COST FUNCTIONS OF COMPONENTS FOR OPTIMAL SYSTEM DESIGN

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Contents

Summary

The optimization of an energy system, given a cost objective function, is a multidisciplinary task. Although a system is born in the discipline of thermodynamics, communication with the disciplines of design, manufacture, and economics is essential to minimize the capital cost of each device of the system for an efficiency target while taking care of technological advances in all the participating disciplines.

This communication may be pre-formulated mathematically to generate equations for the minimized capital costs in terms of thermodynamic variables. The equations are known as costing equations. The mathematical formulation uses the appropriate practice of each discipline in the form of a mathematical model.

Costing equations permit system optimization within the thermodynamic domain using only thermodynamic decision variables. The concept is essentially a decomposition strategy at the discipline level that greatly enhances system optimization.

This article considers a communication scenario that assumes that the design and the manufacture of a device are tailored to fit a system solution by the thermodynamic discipline. The mathematical formulation of this communication is expressed in terms of a device information-exchange matrix. The use of the matrix to generate a costing

equation for the device is described. The communication formulation and the generation of the costing equation are then applied to the super-heater of a simple combined power system.

Examples of design models for a number of energy conversion devices are described in an appendix. The costing equations generated by them given unit manufacture costs are listed. The same communication scenario is used. Alternative communication scenarios and formulations are also discussed.

This article is a step towards the mathematical formulation (continuous or discrete) of information exchange among the participating disciplines of multidisciplinary problems in general.

1. Introduction to Multidisciplinary Problems

Most engineering problems today are multidisciplinary. Security issues, environmental concerns, and rising consumption impose the multidisciplinary approach.

Systems that use or produce power and heat, fossil fuel scarcity, emissions, waste disposal, and an increased world population with a rising standard of living drive the need for higher efficiency at lower cost. Higher efficiency at lower cost calls for more intensive system analysis while the system is still in its design phase. Because of cost considerations, the analysis becomes *multidisciplinary*. 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 accommodates multidisciplinary problems. Initiated in 1962 by Professor Myron Tribus, thermoeconomics was first applied to the design of seawater desalination processes in order to explore 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 only 10% or 20% of today's prices, the impact on the price of desalinated water as compared to conventional water prices was so significant as to warrant a balance between the energy cost and the capital cost of the separating surface of a desalination process. Two publications on the subject followed in 1970.

Later, in the early 1980s, Professor R. Gaggioli initiated the interest in further development of thermoeconomics to handle energy-intensive systems in general. Many researchers responded positively to the initiation. Since the mid-1970s, the development of Thermoeconomics has been impressive in more than one direction. The recent developments by Valero et al, the present author, and G. Tsatsaronis may adequately represent the different directions of development. These directions are not yet free from inconsistencies, and also lack a formal approach to the information exchange among participating disciplines. (Refer to the bibliography of further reading for details.)

In this article, interdisciplinary communication is addressed for the purpose of the optimal design of energy-intensive systems given a cost objective function.

First a communication scenario is introduced. Mathematical models that formulate the experience of the experts of participating disciplines substitute the experts in charge.

The models are synchronized to operate in a way that leads to an optimal system. An information exchange matrix presents the generated information during the search for optimality. The building of the information matrix for a component in a system and the generation of the costing equation of the component are explained and are demonstrated for the super-heater a simple combined cycle. Alternative communication scenarios and costing equations are discussed.

2. A Scenario of Interdisciplinary Communication

The objective of the analysis shapes the scenario of interdisciplinary communication. The objective function is defined in Section 2.1. The scenario of interdisciplinary communication follows.

2.1. 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 single fuel resource, is the production cost J:

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

c_F is a unit cost of the fueling resource F on the prevailing markets, and c_{zi} is the 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 Eq. (1): thermodynamics (F), design and manufacture {Z}, and economics {c_F, c_z}.

Eq. (1) in terms of the variables of the participating disciplines is after dropping the constant C_R:

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

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 component i. The characterizing dimension may be length, mass, area, volume, or a combination of these. 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:

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

2.2. Interdisciplinary Communication

Experts in each of the participating disciplines have their own practices that can be expressed by mathematical models. Figure 1 illustrates one communication scenario among the four disciplines that aims at optimal system design for the minimum production cost given by Eqs. (1) and (1a). Using the models instead of the experts, the thermodynamic model triggers a system solution where the fuel resource F is computed for the given product rate P in terms of thermodynamic decision variables $\{Y_T\}$. These are the efficiency parameters of the system components and few levels of pressure and temperature. The fuel rate F as well the participated variables to the system solution are expressed in terms of thermodynamic variables $\{V_T\}$, which are a mix of decision and dependent variables. The design models use what they need from the thermodynamic variables $\{V_T\}$ for the design models of their components and target minimized characterizing dimension $\{A_{i\ min}\}$ while meeting the efficiency parameters set by the triggered solution. The participating $\{V_T\}$ of a component are all the variables that determine both the inlet and exit states of the component $\{V_{Ti\ in}\}$, $\{V_{Ti\ out}\}$ or alternatively $\{V_{Ti\ in}\}$, $\{\eta_i\}$ where $\{\eta_i\}$ represent the efficiency parameters of the component. The design-blueprints of $\{A_{i\ min}\}$ go through a manufacture procedure of minimized unit manufacture costs $\{c_{ai\ min}\}$. Now the production cost is computed. The thermodynamic decision variables are changed in the direction of lower production cost. The process is iterated until no further improvement in cost is possible. The iterations may be automated by nonlinear optimization techniques.

Obviously if each $Z_i = c_{ai\ min}(\{V_M\}) \times A_{i\ min}(\{V_D\})$ were in terms of thermodynamic variables ($\{V_T\}$), i.e. $Z_i = c_{ai\ min}(\{V_T\}) \times A_{i\ min}(\{V_T\})$, the optimization process could be performed within the domain of thermodynamics with reduced number of decision variables. Further decomposition at the device level adds to the enhancement of system optimization as detailed in the directly related bibliography.

The formulation of the following equation is now addressed:

$$Z_i = c_{ai\ min}(\{V_T\}) \times A_{i\ min}(\{V_T\}) \qquad (2)$$

3. The Concept of Costing Equations

Throughout the optimization iterations, a change in the system's thermodynamic decision variables changes the $\{V_T\}$ parameters and hence the $\{V_{Ti}\}$ of each component i. The procedure of changing the $\{V_{Ti}\}$ parameters of a component i within a range similar to that incurred by the iterations and recording in each change the associated $\{A_{i\ min}\}$ and $\{c_{ai\ min}\}$ establishes the concept of costing equations. A component cost can then be expressed in terms of thermodynamic variables as given by Eq. (2), which is "a costing equation."

The essential thermodynamic parameters $\{V_{Ti}\}$ of $A_{i\ min}(\{V_T\})$ and its form 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 is:

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

The number of thermodynamic parameters n is somewhere between 2 and 6 depending on the process of the component. $\{V_{Ti}\}$ 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, and so on). They may also include severity of operation parameters arising from extreme pressure, temperature, or composition conditions.

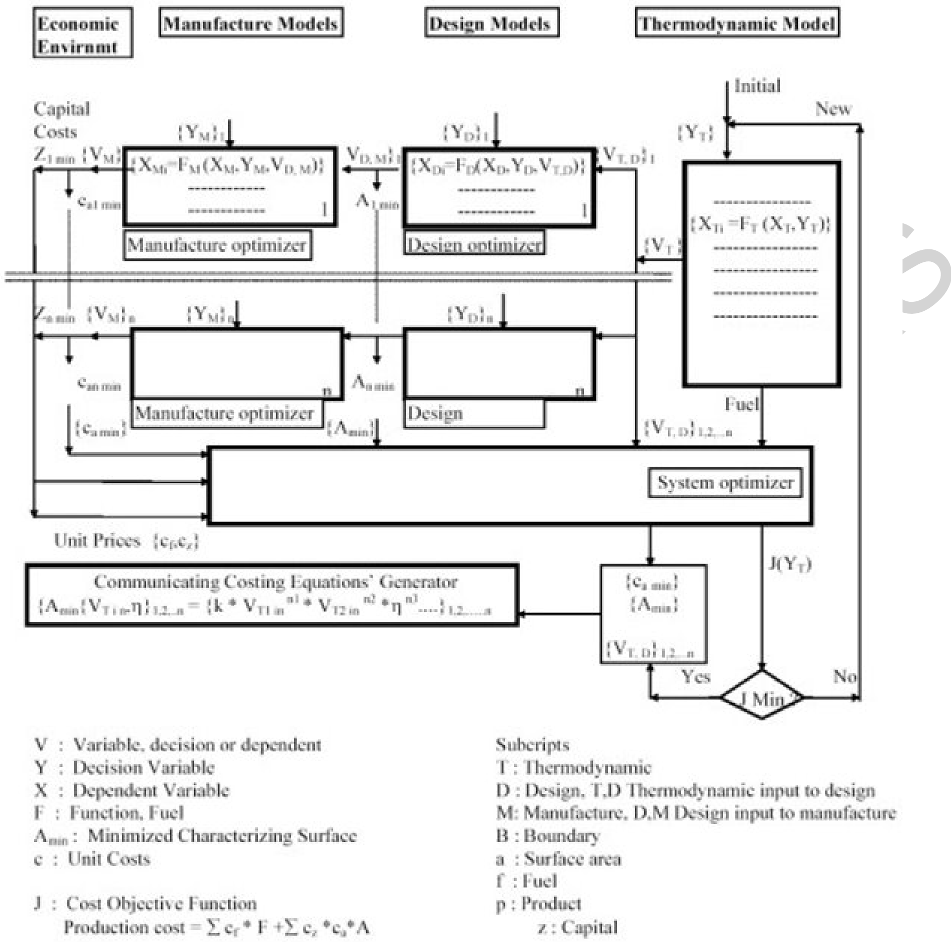

Figure 1. A scenario of interdisciplinary communication

4. The Information Exchange Matrix of a Component

The information exchange matrix of a component relates the variables of the participating disciplines to each other as functions of specific changes. The rows represent the specific changes. The columns represent the parameters of interest in each discipline associated with the change including $\{A_{i\,min}\}$ and $\{c_{ai\,min}\}$.

The specific changes are often sets of some or all the variables $\{V_{Ti}\}$ of Eq. (3). Changing one variable at a time as well as changing by random combinations generates the specific changes of the rows. The number of adequate changes is between 10 and 20. 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. They are divided into four groups of parameters: thermodynamic, design, manufacture, and economic, which correspond to each row change. The parameters of each group are subdivided into parameters of interest including a targeted parameter. The thermodynamic parameters may be subdivided into decision, sizing, and intensity. The targeted parameter may be exergy destruction(s). The design parameters may be subdivided into unchanged and changed geometry and dimensions. The targeted parameter may be the minimized characterizing surface. The manufacture parameters may be subdivided into sequence of processes, process duration, and process cost. The targeted parameter may be the manufacture cost per unit surface. The economic parameters may be subdivided into market-place prices, depreciation, salvage, and taxes. The target parameter may be the capital recovery rate. Table 1 shows examples of the parameters of interest as applied to two major energy conversion devices: heat exchange devices and power devices. In this article, interest is focused more on the thermodynamic and design models. Manufacture and economic models may need further study.

Variables	**Examples**
Thermodynamics	
Boundary variables:	
Heat exchange devices	$(P, T, M)_{in}$ or $(P, T, M)_{in}$ and $\{\eta\}$
Power devices	$(P, T, M)_{in}$ and P_{out}
Decision variables:	
Heat exchange devices	Appropriate subset of: $\eta_{effectiveness}$, ΔP_h, ΔP_c, ΔT_h, ΔT_c
Power devices	$\eta_{adiabatic}$
Sizing variables:	
Heat exchange devices	Appropriate subset of: Q, M_h, M_c
Power devices	W or M
Target variables:	
Heat exchange devices	Exergy destructions $D_T + D_{Mh} + D_{Mc}$
Power devices	Exergy destruction D_{TM}
Design	
Constant parameters:	
Heat exchange devices	Type, materials, fouling, flow direction
Power devices	Type, materials, tip speed, flow velocity, degree of reaction, blade profile
Geometry variables:	
Heat exchange devices	Length, diameter, number and thickness of tubes, pitches p_1/d, p_2/d, shell diameter, number of tube and shell passes.
Power devices	Length, width, number, spacing, and angles of blades, incidence angle
Target variables:	
Heat exchange devices	Total surface area of heat exchange
Power devices	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, salvage values
Target variables:	Capital recovery rate

Table 1. Examples of the variables of the information exchange matrix

5. An Application Example to a Heat Exchange Device

Figure 2 shows a simple combined cycle. The cycle has been analyzed and optimized (see directly related bibliography). The costing equation of the super-heater, component 7 of the heat recovery steam generator, will be derived. A duct shell-and-finned tube type is assumed. The fins are assumed to be circular on the outside (the gas side). The design model of heat exchangers described in the appendix is used. The super-heater is treated as a single phase forced convection heat exchanger. The information exchange matrix is 10 rows and 14 columns.

The boundary parameters P, T, {x}, M at inlets and exits of the exchanger as embedded in the system at one design point for the cycle are changed as the matrix rows. The length, diameter, pitches, number, material, thickness, and fin geometry of the tubes define the exchanger physical surface and its geometry. These parameters are usually more than those 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 thus a matching/minimizing process.

The minimized surface 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 subset of a larger set of performance parameters such as heat loads, mass rates, heat exchange temperature differences, effectiveness, and pressure losses. In this article, the surface (fins and 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 surface. The following form is used:

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

along with the unit manufacture cost c_a to obtain

$$Z = c_a \times A_{min} \quad (5)$$

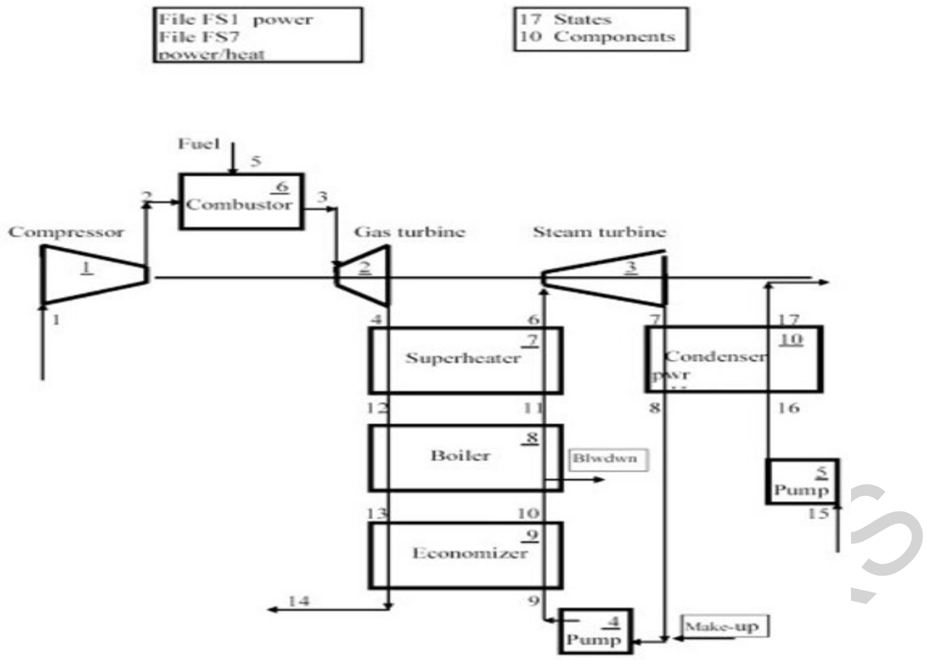

Figure 2. Low firing-temperature simple combined cycle

The unit cost c_a as a function of thermodynamic variables is set as discrete values in terms of material, and the pressure and temperature level of operation. In this example, c_a is assumed per unit total surface of fins and tubes. Changing inlet P, T, M, the allowed pressure losses and effectiveness generated 10 runs of minimized surfaces. Heat load, exit conditions, and logarithmic mean temperature difference are recorded. The parameters that remain fixed are the fin geometry, tube thickness, tube arrangement (staggered), fouling factors, and flow directions (gas horizontal, steam with gravity). In this particular example, the effect of gravity on pressure losses is negligible. Table 2 shows the recorded parameters of the 10 minimized surfaces and the quality of the correlation.

The constant k and the exponent's n_1, n_2, n_3 and n_4 of Eq. (4) are computed by using the surfaces of 5 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 are selected. The simultaneous solution involves the inverse of a matrix 4×4. 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 at all. 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. 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.

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Biographical Sketch

Dr. Yehia M. El-Sayed started his own consulting company "Advanced Energy Systems Analysis" in 1987 in Fremont. California. Before that, as Professor of Mechanical Engineering, he had a teaching carrier that spanned more than 30 years and four educational institutes: Assiut University, Egypt; Tripoli University Libya; Glasgow University, Scotland; and Massachusetts Institute of Technology MIT, Cambridge, MA, USA. He has authored and co-authored more than 60 publications. His most recent works include: *A Desalination Primer* (with Professor K.S. Spiegler); "Repowering second-law-based optimization" (a paper on energy analysis that received the 1996 ASME Edward Obert Award); and "The thermoeconomics of seawater desalination systems" (a paper that received the best paper presentation award at IDA'97, Madrid Spain).

Dr. El-Sayed received his B.Sc. in Mechanical Engineering in1950 from Alexandria University, Egypt, and his Ph.D. in 1954 from Manchester University. He was promoted to Professor at Assiut University, Egypt, in 1966. He became a Fellow of the American Society of Mechanical Engineers in 1990.