JOURNAL OF AIRCRAFT
Vol. 40, No. 1, January–February 2003

Decomposition in Energy System Synthesis/Design Optimization for Stationary and Aerospace Applications

Jules Ricardo Muñoz*
United Technologies Research Center, East Hartford, Connecticut 06108
and
Michael R. von Spakovsky†
Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24060

A number of multilevel methods for energy system synthesis/design optimization exist. Of these approaches the local-global decomposition methods (LGO and ILGO) allow for the modularity and discipline/technology autonomy required for solving large multidisciplinary synthesis/design problems. An example of a large-scale problem for a military aircraft is used to discuss the features of LGO and ILGO. The similarities between these methods and those used by the aerospace multidisciplinary design optimization community are briefly explored. It is believed that the commonalties which exist between the different approaches will permit future synergies and a genuine interdependence at an optimization level between the different disciplines.

Introduction

THE integration between aircraft energy- and non-energy-based subsystems has produced a growing interest by the aerospace community into research done on the thermodynamics and cost optimization of stationary energy systems. Recent efforts have centered on investigating ways in which such methods[1–14] can be best applied to aircraft. These efforts[3] have included identifying opportunities for the use of the Second Law of Thermodynamics (in the form of entropy generation or exergy analysis) as an analysis and perhaps as an optimization tool. A second body of work has focused on integration and system-level synthesis/design optimization challenges.[4–14] The latter efforts are trying to exploit the similarities that exist between stationary and aircraft energy systems and the synergies that might exist between aerospace multidisciplinary design optimization (MDO) methods and the decomposition approaches that have been developed and applied in stationary energy system synthesis/design since the 1960s.

The use of optimization for the synthesis/design optimization of stationary energy systems has, at least in the Second Law academic community, been widespread over the last 30 plus years. A large number of researchers have been and are involved in this field. Some of their research efforts are annually reported in specialized meetings such as the annual International Conference on Efficiency, Cost Optimization, Simulation and Environmental Aspects of Energy and Process Systems as well as periodic meetings organized by the Advanced Energy Systems Division of the American Society of Mechanical Engineers. This is in addition to papers appearing in the many periodicals in the field. The authors of Refs. 4–44 provide just a few examples of such work. The applications that can be found range from relatively simple linear programming and nonlinear programming problems[15,16] to very complex mixed-integer non-linear programming (MINLP) problems.[14,17]

Energy system synthesis/design, at least at the preliminary system design stage, typically employs two disciplines: the thermal sciences and economics. Although the first discipline involves thermodynamics, heat transfer, and fluid mechanics, it is normally referred to as thermodynamics. Other disciplines such as material science and controls are handled indirectly. For example, stress considerations are treated as constraints, and controls are included by using so-called operational variables.

Broadly speaking, one can classify the work done for stationary energy system synthesis/design based on the disciplines used to formulate the optimization problem. The most common optimization problems are to maximize the thermodynamic efficiency (minimize fuel usage) and to minimize the total cost (usually composed of fuel cost plus capital cost). The latter cross-disciplinary approach is known as *thermoeconomics*. There is a very rich body of literature on thermoeconomics, Refs. 15–31 being just a few examples. Another important problem that has gained a lot of attention is minimization of some of the combustion products (minimization of emissions).[31–37] The combination of the preceding disciplines is known as *environomics*. Application examples are given in Refs. 38–41. There are some examples in which reliability and availability considerations have also been included.[18]

Another possible classification of the work on stationary energy systems is based on whether or not one or more forms of decomposition are used.[45] One of these, called *disciplinary decomposition*, decouples a problem's thermodynamics and costs and optimizes each discipline independently.[42,43] Another possibility, called *physical decomposition*, decomposes the system across unit (component or subsystem) boundaries.[5–14,44,45] For dynamic problems it is also possible to divide the independent variables into synthesis/design variables (those which remain constant over time) and control or operational variables (those that can be varied in time). This breakdown is called *conceptual decomposition*. Finally, one additional form of decomposition, called *time decomposition*, decomposes or transforms a dynamic problem into a quasi-stationary one consisting of a series of stationary time segments.

Decomposition in Energy System Synthesis/Design

Disciplinary Decomposition

As just indicated, the decision variables in energy system synthesis/design can be broken down into purely thermodynamic and flow variables v and others that are purely geometrical w. Thermodynamic variables are, for example, component adiabatic efficiencies, pressures, and temperatures. Geometric variables are, for instance, the physical dimensions of a heat exchanger, the number of blades in a turbine, the technology level of the component (including the choice of material), etc.

Presented as Paper 2000-4853 at the AIAA/USAF/NASA/ISSMO 8th Symposium on Multidisciplinary Analysis, Long Beach, CA, 6 Sept. 2000; received 23 January 2001; revision received 18 September 2001; accepted for publication 21 September 2002.

*Research Engineer, 411 Silver Lane, MS 129-90.
†Professor, Energy Management Institute, Department of Mechanical Engineering.

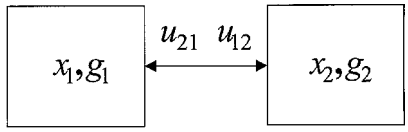


Fig. 1 Simple two-unit energy system.

With the preceding considerations in mind, it is possible to define a two-level optimization problem. At the highest level the problem could be one of minimizing the amount of fuel required to perform a given task. Typically the thermodynamic variables v are chosen by the high-level optimizer. These values are set as boundary parameters for each of the units in the system. The material (cost or weight) used in each component is then minimized using the geometric parameters as the synthesis/design variables. The latter set of low-level problems uses geometry, technology, and material choices as decision variables. Examples of the use of this approach are given in Refs. 42 and 43.

Physical (Unit) Decomposition

In contrast to disciplinary decomposition, unit decomposition tries to isolate the influence that each of the units that form a system has in terms of the overall objective function. The unit's impact might be multidisciplinary. To illustrate the fundamental differences between the leading decomposition methods for energy system synthesis/design, consider the simple two-unit system of Fig. 1.

In Fig. 1, x_1 and x_2 are the decision variables, g_1 and g_2 are the functions that describe the physical processes and constraints imposed upon each of the units, and u_{12} and u_{21} are the functions (or vector of functions) that couple the two units.

The typical objective function f is written as the sum of the contributions of each of the units. In turn, the contribution of each unit is composed of two terms as indicated here:

$$f_1 = k_1 R_1 + Z_1 \tag{1}$$

for given values of u_{12} and u_{21}.

In Eq. (1), R_1 is some external resource used by the unit (typically fuel), Z_1 is a function related to the size of the unit (weight or cost), and k_1 is a conversion factor. In a thermoeconomic problem Z_1 is the capital cost, whereas in a thermodynamic problem Z_1 is ignored altogether.

Calculus Methods of Thermoeconomics

A number of unit-based decomposition methods that have been proposed and used in the past[22,23,29,44] are to a certain extent derivations of the decomposition method proposed in Ref. 30. This method is known as the Evans/El-Sayed formalism. The basics of the method start with the following functional relationships:

$$R_1 = r_1\left(x_1, u_{12}^o\right), \qquad R_2 = r_2\left(x_2, u_{21}^o\right) \tag{2}$$

$$Z_1 = z_1\left(x_1, u_{12}^o\right), \qquad Z_2 = z_2\left(x_2, u_{21}^o\right) \tag{3}$$

$$u_{21} = u_{12}\left(x_1, u_{12}^o\right), \qquad u_{12} = u_{12}\left(x_2, u_{21}^o\right) \tag{4}$$

where u_{ij}^o are the variables associated with the corresponding function u_{ij}. The method typically begins by finding a workable solution (i.e., one that satisfies the vectors of constraints g_1 and g_2) called a reference solution, with values for the objective function f_0 and the independent variables $(x_1)_0$ and $(x_2)_0$. A variation in x_1 and x_2 from the reference solution will cause a corresponding change in the objective function given by

$$\mathrm{d}f = \gamma_1 \,\mathrm{d}x_1 + \gamma_2 \,\mathrm{d}x_2 \tag{5}$$

where γ_1 and γ_2 are some rather involved functions of x_1, x_2, u_{21}, and u_{12}. Under certain circumstances γ_1 and γ_2 would become a function of x_1 and x_2, respectively, thus, effectively decoupling the system and allowing for the definition of two decomposed problems. The proposed algorithm was to vary x_1 and x_2 starting at the reference point in the direction indicated by the γ. The process would be repeated until no further improvements in the objective function were achieved, the γ become identically equal to zero, or limits on the decision variables are reached. The hope and the expectation were that these functions would remain approximately constant so that large "jumps" in the independent variables could be made at any given time. The changes in x_1 and x_2 would be made in the directions indicated by the γ in an iterative fashion. The conditions under which such decomposition is possible are known as those for thermoeconomic isolation.[24,29] The prospects of the method created a great deal of enthusiasm among researchers in the energy area, as indicated by the many efforts devoted to formally understanding and enhancing it.[17–29]

In the original method the connecting functions u_{12} and u_{21} are expressed in terms of exergy. However, it is possible to use energy or other quantities as well.[31] Some drawbacks of the method have been identified. The first is the difficulty in obtaining the required functions in the form given by Eqs. (2–4). Additionally, the original method was not developed for units coupled to non energy systems. The conditions for isolation in those cases have never been studied. Furthermore, the Evans/El-Sayed formalism indirectly assumes that a single group of analysts has access and the expertise to work with all of the disciplines and the different technologies (units) that compose the system.

To overcome some of the difficulties associated with the preceding formulation, two additional methods for physical decomposition are presented in Refs. 5–14, one a classic method and the other an original development by the authors. The methods called local-global and iterative local-global optimization, LGO and ILGO, respectively, have the advantage that they support the link between energy and nonenergy systems and the simulation and optimization of units by groups of different expertise, even if they are geographically dispersed.

In these methods the functional relationships given by Eqs. (2) and (3) are replaced by

$$R_1 = r_1\left(x_1, u_{12}^o, u_{21}^o\right), \qquad R_2 = r_2\left(x_2, u_{12}^o, u_{21}^o\right) \tag{6}$$

$$Z_1 = z_1\left(x_1, u_{12}^o, u_{21}^o\right), \qquad Z_2 = z_2\left(x_2, u_{12}^o, u_{21}^o\right) \tag{7}$$

$$u_{21} = u_{12}(x_1, x_2), \qquad u_{12} = u_{12}(x_1, x_2) \tag{8}$$

A detailed explanation of the method can be found in Ref. 6. A brief presentation of LGO and ILGO follows.

LGO/ILGO

To show some of the features of these methods, consider a more complex system such as the one shown in Fig. 2. Only three units are used to facilitate the presentation of the method. Three is considered a sufficiently large number to reveal their features and properties.

In Fig. 2 the contribution of any unit, say unit 1, to the overall objective function is given by

$$f_1 = f_1(x, x_1, u_{21}, u_{31}, u_{12}, u_{13}) \tag{9}$$

so that the system-level problem is to

Minimize:

$$f = f_1(x, x_1, u_{21}, u_{31}, u_{12}, u_{13}) + f_2(x, x_2, u_{12}, u_{32}, u_{21}, u_{23}) + f_3(x, x_3, u_{13}, u_{23}, u_{31}, u_{32}) \tag{10}$$

with respect to x, x_1, x_2, x_3,

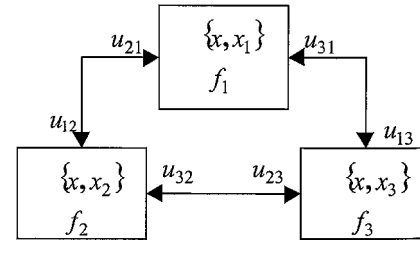


Fig. 2 Coupled energy system.

Subject to:

$$g \leq 0 \tag{10a}$$

The connecting or coupling functions u_{ij} can take the form of energy, exergy, or any other relevant quantity. Under some circumstances it is possible to arbitrarily select values u_{ij}^o for the coupling functions u_{ij} so that a two-level optimization problem can be defined. The values of the coupling functions are such that $u_{ij_{\max}}^o \leq u_{ij}^o \leq u_{ij_{\min}}^o$. The maximum and minimum allowable values of the connecting functions are defined a priori.

At the highest level a system-level problem is to

Minimize:

$$f = \sum_{i=1}^{3} f_i^\bullet \tag{11}$$

with respect to x, u_{ij}^o. In Eq. (11), $f_i^\bullet$ is the result obtained from solving a set of local, that is, unit-level optimization problems. The unit-level problem for unit 1 takes the form:

Minimize:

$$f_1 = f_1\left(x, x_1, u_{12}^o, u_{13}^o, u_{21}^o, u_{31}^o\right) \tag{12}$$

with respect to x_1,

Subject to:

$$g \leq 0 \tag{12a}$$

Note that in Eq. (12a), x is not an independent variable because it is defined by the system-level optimizer. This optimization approach has been called LGO.[6–14] Note that the disciplinary decomposition just mentioned is a special case of LGO. The preceding problem is solved numerous times for different combinations of values for the coupling functions. The way in which the unit-level and system-level problems are solved dictates the use of the two possible variations of the method.

In the first variation, called real-time LGO, the unit-level optimizations [Eq. (12)] are carried out immediately after the system-level optimizer has selected values for x and u_{ij}. In the second version, called off-line LGO, the unit-level problems are solved, and the results are stored for later usage by the system-level optimizer. These data can be correlated or represented by a surface known as the optimum response surface (ORS) of the system.

The main drawback of LGO is that for large numbers of units and/or large numbers of elements for the coupling function vectors the number of required unit-level optimizations might grow to be very large, making it impractical or at the very least very expensive to create the ORS. To overcome this drawback, an alternative to LGO, namely, ILGO, has been proposed. ILGO is based on the fundamental idea that a linear approximation can be used to represent the ORS at any point on its surface. Two implementations of ILGO are possible.

In the first version of the method (ILGO/A), an initial optimum solution for each of the unit-level problems (12) is found for initial arbitrary values of x and u_{ij}, say $(x)_0$ and $(u_{ij})_0$. This is a reference point on the ORS. A Taylor-series expansion of the unit-level objective functions is performed about the ORS reference point, and the linear term is taken so that

$$f_1 = \left(f_1^\bullet\right)_0 + \frac{\partial f_1^\bullet}{\partial x}\Delta x + \frac{\partial f_1^\bullet}{\partial u_{12}}\Delta u_{12} + \frac{\partial f_1^\bullet}{\partial u_{13}}\Delta u_{13} + \frac{\partial f_1^\bullet}{\partial u_{21}}\Delta u_{21} + \frac{\partial f_1^\bullet}{\partial u_{31}}\Delta u_{31} \tag{13}$$

The preceding partial derivatives are seen to correspond to the shadow prices (a type of marginal cost) of the coupling functions typically used in thermoeconomics.[29] Using the notation found in the energy literature, Eq. (13) is rewritten as

$$f_1 = \left(f_1^\bullet\right)_0 + \lambda_x^1\Delta x + \lambda_{12}^1\Delta u_{12} + \lambda_{13}^1\Delta u_{13} + \lambda_{21}^1\Delta u_{21} + \lambda_{31}^1\Delta u_{31} \tag{14}$$

and for units 2 and 3

$$f_2 = \left(f_2^\bullet\right)_0 + \lambda_x^2\Delta x + \lambda_{21}^2\Delta u_{21} + \lambda_{23}^2\Delta u_{23} + \lambda_{12}^2\Delta u_{12} + \lambda_{32}^2\Delta u_{32} \tag{15}$$

$$f_3 = \left(f_3^\bullet\right)_0 + \lambda_x^3\Delta x + \lambda_{31}^3\Delta u_{31} + \lambda_{32}^3\Delta u_{32} + \lambda_{13}^3\Delta u_{13} + \lambda_{23}^3\Delta u_{23} \tag{16}$$

Thus, and by virtue of the fact that the overall objective function is the sum of Eqs. (14–16), the shadow prices become a measure of the relative importance of the coupling functions in terms of the overall system-level objective. In ILGO/A the shadow prices guide the selection of a new set of values for x and u_{ij}. Geometrically, they represent the direction in which (on the ORS) an improvement in the objective function is achieved. The new values are chosen so that the linear representation of the objective functions is maintained.

The problem with ILGO/A is that in many cases arbitrarily chosen values for x and u_{ij} do not lead to feasible solutions in each of the unit-level optimization problems. The alternative in such cases is to use version B of ILGO (ILGO/B). Again taking the linear term of a Taylor-series expansion, one can write the function that connects units 1 and 2 as

$$u_{12} = \left(u_{12}^\bullet\right)_0 + \frac{\partial u_{12}^\bullet}{\partial x_1}\Delta x_1 + \frac{\partial u_{12}^\bullet}{\partial x_2}\Delta x_2 \tag{17}$$

Performing similar expansions on the other connecting functions and combining them with Eq. (14), one gets that

$$f_1 = \left(f_1^\bullet\right)_0 + \lambda_x^1\Delta x + \mu_{\Delta x1}^1\Delta x_1 + \mu_{\Delta x2}^1\Delta x_2 + \mu_{\Delta x3}^1\Delta x_3 \tag{18}$$

where

$$\mu_{\Delta x1}^1 = \lambda_{12}^1\frac{\partial u_{12}^\bullet}{\partial x_1} + \lambda_{13}^1\frac{\partial u_{13}^\bullet}{\partial x_1} + \lambda_{21}^1\frac{\partial u_{21}^\bullet}{\partial x_1} + \lambda_{31}^1\frac{\partial u_{31}^\bullet}{\partial x_1} \tag{19}$$

$$\mu_{\Delta x2}^1 = \lambda_{12}^1\frac{\partial u_{12}^\bullet}{\partial x_2} + \lambda_{21}^1\frac{\partial u_{21}^\bullet}{\partial x_2} \tag{20}$$

$$\mu_{\Delta x3}^1 = \lambda_{13}^1\frac{\partial u_{13}^\bullet}{\partial x_3} + \lambda_{31}^1\frac{\partial u_{31}^\bullet}{\partial x_3} \tag{21}$$

The functions given by Eqs. (19–21) are the shadow prices of the independent variables normally found in the thermoeconomics literature. The shadow prices reveal the effect that the local (unit 1) independent variables and the independent variables of the other units (2 and 3) have on the local contribution f_1 to the overall objective function f. These equations are used to approximate the impact of the vectors of independent variables of each of the units in terms of the overall problem [Eq. (10)]. Furthermore, the shadow prices are a measure of the relative importance of the independent variables within each unit.[6–14]

One of the main differences between ILGO/B and other energy system synthesis/design methods is that in the latter purely local (unit-based) problems are not defined because the concept of unit "isolation" does not exist except on an incidental basis. In ILGO/B system-level unit-based optimization subproblems are defined instead. These problems are obtained by rewriting the overall problem in terms of strictly local decision variables. For unit 1 this subproblem takes the form:

Minimize:

$$f^1 = \left(\mu_{\Delta x1}^1 + \mu_{\Delta x1}^2 + \mu_{\Delta x1}^3\right)\Delta x_1 \tag{22}$$

with respect to x_1,

Subject to:

$$\Delta u_{ij} < \varepsilon \cdot u_{ij}^\bullet \tag{22a}$$

In Eq. (22) the constant terms have been dropped. The constraint (22a) was added so that the values of u_{ij} remain within the range for which the Taylor-series expansion is valid. Clearly, Eq. (22) is one

of minimizing the contribution of the independent variables of unit 1 to the system-level objective. This means that units can be optimized "by themselves" while properly taking into account overall system effects. Three additional problems are defined for x_2 and x_4 and for the common variable x.

The iterative algorithm that results from implementing ILGO consists of finding a new value of the independent variables followed by the calculation of the shadow prices. This new point in the ORS replaces the original as the ORS reference point. The process is repeated until no further improvements are achieved or until the limiting values for the independent variables are reached.

Applications

LGO has been applied to the design of an environmental control subsystem (ECS),[4,5] and ILGO has been successfully applied to the large-scale, *coupled* synthesis/design optimization of the several subsystems of an advanced military aircraft, namely, the propulsion subsystem (PS), the ECS, the transient fuel loop subsystem (FLS), the vapor compression/polyalpha olefin (PAO) loops subsystem (VC/PAOS), and the airframe subsystem (AFS).[6–9,12–14] In these applications the PS is composed of a turbofan engine with afterburner. Furthermore, both LGO and ILGO have been successfully applied to the synthesis/design optimization of a fuel-cell-based total energy system for stationary applications composed of three subsystems, that is, a fuel processing subsystem, a stack subsystem, and a heat-pump subsystem.[10,11]

The smaller of the applications found in Refs. 6–9 and 12–14, that is, the coupled ECS-PS synthesis/design optimization problem for the hypothetical combat mission of an air-to-air fighter given in Ref. 46, is presented here. Fifteen segments were chosen to represent the mission either because their fuel consumption is significant or the operating conditions are very stringent for the two subsystems being synthesized/designed. The remaining subsystems present in the aircraft, the expendable and permanent payloads, EPAY and PPAY, respectively, and the AFS were taken into account but with 0 deg of freedom (as opposed to the 154 deg of freedom present with the ECS and PS). The coupling of the subsystems is represented in Fig. 3.

Three synthesis/design problems were solved using three different objective functions: takeoff gross weight (WTO), total fuel consumption, and total cost. The total weight is composed of the weight of the PS, the ECS, the fuel, the payload (permanent and expendable), and the airframe (AFS). The weight of the airframe was calculated using a simple function that correlates it to the WTO. The function was obtained from curve fits of existing data. The cost model for the airframe was obtained from Ref. 47. For the AFS cost calculation it was assumed that four test and 350 production aircraft are built.

The components of the PS are shown in Fig. 4. The on- and off-design performance of the engine was simulated using a modern performance code developed by an engine manufacturer for modeling any type of aircraft engine system. The model of the engine uses typical component maps (e.g., compressor, fan hub, fan tip, turbine, burner, and compressor maps) and functional relationships and numerical constants that modify the maps to make the simulation as

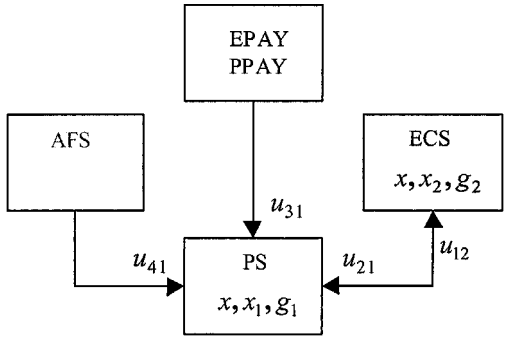


Fig. 3 Subsystem coupling for the energy system synthesis/design optimization application found in Refs. 6–9.

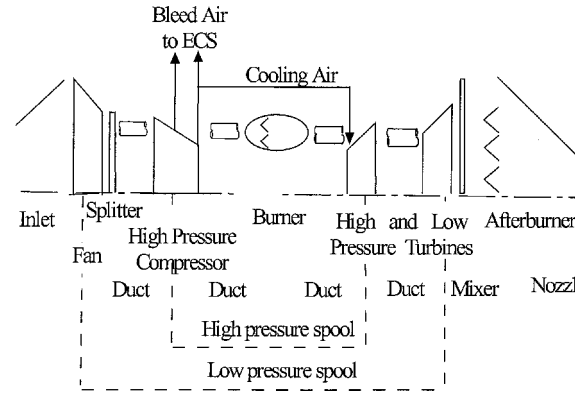


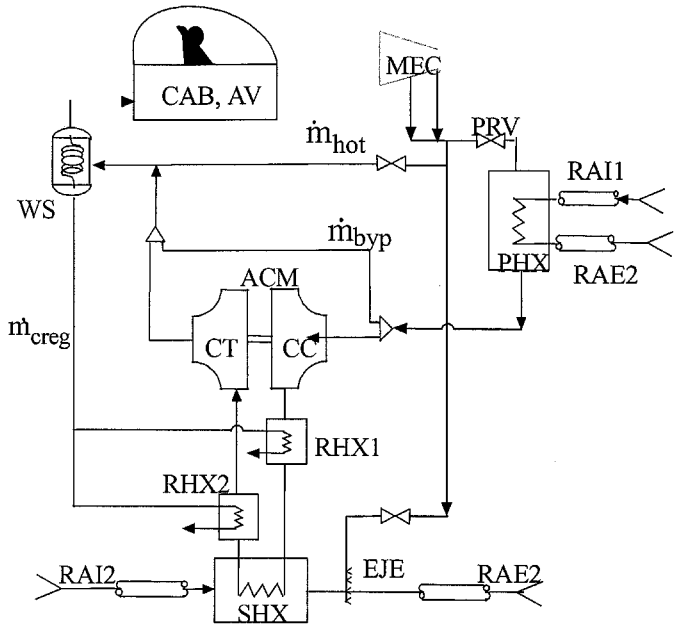
Fig. 4 PS components.

realistic as possible. The component maps are chosen from several alternatives depending on the design pressure ratio. The computer program has its own set of solvers to carry out the mass, momentum, energy, and shaft speed balances. Results from the simulation are the thermodynamic properties at each of the engine stations (pressure, temperature, Mach number, etc.), the inlet airflow rate, nozzle areas, and the fuel consumed in the combustor and afterburner adjusted to provide the thrust required during the different segments of the mission. The thrust requirements were calculated using the flight dynamics equations and the mission requirements. Simple compressible flow models were used to calculate the inlet and nozzle drags. The weight and dimensions of the PS were calculated using NASA's WATE code.[48] The capital cost of the engine was obtained from the model of Ref. 49 properly adjusted for inflation. The cost model includes development and production costs through the thousandth production engine. Other maintenance and operating costs (with the exception of fuel) were not included.

The ECS considered was a bootstrap subsystem, as shown in Fig. 5. The ECS provides conditioned air to the cockpit and avionics. Flow into the ECS is varied by a pressure-regulating valve at the ECS inlet. This valve also limits maximum inlet pressure to the ECS's primary heat exchanger and bootstrap compressor. Air is compressed and cooled in the bootstrap ECS. After compression, the air is cooled in a counterflow, secondary heat exchanger using ram air from scoop inlets. Air from the secondary heat exchanger is then cooled in the regenerative heat exchanger before it is cooled further by expansion in the bootstrap turbine. Most of the water condensed during the cooling of the air in the turbine is removed in a low-pressure water separator.

The mass flow rate and the required pressure of the bleed air will in general depend on the pressure and temperature at which the cold air must be delivered to the cockpit and avionics and the design of the ECS. The energy or exergy of the air that can then be had from the main engine compressor is not a continuous function but rather is limited by the fact that it can only be extracted from discrete stages of the compressor. Typically, modern ECSs have a bleed port at a low-pressure and one at a high-pressure stage, as indicated in Fig. 5. The bleed temperature and pressure are a very strong functions of engine design, throttle settings, and the operating conditions dictated by the mission. In this paper it is assumed that the high-pressure bleed air is taken from the last compressor stage. The low-pressure bleed port is assumed to be located at a point in the high-pressure compressor (HPC) with a pressure ratio equal to the square root of the overall HPC pressure ratio

The ram air inlets create a penalty in the system, which is proportional to the drag force created by the inlets D_{ECS}. Quantitatively, the drag force created by the inlet heat exchanger exit assembly is defined as the cooling airflow's rate of momentum change. In addition to this, there will be the profile drag of the inlet and exit and perhaps some interference drag as a result of unfavorable interactions. The thermodynamic, physical, and cost models for the ECS can be found Ref. 4. The cost models were obtained from a combination of catalog data, existing reports, and data provided by manufacturers.



WS	Water separator	MEC	Main Engine Compressor
MEC	Main Engine Compressor	RAI1 RAI2	First and Second Ram Air Inlets
PRV	Pressure Regulating Valve	RAE1 RAE2	First and Second Ram Air Exits
CC CT	Centrifugal Compressor and Turbine	AV	Avionics
		ACM	Air Cycle Machine
CAB	Cabin	EJE	Ejector
RHX 1 RHX 2	1st and 2nd Regenerative Heat Exchangers	$\dot{m}_{creg}$	Regenerative Heat Exchanger Cold air flow rate
PHX SHX	Primary and Secondary Heat Exchangers	CC CT	Centrifugal Compressor and Turbine
$\dot{m}_{hot}$	Hot bleed air	$\dot{m}_{byp}$	Bypass air

Fig. 5 ECS components.

Some of the decision variables (x_1 and x_2) for the PS are given here: fan bypass ratio; fan design pressure ratio (tip and hub); high-pressure compressor design pressure ratio; high-pressure turbine design pressure ratio; low-pressure turbine design pressure ratio; mixer Mach number; turbine inlet temperature; and cold, hot, and non-flow core length for four heat exchangers. Some of the ECS decision variables are as follow: compressor design pressure ratio, turbine design pressure ratio, existence-nonexistenceof the two regenerative heat exchangers in configuration, areas of two ram air inlets, type of fin in primary and secondary heat exchangers (from a set of 10), pressure regulating valve setting, bypass and hot airflow rate, and regenerative heart exchanger cold airflow rate. Other important design variables and the constraints for the problem are given in Ref. 7. A total of 154 independent variables were involved. Additionally, the settings (i.e., on or off) of two bleed ports are the common variables x for both subsystems.

As just mentioned, the synthesis/design of the ECS is heavily influenced by the engine operating settings and design. In turn, the PS is affected by the ECS bleed air requirements and weight and the momentum drag created by the ram air inlets. Therefore, the coupling between the two subsystems is quite tight. The coupling functions for all of the units considered are given in Table 1.

The unit-based system-level optimization problems for the ECS and PS were solved concurrently. The process starts by using assumed values for u_{21} in the PS optimization. Once a PS design is obtained, the vector u_{12} and its shadow prices (λ_{bleed}, λ_{wecs}, and λ_{decs}) are calculated for use in the ECS optimization. A schematic of the PS modeling and optimization approach is given in Fig. 6.

Table 1 Coupling functions for the system of Fig. 3

Unit	Function
u_{12}	Bleed air temperature and pressure
u_{21}	Ram air momentum drag, ECS weight, bleed air requirement
u_{31}	Weight of the permanent and expendable payload
u_{41}	Drag and lift coefficients at different Mach numbers, weight of the airframe

In Fig. 6 the subscripts bleed, drag, and wecs refer to bleed airflow rate, ram air inlet drag, and ECS weight, respectively. The engine is "flown" on paper to obtain the fuel consumption. An iterative procedure is used to obtain convergence on the takeoff gross weight. Once the W_{TO} calculation is complete, the solution is sent to the optimizer for evaluation. Because of the large number of variables in the ECS problem, conceptual and time decompositions in the manner just described were used. The design point for the ECS corresponds to the subsonic mission segment with the highest altitude. This mission leg is used to obtain a set of the most promising solutions (identified with the subscript feasible in Fig. 7). Each of these (typically five) provides constant values for the ECS synthesis/design decision variables, which are then used in the remaining (14) off-design optimization problems. At the operational level these problems are

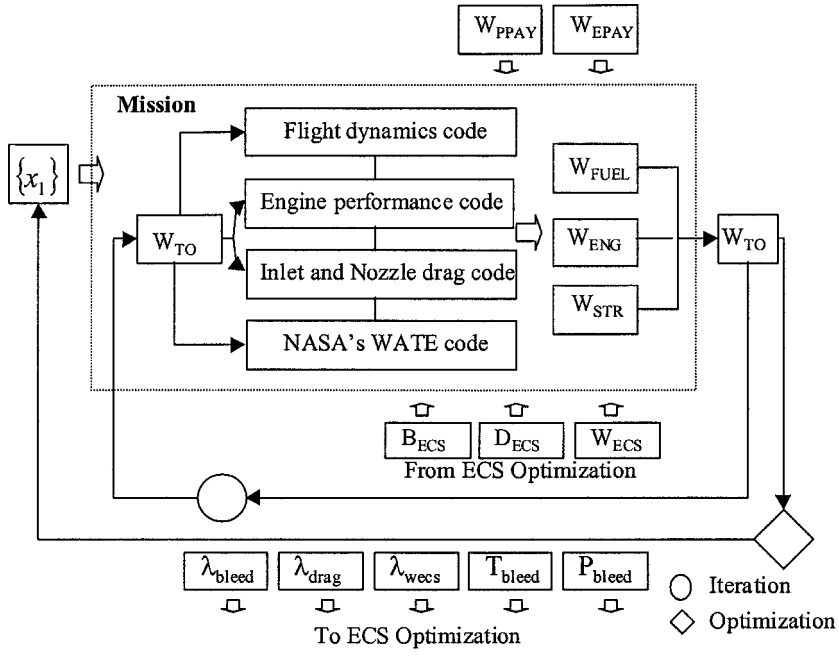


Fig. 6 PS decomposed optimization approach for the problem with W_{TO} as the objective function.

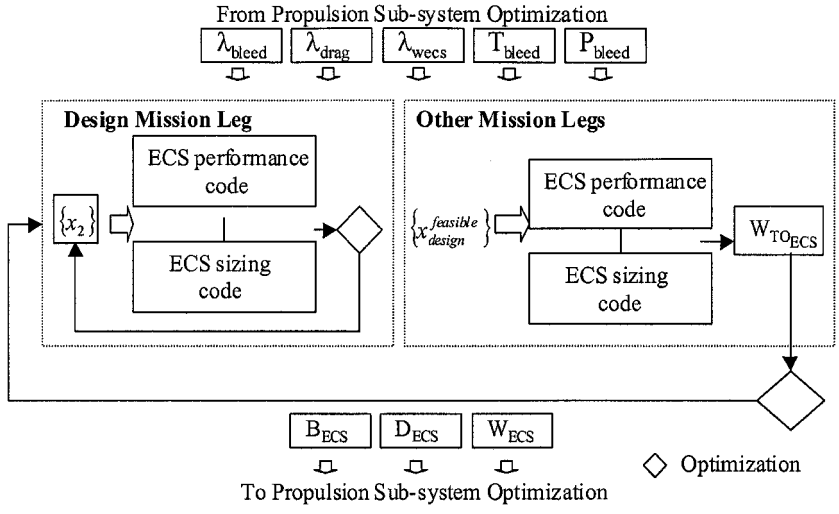


Fig. 7 ECS decomposed optimization approach for the problem with W_{TO} as the objective function.

resolved each with respect to the operational decision variables for each leg. The optimization procedure for the ECS is shown in Fig. 7. In Fig. 6, $W_{TO_{ECS}}$ refers to the ECS contribution to the takeoff gross weight.

All of the optimization problems were solved using the commercial optimization package iSIGHT.[50] Each optimization iteration typically consists of two steps. The first uses a genetic algorithm (GA) to deal with the mixed integer variables and possible local minima problems in each of the unit-level (subsystem) optimizations. Each GA optimization run has a minimum population size equal to three times the number of variables with a minimum of 50. The minimum number of iterations for the GA is set to 100 and 1000 times the population size for the PS and ECS optimization problems, respectively. In the first step the convergence criterion for the calculation of the takeoff gross weight is set at 0.2%. This means that the value of W_{TO} sent to the optimization algorithms has an error of approximately ±200 N. The second step uses the top two or three solutions obtained with the GA to narrow down the best solutions using a gradient-based algorithm (Method of Feasible Directions). For the second step the convergence criterion in the takeoff gross weight calculation is set at 0.1%.

The number of iterations required to achieve an optimum was four in all cases. The final answer was the same for all of the different objective functions considered: W_{TO}, W_{FUEL}, and capital cost. The last result came as no surprise because the cost correlations used were linear with respect to weight. The evolution of some the objective functions and some other dependent variables are given in Fig. 8. The final results are shown in Table 2.

Table 2 ECS and PS optimum results

Objective function	Optimum result
W_{TO}/g, kg	10,134
W_{FUEL}/g	3,308
W_{STR}/g	4,526
W_{ENG}/g	1,075
ΔW_{TOECS}/g	852
W_{ECS}/g	272
Cost-ECS[a]	541
Cost-PS	5,642
Cost-STR	1,414

[a]All costs are given in thousands of 1999 U.S. dollars.

The global convergence properties of ILGO are discussed in Ref. 6. The authors theorize and have shown in the context of four complex, high-degree-of-freedom applications[6–10,12–14] that ILGO

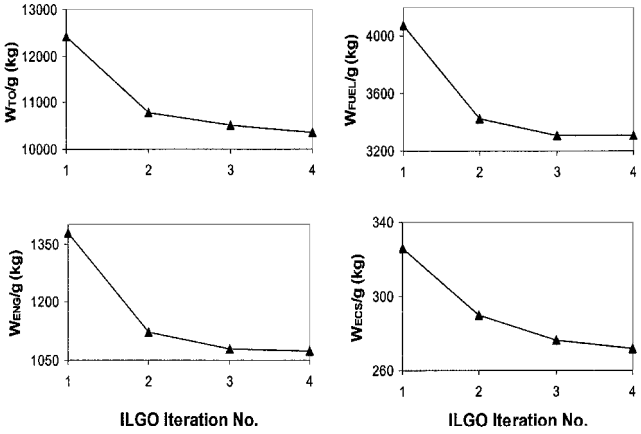


Fig. 8 Evolution of the takeoff gross weight, fuel, and ECS and engine weight at different points of the ILGO approach.

will converge to a global optimum if the system-level objective is convex in the domain of the coupling functions (the ORS). To verify this finding in, for example, the application just presented, the entire MINLP ECS/PS problem was solved with a reduced number of variables. This was done by coupling the different codes to the optimizer as a single simulator. It was found that the solution obtained by solving the entire problem was essentially the same as that obtained using ILGO, that is, within 10% and with the latter producing the better result. The authors furthermore present a graphical representation of the ORS and an analysis of the results in Ref. 7. For the given problem the shadow prices for the coupling functions remained approximately constant from iteration to iteration indicating that the ORS is in fact a hyper/plane, a result that was verified graphically.

Conclusion

A number of optimization methods for stationary energy system optimization have been proposed and used. From these, the local-global techniques initially presented in Refs. 5–9 and summarized here and in Refs. 6–14 are seen to be the most amenable for large multidisciplinary analysis and optimization. These methods are capable of using dissimilar modeling codes, possibly written for different platforms. In addition, they are modular and can be implemented in a concurrent or parallel fashion. Thus, analysis and optimization problems are divided into clearly separated tasks assigned to the different engineering specialties. Responsibility for the effect that each group has in terms of the objective functions of the other units is quantified. Changes in a particular unit are made in order to improve the overall system even if such changes do not seem optimal from the point of view of a unit alone. The synthesis/design process can be halted at any step, and some improvement over the starting point is likely to be achieved. As to using LGO or the original development by the authors, namely, ILGO, the latter is a significant advance over the former because of the following:

1) It eliminates the nested optimizations required in standard LGO decomposition approaches. This in fact leads to what in the thermoeconomic literature is called a close approach to thermoeconomic isolation,[24,29] which is defined as the ability to optimize independently each unit of a system and yet still arrive at the optimum for the system as a whole.

2) It uses an intelligent search based on shadow prices to effectively search the system-level optimum response surface without having to actually generate it or the unit-level ORSs.

3) ILGO ensures consistency between all local objectives and the system-level objective.

4) It introduces no constraint inconsistencies from one subproblem to another.

5) ILGO is conducive to the parallelization of the various subproblem optimizations.

As to some of the methods used by the aerospace multidisciplinary design optimization (MDO) community, the similarities between these and LGO and ILGO should be evident. For example, the use of piece-wise linear approximations of system behavior in the vicinity of a design point are commonalties of ILGO and some of the leading MDO methods (e.g., CCSO[51]). The shadow prices for the coupling functions and the independent variables are mathematical representations of the interdependence of the different units or technologies that comprise a system. They also serve as indicators of the relative importance of the decision variables and of the effects that changes in values of the coupling functions might have in terms of the overall objective function. Therefore, the shadow prices commonly used in stationary system synthesis/design optimization are seen to be mathematically and conceptually similar but *not* identical to the partial derivatives associated with the Global Sensitivity Theory[52] and the MDO methods that make use of them. Finally, the approaches just presented, in particular ILGO, make it possible to consider optimizing the synthesis/design of highly complex and dynamic systems. This is particularly underscored by the successful application (with 553 deg of freedom) of this method to the concurrent synthesis/design optimization of the PS, ECS, FLS, VC/PAOS, AFS, EPAYS, and PPAYS of an advance fighter aircraft.[13,14] Of course, any future success of such a large multidisciplinary effort will depend a great deal on the ability of different specialty groups to closely interact with and interdepend upon each other. However, the necessary, common, mathematical framework and understanding needed to achieve this goal now exists.

References

[1]Newberry, C. F., "Exergy—The Aircraft Design Variable of Choice?," AIAA Paper 2000-4851, Sept. 2000.

[2]Paulus, D., and Gaggioli, R., "Rational Objective Functions for Vehicles," AIAA Paper 2000-4852, Sept. 2000.

[3]Bejan, A. R., "A Role for Exergy Analysis and Optimization in Aircraft Energy-System Design," AIAA Paper 2000-4855, Sept. 2000.

[4]Muñoz, J. R., and von Spakovsky, M. R., "A Second Law Based Integrated Thermoeconomic Modeling and Optimization Strategy for Aircraft/Aerospace Energy System Synthesis and Design," (Phase I—Final Report) U.S. Air Force Office of Scientific Research, Final Rept., New Vista Program, Arlington, VA, Dec. 1999.

[5]Muñoz, J. R., and von Spakovsky, M. R., "An Integrated Thermoeconomic Modeling and Optimization Strategy for Aircraft/Aerospace Energy System Design," American Society of Mechanical Engineers, July 2000.

[6]Muñoz, J. R., and von Spakovsky, M. R., "The Use of Decomposition for the Large Scale Synthesis/Design Optimization of Highly Coupled, Highly Dynamic Energy Systems: Part I—Theory," American Society of Mechanical Engineers, Nov. 2000.

[7]Muñoz, J. R., and von Spakovsky, M. R., "The Use of Decomposition for the Large Scale Synthesis/Design Optimization of Highly Coupled, Highly Dynamic Energy Systems: Part II—Applications," American Society of Mechanical Engineers, Nov. 2000.

[8]Muñoz, J. R., and von Spakovsky, M. R., "The Application of Decomposition to the Large Scale Synthesis/Design Optimization of Aircraft Energy Systems," *International Journal of Applied Thermodynamics*, Vol. 4, No. 2, 2001, pp. 61–75.

[9]Muñoz, J. R., and von Spakovsky, M. R., "A Decomposition Approach for the Large Scale Synthesis/Design Optimization of Highly Coupled, Highly Dynamic Energy Systems," *International Journal of Applied Thermodynamics*, Vol. 4, No. 1, 2000, pp. 19–33.

[10]Georgopoulos, N., von Spakovsky, M. R., and Muñoz, J. R., "A Decomposition Strategy Based on Thermoeconomic Isolation Applied to the Optimal Synthesis/Design and Operation of a Fuel Cell Based Total Energy System," American Society of Mechanical Engineers, Nov. 2002.

[11]Oyarzabal, B., von Spakovsky, M. R., Ellis, M. W., and Georgopoulos, N., "Application of a Decomposition Strategy to the Optimal Synthesis/Design of a Fuel Cell Sub-System for Residential Applications," American Society of Mechanical Engineers, Nov. 2002.

[12]Muñoz, J. R., and von Spakovsky, M. R., "Decomposition in Energy System Synthesis/Design Optimization for Stationary and Aerospace Applications," AIAA Paper 2000-4853, Sept. 2000.

[13]Rancruel, D., von Spakovsky, M. R., and Muñoz, J. R., "A Second Law Based Integrated Thermoeconomic Modeling and Optimization Strategy for Aircraft/Aerospace Energy System Synthesis and Design," U.S. Air Force Office of Scientific Research, Arlington, VA, Grant F49620-00-1-0142—Annual Rept., New Vista Program, Dec. 2001.

[14]Rancruel, D., "A Decomposition Strategy Based on Thermoeconomic Isolation Applied to the Optimal Synthesis/Design and Operation of an Advanced Fighter Aircraft System," M.S. Thesis, Dept. of Mechanical Engineering, Virginia Polytechnic Inst. and State Univ., Blacksburg, VA, Nov. 2002.

[15] von Spakovsky, M. R., "Application of Engineering Functional Analysis to the Analysis and Optimization of the CGAM Problem," *Energy: The International Journal*, Vol. 19, No. 3, 1994, pp. 343–364

[16] Frangopoulos, C. A., "Application of Thermoeconomic Optimization Methods to the CGAM Problem," *Energy: The International Journal* (special ed.) Vol. 19, No. 3, 1994, pp. 323–342.

[17] Olsommer, B., von Spakovsky, M. R., and Favrat, D., "An Approach for the Time-Dependent Thermoeconomic Modeling and Optimization of Energy System Synthesis, Design and Operation (Part I: Methodology and Results)," *International Journal of Applied Thermodynamics*, Vol. 2, No. 3, 1999, pp. 96–114.

[18] Olsommer, B., von Spakovsky, M.R., and Favrat, D., "An Approach for the Time-Dependent Thermoeconomic Modeling and Optimization of Energy System Synthesis, Design and Operation (Part II: Reliability and Availability)," *International Journal of Applied Thermodynamics*, Vol. 2, No. 4, 1999, pp. 177–186.

[19] Hua, B., Yin, Q., and Wu, G., "Energy Optimization Through Exergy-Economic Evaluation," *Journal of Energy Resources Technology*, Vol. 111, Sept. 1989, pp. 148–153.

[20] Frangopoulos, C. A., Lygeros, A. I., Markou, C. T., and Kaloritis, P., "Thermoeconomic Operation Optimization of the Hellenic Aspropyrgos Refinery Combined-Cycle Cogeneration System," *Applied Thermal Engineering*, Vol. 16, 1996, pp. 949–958.

[21] Manolas, D. A., Frangopoulos, C. A., Gialamas, T. P., and Tsahalis, D. T., "Operation Optimization of an Industrial Cogeneration System by a Genetic Algorithm," *Energy Conversion and Management*, Vol. 38, 1997, pp. 1625–1636.

[22] von Spakovsky, M. R., "A Practical Generalized Analysis Approach for the Optimal Thermoeconomic Design and Improvement of Real-World Thermal Systems," Ph.D. Dissertation, School of Mechanical Engineering, Georgia Inst. of Technology, Atlanta, 1986.

[23] Frangopoulos, C. A., "Thermoeconomic Functional Analysis: A Method for Optimal Design or Improvement of Complex Thermal Systems," Ph.D. Dissertation, School of Mechanical Engineering, Georgia Inst. of Technology, Atlanta, 1983.

[24] Frangopoulos, C. A., and Evans, R. B., "Thermoeconomic Isolation and Optimization of Thermal System Components," *Second Law Aspects of Thermal Design*, HTD Vol. 33, American Society of Mechanical Engineers, New York, Aug. 1984, pp. 87–94.

[25] Frangopoulos, C. A., "Thermoeconomic Functional Analysis: An Innovative Approach to Optimal Design of Thermal Systems," *Second Law Aspects of Thermal Design*, HTD Vol. 33, American Society of Mechanical Engineers, New York, Aug. 1984, pp. 77–85.

[26] Frangopoulos, C. A., "Optimal Synthesis and Operation of Thermal Systems by the Thermoeconomic Functional Approach," American Society of Mechanical Engineers, AES 10-3, 49, New York, 1989.

[27] Frangopoulos, C. A., and von Spakovsky, M. R., "The Environomic Analysis and Optimization of Energy Systems (Part I)," *Proceedings of the International Conference on Energy Systems and Ecology: ENSEC'93*, Vol. I, American Society of Mechanical Engineers, New York, 1993, pp. 123–132.

[28] Gaggioli, R., and El-Sayed, Y., "A Critical Review of Second Law Costing Methods," *Journal of Energy Resources Technology*, Vol. 111, 1989, pp. 1–15.

[29] von Spakovsky, M. R., and Evans, R. B., "Engineering Functional Analysis (Part I)," *Journal of Energy Resources Technology*, Vol. 115, No. 2, 1993.

[30] El-Sayed, Y. M., and Evans, R. B., "Thermoeconomics and the Design of Heat Systems," *Journal of Engineering for Power*, Vol. 92, No. 27, 1970.

[31] Valero, A., Serra, L., and Lozano, M. A., "Structural Theory of Thermoeconomics," *Thermodynamics and the Design, Analysis and Improvement of Energy Systems*, AES-Vol. 30, American Society of Mechanical Engineers, New York, 1993.

[32] Swanson, L. W., "Thermodynamic Optimization of Irreversible Power Cycles with External Reservoir Temperatures," *Journal of Engineering for Gas Turbines and Power*, Vol. 113, Oct. 1991, pp. 505–510.

[33] Silvestri, G. J., Bannister, R. L., Fujikawa, T., and Hizume, A., "Optimization of Advanced Steam Conditioning Plants," *Journal of Engineering for Gas Turbines and Power*, Vol. 114, Oct. 1992, pp. 612–620.

[34] Bruno, J. C., Fernandez, F., Castells, F., and Grossmann, I. E., "MINLP Model for Optimal Synthesis and Operation of Utility Plants," *Transactions of the Institution of Chemical Engineers*, Vol. 76, 1998, pp. 246–258.

[35] Wu, Y., and Burke, T. J., "Intelligent Computer Aided Optimization on Specific Power of an Otec Rankine Power Plant," *Applied Thermal Engineering*, Vol. 18, 1998, pp. 295–300.

[36] Lindenberger, D., Bruckner, T., Groscurth, H.-M., and Kümmel, R., "Optimization of Solar District Heating Systems: Seasonal Storage, Heat Pumps, and Cogeneration," *Energy*, Vol. 25, 2000, pp. 591–608.

[37] Bojic, M., Stojanovic, B., and Mourdoukoutas, P., "MILP Optimization of Energy Systems with a Condensing Turbine," *Energy*, Vol. 23, 1998.

[38] Curti, V., von Spakovsky, M. R., and Favrat, D., "An Environomic Approach for the Modeling and Optimization of a District Heating Network Based on Centralized and Decentralized Heat Pumps, Cogeneration and/or Gas Furnace (Part I: Methodology)," *International Journal of Thermal Sciences*, Vol. 39, No. 6, 2000.

[39] Curti, V., Favrat, D., and von Spakovsky, M. R., "An Environomic Approach for the Modeling and Optimization of a District Heating Network Based on Centralized and Decentralized Heat Pumps, Cogeneration and/or Gas Furnace (Part II: Application)," *International Journal of Thermal Sciences*, Vol. 39, No. 6, 2000.

[40] Pelster, S., von Spakovsky, M. R., and Favrat, D., "The Thermoeconomic and Environomic Modeling and Optimization of the Synthesis, Design and Operation of Combined Cycles with Advanced Options," *Journal of Engineering for Gas Turbines and Power* (to be published).

[41] Agazzani, A., Massardo, A. F., and Frangopoulos, C. A., "Environmental Influence on the Thermoeconomic Optimization of a Combined Plant with NOx Abatement," *Journal of Engineering for Gas Turbines and Power*, Vol. 120, 1998, pp. 557–566.

[42] El-Sayed, Y., "A Decomposition Strategy for Thermoeconomic Optimization," *Journal of Energy Resources Technology*, Vol. 111, 1989, pp. 1–15.

[43] Zimering, B., Burnes, D., Rowse, J., and Bonis, R., "Gas Turbine Power Generation System Configuration Study and Optimization," 1999 International iSIGHT Users Conference, Chapel Hill, NC, Oct. 1999.

[44] El-Sayed, Y., "A Second-Law-Based Optimization: Part I Methodology & Part 2 Application," *Journal of Energy Resources Technology*, Vol. 118, 1996, pp. 693–703.

[45] Frangopoulos, C. A., von Spakovsky, M. R., and Sciubba, E., "A Brief Review of Methods for the Design and Synthesis Optimization of Energy Systems," American Society of Mechanical Engineers, July 2002.

[46] Mattingly, J. D., Heiser, W. H., and Daley, D. H., *Aircraft Engine Design*, AIAA Education Series, AIAA, New York, 1987.

[47] Resetar, S. A., Rogers, J. C., and Hess, R. W., "Advanced Airframe Structural Materials: A Primer and Cost Estimating Methodology," RAND, R-4016-AF, Jan. 1991.

[48] "WATE User's Guide," NASA, Jan. 1999.

[49] Birkler, J. L., Garfinkle, J. B., and Marks, K. E., "Development and Production Cost Estimating Relationships for Aircraft Turbine Engines," RAND, N-1882-AF, Oct. 1982.

[50] iSIGHT Designer and Programmer Guides, Engineous Software, Cary, NC, Ver. 5, 1999.

[51] Sobieszczanski-Sobieski, J., "Optimization by Decomposition: A step from Hierarchic to Non-Hierarchic Systems," NASA CP-3031, Part 1, 1989.

[52] Sobieszczanski-Sobieski, J., "Sensitivity of Complex, Internally Coupled Systems," *AIAA Journal*, Vol. 28, No. 1, 1990, pp. 153–161.