Int.J. Applied Thermodynamics,
Vol.2 (No.1), pp.5-18, March-1999
ISSN 1301-9724

Thermodynamics and Thermoeconomics

Yehia M. El-Sayed
Advanced Energy System Analysis
41658 Higgins Way, Fremont, CA 94539 - USA
Tel/Fax: 510 656 2783 E-Mail: aesa87@aol.com

Abstract

Raising the efficiency of an energy system is within the domain of thermodynamics. Raising the efficiency cost-effectively (Thermoeconomics) is a multi-disciplinary problem in which thermodynamics interfaces other disciplines of knowledge which in this particular case are design, manufacture and economics. This paper deals with a communication/optimization strategy, via the concept of costing equations, whereby the system can be analyzed and optimized for minimum cost within the domain of thermodynamics. The communication/optimization strategy is explained. The generation of costing equations is demonstrated. A gas turbine power system and seawater distillation process system are used as examples for improved design point and improved configuration. The results of their optimized design points for configurations in order of increasing complexity are displayed on cost-efficiency coordinates.

Key words: second law analysis, costing, thermoeconomics, optimization.

1. Introduction

One of the cornerstones of sustainable development is the cost-effective fuel saving of systems that use or produce useful energy. This, in turn, calls for more intensive and extensive system analysis while the system is still in its design phase. Such analysis has to be multi-disciplinary. Accessing the analysis from the discipline of thermodynamics is the advantage of Thermo-economics.

Thermoeconomics was first developed during the sixties. The name was coined by professor M. Tribus (1962). Seawater desalination processes were of prime concern to gain insight in the interaction between the surface of separation and the energy requirement. Even though at that time oil prices were 0.1 to 0.2 today's prices, the impact on the price of water was significant compared to conventional water prices. The publication by El-Sayed and Evans (1970) was perhaps one of earliest on the subject matter. Later the interest in further development of Thermoeconomics to handle energy-intensive systems in general was initiated by professor R. Gaggioli (1980, 1983). Many researchers responded positively to the initiation. In the last 25 years, the development of thermoeconomics has been impressive in few directions. Valero et al (1994, 1996), El-Sayed (1996) and Lazzaretto and Tsatsaronis (1997) may represent the different directions of development. The directions are not yet free from inconsistencies (Cerqueira and Nebra 1998).

This paper follows the second direction by the author. Costing equations are introduced as rational carriers of the essential information needed for optimal system design given a cost objective function. The results of two previous applications (El-Sayed 1996, 1997b) of the concept and its optimization algorithm are presented. Recently in other publications, the concept has been extended with almost no added information (El-Sayed 1997a, 1998) to the prediction of the system's part-load performance equation and to the optimal operation of a group of systems of known part-load performance equations

In this paper, the need for a communication/ optimization strategy to handle the complexity of multi-disciplinary system optimization is first considered. The extraction of relevant information for optimal system design from design models representing current or innovative design practices of the system devices is then explained using a design model for a heat exchanger as an example. The extracted information is presented as a costing equation for each considered device. This procedure is the *added burden* to purely thermodynamic analysis. An application to a power system (gas turbine) and another to process system (seawater distillation) are then considered for improved design point and improved configuration.

2. The Communication/Optimization Strategy

Any attempt claiming system improvement should be explicitly characterized by an objective function, decision variables that are the degrees of improvement freedom, and an approach to system decomposition. These three features are not independent from each other. They have to be considered simultaneously to establish a communication/optimization strategy.

A cost objective function suitable for the design phase of an energy-intensive system is the production cost for a given capacity:

$$J = \sum c_F * F + \sum c_z * Z + C_R \tag{1}$$

or the net cost function

$$J = \sum c_F * F + \sum c_z * Z - \sum c_P * P + C_R \tag{1a}$$

where J is a cost, c_F and c_P are unit prices of feeds F and products P as occurring in the market place and c_z is a capital discount rate. C_R is a constant remainder cost as far as the design phase is concerned. Equation (1a) suits more multi-product systems, such as cogeneration, since it responds to the relative values of the products as perceived in the market place. The negative of its J is a profitability that is maximized. It also reduces to the production cost of Equation (1) for single product systems of given product rate since $\sum c_P * P$ reduces to a constant. Equation (1) can be applied to a multi-product case, but assumptions equal to the number of products less one are needed to allocate the production cost to each product.

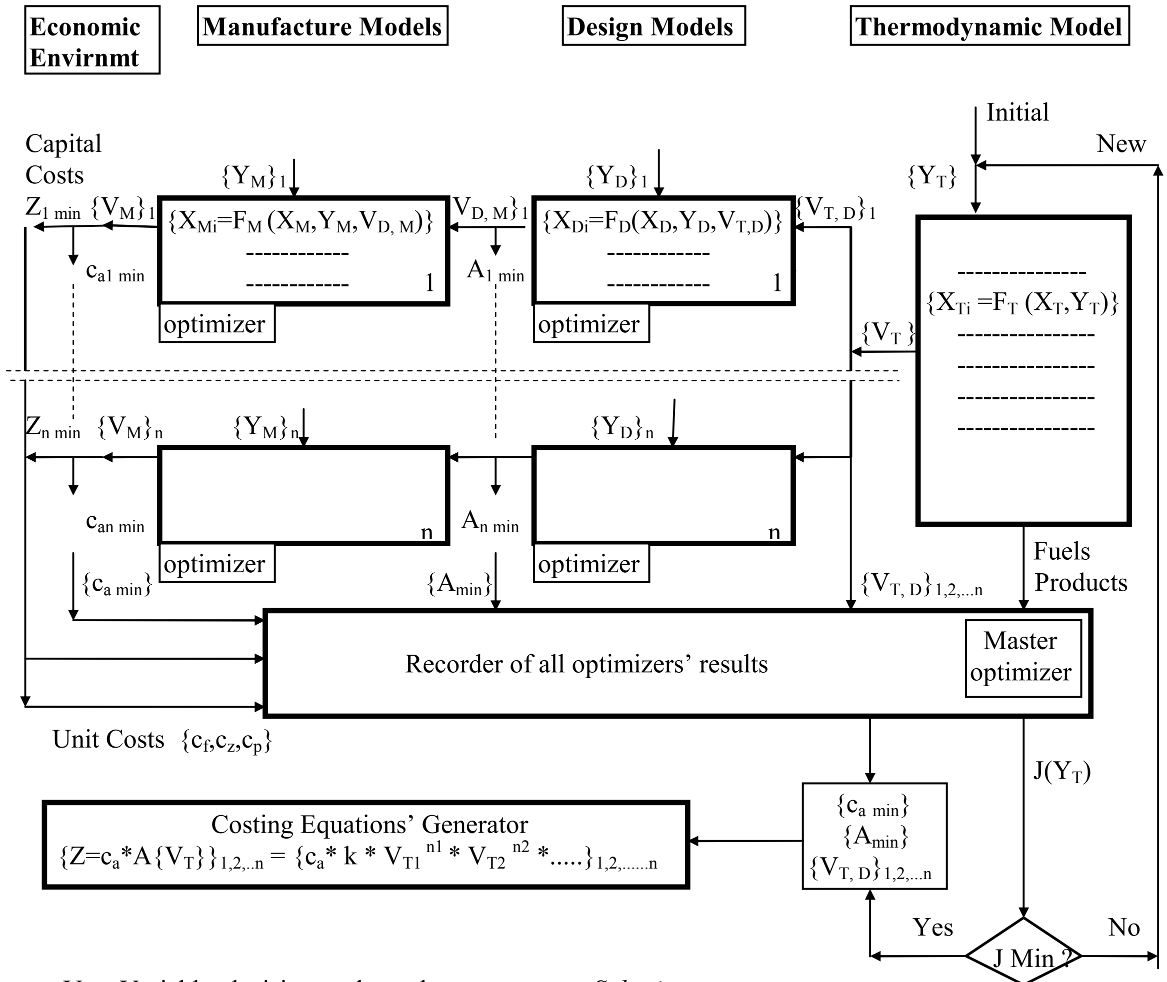
Z is a capital cost of a device that is further expressed as $c_a * A$ or $\sum c_a * A$ where c_a is a unit cost of a characterizing surface or volume of the device. The cost minimization of an energy system of interconnected devices interfaces at least four disciplines of knowledge: Thermodynamics {F,P}, Design {A}, Manufacture $\{c_a\}$ and Economics $\{c_F, c_P, c_z\}$.

To enhance optimization, decomposition is needed at the discipline level as well as the device level. Since the creation of a system occurs in the discipline of thermodynamics, the selection of the system decision variables to be thermodynamic variables follows naturally. These decisions will be mostly efficiency coefficients of the system devices (adiabatic efficiency, effectiveness, pressure loss ratios, heat loss ratios, temperature differences, extent of reaction....) beside few decisions that belong to the system as a whole such as pressure and temperature levels.

2.1. Decomposition at the Discipline Level

Expressing {c} and {A} in terms of thermodynamic variables allows treating the optimization process within the thermodynamic domain and hence the system is decomposed at the discipline level. In many situations {c} can be treated as constants depending on time and location. The costing equations described in the next section give {A} in terms of thermodynamic variables. In this paper {c} are treated as constants.

Figures 1, 2 illustrate the concept of costing equations. Figure 1 shows a theoretical scenario in which the disciplines of thermodynamics, design and manufacture communicate directly while being embedded in a given economic environment. Each discipline assumes a suitable computation model of inputs (decisions variables {Y}), constraining relations, and outputs (dependent variables {X}). The decision variables {Y} depend on the flow of information from the discipline of thermodynamics. The objective of thermodynamics is to minimize fuel and/or maximize products by targeting the highest possible system efficiency. The objective of design is to minimize materials given the efficiency levels of the respective devices. The objective of manufacture is to minimize the labor and the energy of shaping these materials. Each discipline has its own optimizer. A master optimizer iterates all minimization processes and records all rounds of optimization until the cost objective function is minimized. The minimized cost $c_{amin} * A_{min}$ of each device is then listed against its corresponding input thermodynamic variables to its design model $\{V_{T,D}\}$. The resulting correlation establishes the concept of costing equations. The quality of the correlation determines the quality of the costing equation. *Figure 2* assumes thermodynamics as the active discipline and shows an indirect communication with the disciplines of design, manufacture and economics through costing equations and a set of economic prices $\{c_f, c_p, c_z\}$. Of course if the costs of devices are available as function of loading and efficiency, there would be no need for costing equations. At the moment this is not the case and probably will not be the case. Prices of devices in



V	Variable, decision or dependent	*Subcripts*	
Y	Decision Variable	T	Thermodynamic
X	Dependent Variable	D	Design, T,D Thermodynamic input to design
F	Function, Fuel	M	Manufacture, D,M Design input to manufacture
Z	Minimized Capital Cost of a Device	B	Boundary
A	Minimized Characterizing Surface	a	Surface area
C	Unit Costs	f	Fuel
J	Cost Objective Function	p	Product
	$= \sum c_f * F + \sum c_z * Z - \sum c_p * P$	z	Capital

Figure 1. Direct interdisciplinary exchange of information.

the market place are not responsive to efficiency changes and do lack rationality sometimes. This is at least one step towards rationalizing the costs of energy conversion devices for engineering analysis.

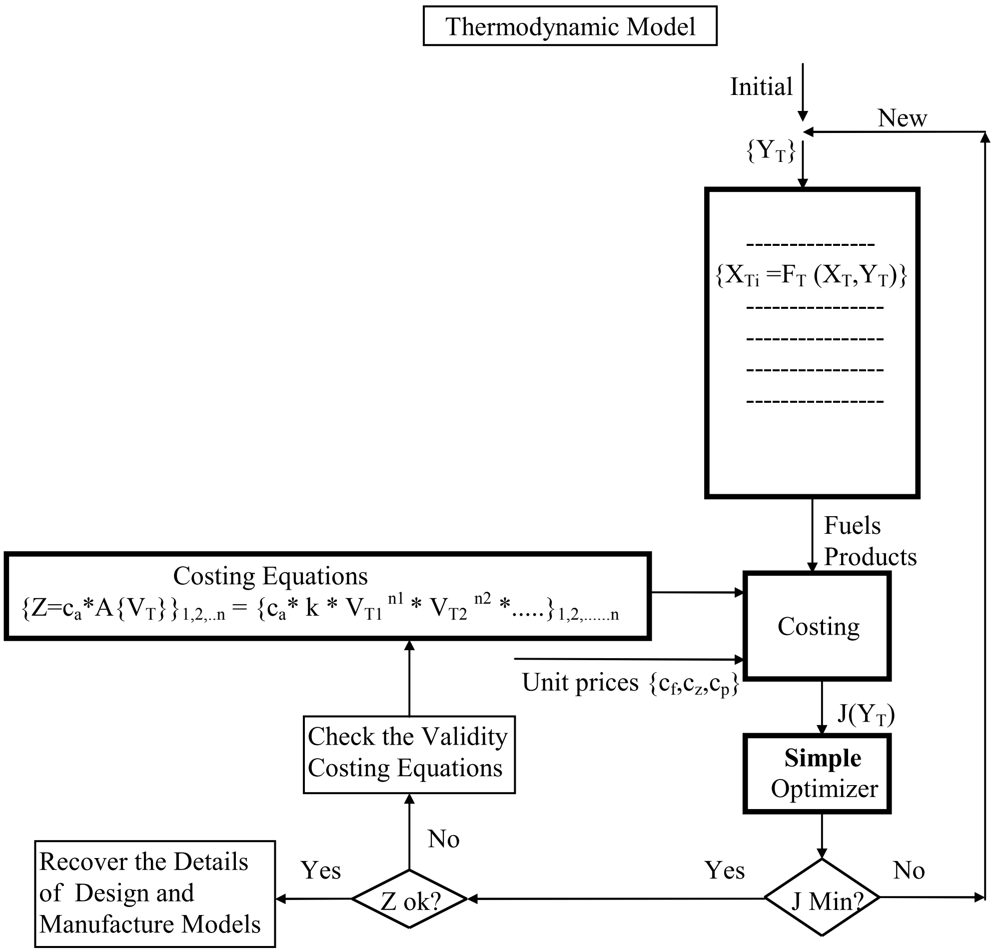
2.2. Decomposition at the Device Level

Decomposition at the device level takes off smoothly from second-law analysis and is achieved for most of the decision variables as follows:

The overall system exergy balance is

$$0 = \sum E_p + \sum D + \sum E_j - \sum E_f \quad (2)$$

where $\{E_p, E_f\,)$ are the exergies of feeds and products, $\{D\}$ exergy destructions by the devices and $\{E_j\}$ exergy of wasted streams. Convert $\{c_F, c_P\}$ of the objective function to be per unit corresponding exergies $\{c_f, c_p\}$. Add equation (2) as a constraint priced at an exergy destruction price c_d where c_d is an undetermined Lagrange multiplier. Augment the objective to a Lagrangian to obtain for equation (1):



V	Variable
Y	Decision Variable
X	Dependent Variable
Z	Minimized Capital Cost of a Device
A	Minimized Characterizing Surface
C	Unit Costs
J	Cost Objective Function $= \sum c_f * F + \sum c_z * Z - \sum c_p * P$

Subcripts

T	Thermodynamic
f	Fuel
p	Product
z	Capital

Figure 2. Indirect interdisciplinary exchange of information via the concept of costing equations.

$$L=\sum(c_d*D+c_z*c_a*A) +\sum c_d*E_j+\sum(c_f-c_d)*E_f + \sum c_d*E_p$$

and for equation (1a)

$$L=\sum(c_d*D + c_z*c_a*A) +\sum c_d*E_j+\sum(c_f-c_d)*E_f - \sum(c_p-c_d)*E_p = J_2 +J_R \quad (3)$$

where

$$J_2 = \sum(c_d*D+c_z*c_a*A) \quad (3a)$$

For objective function (1)

$$J_R = \sum c_d*E_j+\sum(c_f-c_d)*E_f + \sum c_d*E_p \quad (3b)$$

For objective function (1a)

$$J_R =\sum c_d*E_j+\sum(c_f-c_d)*E_f - \sum(c_p-c_d)*E_p \quad (3b)$$

J_2 is a second-law-based objective function pairing dissipations and dissipaters and J_R is a remainder objective, both to be minimized.

2.2.1. Local Optimization: J_2 involves strong trade-off between D and A with respect to efficiency parameters. Idealizing the trade-off as local to each device, the devices are optimized individually. The objective function of a device i is:

$$\underset{\eta_i}{\text{Minimize}}\ \ j_i = c_d * D_i + c_z * c_a * A_i \tag{4}$$

where

$$A_i = k_a * \eta_i^{\,na} \tag{4a}$$

$$D_i = k_d * \eta_i^{\,nd} \tag{4b}$$

where η_i is an efficiency related variable, k_a and k_d are constant coefficients and n_a and n_d are exponents of different signs. The analytical solution is:

$$\eta_{i\ opt} = [-(k_a * n_a) / (k_d * n_d)]^{1/(nd-na)} \tag{5}$$

If k_a and k_d are actually constants, the optima of all the system efficiency variables $\{\eta\}$ are obtained in one system computation. Since the decisions affect other parts of the system through mainly changes in mass rates, k_a and k_d are not actually constants but they converge, fairly fast, to constants irrespective of the number of devices. Using the following updating equation, convergence occurs in 4 to 6 system computation:

$$\eta_{i\ new} = \\ = \eta_{i\ old} * [-(n_a/n_d)/(c_z * c_a * A_i)/(c_d * D_i]^{1/(nd-na)} \tag{6}$$

where A_i and D_i are substituted for k_a and k_d.

Note that any positive dissipation price c_d minimizes J_2. The one to use is that which also minimizes J_R. J_2 increases with c_d and J_R decreases and their sum passes through a relatively flat minimum. The average exergy destruction price c_{da} gives a reasonable starting exergy destruction price and sometimes sufficient

$$c_{da} = (\sum c_F * F + \sum c_p * P) / (\sum E_p + \sum E_f) \tag{7}$$

Within a system, exergy destruction prices are expected to vary between the lowest exergy price of input exergy resources and the highest exergy price of output products. The average price c_{da} is the weighted average of all exergy input resources and all exergy output products.

The use of one exergy destruction price is one extreme. The other extreme is to use a different price for each exergy destruction by augmenting the objective function by the exergy balance equation of each device priced at a Lagrange multiplier yet to be determined by the conditions of optimality. Until there is a fast way to determine these multipliers and to show their significant influence on system optimality, the overall exergy balance is the second best choice.

2.2.2. Global Decisions: Devices may provisionally be decomposed with respect to all efficiency decisions which constitute most of the decision variables. Devices are not decomposed with respect to few decisions of global effect such as pressure levels and temperature levels. Such decisions may influence many devices simultaneously. An efficiency decision showing global effect is treated once more as global decision.

A suitable nonlinear programming algorithm must be invoked. A simplified gradient-based method that ignores cross second derivatives may be used. It has the following updating equation:

$$Y_{new} = Y_{old} \pm \Delta Y \tag{8}$$

$$\Delta Y = ABS\{.5*(Y_2-Y_1)/(g_2-g_1)*(-g_1)\} \tag{8a}$$

$$g_1 = (J_o-J_1) / (Y_o-Y_1) \tag{8b}$$

$$g_2 = (J_2-J_o) / (Y_2-Y_o) \tag{8c}$$

$$Y_2 > Y_o > Y_1 \tag{8d}$$

Updating requires 3 system computations (say Y_o,1.05 Y_o and .95 Y_o) per decision The $\pm$ sign is selected to direct the change in the favored direction because zero gradient represents both maximum and minimum.

3. The Design Model of a Device for its Cost

The example device considered is a forced convection heat exchanger. It is assumed to be the superheater of the heat recovery steam generator of the simple combined cycle shown in *Figure 4.* A duct shell-and-finned tube type is assumed. The fins are assumed circular on the outside which is the gas side. The equation for costing the superheater is derived using the design model of heat exchangers (El-Sayed 1996). The model is basically for forced convection heat transfer and pressure drops for single phase and two-phase (liquid-vapor) fluids. It contains more than hundred equations for film coefficients and friction factors. A heat exchanger can be composed from 4 generic geometries:double-tube, fin-plate, shell-and-tube, plain or outside-finned tubes. Shell may be cylindrical or duct-type. The flow may be pure counter or cross-counter. The design models of other devices are described in the same reference (El-Sayed 1996). Their sources are listed here with the references. Note that improving, updating and reviewing design models for use in other applications is an ongoing process.

3.1 Costing equation

The boundary parameters P, T, {x}, M at inlets and exits of the exchanger as embedded in the system at a design point for the system are used. The exchanger physical surface and its geometry are defined by length, diameter, pitches, number, material, thickness and fin geometry of the tubes. These parameters are usually more than needed to adjust in order to match the computed surface and pressure drops by film coefficients and friction factors for the given heat load and its temperature profile. Any extra design degrees of freedom are used to minimize the surface and/or to satisfy reliable design practices. The design process is therefore a matching/minimizing process.

The costing equation is generated by repeating this design process for different boundary parameters within a range relevant to the optimization of the system. A specific geometry of minimized surface is obtained for each set of boundary parameters. The surface is then expressed by an appropriate set of performance parameters such as heat loads, mass rates, heat exchange temperature differences, effectiveness and pressure losses. In this paper, the surface as fins and tubes is expressed in terms of heat load, the logarithmic mean temperature difference and pressure losses on the shell side and on the tube side. The following form is used:

$$A = k * Q^{n1} * \Delta T_m^{n2} * \Delta p_t^{n3} * \Delta p_s^{n4} \qquad (9)$$

along with the cost conversion equation:

$$Z = c_a * A \qquad (10)$$

The unit cost c_a is function of material, manufacture and severity of operation. It is time and location dependent. It may be assumed independent of A because the economy of scale may be irrelevant for size changes in the design optimization of a system of a given duty.

In this example, c_a is assumed per unit total surface of fins and tubes. Ten minimized surfaces were generated by changing inlet P,T, M, the allowed pressure losses and effectiveness; optimizing exchanger dimensions; and recording heat load, exit conditions, and logarithmic mean temperature difference. The parameters kept fixed are the fin geometry, tube thickness, tube arrangement (staggered), fouling factors, flow directions (gas horizontal, steam with gravity). In this particular example the effect of gravity on pressure losses is negligible. TABLE I shows the recorded parameters of the 10 minimized surfaces and the quality of the correlation.

TABLE I. The Superheater Minimized Surfaces.

a) Surface vs. Thermodynamic Parameters

Run	A_{tube} m^2	Q MW	ΔT_{lm} C	η	Δp_t kPa	Δp_s kPa
1	486	15.76	66	.921	42	.462
2	915	66.80	128	.609	41	.475
3	620	17.32	49	.883	42	.544
4	897	31.50	66	.921	48	.627
5	856	34.66	66	.921	37	1.192
6	976	34.28	39	.921	82	.903
7	188	7.88	66	.921	90	.834
8	276	8.67	66	.921	90	.227
9	355	9.52	66	.919	21	.234
10	112	9.52	126	.400	83	.965

b) Surface vs. Geometrical Parameters

Run	A_{tube} m^2	L_{tube} m	d_o cm	W_{sh} m	Pitch1&2 cm		A_{fin}/A_i	N_{tube}	N_{pass}
1	486	20.4	2.5	11.9	5	4.52	11.8	364	1
2	915	5.8	2.5	52.1	5	4.52	11.8	2397	2
3	620	29.6	2.5	8.8	5	4.52	11.8	321	1
4	897	20.4	2.5	20.4	5	4.52	11.8	673	1
5	856	16.8	2.5	20.1	5	4.52	11.8	776	1
6	976	12.2	5	15.5	10	9.04	19.7	1258	8
7	188	85.3	7.6	.91	15	13.6	27.8	10	1
8	276	45.7	3.8	3.7	7.6	6.78	15.7	57	1
9	355	29.6	3.8	6.4	7.6	6.78	15.7	114	1
10	112	34.1	7.6	2.1	15	13.6	27.8	15	1

Scatter of the Correlating Costing Equation

run	1	2	3	4	5
A_{eqn}/A_{table}	.965	1.10	1.08	.98	1.06
run	6	7	8	9	10
A_{eqn}/A_{table}	.92	1.02	.92	.976	1.08

The constant k and the exponents n_1, n_2, n_3 and n_4 of equation (9) are computed by using the surfaces of five cases simultaneously. These five cases are selected randomly from the total number of cases. The computed constant and exponents that best fit the surfaces of all the cases is selected. The simultaneous solution involves the inverse of a matrix 4x4. When the matrix determinant is relatively too small, unreasonable exponents are obtained and have to be rejected. Also some selections may give rise to singular solutions and fail to give any values altogether. There are however many sets that give solutions. There is also a room to round off the best-fit exponents along with a modified value of the constant k such that the quality of the fit is not changed. The best fit is identified by comparing the fits by the various sets. No further improvement of the best fit is made by applying a multiple regression approach.

The obtained constant and exponents were k=30.71, n_1=1, n_2=-1, n_3=-0.15 and n_4=-0.14, applicable for Q 8-66 MW, ΔT_m 38-130 C, Δp_t 20-90 kPa, and Δp_s .2-1.2 kPa with average scatter ±8%, max +10%. Inside tube surfaces covered the range 110 - 975 m^2. TABLE II lists all the costing equations used in the application examples.

Note that the off-design performance equation of a device can be generated using the same design model in a different mode of computation from that of the costing equation. The geometrical parameters of a design case are kept *constant* at their design point while the boundary parameters are varied.

TABLE II. Costing Equations and the Local Objective Functions.

Costing Equation: Z=ca*A Local Objectives: J(Y)
A = k * x_1^{n1} *x_2^{n2} * x_3^{n3} * x_4^{n4} c_d*D+c_z*Z =k_e*Y^{ne}+k_z*Y^{nz}
component c_a k\$ k x_1^{n1} x_2^{n2} x_3^{n3} x_4^{n4} Y $n_e n_z D_{trading}$
units IP/SI ranges of {x},units IP/SI

----

1 Compr 50 .15 M^1 $Pr^{.45}$ $e^{.45}$ e –.95 .45 D_{PT}
axial 538 .0063 50-1000, 5-15, 2 .3-11.5
25-455, 5-15, 2 .3-11.5

2 G turbine 50 .32 M^1 $Pr^{.5}$ $e^{.85}$ e -.8 .85 D_{PT}
538 .0135 50-1000, 5-15, 4-19
25-455, 5-15, 4-19

3 St turbine 50 .90 $M^1(T_i/P_i)^{.05}P_e^{-.75}$ $e^{.9}$ e -.8 .90 D_{PT}
538 1.978 25-100, 1.5-30, 1-150, 4-19
11-45, 120-2400, .0071-1.03, 4-19

4 Feed pmp 3 .0025 $M^{.55}$ $\Delta P^{.55}$ $e^{1.05}$ e -1 1.05 D_{PT}
32 .000435 5-70, 14-900, 1.8-9
2-32, 100- 6200, 1.8-9

5 C.W pmp 3 .0063 M^1 $\Delta P^{.1}$ $e^{.7}$ e -1 .7 D_{PT}
32 .00183 100-500,2-25,4-14
45-230,14-170,4-14

6 Fan/Blwr 3 .063 M^1 $\Delta P^{.1}$ $e^{.7}$ e -1 1.05 D_{PT}
32 .0183 100-500,.1-.6, 2-9
45-230,.7-4, 2-9

7 Combustor.2 5.85$M^{.5}$ $P^{.24}$ $dp^{-.75}$ dp 1 -.75 D_P
2.15 .261 400-900,50-200,.01-.3
180-410,.34-1.38,.01-.3

8 Superhtr .03 340 Q^1 ΔT_m^{-1} $dP_t^{-.15}$ $dP_s^{-.14}$ ΔT_m 1 -1 D_T
convective .32 32.48 10-15, 100-200, 6-13, .06-.44dP_t 1 -.15 D_{Pt}
10-15, 55-110, 40-90, .4-3 dP_s 1 -.14D_{Ps}

9 Boiler .03 340 Q^1 ΔT_m^{-1} $dP_t^{-.33}$ $dP_s^{-.26}$ ΔT_m.45 -1 D_T
convective.32 18.19 25-55, 75-200, 6-13, .06-.44dP_t 1 -.33 D_{Pt}
25-55, 40-110, 40-90, .4-3 d P_s 1 -.26 D_{Ps}

TABLE II. (continued)

Costing Equation Z=ca*A Local Objectives J(Y)
A=k * x_1^{n1} *x_2^{n2} * x_3^{n3} * x_4^{n4} c_d*D+c_z*Z =k_e*Y^{ne}+k_z*Y^{nz}
component c_a k\$ k x_1^{n1} x_2^{n2} x_3^{n3} x_4^{n4} Y $n_e n_z D_{trading}$
units IP/SI ranges of {x},units IP/SI

----

10 Econmizr .03 310 Q^1 ΔT_m^{-1} $dP_t^{-.16}$ $dP_s^{-.125}$$\Delta T_m$ .45 -1 D_T
.32 29.89 15-40, 70-105, 6-26,. 7-.56 dP_t 1 -.16 D_{Pt}
15-40, 38-60, 40-180, 5-4 dP_s 1 -.125 D_{Ps}

11 Brine Htr .04 3.3 Q^1 $\Delta T_t^{-.7}$ $dP_t^{-.08}$ $dP_s^{-.04}$ ΔT_t .9 -.7 D_T
Feed Htr .43 .367 40-185, 5-15, .1-7, .001-1.3 dP_t 1 -.08 D_{Pt}
Condnsr 40-185,2.5- 8, .7-50, .007-9 dP_s 1 -.04 D_{Ps}

12 MSF .04 10 $Q^1\Delta T_n^{-.75}$ $\Delta T_t^{-.5}$ $dP_t^{-.1}$ Δt_n 1.5 -.75 D_T
.43 1.6 14-110, 3-10, 3-12, .2-10 ΔTt 1 -.5 D_T
14-110, 1.7-6, 1.7-7, 13-70dP_t1 -.1 D_{Pt}

13 Radiant .06 .039Q^1 $\Delta T_r^{-.2}$ no trade-offs
Boiler 648 .039 50-600,.1-1
dP_t = .0004 A - .25 dependent on surface
dP_t = .000037 A - 1.72

14 Air Prhtr.008 37000 Q^1 ΔT_m^{-2} $dP_h^{-.3}$ $dP_c^{-.3}$ ΔT_m1 -2D_T
Plate-fin .086 3496 10-100,50-150,.03-1.5, .03-1.5dP_h 1-.3D_{Ph}
10-100,28-83,.2-10, .2-10 dP_c 1 -.3 D_{Pc}

15 Air Prhtr.03 2750 $Q^1\Delta T_m^{-1.5}$ $dP_t^{-.3}$ $dP_s^{-.2}$ ΔT_m1 -1.5 D_T
shell-and tube.32 235 10-100,50-150,.03-1.5, .03-1.5dP_t 1-.3D_{Ph}
10-100,28-83,.2-10, .2-10 dP_s 1-.2 D_{Pc}

16 Throt Vlv .75 .45 $M^1(T_i/P_i)^{.05}P_e^{-.75}$ no trade-off
Ejectors 1.5 .45 5-20,1.5-5,.5-100 no trade-off
8.07/16.14 0.989 2-9,120-400,.003-.7

17 Mix Chmb 30 1 V^1 no trade-off
1060 1

18 c_a Press Factor ---- .191 $P^{.3}$ no trade-off
.850

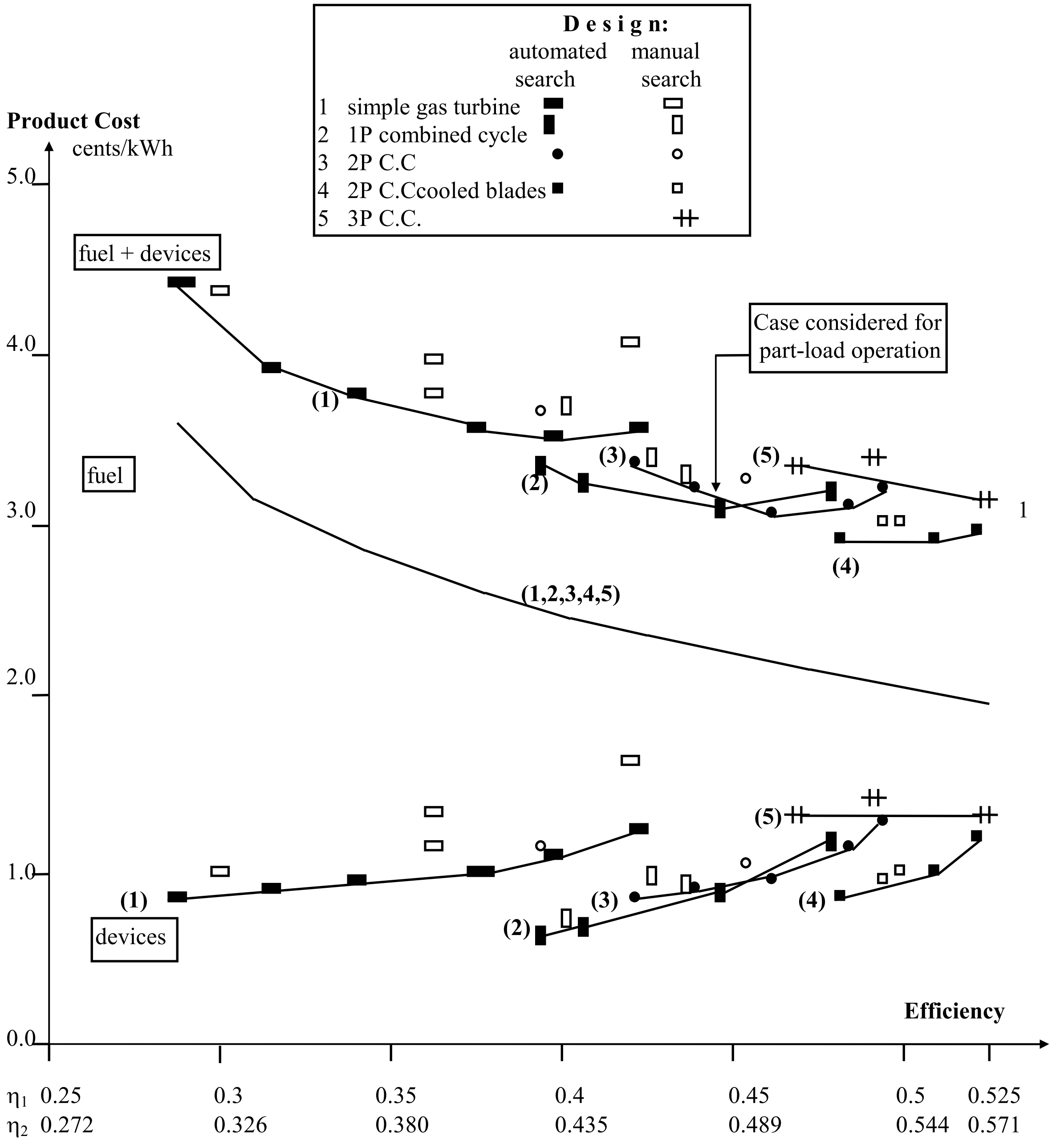
19 Evap/ .04 6.2 $Q^1\Delta T_m^{-1}dP_t^{-.01}dP_s^{-.1}$ ΔT_m1 -1 D_T
Condnsr .43 . 582 150-800,4-40,.01-.05,.01-.04dP_t 1 -.01D_{Ph}
150-800,2-22,.06-.35,.06-.03dP_s 1 -.1D_{Pc}

20 VC 9 .0018 M^1 Pr^1 $e^{.7}$ e -.95 .7 D_{PT}
Radial 96.9 .000076 50-1000, 1.1-2, 2.3-11.5
22-455, 1.1-2, 2.3-11.5

21 Hx .04 5 $Q^1\Delta T_m^{-1}dP_t^{-.15}dP_s^{-.15}$ ΔT_m.5 -1D_T
General .43 . 469 15-100,4-40,.05-1,.03-.4 dP_t 1 -.15 D_{Ph}
Approx 15-100,2-22,.3 -7,.2-.3 dP_s 1 -.15 D_{Pc}

Units of Table 2: IP units are on upper line. SI units on next
Q kW, D kW,range of Q MW, c_d \$/kWh
IP units: c_a k\$/ft^2,A ft^2, M lb/s, P_i, P_e psia, T_i R, ΔT F, ΔP,dP psi, V ft^3/s

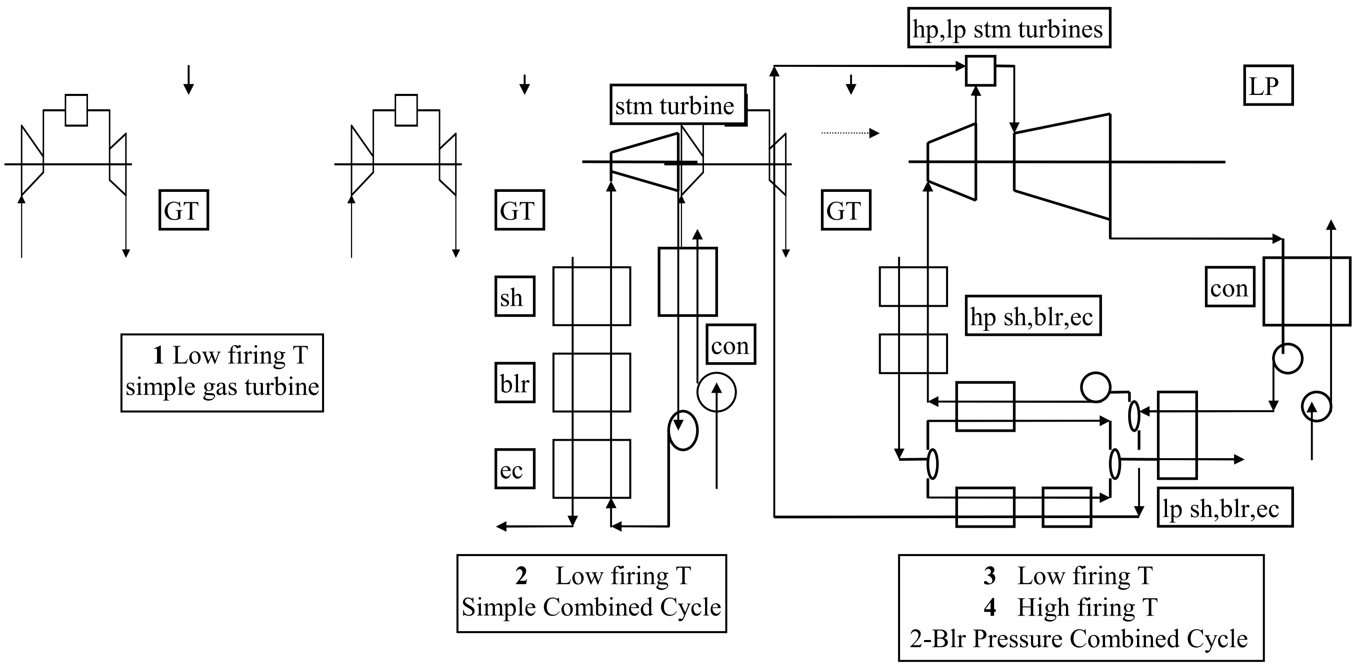
SI units: c_a k\$/m^2, A m^2, M kg/s, P_i, P_e Mpa, T_i K, ΔT C,
ΔP, dP kPa, V m^3/s
D=exergy destruction=$D_P+D_T+D_C$, $D_{PT}=D_P+D_T$, c_d=unit exergy destruction cost
Pr=pressure ratio, $e=\eta/(1-\eta)$, $\Delta T_r = (T_{gas}/T_{flame})^4 - (T_{stm}/T_{flame})^4$

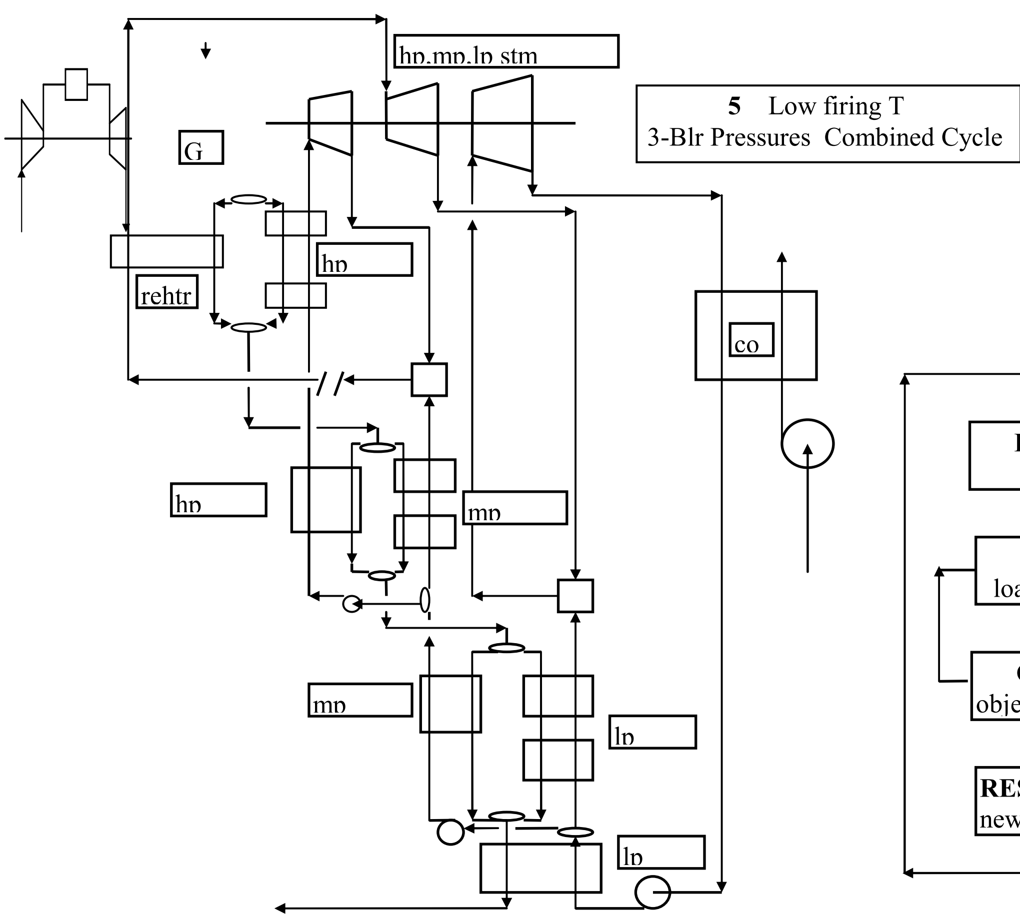


η_1 First law efficiency (using higher heating value of fuel)

η_2 Second law efficiency (wasting leaving streams)

Figure 3. Comparing five gas turbine design concepts on a cost-efficiency plane.





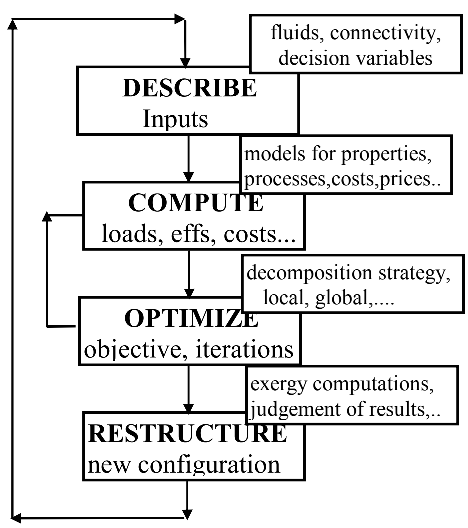


Figure 4. Energy analysis tool and the gas turbine power configurations analyzed.

4. Optimized System Design

The decomposition strategy described earlier has been incorporated in a computer program serving as an energy analysis tool. A power system and a process system are considered as examples of optimal design analysis. The objective function is the production cost rated per unit product.

4.1 The gas turbine power systems

The program was used to optimize the design of five gas turbine configurations, 100 MW nominal power production each operating under same boundary conditions. These are the simple gas turbine, the gas turbine systems with 1, 2 and 3 boiler pressures all of maximum firing temperature 870 C and a 2-pressure, blade-cooled turbine of maximum firing temperature 1200 C. The search for optimum was both automated and manual to compare their effectiveness. In this study, the automated search proved to be more effective. The program displays the results in detail by state properties of each stream, performance of each process, distributions of exergy destructions {D}, characterizing surfaces{A}and costs. *Figure 3* is a summary of the investigation on a cost-efficiency plane and *Figure 4* illustrates the analysis tool used and shows the flowsheets of the five systems. The fuel price c_F is assumed .01 $/kWh higher heating value. The $\{c_a\}$ set of TABLE II is assumed. The unit power production cost is the break-even cost and the efficiency is the conventional first law efficiency along with the corresponding second law efficiency that assumes the exergy of the finally leaving streams is wasted. The 2-pressure blade-cooled configuration,case 4, shows the most cost-effective improvement. The saving of fuel cost per unit product by raising efficiency was not eaten up by increases in the cost of devices for the first 4 cases whereafter, a point of diminishing returns is approached. For the 3-pressure system, case 5, the raising of efficiency became cost-ineffective.

4.2. The seawater distillation systems

The six systems considered are all 1860 m^3/h (10 mgd) receiving sea water at 1 atm, 27 C, .045 salt mass fraction, rejecting brine at .065 salt . The multi-stage flash unit operates in the temperature range 100-38 C and the vapor compression below 60 C. The first is the simplest. In this system 80% of the fuel exergy is destructed before reaching the MSF unit and 90% of the destruction occurs in 4 units: the combustor, boiler, throttle valve and the recovery stages. There is no way to improve the first three losses since destruction moves from unit to the other. The next three are low capital cost improvement and the last two are high capital cost improvement. The first three import their power needs, the fourth produces its power needs only. The fifth cogenerates power and water. The sixth produces power to produce water. Each system has a reference design and an improved one by optimization.

TABLE III and *Figure 5* compares the six distillation systems. One reverse osmosis system is included for comparison with distillation. Curves 5a and 5b bound the water cost by reasonable allocation assumptions of the production cost to

TABLE III. Summary Results of the Six Distillation Systems.

Case	System	Break-even water cost $/ton		Fuel & Power kWh/ton		Input energy cost $/ton		Capital cost $/ton		Efficiency⁺ W_{ideal}/W_{actual}	
		Ref.	Impr.	Ref.	Impr.	Ref.	Impr.	Ref.	Impr.	Ref.	Impr.
1	blr+msf	1.557	1.514	99.3 2.0	84.8 1.9	1.083	0.934	0.474	0.580	0.0383	0.0445
2	blr+msf+2s ejector	1.454	1.407	89.2 2.2	70.5 1.9	0.990	0.790	0.464	0.616	0.0421	0.0530
3	blr+msf+tc-effect	1.519	1.454	96.5 2.1	79.3 1.8	1.058	0.875	0.461	0.582	0.0393	0.0477
4	blr-msf+aux pwr	1.495	1.463	102 ---	91.3 ---	1.020	0.913	0.477	0.551	0.0395	0.0443
5	blr+msf+pwr	1.001*	0.954*	58.8 ---	44.7 ---	0.588	0.447	0.413	0.507	0.0709	0.0925
6	blr+msf+vc-effect⁰	1.034	0.958	53.2 ---	34.4 ---	0.532	0.344	0.502	0.615	0.0759	0.1173
7	One RO case	1.050		--- 10		0.450		0.600	?	0.1345	

* Cost allocation: Fuel by the ratio of produced powers+msf unit. Proportional higher (1.171, 1.119)

[o] Attractiveness of case 6 is retained for a VC cost up to \$1000/kW or \$10000/ft^2 blade surface. Efficiency measures around 20 on the gained output ratio scale.

[+] W_{ideal} = ideal separation work from sea water .045 salt content at 80 F= 1.345 kWh/ton.

W_{actual} = any work input + input fuel/3 (work that input fuel produces in a power plant 33% efficient)

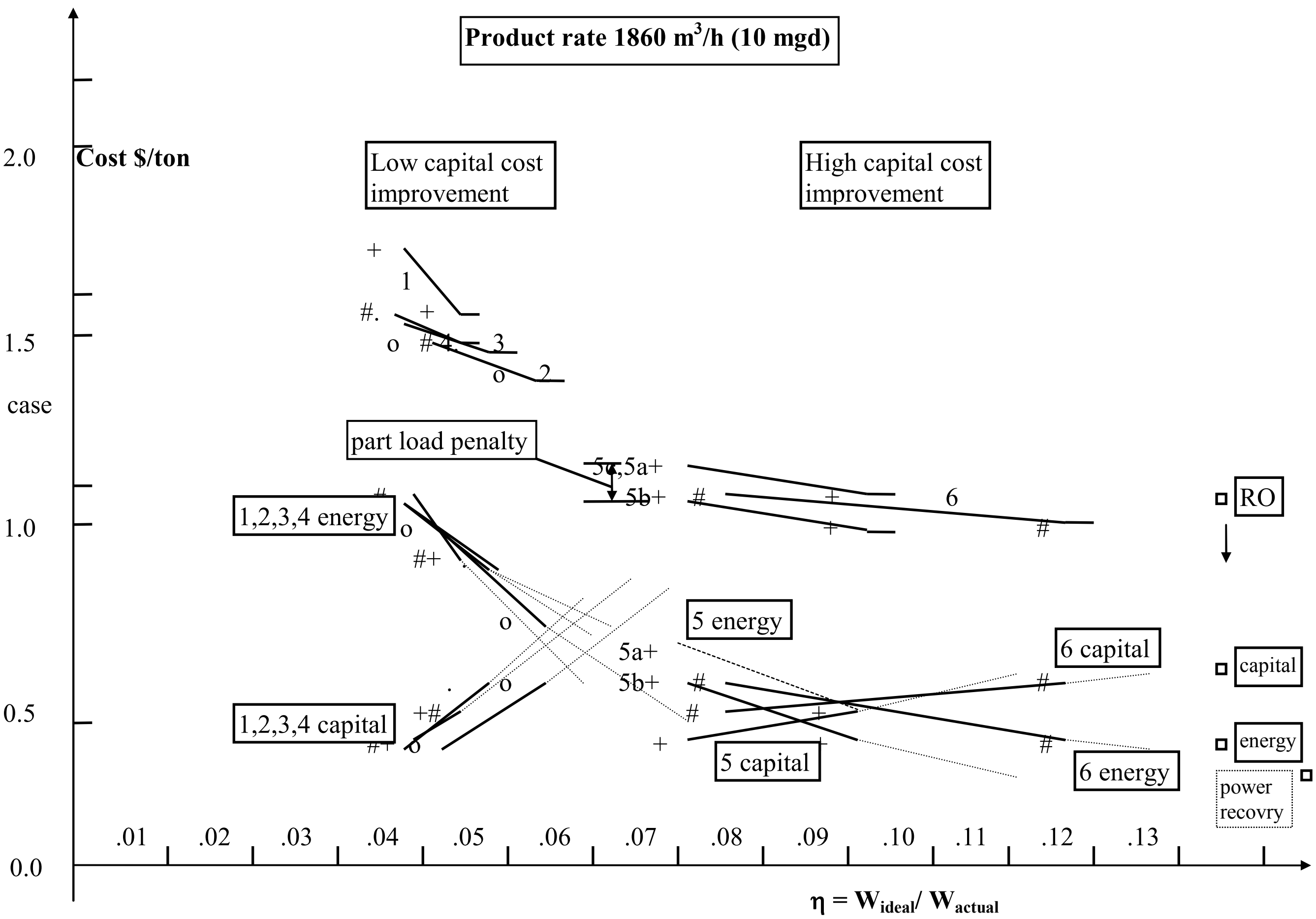


Figure 5 : The six cases compared on a cost-efficiency plane.

power and water for the cogeneration case, system 5. The sixth system has a good economic potential but does not exist yet. Compressors in use today are centrifugal compressors that can handle only 1/10 the unit capacity of the MSF and they should handle about the same capacity or even larger. Specially designed compressors are needed. *Figure 6* shows the distillation flowsheets.

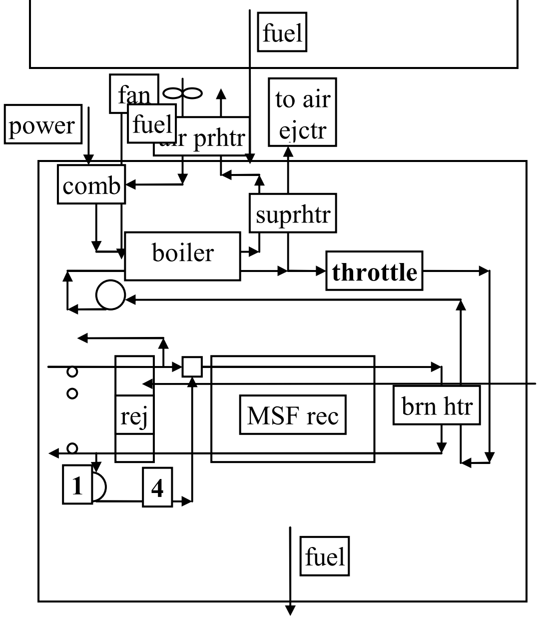
Two observations are noticed when comparing the gas turbine case with the distillation case:

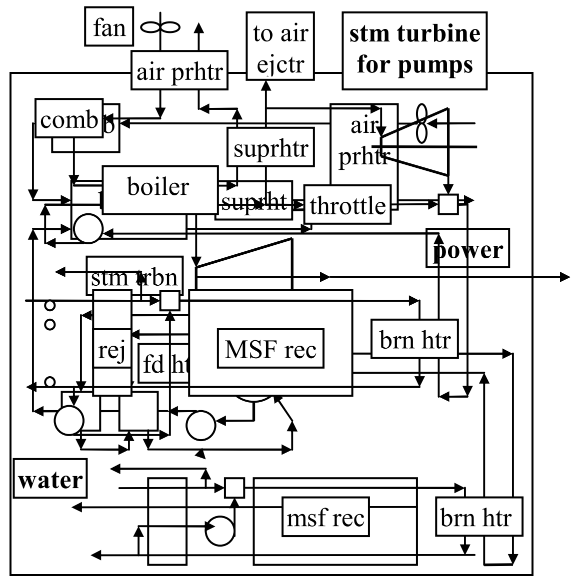
- The direction of a cost effective improvement in both cases is lower unit product cost at higher efficiency created usually by more capital investment that produces more product.
- The range of second law efficiency in power generation is 20 to 55% while that for seawater desalting is only .04 to .13% a case shared by many industrial processes. A room for future improvement of many industrial processes does exist waiting for improved and innovative processes.

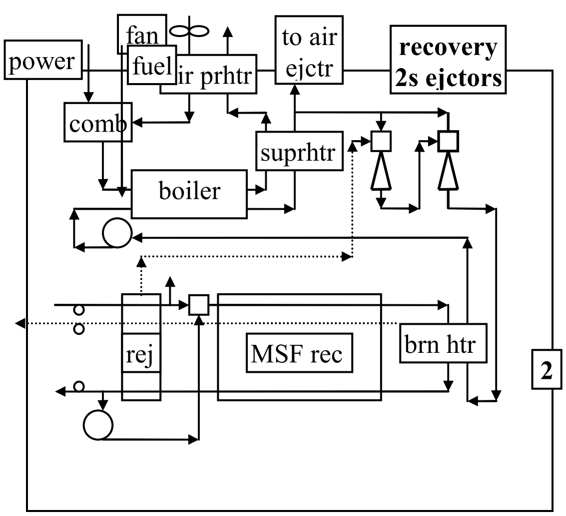
5. Concluding Remarks

- Design practices and design innovations in form of design models of the devices of a system are rich resources for predicting the cost and the performance of a system while still in its design phase.

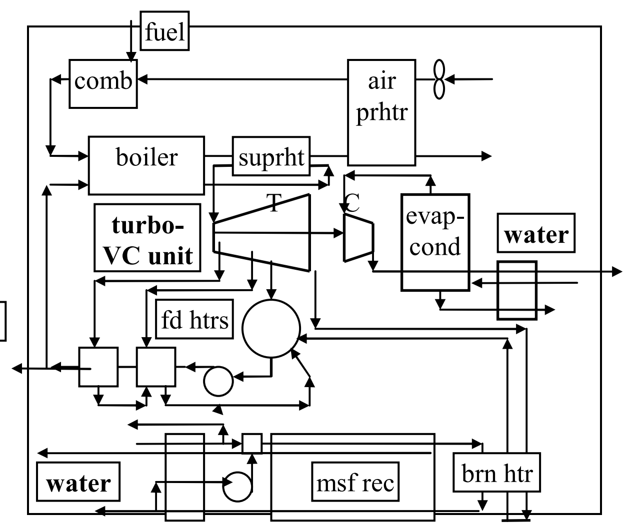
- Condensing information in a way relevant to a particular analysis proves to be an effective approach to manage the large number of variables involved and to enhance system analysis and optimization.







5



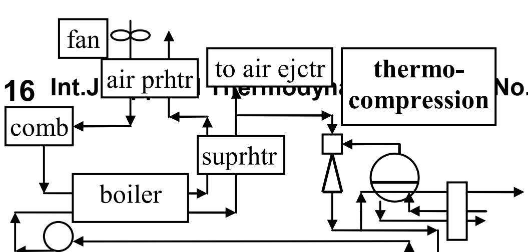


Figure 6. Analyzed seawater distillation design concepts.

Nomenclature

A Constant.
A Heat exchange surface, flow passage surface, constant.
B Constant
C Cost $ rate
C Unit price: c_F of fuel, c_P of electricity, c_f, c_p per unit exergy, c_d of dissipation per unit exergy destruction, c_z of capital cost, c_a of a characteristic surface
C_p Constant pressure specific heat.
D Infinitesimal change.
D Exergy destruction in a device
Exc Excess air ratio
H Film coefficient of heat transfer.
H Enthalpy, enthalpy per unit mass
IP Inch-pound (British system of units).
J An objective function, J2 by second law transformation.
K Constant coefficient, thermal conductivity
L Lagrangian.
M Mass rate.
N Number of units.
N exponent.
P Pressure, P_o for dead state pressure, power.
PR Pressure ratio.
Q Heat rate, Q_f by fuel
R Gas constant.
Rp Pressure loss ratio $\Delta P/P_{in}$, rp_h hot stream, rp_c heated stream
S Entropy, entropy per unit mass.
SI International system of units
T Temperature, absolute temperature, T_o for dead state temperature.
U A decision design variable, {U} a decision vector, an overall heat transfer coefficient.
V Specific volume, A variable dependent or decision: $_{VT}$ of thermodynamic, V_D of design, V_M of manufacture, $V_{T,D}$ thermodynamic input to design, $V_{D,M}$ design input to manufacture
W Work.
X A dependent variable : X_T thermodynamic, X_D, design, X_M manufacture, {X} state vector.
X Species {x} composition vector
Y A decision variable: Y_T thermodynamic, Y_D design, Y_M manufacture, {Y} a decision vector.
Z An equipment capital cost.

Greek symbols

δ A small change.
Δ A difference, ΔT a temperature difference, ΔT_m logarithmic mean temperature difference, ΔP a pressure loss, ΔPh pressure loss of a heating stream, ΔPc of a heated stream. ΔP_s shell side, ΔP_t tube side.
∂ Partial derivative.
η Adiabatic efficiency, heat exchange effectiveness.
λ An internal price, Lagrange multiplier.
μ Chemical potential, viscosity.
$\sum$ Summation.
Ψ Loading or head coefficient, Ψ_r reference.
Φ Flow coefficient, Φ_r reference

References

El-Sayed, Y., 1998, "Revealing the cost-efficiency trends of the design concepts of energy-intensive systems", *ECOS'98,* Nancy, France*,* Vol. I, pp.263-274.

El-Sayed, Y., 1997a, "Predicting Part-load Performance of an Energy System Concept", *TAIES'97, Thermodynamic Analysis and Improvement of Energy Systems Proceedings,* Beijing, China.

El-Sayed, Y., 1997b, "The Thermoeconomics of seawater desalination systems", *IDA world congress on Desalination and Water reuse,* Madrid, Spain,Vol. IV pp.149-166.

El-Sayed, Y., 1996, "A second-Law Based Optimization, Parts 1 and 2", *Journal of Engineering for Gas Turbine and Power,* October 1996, vol 118, pp.693-703.

El-Sayed, Y. and Evans, R., 1970 "Thermo-economics and the Design of Heat Systems" *Journal of Engineering for Power,* January 1970, pp.27-35.

El-Sayed, Y. and Aplenc, A., 1970, "Application of the Thermoeconomic Approach to the Analysis and Optimization of a Vapor Compression Desalting System", *Journal of Engineering for Power,* January 1970, pp.17-26.

Gaggioli, R. (Editor), 1980, "*Thermodynamics: Second-Law Analysis",* ACS Symposium Series 122.

Gaggioli, R. (Editor), 1983, "*Efficiency and Costing",* ACS Symposium Series 235.

Lazzaretto, A. and Tsatsaronis, G., 1997, "On the quest for objective equations in exergy costing", *AES-Vol. 37, Proceedings of ASME Advanced Energy Systems Division,* pp.197-210.

Tribus, M. and Evans, R., 1962 "The Thermo-economics of Seawater Conversion", UCLA Report No.62-63, August 1962.

Valero, A., Tsatsaronis, G., von Spakovski, Frangopoulos, C., Lozano, M., Serra, L. and Piza, J., 1994, "CGAM Problem: Definition and conventional solution", *The International Journal of Energy,* Vol 19, No. 3.

Valero, A., et. al., 1993, "Structural Theory of Thermoeconomics" *ASME AES-Vol 30*, pp.189-198.

Design Models' References

Cohen H., RogersG. and Saravenamuttoo, H., 1987 "*Gas Turbine Theory "*, Third Edition, John Wiley.

Hegetschweiler, H. and Bartlet, R., 1957, "Predicting performance of large steam turbine-generator units", *Transactions ASME*, July 1957, pp.1085-1114.

Rohsenow, W., Hartnett, J. and Ganic, E., 1985, *Handbook of heat transfer applications*, Second Edition, McGraw Hill Book Company

Sabersky, R., Acosta, A. and Hauptmann, E., 1989, *Fluid Flow, A first course in fluid mechanics*, third edition, Macmillan Publishing company.

Sehra, A., Bettner, J. and Cohen, A., 1992, "Design of a high performance axial compressor for utility gas turbines", *Journal of Turbomachinery*, Vo,. 114, No 2, April 1992, pp.277-286.