process-air heater depending on operating parameters (T_9, P_9, M_9,M_a and η_9) and economic parameters (cs and ca). Moreover, minimization of the product cost of process-air heater (PAH9) is selected as the optimization objective function:-

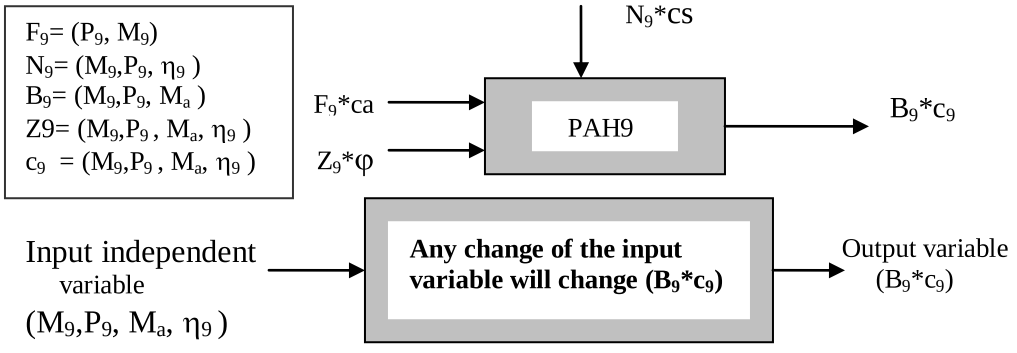


Figure (6): Process-air heater modeling

Objective function

$$\text{Min } c_9=(F_9*ca+N_9*cs+ 6.7 *10^{-9}*Z_9)/B_9 \qquad (26)$$

$$B_9=M_{9e}[(h_{9e}- 104.9) - 298*(s_{9e} - 0.3987)] \qquad (27)$$

$$F_9= M_9 ((h_{9i} - 104.3) - 298 (s_{9i}-0.3987)) \qquad (28)$$

$$N_9= M_{9i}*T_0 (s_{9e} - s_{9i}) \qquad (29)$$

$$Z_9=(1000*0.02*3.3*Q_9)/((0.4)^{0.04}*abs(1/TTD9-5)^{0.1} (0.7)^{0.08}) \quad [1] \qquad (30)$$

$$Q_9= M_9 (h_{9i}-h_{9e}) \qquad (31)$$

$$h_{9i}= 2762.33 exp(0.000695*P_9) \qquad (32)$$

$$s_{9i}= 6.799 exp (-0.003573*P_9) \qquad (33)$$

$$h_{9e}= 660.354 exp (0.016394*P_9) \qquad (34)$$

$$s_{9e}= 1.93564 exp (0.01187*P_9) \qquad (35)$$

Subject to

$14 \le P_9 \le 17$ bar, $3 \le M_9 \le 3.6$ t/h, , $6.5 \le M_a \le 6.909$ kg/s and

$63 \le \eta_9 \le 100$ %, (36)

<u>3.4 Process-Brine Heater (PBH11)</u>:

In Fig. 7, the modeling system for the process-brine heater (PBH11) is presented. This model shows the product cost of process-brine heater depending on operating parameters (T_{11}, P_{11}, M_{11}, Mb and η_{11}) and economic parameters (cs and ca). Minimization of the product cost of the process-brine heater (PBH11) is selected as the optimization objective function:-

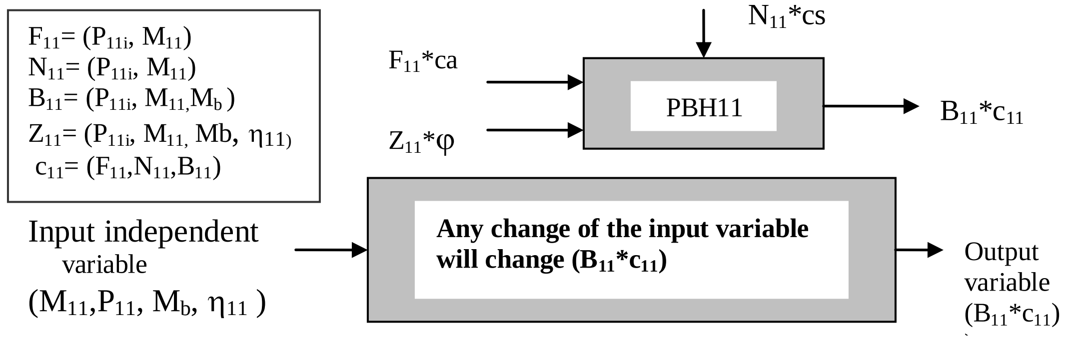


Figure (7): Process-brine heater modeling

Objective function

Min $c_{11}=(F_{11}*ca+1.068*10^{-6}*N_{11}+6.7*10^{-9}*Z_{11})/B_{11}$ (37)

$B_{11}=M_{11e}[(h_{11e}-104.9)-298*(s_{11e}-0.3987)]$ (38)

$F_{11}=M_{11}((h_{11i}-104.3)-298(s_{11i}-0.3987))$ (39)

$N_{11}=-298*(M_{11}*s_{11e}-M_{11}*s_{11i})$ (40)

$Z_{11}=(1000*0.02Q_{11})/((0.06)^{0.04}*abs(1/37)^{0.1}(0.7)^{0.08})$ (41)

$h_{11i}=2690.51exp(0..0043578P_{11})$ (42)

$s_{11i}=7.2493\ exp(-0.01229P_{11})$ (43)

$h_{11e}=463.761\ exp(0.06537P_{11})$ (44)

$s_{11e}=1.4417\ exp(0.05116P_{11})$ (45)

$ca=0.000003211\ exp(0.0266P_{11})$ (46)

$Q_{11}=M_{11}(h_{11i}-h_{11e})$ (47)

Subject to

$3 \le P_{11} \le 5$ bar, $12.5 \le M_{11} \le 15$ t/h, $50 \le M_b \le 52.3$ kg/s and $63.5 \le \eta_{11} \le 100$ %,

4. Results of Case Study:

Thermoeconomic optimization of the co-generation plant has been performed for the design operating conditions of the plant.

4. 1 Design Conditions and Data of Co-Generation Plant:

The flow diagram for this case study (design conditions) is shown in Fig.1. The maximum steam generated from the boiler and the net electric power are 35 t/h and 4.15 MW, respectively. A process steam flow rate of 14.184 t/h is used for the brine heating.

4.2 Results and Discussion:

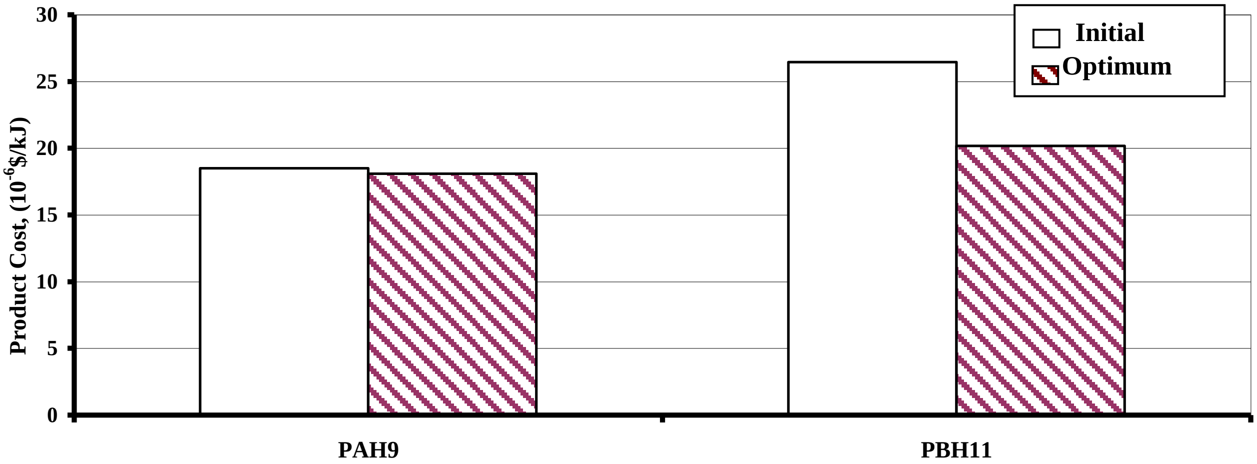
The co-generation plant has been analyzed using thermoeconomic analysis based on productive structure at different operating parameters. The optimization problem has been solved for the parameter values given in Table 3. The optimum values of each variable was calculated, minimizing the production cost of the main components represented by that variable. Thermodynamic optimization requires η_1, η_2, η_6 and η_9 to take the maximum possible value, ideally to be equal to 1. Since this is impossible, these variables are set equal to their optimum values of the thermoeconomic optimization. Also, the comparison between the initial and optimum efficiencies is presented in Fig. 9. This figure shows that the boiler efficiency increases from 81 % for the initial (normal) operating conditions to 90.48 % for the optimum operating conditions. On they other hand, the process-air heater (PAH9) efficiency increases from 63.5% for the initial (normal) operating conditions to 64.5 % for the optimum operating conditions.

Table 3 shows some of the most significant flow streams in design and optimum conditions using the thermoeconmic optimization process. Note that the optimum product cost in steam system decreased with respect to the initial values without the condensate pump product cost (c_4) and desuperheater product cost (c_{10}). As shown in Table 4, the comparison between the initial and optimum product costs of the main components for the steam system is presented. This table shows that the total product costs decreases from $86.63*10^{-6}$ \$/kJ for the initial (normal) operating conditions to $76.64*10^{-6}$ \$/kJ for the optimum operating conditions. Moreover, approximately 11.53% of the total product cost was saved according to the optimization results in the normal operating conditions. The results agree with the results of the previous studies [3]. This is may be due to the lower the cost of fuel and, consequently, lower the interior cost and negentropy cost of the main components for the system.

Table (3): Optimization results of the local variables for process- steam plant

Variable	**Initial**	**Optimum**
M_f (kg/s)	0.4809	0.45
M_1 (kg/s)	9.444	9.444
T_1 (^oC)	460	470
P_1 (bar)	60	65
η_1 (%)	83.8	90.48
M_{2i} (kg/s)	8.055	8.611
η_2 (%)	75.58	84.8
M_{3i} (kg/s)	3.333	3.194
T_{6e} (^oC)	133	135
η_6 (%)	93.13	93.18
M_9 (kg/s)	0.889	0.8333
M_a (kg/s)	6.909	6.907
P_9 (bar)	16	16
T_{10i} (^oC)	190	200
η_9 (%)	63	64.5
M_b (kg/s)	52.3	50.697
P_{11} (bar)	5	5
M_{11} (kg/s)	3.61	3.47
η_{11} (%)	63.5	63. 9
T_{5i} (^oC)	190	200

From Fig. 8, the product cost of the process-air heater and process-brine heater decreases from $18.51*10^{-6}$ \$/kJ & $26.46*10^{-6}$ \$/kJ for the initial (normal) operating conditions to $18.09*10^{-6}$ \$/kJ & $20.18*10^{-6}$ \$/kJ, respectively, for the optimum operating conditions. This may be due to the increase of the efficiency for the process-air heater and process-brine heater. From Fig. 10, the results agree with the results of the previous studies [2].



Figure(8) : Comparison between initial and optimum product costs for process-air heater and process-brine heater .

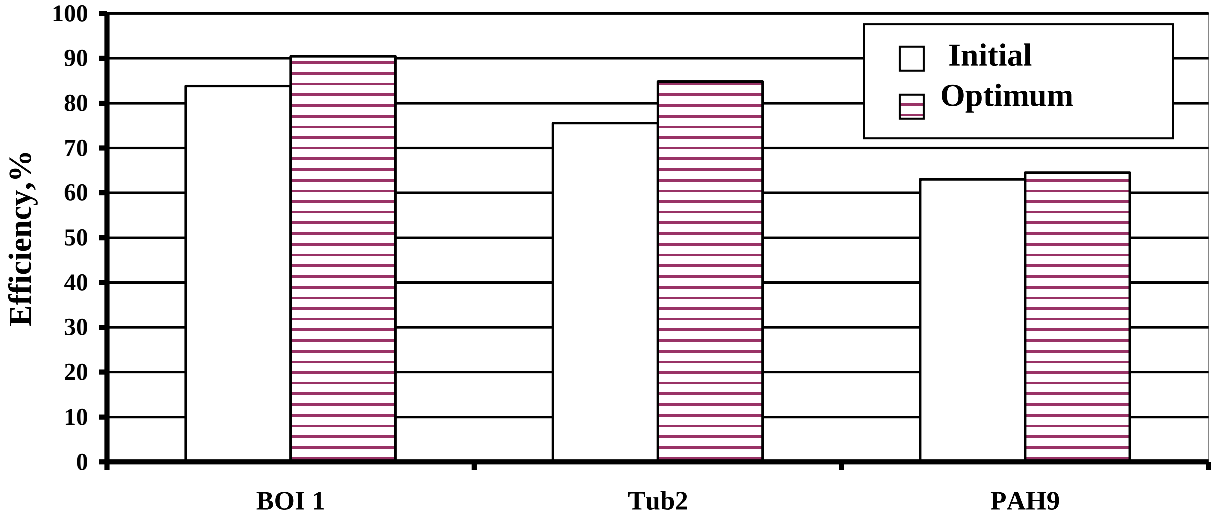


Figure (9): Comparison between initial and optimum efficiencies for boiler, turbine, and process-air heater .

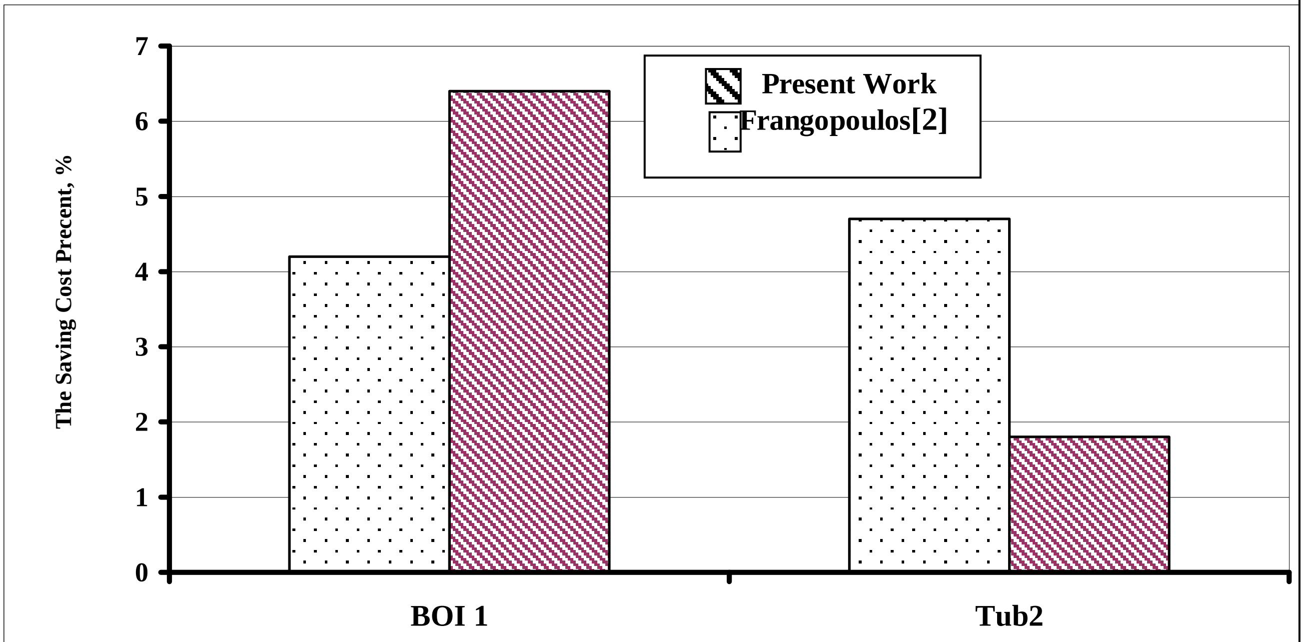


Figure 10: The value of the saving cost according to the optimization results in the normal operating conditions for boiler and turbine.

Table (4): Values of product costs at the optimum point (10^{-6}\$/kJ) for co- generation plant .

Product Cost	Initial	Optimum	Variance (Initial – Optimum)	Variance % (100* Variance/ Initial)
c_1	3.661	3.597	**0.064**	**1.748**
c_2	10.08	8.83	**1.25**	**17.659**
c_3	0.7508	0.7325	**0.0183**	**2.437**
c_4	1.221	1.43	**-0.209**	**-17.1**
c_5	6.41	5.324	**1.086**	**16.94**
c_6	2.444	2.12	**0.324**	**13.26**
c_7	4.388	3.728	**0.66**	**15.04**
c_8	3.056	2.973	**0.083**	**2.72**
c_9	18.51	18.09	**0.42**	**2.27**
c_{10}	3.788	3.972	**-0.184**	**-4.86**
c_{11}	26.46	20.18	**6.28**	**23.73**
c_{12}	5.035	4.92	**0.115**	**2.28**
c_{13}	0.8323	0.75121	**0.08109**	**9.74**
Total cost	**86.63**	**76.64**	**9.99**	**11.53**

5. CONCLUSIONS:

Optimization mathematical models of the main components for the steam system are carried out. Such models can be used to solve the steam system problems in order to achieve the optimization of the system operation. The solution methodologies for optimization mathematical models adopted are based on the quadratic algorithm.

The optimum values for operating parameters of the co-generation plant are investigated. The results show that the boiler efficiency increases from 81% for the initial (normal) operating conditions to 90.48% for the optimum once. On the other hand, the process-air heater efficiency increases from 63 % to 64.5% for the optimum operating conditions. Moreover, as a global result, about 11.53 % of the total product cost for all components of the plant when using optimum operating conditions other than normal once. As a result of the optimization for the steam system at different operating and economic parameters, the following recommendations could be outlined:

1- The optimum operating conditions for boiler are steam pressure 65 bar and steam temperature 470o^{C}.
2- The optimum operating conditions for process-brine heater (PBH11) are steam pressure 16 bar and steam mass flow rate 0.83kg/s.
3- The optimum operating conditions for process-air heater (PAH9) are steam pressure 5 bar and steam mass flow rate 3.47 kg/s.
4- The optimum operating conditions for turbine are inlet steam mass flow rate 8.611kg/s and exhaust mass flow rate 3.194kg/s .

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Nomenclature

B	Exergy rate, kW	T	Temperature, K or ^{o}C
c	Cost of product, $/kJ	TTD	The terminal temperature difference, ^{o}C
ca	Cost of junction product, $/kJ	V	Velocity, m/s
cb	Cost of electric power, $/kJ	W_T	Power of turbine, kW
cs	Cost of negentropy flow, $/kJ	W_P	Power of pump, kW
c_f	Cost of fuel, $/kJ	**Greek Symbols**	
C	Chemical exergy of fuel, kW	φ	The amortization factor
e	Parametric efficiency	Φ	The maintenance factor
F	Feeding exergy flow, kW	η_r	Reference efficiency
FCR	Annual fixed charge rate percent	$	Dollars
g	Correction factor	**Subscripts:**	
g_η	Correction factor of efficiency	1,2..13	Thermodynamic states
g_p	Correction factor of pressure	B	
g_T	Correction factor of temperature	BOI	Boiler
h	Specific enthalpy, kJ/kg	CND	Condenser
M	Mass flow rate, t/h or kg/s	CNT	Condensate tank
P	Pressure, bar	Desup	Desuperheater
ΔP_s	The losses inside shell **,** bar	$	Dollars

ΔP_t	The losses inside tube, bar	E	Exit
S	Negentropy, kW	F	Fuel
N	Negentropy flow, kW	FWP	Feed-water pump
s	Specific entropy, kJ/kg K	PAH	Process-air heater
V	Volume flow rate, m^3/s	PBH	Process-brine heater
ΔP_s	The losses inside shell **,** bar	O	Surroundings
ΔP_t	The losses inside tube, bar	St	Steam
Ý	Rate output from the power, kW	Thv	Throttling valve
Z	Capital cost of device, $	Tub	Turbine
$\dot{Z}$	Capital cost rate of device, $/s	W	Water

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Table (2): *Rule base for the position controller*

e	NB	NM	NS	ZE	PS	PM	PB

ce							
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

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6. Conclusions:

This paper presents the effect of damping constant and rotor inertia constant of the machines on the behavior of electromechanical wave propagation in a one-dimensional ring power system. The analyzed system is continuum, and it is discretized for simplicity of analysis. From the simulation results, it is clear that the higher oscillatory wave vanishes with the increase of damping constant and it suppresses the disturbance wave from its propagation through the entire network. Also, the increase of rotor inertia constant leads to the electromechanical wave propagation velocity decrease.

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Nomenclatures:

□ … Power angle
□ … Rotor speed
a … Acceleration
b … Conductance

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