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The Mathematical Formulation of Inter-Disciplinary Communication A Thermodynamic/Design Example

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Abstract

Most engineering problems today are multi-disciplinary. Security issues, environmental concerns, rising consumptions, depleting resources and globalization are issues that impose the multi-disciplinary task. The mathematical formulation of the communication among participating disciplines should deserve special attention. In this paper, a framework for handling the communication in multi-disciplinary problems in general is established in terms of a purpose of analysis and a protocol for the flow of information. The formulation that evolved from the optimal design of an energy-conversion system given a cost objective function is reviewed. The focus is then set on the communication between the disciplines of thermodynamics and design and on the mathematical formulation of the communication.

Key words: multi-disciplinary problems, the active discipline, matrices of information exchange, enhanced decision-making, enhanced optimal design

1. Introduction

Fossil fuel scarcity, emissions, waste disposal, and increased world population at rising standard of living drive the need for higher efficiency at lower cost for systems that use or produce power and heat. Higher efficiency at lower cost calls for more intensive system analysis while the system is still in its design phase. Because of cost consideration, the analysis becomes *multi-disciplinary.* Four main disciplines participate in the optimal design of energy-intensive systems. These are: Thermodynamics, Design, Manufacture and Economics. Thermoeconomics is an intensive analysis methodology that can accommodate multi-disciplinary problems.

Thermoeconomics, initiated in 1962 by professor Myron Tribus (Tribus and Evans, 1962), was first applied to the design of seawater desalination processes in an attempt to gain insight in the economic interaction between the surface of separation (design/manufacture) and the energy required for separation (thermodynamics). Even though at that time oil prices were 0.1 to 0.2 today's prices, the impact on the price of water as compared to conventional water prices was so significant to warrant a balance between the energy cost and the capital cost of the separating surface of a desalination process. The publications El-Sayed and Evans (1970), El-Sayed and Aplenc (1970) are two of earliest on the subject matter.

Later in the early eighties, professor R. Gaggioli (Gaggioli, 1980 and Gaggioli, 1983) initiated the interest in further development of Thermoeconomics to handle energy-intensive systems in general. Many researchers responded positively to the initiation. In the last 25 years, the development of Thermoeconomics has been impressive in more than one direction. The recent developments by Valero et al.,(1993 and 1994), El-Sayed (1996) and Lazzaretto and Tsatsaronis (1997) may adequately represent the different directions of development. These directions are not yet free from inconsistencies (Cerqueira and Nebra, 1998).

1.1 The absence of a formal approach to multidisciplinary problems

In spite of the current state of development of thermoeconomics, a formal approach to the multi-disciplinary problems is absent.

Today, most engineering problems are multi-disciplinary problems. Security issues, environmental concerns, rising consumptions, depleting resources and globalization are major issues that impose the multi-disciplinary approach. This paper is meant to be a step towards a formal approach to multidisciplinary problems.

First a framework for multi-disciplinary communication is established. The application of the framework to the optimal design of an energy-conversion system given a cost objective function is then reviewed. The communication between the disciplines of thermodynamics and design is then formulated in detail as an application example of the communication between two authorities of knowledge.

2. A Framework for Inter-Disciplinary Communication

The analysis of a multi-disciplinary problem requires a communication among the participating authorities of information. If the communication can be formulated mathematically, then one authority can perform the analysis much faster and more effectively. This authority is the highest in the hierarchy of the participating authorities for the problem considered and may be called the active authority.

The essential elements of a mathematical formulation of interdisciplinary information exchange are:

- The entities of the problem and their connectivity
- A formulated purpose of communication
- The identification of the active authority
- The updated practices of all the participating authorities of knowledge expressed by mathematical models
- The identification of the decision and dependent variables of each model
- A correlation that condenses the exchanged information in terms of the variables of the active authority

The purpose is often expressed by an objective function. The discipline that most conveniently sets the sequence of information flow is often at the top level of the hierarchy and is selected as the active discipline. An information exchange matrix per entity is generated for processing the communicated information. The columns of the matrix are divided into groups. Each group belongs to one authority. The columns of the group are allocated to the variables (independent and dependent) that are of interest to all authorities. A sub group of the columns of the active discipline (input columns) is allocated to the matrix input variables that trigger different entity states and tie all the rows together for each state. The range of entity states is a range of interest to the problem analysis. A correlation is then sought using the jargon of the active discipline. The correlation may be a continuous function or discrete values. The smaller the range of the entity states and the larger the number of columns and rows, the better is the quality of the correlation and the smaller is its scatter. The problem matrix is a three dimensional matrix that contain all the problem entities.

3. Application to the Optimal Design of an Energy-Conversion System

Thermoeconomics accommodate multidisciplinary. The accommodating aspects of thermoeconomics are reviewed briefly as follows. Details are given in El-Sayed (2002).

3.1 The objective function

A cost objective function, in monetary units, suitable for the design phase of an energy-intensive system of a specified product rate P driven by a single fuel resource, is the production cost J:

$$J= c_F*F+\sum^i c_{zi}*Z_i +C_R \qquad (1)$$

c_F is a unit cost of the fueling resource F as occurring in the market place and c_{zi} is a capital discount rate of a device i of capital cost Z_i. C_R is a constant remainder cost as far as the system design is concerned. When a design becomes a project, C_R may become a variable with respect to other non-system-design decisions.

Four disciplines of knowledge are involved in the objective function of equation (1):

Thermodynamics (F,P), Design and Manufacture {Z} and Economics $\{c_F, c_z\}$.

Equation (1) in terms of the variables of the participating disciplines after dropping C_R is:

$$J= c_F(\{V_E\})*F(\{V_T\}) +\sum^i c_{zi}(\{V_E\})*Z_i(\{V_D\},\{V_M\}) \qquad (1a)$$

Where $\{V_E\}$ are economic variables, $\{V_T\}$ thermodynamic variables, $\{V_D\}$ design variables and $\{V_M\}$ manufacture variables.

Z_i ($\{V_D\}$, $\{V_M\}$) may be written as c_{ai} ($\{V_M\}$) * A_i ($\{V_D\}$) where c_{ai} is a unit manufacture cost and A_i is a characterizing dimension of device i. The characterizing dimension may be length, mass, area, volume or combination. Quite often, one surface area representing either a flow passage, a surface of heat and/or mass exchange or a surface of momentum exchange (blades) is an adequate representation of the design aspects of Z_i. Thus the expression of objective function takes the form:

$$J= c_F(\{V_E\})* F(\{V_T\}) + \sum^i c_{zi}(\{V_E\})*c_{ai}(\{V_M\}) * A_i(\{V_D\}) \qquad (1b)$$

3.2 The active discipline

The objective function involves four disciplines of knowledge: Thermodynamics, Design, Manufacture and Economics. Since energy conversion systems are born within the discipline of thermodynamics, which is also the only discipline that looks over all parts of a system, it is appropriate to consider thermodynamics as the active discipline.

3.3 The sequence of information flow

Figure 1 illustrates a sequence of information flow among the experts of the four disciplines after substituting the experts by mathematical models expressing their expertise. The thermodynamic model as the active discipline triggers a system solution where the fuel resource F is computed for the given product rate P in terms of a set of thermodynamic decision variables $\{Y_T\}$. These decisions are the efficiency parameters of the system devices and few levels of pressure and temperature. All dependent variables of interest with the fuel rate F in the lead are expressed by purely thermodynamic variables. The variables $\{V_T\}$ are a mix of decision and dependent variables. The design models use what they need from the thermodynamic variables $\{V_T\}$ for their design models and target minimized characterizing dimensions $\{A_{i\ min}\}$ while meeting the efficiency parameters set by the triggered solution. The $\{V_{Ti}\}$ of a device are the essential variables that determine both the inlet and exit states of the device $\{V_{Ti\ in}\}$, $\{V_{Ti\ out}\}$ or alternatively $\{V_{Ti\ in}\}$, $\{\eta_i\}$ where $\{\eta_i\}$ represent the efficiency parameters of the device. The design-blueprints of $\{A_{i\ min}\}$ go through manufacturing procedures of minimized manufacture costs where by the minimized unit costs $\{c_{ai\ min}\}$ are obtained. Now the objective-function production cost can be computed. The thermodynamic decision variables are changed in the direction of lower production cost. The process is iterated until no further reduction in cost is possible.

Obviously if each $Z_i = c_{ai\ min}(\{V_M\}) * A_{i\ min}(\{V_D\})$ were in terms of thermodynamic variables $(\{V_T\})$ i.e. $Z_i = c_{ai\ min}(\{V_T\}) * A_{i\ min}(\{V_T\})$, the cost minimization can be performed within the domain of thermodynamics with a reduced number of decision variables. A two-level automated optimization procedure is described in (El-Sayed, 1996).

The device capital cost in terms of thermodynamic variables (capital costing equation):

$$Z_i = c_{ai\ min}(\{V_{Ti}\}) * A_{i\ min}(\{V_{Ti}\}) \qquad (2)$$

is formulated by the information exchange matrix.

3.4 The information exchange matrix

The matrix entity in an energy system is an energy conversion device. The information exchange matrix of a device relates the variables of the participating disciplines to each other as functions of the boundary states of the device arising from changing the design point of the system. The columns are divided in four groups: thermodynamic, design, manufacture and economic. The input columns are a subset of the thermodynamic columns. The rows of the input columns give the device boundary states over a range of interest to system design. Changing one or more boundary variable at a time generates the input rows. The change may be systematic and/or random. The rest of the columns list the associated parameters of interest in each discipline including the targeted parameters $\{A_{i\ min}\}$ and $\{c_{ai\ min}\}$.

The number of adequate rows is often between 10 and 20 depending on the applicable range of a sought correlation. The columns may range from 10 to 100 depending upon the parameters of interest in each discipline and the level of sophistication of the models used. The parameters of each group are a mix of independent variables, dependent variables, parameters of interest to particular disciplines and targeted parameters. For example, the thermodynamic parameters may be a mix of decisions, sizing, intensity and correlating parameters. The targeted parameter is often exergy destruction(s). The design parameters may be a mix of fixed and changeable dimensions. The targeted parameter is often the minimized characterizing surface. The manufacture parameters may be divided into a sequence of processes, process duration, and process cost. The targeted parameter is often the manufacture cost per unit surface. The economic parameters may be divided into market-place prices, depreciation, salvage and taxes. The target parameter is often the capital recovery rate. TABLE I shows examples of the parameters of interest as applied to two major types of energy conversion devices: heat exchange devices and power devices.

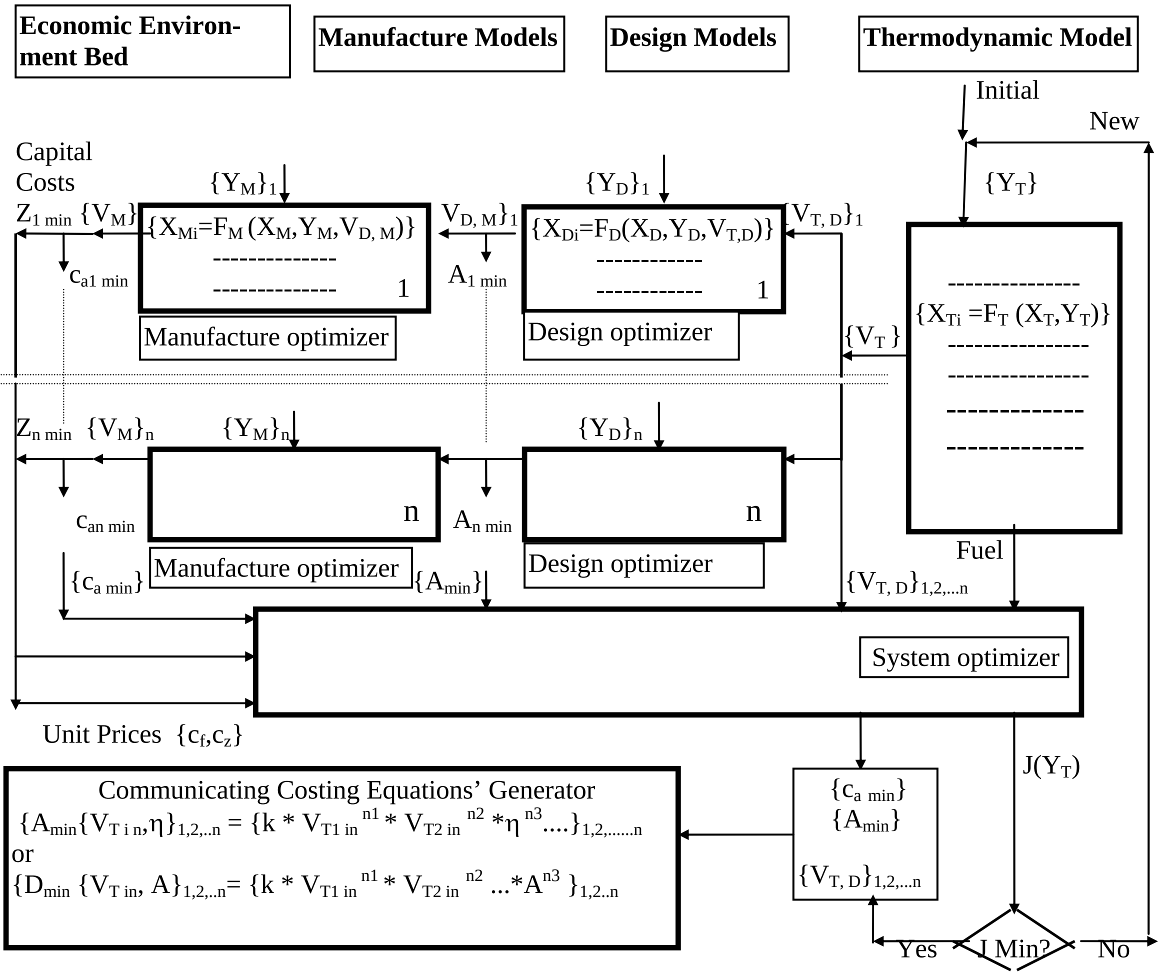
3.5 The concept of costing equations

The generation of equation (2) via the information exchange matrix establishes the concept of costing equations.

The essential thermodynamic parameters $\{V_{Ti}\}$ expressing $A_{i\ min}(\{V_T\})$ and the form of its equation are not unique but the number of parameters is. The number should give unique values to the costing equation. A form that handles itself well in optimization for $A_{i\ min}$ is:

$$A_{i\ min} = k * \prod_{i=1}^{N} V_{Ti}^{\ ni} \qquad (3)$$

Where k is a constant coefficient and $\{n_i\}$ are exponents. The number of thermodynamic parameters N is somewhere between 2 and 6 depending on the process of the device. $\{V_{Ti}\}$ essentially represent a sizing parameter (mass rate, heat rate or power) and efficiency parameters (adiabatic efficiency, effectiveness, friction pressure losses, heat transfer temperature differences, heat leak losses,….).



V: Variable;decision or dependent

Y: Decision variable

X: Dependent variable

F: Fuel rate

c: Unit cost or price

$A_{i\,min}$: Minimized characterizing surface

J: Objective function=Production cost = $c_f * F + \sum c_z * c_a * A$

Subcripts

T: Thermodynamic

D: Design

T,D: Thermodynamic input to design

M: Manufacture

D,M: Design input to manufacture

B: Boundary

a: Surface area

z: Capital

Figure 1. A Sequence Of Information Flow

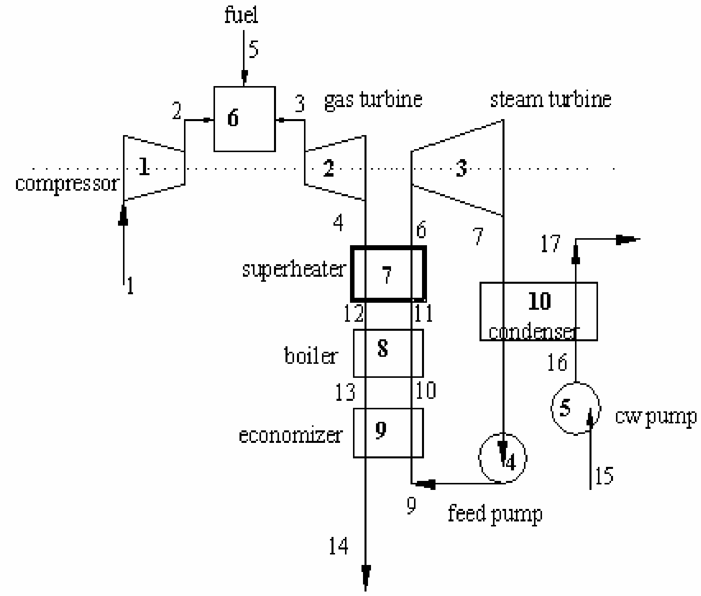


Figure 2. Low-Firing Temperature Simple Combined Cycle

The unit cost $c_{ai\ min}$ may be expressed in a similar way where $\{V_{Ti}\}$ are the materials, allowed levels of pressure and temperature and the maximum contents of erosive and corrosive species.

4. The Communication Between the Disciplines of Thermodynamics and Design

The communication between the disciplines of thermodynamics and design is central for the optimal design of energy conversion systems. It is also central for predicting the off-design performance of the system devices and hence the overall off-design performance of the system.

For optimal system design, thermodynamics often uses efficiency parameters of a device as decision variables to solve for the system and obtain the sizing parameters for the devices as dependent variables. The geometry of the devices is completely avoided. Design often uses the sizing parameter of a device and its geometry parameters as decision variables. Efficiency parameters are obtained as dependent variables. A suitable formulation of the communication between thermodynamics and design can take the unavoidable iterative loops between the two disciplines outside the system optimization loops.

This greatly enhances system optimization and this is just what costing equations do.

Two cases of communication are considered for a heat-exchange device. The discipline of thermodynamics is in control (case 1). The design discipline is in control (case 2).

The prediction of the off-design performance of a system requires the off-design performance of each of its devices. A third communication case is therefore considered for the same heat exchange device (case 3)

4.1 Applications to a heat-exchange device

Figure 2 shows a simple combined cycle. The cycle has been analyzed and optimized in El-Sayed, 1996. The minimized heat exchange surface of the super-heater, device 7 of the heat recovery steam generator will be derived. A duct shell-and-finned tube type is assumed. The fins are assumed circular on the outside (the gas side). The design model of heat exchangers described in El-Sayed, 1996 is used. The superheater is treated as a single phase forced convection heat exchanger.

4.1.1 Case 1: Thermodynamics in control

Thermodynamics forces the device performance efficiency parameters on design. In other words, the designer has to satisfy prescribed exergy destruction (given inlet and exit states).

The information-exchange matrix shown in F*igure 2* covers 10 different system solutions as indicated by the number of rows. The columns that cover all variables of interest are almost 40 columns. TABLE II shows only 14 as examples. The correlating parameters are listed in the first four columns. The values correspond to the boundary parameters (not listed) P, T, {x}, M at inlets and exits of the exchanger for different design points for the cycle. Design seeks the geometry parameters of the exchanger that minimizes the heat exchange surface. The geometry parameters are length, diameter, pitches, number, material, thickness and the fin geometry of the tubes. The table shows seven dimensions were subject to change to minimize the surface.

TABLE I. EXAMPLES OF THE INFORMATION MATRIX PARAMETERS FOR OPTIMAL SYSTEM DESIGN

Variables	**Heat Exchange Devices**	**Power Devices**
	THERMODYNAMICS	
Boundary Variables	$(P, T, M)_{in,out}$ or $(P, T, M)_{in}$ and $\{\eta\}$	$(P, T, M)_{in}$ and P_{out}
Decision Variables	$(\Delta P_h, \Delta P_c, \Delta T_h, \Delta T_c)$ or $(P,T)_{in,h,c}, \eta_{effectiveness}$	$\eta_{adiabatic}$
Sizing variables	Q or (M_h, M_c)	W or M
Target variables	Exergy destructions $D_T + D_{Mh} + D_{Mc}$	Exergy destruction D_{TM}
	DESIGN	
Constant parameters	Type, materials, fouling flow direction	Type, materials, tip speed, flow velocity, degree of reaction, blade profile
Geometry variables	Length, diameter, number and thickness of tubes, pitches p_1/d, p_2/d, shell diam., tube and shell passes.	Length, width, number, spacing, and angles of blades, incidence angle
Target variables	Total surface area of heat exchange	Total surface of momentum exchange (fixed and moving blade surfaces)
	MANUFACTURE	
Constant parameters	Available material for processing and shaping machines	
Processing variables	Processing sequence, process duration and Itemized costs	
Target variables	Manufacture unit cost per unit characterizing surface	
	ECONOMICS	
Constant parameters	Market-place environment (by location and time)	
Market variables	Fuel, power and heat prices, interest rates, equities, depreciation rates, market volatility, salvage values.	
Target variables	Capital recovery rate	

TABLE II. THE SUPERHEATER INFORMATION EXCHANGE MATRIX BY THE DESIGN PRACTICE

Minimized Surface vs. Thermodynamic and Geometrical Parameters

Run	**Thermodynamic Parameters**					**Geometrical Parameters**								
	Q* MW	ΔT_{lm}^* C	Δp_t* kPa	Δp_s* kPa	η	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	15.76	66	42	0.462	0.921	486	20.4	2.5	11.9	5	4.52	11.8	364	1
2	66.80	128	41	0.475	0.609	915	5.8	2.5	52.1	5	4.52	11.8	2397	2
3	17.32	49	42	0.544	0.883	620	29.6	2.5	8.8	5	4.52	11.8	321	1
4	31.50	66	48	0.627	0.921	897	20.4	2.5	20.4	5	4.52	11.8	673	1
5	34.66	66	37	1.19	0.921	856	16.8	2.5	20.1	5	4.52	11.8	776	1
6	34.28	39	82	0.903	0.921	976	12.2	5	15.5	10	9.04	19.7	1258	1
7	7.88	66	90	0.834	0.921	188	85.3	7.6	0.91	15	13.6	27.8	10	1
8	8.67	66	90	0.227	0.921	276	45.7	3.8	3.7	7.6	6.78	15.7	57	1
9	9.52	66	21	0.234	0.919	355	29.6	3.8	6.4	7.6	6.78	15.7	114	1
10	9.52	126	83	0.965	0.400	112	34.1	7.6	2.1	15	13.6	27.8	15	1

Target

* Correlating parameters of capital costing equation

Scatter of the correlating costing equation

Run	1	2	3	4	5	6	7	8	9	10
A_{eqn}/A_{table}	0.965	1.10	1.08	0.98	1.06	0.92	1.02	0.92	0.976	1.08

Geometry parameters are often more than is needed to meet the prescribed performance. Extra design degrees of freedom are used to minimize the surface and/or to satisfy reliable design practices. The design process is thus a matching/minimizing process.

In TABLE II the surface (fins plus tubes) is expressed in terms of the heat-load, the logarithmic mean temperature difference and pressure losses on the shell side and on the tube side. The first is a sizing parameter and the remaining three are efficiency parameters. The four parameters are adequate to give a unique value to the minimized surface for prescribed performance. The following form is used:

$$A_{min} = k * Q^{n1} * \Delta T_m^{\ n2} * \Delta P_t^{\ n3} * \Delta P_s^{\ n4} \qquad (4)$$

Given a unit surface manufacture cost c_a, the costing equation becomes

$$Z = c_a * A_{min} \qquad (5)$$

The unit cost c_a is assumed per unit total surface of fins plus tubes. 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.

The constant coefficient k of equation (4) and the exponents: n_1, n_2, n_3 and n_4 are computed by using the surfaces of five of the 10 runs simultaneously. These five runs are selected randomly from the total number of runs. 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 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. Comparing the fits by the various sets identifies the best fit. A multiple regression approach to further improve the fit was not applied.

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.

Design models of a number of energy conversion devices along with 20 generated costing equations are given in El-Sayed, 2001.

4.1.2 Case 2: Design is in Control

Several information flow sequences do exist depending on which discipline leads the information and which follows. For example, two popular practices of deciding the characteristic dimension A are commonly used. These are "*The Design Practice* " and "*The Selection Practice*". In the design practice, the minimized characterizing dimension A is tailored for a given performance (exergy destruction). In the selection practice, A is selected from an available series of designs. The selection minimizes exergy destruction (maximizes performance). The design practice meets exactly a system solution. The selection practice is more pragmatic but does guarantee that the device design point matches that of the sought system solution. The more the options of selection are, the closer is the device performance design point to that of the system solution.

With the selection practice, the design discipline is in control. The thermodynamic discipline loses part of its active role when the design is in control. The design model declares the available types and sizes of the device that is a candidate for embedding in the system. The thermodynamic model sends to the design model the essential input variables $\{V_{Ti\ in}\}$ only, without the efficiency parameters, over the range of variation of interest to the system. The design model responds with the minimum exergy destructions D_{min} as function of the characterizing dimension A and the input variables $\{V_{Ti\ in}\}$. The sought correlation becomes $D_{i\ min} = D(\{A\},\{V_{Tiin}\})$ rather than $A_{i\ min} = A(\{V_{Ti\ in}\}, \{\eta_i\})$. From a selection viewpoint, expressing D as function of A occurs naturally:

$$D_{min} = k_d * A^{nd} \qquad (6)$$

where

$$k_d = k' (V_{Ti\ in}) \qquad (6a)$$

Equation (6) refers to the selection practice. The equation is a minimum exergy destruction equation D_{imin} by selection from a series of available designs {A} given boundary inputs i.e.$D_{i\ min}=D(\{A\},\{V_{Ti\ in}\})$.

Note that equation (3) refers to the design practice. The equation is a device capital costing equation expressing capital cost as $c_{a\ i\ min}*A_{imin}$ where $A_{imin}=A(\{V_{Ti\ in}\}, \{\eta_i\})$.

A selection from available line of super-heaters seeks the surface A that minimizes exergy destruction as shown by equation (6). The constant k_d and the exponent n_d are functions of the essential input thermodynamic variables P, T, mass rates at the inlets of the super-heater.

TABLE III. THE SUPERHEATER INFORMATION EXCHANGE MATRIX BY THE SELECTION PRACTICE

IIIA. Coefficient k_d and Index n_d of the Fuel Costing Equation.

Input State	k_d	n_d	m_h (M lb/h)	m_c (Mlb/h)	ΔT_{max} (F)
1	371	–0.412	4.0	0.722	314
2	559	–0.440	3.0	0.678	314
3	1719	–0.404	4.5	1.422	418
4	459	–0.369	3.5	0.741	383
5	323	–0.389	3.7	0.479	383
6	1310	–0.434	5.0	1.792	314

Correlation

n_d =constant =–0.04 $k_d = k * m_h^{n1} * m_c^{n2} * \Delta T_{max}^{n3}$ k =0.76 n_1=–1.3 n_2= 1.6 n_3=1.5

Quality of correlation

	1	2	3	4	5	6
$n_d/n_{d\ eqn}$	1.03	1.10	1.01	0.90	0.97	1.09
$k_d/k_{d\ eqn}$	0.954	0.835	0.80	1.29	0.850	0.80

IIIB. Input Case 1 to Compute its k_d and n_d

Input Variables

m 10^6 lb/h hot=4 cold=.722

T F hot=800 cold=486 sat. vapor

P psia hot=14.8 cold=600

Exergy destruction vs. Surface

Run	Thermodynamic Parameters						Geometrical Parameters			
	A ft^2	D Mbtu/h	Q Mbtu/h	η	Δph psi	Δpc psi	L ft	W ft	d inch	Nps
1	3495	17.0	101	0.637	0.476	7.55	15	69	1	2
2	3495	13.4	92	0.570	0.356	2.00	21	49	2	2
3*	3495	12.9	78	0.463	0.358	0.33	11	98	2	2
4	3495	24.1	109	0.698	0.734	16.8	15	68	0.5	1
5	6990	9.1	115	0.739	0.145	5.54	22	98	1	2
6	6990	7.6	100	0.630	0.108	0.565	22	98	2	2
7*	6990	7.6	100	0.630	0.108	0.565	22	98	2	2
8	6990	11.7	122	0.794	0.225	12.7	22	98	0.5	1
9	13979	6.4	126	0.827	0.044	4.12	31	139	1	2
10	13979	5.9	108	0.685	0.033	0.162	22	196	2	2
11*	13979	5.9	120	0.781	0.033	1.04	43	98	2	2
12	13979	7.6	132	0.871	0.069	9.62	31	139	0.5	1
13	20696	5.7	132	0.870	0.022	3.48	37	170	1	2
14	20696	5.5	112	0.716	0.016	0.079	22	294	2	2
15*	20696	5.4	129	0.851	0.016	1.52	65	98	2	2
16	20696	6.5	136	0.907	0.035	8.18	37	170	0.5	1
17	34949	5.1	137	0.914	0.009	2.82	48	219	1	2
18	34949	5.2	117	0.753	0.007	0.032	22	490	2	2
19*	34949	5.0	137	0.917	0.007	2.48	108	98	2	2

*Least exergy destruction of a surface to compute kd&nd

IIIC. The shell and tube sides n_d and k_d of exergy destruction by pressure losses

Input State	$k_d/10^6$	n_d	k_d*10^6	n_d
	shell-side		tube-side	
1	12	–1.74	25.25	0.908
2	36	–1.73	3.56	0.950
3	2553	–1.78	6.60	0.883
4	136	–1.72	2.22	0.930
5	17	–1.73	4.79	0.903
6	227	–1.78	42.85	0.883

Correlation

$$k_d = k * m_h^{n1} * m_c^{n2} * \Delta T_{max}^{n3}$$

Shell-side	n_d =constant =–1.75	$k=5.3*10^{-14}$	n_1=–4.9	n_2= 4.7	n_3=9.6
Tube-side	n_d =constant =0.93	k=5000	n_1=5.4	n_2=–0.3	n_3=–4.7

Quality

Run	1	2	3	4	5	6
Shell-side $n_d/n_{d\ eqn}$	0.994	0.989	1.017	0.983	0.989	1.017
Shell-side $k_d/k_{d\ eqn}$	0.986	1.00	0.996	1.29	1.020	0.997
Tube-side $n_d/n_{d\ eqn}$	0.976	1.022	0.95	1.00	0.971	0.950
Tube-side $k_d/k_{d\ eqn}$	0.716	1.090	1.10	1.50	1.100	1.090

TABLE IV. OFF-DESIGN PERFORMANCE OF THE SUPERHEATER

Run	Gases tons/h	Steam tons/h	Effectiveness η	ΔP_t kPa	ΔP_s kPa	$(P\ \&T)_{in\ h}$ Mpa	C	$(P\&T)_{in\ c}$ Mpa	C
1 design	1818	134	0.921	42	0.468	0.102	427	4.169	253
2	1818	569	0.532	565	0.510	0.102	516	4.169	253
3	2000	161	0.823	24	0.550	0.102	427	9.453	307
4	3636	268	0.863	146	1.540	0.102	427	4.169	253
5	4000	295	0.855	174	1.510	0.123	427	4.169	253
6	4400	331	0.830	176	2.130	0.102	427	5.002	251
7	1100	160	0.811	57	0.193	0.102	427	4.169	253
8	909	67	0.949	12	0.145	0.102	427	4.169	253
9	1000	74	0.945	14	0.207	0.081	427	4.169	253
10	1100	79	0.950	21	0.200	0.102	427	3.335	240

Scatter of the correlating performance equations

Run	1	2	3	4	5	6	7	8	9	10
η_{eqn}/η_{table}	1.02	1.10	1.01	1.10	1.06	1.02	0.98	0.96	0.93	1.04
$\Delta P_{h\ eqn}/\Delta P_{h\ table}$	1.03	0.94	1.01	0.98	1.02	1.04	1.01	1.01	1.05	0.99
$\Delta P_{c\ eqn}/\Delta P_{c\ table}$	1.01	0.99	1.02	0.98	1.02	1.02	1.06	1.06	1.07	1.01

The variations of inlet pressures are expected to be negligible. Therefore the maximum temperature range ΔT_{max} and the mass rates of the heating and heated fluids are here chosen to describe the input thermodynamic variables $\{V_{Ti\ \ in}\}$. The correlation for k_d and n_d is assumed as:

$$k_d = k *m_h^{n1} * m_c^{n2} * \Delta T_{max}^{n3} \qquad (7)$$

$$n_d = k' *m_h^{n4} * m_c^{n5} * \Delta T_{max}^{n6} \qquad (7a)$$

where k, n_1, n_2 , n_3 , k', n_4 , n_5, n_6 depend on the range of variation of the input thermodynamic variables. The exergy destruction is the sum of a thermal destruction arising from temperature difference and two mechanical destructions arising from pressure losses tube side and shell side. Formulating the mechanical destructions by similar equations as (7) and (7a) allows the unique determination of the three components of exergy destruction and hence the three efficiency variables of the super-heater. TABLE IIIA shows six variations of thermodynamic input variables, the resulting correlations and their qualities. Each set of the six inputs assumes 5 sizes and 4 types that may differ in tube length, duct width, tube diameter and number of tube passes (120 design choices). The design having $D_{i\ min}$ is selected as optimal. For each set of inputs the coefficient k_d and the exponent n_d are computed considering $D_{i\ min}$ to be the sum of three components of exergy destruction. TABLE IIIA show that n_d is almost constant at -.04 i.e. $D_{i\ min}$ varies as $A^{constant}$. TABLE IIIb shows the matrix for one input case for determining k_d and n_d. TABLE IIIc shows the correlation of k_d and n_d of the mechanical components of the exergy destruction and its quality for the same 6 inputs. The quality of the mechanical components is not very satisfactory.

A better correlation, once $D_{i\ min}$ is identified, may be to formulate effectiveness as function of A and pressure losses as function of flow areas rather than the heat exchange area. All the exchanger dimensions are available wok out this correlation. Moreover the link with the inputs to the thermodynamic model becomes direct. This shows that more than one formulation of the minimized exergy destruction $D_{i\ min}$ and its thermal and mechanical components are possible.

4.1.3 Case 3: predicting the off-design performance of a device

The off-design performance of a device can be generated using its design model in a different mode of computation from that of the capital costing equation or the fuel costing equation. The geometrical parameters of a design case are kept *constant* at their design point while the boundary parameters are varied. Selected boundary parameters are varied from their design values to cover the expected changes in the boundary conditions of the device due to a load change or a disturbance at the system boundary.

Consider the same heat exchange device (the super-heater). Generally, changes in P, T, {x} and M at the inlets of the heating and heated streams are sufficient to determine all off-design performance parameters of interest. In this study only the effects of mass rates are assumed significant. The following correlations for computing off-design effectiveness and the pressure losses are used:

$$\eta/\eta_d = (M_s/M_{sd})^{n1} * (M_t/M_{td})^{n2} \tag{8}$$

$$\Delta P_s/\Delta P_{sd} = (M_s/M_{sd})^{n} \tag{9}$$

$$\Delta P_t/\Delta P_{td} = (M_t/M_{td})^{n} \tag{10}$$

With the surface dimensions and geometry of the first case of generating costing equations held fixed, 10 off-design cases were generated. Output parameters of the exchanger were recorded for each case. TABLE IV shows the correlating matrix of information exchange and the quality of the correlation. The exponents of the best fits are decided by comparing different fits. A regression approach was not applied to improve the fit. The exponents obtained were n1=.2, n2=–.15 for efficiency (eqn. 8), n=1.75 for shell-side pressure loss (eqn. 9) and n=1.8 for tube side pressure loss(eqn. 10) all applicable for mass rate changes in t/h 540–770 shell-side and 45–365 tube side, within average scatter ± 8%, max. +10%.

5. Concluding Remarks

- The mathematical formulation of interdisciplinary communication deserves special attention due to the increasing complexity of engineering problems. The formulation in terms of a purpose, a sequence of flow of information, and an information exchange matrix for information processing is at least a suitable start.
- Condensing information in a correlation by information processing and recovering it later in full by the information exchange matrix is an effective approach to manage the complexity of high dimensionality optimization problems.
- Design models of the devices of an energy system are rich resources for predicting the cost and the performance of the system while still in its design phase. Besides, innovative design models lead to innovative systems.

Nomenclature

A	Heat exchange surface, flow passage surface, characterizing dimension of a device, constant.
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 characterizing surface.
d	Infinitesimal change, d_o tube outside diameter.
D	Exergy destruction in a device
E	Exergy, E_f of fuel, E_p of product, E_j of dumped exergy
h	Film coefficient of heat transfer.
H	Enthalpy, enthalpy per unit mass
J	An objective function.
k	Constant coefficient, k_d of exergy destruction.
L	Length, L_{tube} tube length.
M	Mass, mass rate, m_h of heating stream, m_c of heated stream.
N	Number of units, N_{tube} of tubes, N_{pas} of tube passes in a heat exchanger.
n	Exponent, n_d of exergy destruction.
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.
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: V_T 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, width of a duct.
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_L local, Y_G global, $\{Y\}$ 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, ΔP_h loss of a heating stream, ΔP_c of a heated stream. ΔP_s shell side, ΔP_t tube side.
η	An efficiency variable, adiabatic efficiency, heat exchange effectiveness, pressure loss ratio, heat leak ratio, heat transfer temperature difference.
Σ	Summation

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