DESIGN AND SYNTHESIS OPTIMIZATION OF ENERGY SYSTEMS

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Summary

The optimization of energy systems is of crucial importance for a rational use of natural and economic resources and for minimizing their adverse effects on the environment. Optimizing such systems may be considered at three levels: synthesis (configuration), design (component characteristics), and operation. The first two of these levels are examined in this article. After a discussion on the uniqueness of the solution and the possibility of finding this solution, the principal approaches and methods for solving the optimization problem are described in brief. To clarify the concepts and procedures, two application examples on energy systems are presented.

1. Introduction

When the energy needs of a group of consumers of any size (house, city, industrial unit, region, and so on) are identified, questions such as the following arise:

- Given the energy needs, what is the best type of energy system to use?
- What is the best system configuration (components and their interconnections)?
- What are the best technical characteristics of each component (dimensions, material, capacity, performance, etc.)?
- What are the best flow rates, pressures, and temperatures of the various working fluids?
- What is the best operating point of the system at each instant of time?

The best or "optimum" system is the one that satisfies a criterion of optimality, that is, the one that minimizes (or maximizes) an objective function. Examples of objective functions are given in *Optimization Methods for Energy Systems*. In the same article, three levels of optimization are identified: (A) synthesis, (B) design, and (C) operation; and the complete optimization problem is stated by the following question: What is the synthesis of the system, the design characteristics of the components, and the operating strategy that lead to an overall optimum?

Level C, which appears when the synthesis and design of a system are given, is presented in the article *Operation Optimization of Energy Systems*. Levels A and B are the subject of this article.

2. Discussion on the Uniqueness of the Solution of the Synthesis and Design Optimization Problem and on the Possibility of Finding this Solution

In mathematical optimization, the best system is the one that minimizes (or maximizes) an objective function. Let us assume that minimization of the total cost is the objective and that the optimization problem has a solution; that is, a system has been determined that satisfies the objective. Is this indeed the solution sought or must one also compare the performance of this system with the performance of other (non-optimal) systems based on other points of view, for example, maintainability or environmental effects?

There may be cases when such a comparison shows that the “optimal” with respect to the cost of the system is not at all good when these other points of view are considered (attempts to translate other aspects into cost are made but there may still be aspects that cannot be handled in this way). Multi-objective optimization is an attempt to correct such deficiencies. However, the solution then depends on subjective weighting factors or additional criteria. The point of all this is that the optimal solution may not be unique and is “optimal” only in the strict mathematical sense. Thus, even if the design procedure can be automated, expert human intervention is needed to evaluate the results and reach a final decision.

Another issue is the following. In the usual design process of an energy system, the designer uses his or her knowledge and experience to select the type, configuration, and technical characteristics of a workable system (that is, a system that is technically feasible and satisfies a given set of needs), and then evaluates this system for its technical and economic performance and for ways of improving it. If the system synthesis (type and configuration) is given, the decisions to be taken are of a rather quantitative nature. If, however, the synthesis is not given, then in addition to quantitative decisions there is a need for many qualitative decisions, which may be non-deterministic. In such a case, innovation and creativity play a vital role. Given the multitude of energy system types and the variations in each type, one may question whether it is ever possible to replace the experienced designer’s mental process with an algorithm consisting of a set of formulae and rules. On the other hand, in today’s complex world, this same multitude of types and variations makes it virtually impossible for even an experienced designer to evaluate all possible alternatives. Consequently, an automated procedure, if properly used, can be of invaluable help to the designer.

Several methods have been developed for the synthesis optimization of processes and systems. Some of these are applicable only to particular classes of systems (for instance, heat exchanger networks). Other methods are applied to more complex energy systems. However, up until now there has been no single method that can tackle the synthesis optimization problem in all its generality and completeness. The field is, thus, still open to research. In the following sections, a brief introduction to the subject is attempted.

3. Approaches to the Optimal Synthesis of Energy Systems

The various methods that have appeared in the literature on the optimal synthesis of energy systems can be classified into three groups:

- Methods based on heuristics and evolutionary search.
- Methods attempting to reach pre-determined targets, which have been identified by application of physical rules.
- Methods starting with a superstructure, which is reduced to the optimal configuration.

In class (a), rules based on engineering experience and on physical concepts (for example, exergy) are applied to generate feasible configurations, which are subsequently improved by applying a set of evolutionary rules in a systematic way.

These rules may come from special techniques, such as exergy analysis. Artificial intelligence and expert systems have proven effective in generating appropriate configurations. For each acceptable configuration, a figure of merit or performance indicator is evaluated (for instance, efficiency, cost, and so on) and the system with the best performance is selected. The best of a certain set of configurations, however, does not guarantee that the optimal configuration has been revealed, although in most cases at least a near-optimal configuration has been obtained.

In class (b), principles from thermodynamics and other physical sciences are applied to obtain targets for the optimal system configuration. These targets can correspond to upper or lower bounds on the best possible configuration and provide vital information for improvement of existing configurations. In addition, many configurations are excluded from further investigation, thus reducing the search space for the best system. If the physical target is the optimization objective (for example, minimization of energy utilization), then these methods provide the solution to the optimization problem. However, if the optimization objective is economic (for instance, minimization of the total cost), then these methods are not very appropriate. Attempts have been made to introduce economics at a second level, but the whole approach is mathematically non-rigorous and, consequently, the configuration obtained may be non-optimal.

In class (c), a superstructure is considered with all the possible (or necessary) components and interconnections. An objective function is specified and the optimization problem is formulated. The solution of the optimization problem gives the optimal system configuration, which, inevitably, depends on (and is restricted by) the initial superstructure. The main advantages of such an approach are that it can work with any objective function and that it automatically reveals the optimal system configuration. The difficulty with these methods is that the size of the optimization problem may be such that the available mathematical optimization algorithms may not be capable of a rigorous solution. Thus, the need arises for advances in optimization theory and algorithms. It goes without saying that the methods of class (c) can find the optimal configuration only out of those represented in the superstructure.

It should be noted that the distinction among the three classes might not be so clear-cut. For example, the targets of class (b) can serve as heuristics or rules in class (a) and they can be embedded in the optimization procedures of class (c) to the benefit of the whole process.

4. Mathematical Statement of the Complete Optimization Problem

The objective function of the complete optimization problem (that is, synthesis, design, and operation) is written in the general form:

$$\underset{\mathbf{x},\mathbf{w},\mathbf{z}}{\operatorname{minimize}}\ \mathrm{F}(\mathbf{x},\mathbf{w},\mathbf{z}) \tag{1}$$

subject to the constraints

$$\mathrm{h_i}(\mathbf{x},\mathbf{w},\mathbf{z}) = 0 \quad \mathrm{i} = 1, 2, \ldots, \mathrm{I} \tag{2}$$

$$g_j(\mathbf{x},\mathbf{w},\mathbf{z}) \leq 0 \quad j = 1,2,\ldots,J \tag{3}$$

Where

x set of independent variables for operation optimization (load factors of components, mass flow rates, pressures and temperatures of streams, and so on);
w set of independent variables for design optimization (nominal capacities of components, mass flow rates, pressures and temperatures of streams, and so on);
z set of independent variables for synthesis optimization; there is only one variable of this type for each component, indicating whether the component exists in the optimal configuration or not; it may be a binary (0 or 1), an integer, or a continuous variable such as the rated power of a component, with a zero value indicating the non-existence of a component in the final configuration;
$h_i(\mathbf{x},\mathbf{w},\mathbf{z})$ equality constraint functions ("strong" constraints), which constitute the simulation model of the system and are derived by an analysis of the system (energetic, exergetic, economic, and so on); and
$g_j(\mathbf{x},\mathbf{w},\mathbf{z})$ inequality constraint functions ("weak" constraints) corresponding to design and operation limits, state regulations, safety requirements, and so on.

Several objectives pertinent to thermal systems can be written in the form of Eq. (1). For example, F can be the fuel consumption, exergy destruction, annualized cost of owning and operating the system, lifecycle cost (including environmental considerations, if needed), and so on. Multi-objective optimization can also be written in the form of Eq. (1), but only if the various objectives are combined into one objective function by means of weighting factors.

For a given synthesis (structure) of the system, that is, for given **z**, the optimization problem becomes one of design and operation:

$$\min_{\mathbf{x},\mathbf{w}} \text{imize}\, F_d(\mathbf{x},\mathbf{w}) \tag*{(1)$_d$}$$

Furthermore, if the system is completely specified (both **z** and **w** are given), then an operation optimization problem is indicated:

$$\min_{\mathbf{x}} \text{imize}\, F_{op}(\mathbf{x}) \tag*{(1)$_{op}$}$$

5. Representative Methods for the Solution of the Synthesis Optimization Problem

As mentioned in the introduction, the design optimization problem can be solved by any one of the methods described in *Optimization Methods for Energy Systems*. In this section, representative methods for the solution of the synthesis optimization problem are described in brief, no matter whether they locate the near-optimum solution (classes (a) and (b)) or the optimum one (class (c)) within the constraints and limitations mentioned in Section 3.

5.1. The Connectivity Matrix Method

This method is a direct application of graph theory to process design. It consists of the following steps:

- Create a logical process scheme. This is a very general task and does not imply the selection or placement of any component. It entails, though, the selection of the chemical/physical subprocesses that constitute the main process.
- Construct the connectivity matrix (CM) for the logical process scheme. The rows of CM represent fluxes of matter or of energy, while the columns represent "operations" to be performed on these fluxes. A "1" in position *ij* signifies that flux *i* undergoes transformation *j*; a "0" signals no interaction of flux *i* with subprocess *j*. A logical process scheme and its connectivity matrix are shown in Figure 1.
- "Translate" each operation listed in CM into a series of physical transformations and devise one elementary subprocess scheme for each transformation. For example, the operation "boiling" is translated into "pressurized, then fed into a boiler, then superheated, then throttled, then exhausted." Introduce these subprocess schemes into each one of the applicable columns of CM: this corresponds to expanding the matrix by adding several additional columns.
- Substitute into each transformation in every subprocess the component that performs it. Notice that at this point technical and operational constraints may come into play and limit or deny altogether the feasibility of a certain solution.
- The resulting matrix is the connectivity matrix of the real process P. A proper quantitative simulation of P must now be performed to obtain the optimal set of operational parameters.

Component ⇒ / Stream ⇓	C_1	C_2	C_3	C_4	C_5	C_6
1	1	0	0	0	0	0
2	0	1	0	0	0	0
3	0	1	0	1	0	0
4	0	0	0	1	0	1
5	1	0	1	0	0	0
6	1	0	0	0	1	0
7	0	0	1	0	0	0
8	0	0	1	0	0	1
9	0	0	0	0	1	1
10	0	0	0	0	0	1

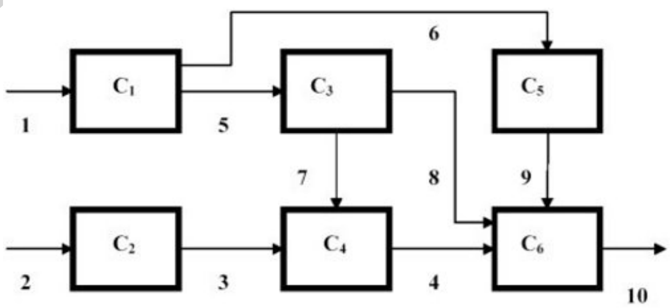

Figure 1. A logical process scheme and its connectivity matrix

It is apparent that this method is a direct translation of the "mental scheme" a process engineer applies to a design task, and it is entirely deterministic. Unfortunately, it is also clear that the method is strongly biased by the choices made in points 1 and 3. Choosing a process scheme in fact sets a major structural constraint on the resulting process configuration, and this step is entirely left to the "experience" of the designer. Similarly, splitting a process into subprocesses can be done in more than one way, and selecting one or another corresponds to biasing the entire procedure. In spite of its limitations, this method has been reported here because it has many similarities with the AI methods that will be discussed later.

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Biographical Sketches

Christos A. Frangopoulos is Professor at the Department of Naval Architecture and Marine Engineering, National Technical University of Athens (NTUA), Greece. He received the Diploma in Mechanical and Electrical Engineering from the NTUA in 1971. After his military service (1971–1973), he worked as Superintendent Engineer of ship-owning companies, and as Head of the Diagnostic Center of a ship repairing company in Greece (1973–1979).

He undertook graduate studies in Mechanical Engineering with major in Thermal Sciences at the Georgia Institute of Technology, Atlanta, Ga., USA, leading to an M.Sc. degree (1980) and Ph.D. degree (1983). He joined the Department of Naval Architecture and Marine Engineering (NTUA) as a faculty member in 1985. He lectures on marine engineering, as well as marine and land-based energy systems in both undergraduate and inter-departmental graduate courses.

His research activity is related to the development and application of methods for analysis, evaluation and optimal synthesis, design and operation of energy systems (power plants, propulsion plants, heat recovery systems, cogeneration systems, etc.) by combining thermodynamic, economic, and environmental considerations. Second Law (exergetic) analysis and internalization of environmental externalities are two particular subjects of this work. He has often given invited lectures on the results of his research in several countries.

Among his publications are more than 40 papers in journals and international conferences and a book on cogeneration (in Greek).

Michael R. von Spakovsky is Professor at the Department of Mechanical Engineering and Director of the Energy Management Institute at the Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA. He has over 13 years of teaching and research experience in academia and over 17 years of industry experience in mechanical engineering, power utility systems, aerospace engineering, and software engineering. He was at NASA from 1970 to 1974, in the power utility industry from 1974 to 1989, and at the Swiss Federal Institute of Technology from 1989 to 1996.

He teaches courses in thermodynamics, industrial energy systems, fuel cell systems, and energy system design. His research interests and activities include computational methods for modeling and optimizing complex energy systems, methodological approaches for the integrated synthesis, design, operation, and diagnosis of such systems (stationary power as well as high- performance aircraft systems), theoretical non-equilibrium and equilibrium thermodynamics, as well as the unified quantum theory of mechanics and thermodynamics, and fuel cell applications for both transportation and distributed power generation.
He has published widely in scholarly journals, conference proceedings, and so on (approximately 100 publications) and has given talks, seminars, and short courses worldwide.

Enrico Sciubba is Professor at the Department of Mechanical and Aeronautical Engineering of the University of Roma 1 “La Sapienza” (UDR1), Roma, Italy. He received a Master’s degree in Mechanical and Electrical Engineering from UDR1 in 1972. From 1972 to 73, he was a Research Assistant at the Chair of Turbomachinery in the same University. From 1973 to 75, he worked as Research Engineer in the Research and Development Division of BMW, Munich, Germany, where his tasks included the design, development, and testing of advanced i.c. engines.

After returning to UDR1 as a Senior Research Assistant from 1975 to 1978, he enrolled in the Graduate School of Mechanical Engineering with a major in Thermal Sciences at the Rutgers University, New Brunswick, NJ, USA, where he was granted his Ph.D. in 1981. From 1981 to 1985 he was Assistant Professor at the Catholic University in Washington DC, teaching Thermal Sciences. He returned to the Department of Mechanical and Aeronautical Engineering of UDR1 as a faculty member in 1986. He lectures on Turbomachinery and Energy Systems Design, in both Master’s and Ph.D. level courses.

His research activities are equally divided in three main fields: turbomachinery design and CFD applications; energy systems simulation and design; and applications of AI-related techniques and procedures to the design, synthesis and optimization of complex energy systems.

His publications include more than 30 journal articles (mostly in international refereed Journals in the field of energy and applied thermodynamics), and over 80 refereed papers at international conferences. He has published a book on AI applications for the types of NOVA Science, USA, and is writing a Turbomachinery book for J. Wiley. Dr. Sciubba is Associate Editor for three major international journals in the field of energy conversion and a reviewer for several more.