ARTIFICIAL INTELLIGENCE AND EXPERT SYSTEMS IN ENERGY SYSTEMS ANALYSIS

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Contents

Summary

This chapter is an introduction to the field of artificial intelligence (AI) applications to the design and monitoring of energy systems, and serves as a compendium for the

related chapters that follow under this topic. After a brief discussion of the characteristics that make AI useful for engineering applications, a concise definition of terms and concepts is given. The presentation style has been tailored to provide readers with a general introduction to AI topics, without burdening them with excessive formalism. Since our goal is to describe engineering applications to thermal design, emphasis on the applicative side has been stressed.

1. Introduction

This chapter describes in detail the general activities connected with the application of a powerful set of the so-called AI-procedures to the selection, synthesis, design and control of energy systems. Since the field is very broad, we shall restrict our treatment, and employ only a sub-set of AI, called Expert Systems (ES), to the above tasks: other tools, like Neural Networks (NN) and Fuzzy Logic (FL) are treated only marginally. The general principle is to implement a computer-assisted procedure that possesses, in a form that will be discussed in detail for each implementation, some of the "intelligence" of the human designer. The process is in principle quite simple, and it is based on the premise that for each "design" task (the type and structure of these tasks shall be also discussed in detail) there exists a set of general guidelines, derived from engineering experience formalized and catalogued in the form of either design manuals or textbooks or otherwise published and accepted design procedures. An ES is therefore a computer code that mimics not so much the human reasoning, but rather the way this reasoning can be (and has been) organized at the present stage of technology. The first point to argue is clearly that there is indeed *one* general design protocol for all types of design problems: this is crucial to our thesis, and is in fact the justification for the search for AI-based "Design Assistants". Once the existence of such a protocol has been established, it is a simple matter to show that the two fundamental design tasks encountered by an engineer, namely the direct (simulation) and inverse (design) problem, can be considered embedded into a single meta-procedure. The individual chapters under this Topic discuss the application of this meta-procedure to the synthesis of a process, to the design and/or choice of components, and to the development of intelligent monitoring and control systems.

2. Is there a "Universal" Design Paradigm?

To answer the fundamental question whether it is possible to construct a "universal" design paradigm that can describe every conceivable act of design, it is necessary to examine first what a design task consists of. A thorough analysis of the existing procedures shows that an essential feature of most design tasks is that they are posed as *ill-structured problems*. An ill-structured problem is one that:

1. cannot be described solely in terms of numerical variables;
2. possesses goals that cannot be specified in terms of a well-defined objective function; and
3. admits of no algorithmic solution.

Ill-structured problems are also called ill-defined or ill-posed, and their most striking feature is that their solutions are *unpredictable*, in the sense that the environment in which the solution is to be sought for has a strong influence on the existence, uniqueness and type of solution. In the search for a solution, an engineer relies on judgment, experience, heuristics, intuition and analogy rather than on specific knowledge of solution procedures applicable *per se*. The question whether ill-structured problems can be solved by some kind of structured engineering reasoning has been answered in the affirmative long ago, in direct and indirect ways. It will be shown in *AI in Process Design* that what goes under the name of "design activity" is in reality a concatenation of several complex actions, only some of which fall within the responsibilities of the engineer. Moreover, if we compile a detailed list of the tasks that constitute a "design procedure", it becomes apparent that, with few exceptions, most of the activities are common to every design task, as if they were logical building blocks of the design procedure: this reinforces our intuitive idea that there must be a universal underlying paradigm in the solution of every engineering task. Though there is no logically complete proof that this is indeed the case, heuristic evidence abounds.

2.1. The "Universal Design Procedure": a possible Flowchart

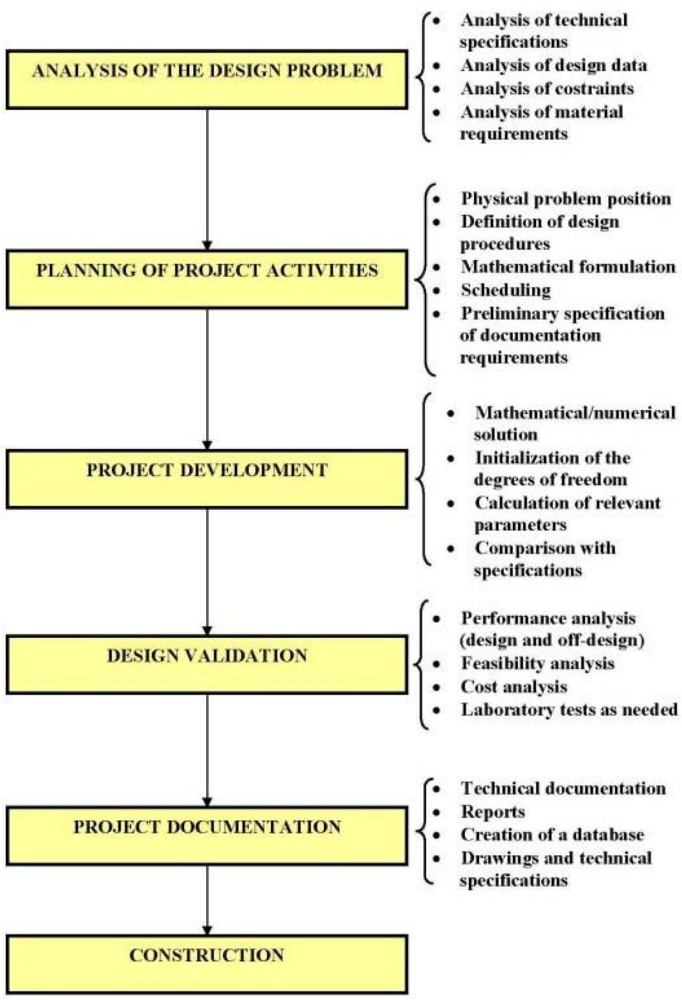

Figure 1: Block scheme of a possible "Universal Design Procedure"

In the real world, a design project includes both technical and non-technical tasks: often, the physical "design" (if we take this word in its restrictive meaning of "quantitative sizing of units and systems") is a minor activity in the general project perspective. Several other activities are of importance before the "sizing", during (i.e., concurrently with) it and after its conclusion, and it is their coordinated sequence that constitutes the actual "design" task and is accordingly managed in its totality. Extrapolating from design manuals and textbooks, a "Universal Design Procedure" can be identified and is presented in Figure 1. This flowchart shall be discussed in greater detail in *AI in Process Design*, where the single activities shall be examined in detail. We discuss here only those that are more closely related to "design" in the layman meaning of the word.

2.1.1 Definition of Needs and Objectives

Scope of this task is to formulate an explicit and complete explanation of the reasons that justify the investment of resources in a specific project. The "needs" as well as the "objectives" of a project are not necessarily formulated in terms of economic convenience: often, social equity requirements, social opportunity, macro-economics or even political interests are valid criteria to include in the description of needs and objectives. Though this phase is usually advocated by the "Management", there is a growing tendency to allow for some "input from below", i.e., from the more technical portion of the organization. If present, the R&D Department can also co-operate in the definition of needs and objectives.

2.1.2 Preliminary Estimate of the Design Costs

This task is usually performed by a specific division, responsible for technological methods and production scheduling, on the basis of detailed specific information provided by the technical and commercial support structure. Errors made in this phase can be very costly: since the specific design problems are usually unknown in detail at this stage, care must be exercised both to limit the risk of cost overruns (that would produce a net loss at the end of the project), and to avoid overestimating the costs (and thus preliminarily reject a lucrative project).

2.1.3 Feasibility Study

This is a well-codified engineering activity, aimed at determining whether all conditions that make the project feasible are met at the time of its foreseen realization and in the operative conditions under which the project will be undertaken. To be feasible, a project must be:

- technically possible
- pperationally reliable
- industrially sustainable
- economically advantageous
- legally acceptable

2.1.4 Final Design

This is what is usually called "design": a very complex activity rich of interdisciplinary details, in which the item, unit or system to be built is completely designed to specifications, by means of a concerted co-operation of process-, structural-, industrial-, mechanical-, chemical-, material-, environmental- and control engineers, possibly assisted by field experts for specific problems.

2.1.5 Construction

This task is directly supervised by specialist mechanical-, chemical-, structural-, or civil engineers, who have specific knowledge and experience in the "construction" field (where by *construction* we mean all of the possible production technologies that lead from the raw materials to the end products).

2.1.6 Testing and Customer's Acceptance

This task is performed by Quality Assurance (Q&A) specialists, with the assistance of design engineers. Usually, two teams work jointly on this activity: that of the constructor and that of the customer. If required, a third independent party can co-ordinate the activities of the first two ("Arbitrate").

2.1.7 Modifications and Improvements

This is one of the activities of the R&D Division, but requests for modifications are mostly originated by the Process Engineers responsible for the maintenance and operation of the hardware. Very useful for proving the technological production line but potentially wasteful if too many unjustified modifications are proposed, because the amount of resources that must be allocated for the analysis of each unsuccessful process modification may become too costly.

3. Application of the Universal Design Procedure to Process Synthesis

3.1 Formulation and Position of a Process Engineering Design task

A synthesis design task is quite different from what normally goes under the name of "design". The difference can be reduced to the concepts of "direct" and "inverse" design problems. In a "direct" design problem, the structure of the process is assigned *a priori*: task of the designer is that of selecting or/and sizing the components and "optimize" the overall plant performance and cost effectiveness. In an inverse problem, the goal is prescribed in terms of the expected product, an expected global performance indicator and the expected cost effectiveness, and the task of the designer is first that of selecting a convenient (the most convenient) process flowchart, and then of executing a further "optimization" on it by performing a direct design exercise. Clearly, inverse problems are more difficult. What is not often pointed out, however, is that their difficulty is not related to the additional work to perform, but almost exclusively to the *nature* of this additional work. To synthesize a process means to devise its structure, and this is a highly non-quantitative task that cannot be performed algorithmically (even the so-called deterministic synthesis methods like *simulated annealing* require a non-deterministic decision on the first trial structure). Historically, engineers have relied on experience and technical common sense in deciding about the most convenient process layout, and neither one of these "mental tools" are amenable to be expressed by a set of formulae. Here is where our Universal Design Procedure can be put to work: we can try to express the single "actions" that constitute the general engineering design task in the form of "rules" or "propositions", and apply the tools of propositional calculus to translate them into "Artificial Intelligence" procedures. Since this leads to the implementation of paradigms that are very much different from the quantitative procedures we are accustomed to, a more detailed discussion is in order. First of all, we must accept that, however accurate the problem formulation has been, the result is an ill-posed design problem. More correctly, such problems are usually incompletely, or fuzzily, specified. Thus, the first subtask is that of defuzzifying the problem position, which can be achieved in three steps:

1. First, examine the (assumedly fuzzy) set of input data. Determine what are the actual inputs, what is their quantitative availability, what are their respective chemical and physical properties, how and at which cost are they supplied at the boundary of our design control volume;
2. Then, perform a similar examination on the desired outputs. To minimize the risk of over-specifying the problem, it is useful to operate a distinction between mandatory and accessory goals: mandatory goals are "musts", and they are included by force in the general set of criteria for success of the system we are about to design; accessory goals are "wants", and while they may be absent at all from the final solution, yet their presence in one of the proposed process layouts can be seen as a "bonus point" that makes that layout more desirable for the final customer. We must keep in mind that the selection is dynamic, and that an accessory goal may become a mandatory one as the design activity proceeds;
3. Analyze the constraints. Interpret them: it is usually safer to pose all weak constraints in their strong form first, and relax them only after a solution has been found.

After these three steps have been sequentially performed, the problem formulation will be found to be somewhat different from the original one: in any case, it is now in such a form that the general design procedure may be applied to it.

3.2 Towards a General Process Synthesis Paradigm

Strongly connected with the idea of "design" are the ideas of "innovation" and of "creativity". This is not a naive statement: it is actually the principle on which to develop a non-quantitative *process synthesis* paradigm. *At the "Synthesis" stage, all options must be explored*, and only the clearly unfeasible ones discarded*: creativity rather than exactness must be the leading principle*. A general paradigm ought to contain some or all of the following guidelines:

1. Consider all possible processes that may lead from the available inputs to the specified output. Rank them from the simplest to the more complex. At this stage, no alternative ought to be discarded on the grounds of commercial prejudices (components difficult to find, or too expensive) or technical biases (mature technology, non-standard solutions). However, processes that have been proven faulty in the past under similar conditions, or require components off scale of more

than one order of magnitude, or that require extensive input- or output treatments, may be legitimately discriminated against (eliminated) in this phase.

2. Perform a detailed conceptual analysis of the more promising configurations. These configurations may be chosen on the basis of expert's advice, engineering intuition, customer's preference: it is important that a clear ranking is assigned to each source, so that decisions may be traced back later.
3. If in the course of this analysis new configurations are discovered, add them to the existing list and examine them in turn. By such a selective pruning, the list ought to be reduced to relatively few alternatives (the number depends on the resources dedicated to the project, but it is to be expected that for most processes of current technological level up to 10 alternatives have survived at this point).
4. Screen the resulting list carefully, applying the constraints identified in the problem formulation phase. If necessary, introduce new constraints based on experience or common sense (always clearly identifying them so that the path to the solution may be later retraced). Scope of this step is to reduce the number of surviving alternatives so that a quantitative calculation may be performed on each one of them. Again, the number of process configurations comprised in this final list is determined by the complexity of the subsequent simulation and by the availability of computer resources and tools (software).
5. Perform a simplified simulation of each alternative. Neglect conceptually secondary items, like pressure loss in pipes, heat loss to surroundings, etc. Compute all required performance indices, and generate (or estimate) a gross preliminary sizing for the major components, and especially of non-standard equipment.
6. Refine or re-formulate the objective function that assesses the absolute or relative performance of each configuration. Rank the alternatives according to the values attained by this objective function, calculated on the basis of the approximate simulations previously performed.
7. Select the few alternatives for which this objective function clearly attains its "near-optimum" range. Perform a sensitivity study on each of them, at design and off-design points as specified by the operational characteristics of the problem position. If possible, perform a Life-Cycle analysis.
8. Finally, choose two or three of the "best" surviving configurations and discuss them in depth with the final customer and possibly with some independent field expert. If necessary, repeat the simulations adding the previously neglected second-order effects.
9. Proceed with final design and sizing of the chosen configuration.

4. “Design” and “Optimization”

The term *optimization* is often misused in the field of engineering. In a disturbingly large number of technical reports and archival publications there is confusion about *what* is being optimized *with respect to what*, or what was to be *kept constant*. What is even more disappointing for engineering purposes, operation and maintenance issues are frequently neglected or grossly underestimated, and any solution obtained via a purely mathematical procedure is presented as *the* solution to the given design-and-optimization problem. Thus, neighboring “quasi-optima” are disregarded, that in real applications often represent the most convenient solution. One of the possible causes for this is surely the sharp separation maintained in textbooks between the two concepts: it appears that the main goal of the design activity is to generate some working solution, and the purpose of optimization is to intervene on the final solution to "prove it". This is a wrong and dangerous misconception: *nobody ever has tackled a design task without an at least implicit self-posed constraint of "optimality" of the final outcome*. Design and optimization are both essential steps in any design activity, and they cannot be separately performed without incurring in the risk of producing the wrong answer to the question posed in the design problem formulation. With this concept in mind, we can now better understand the quite different, "systemic" approach that will be proposed here below.

It is definitely useful to review the terms in which a design-and-optimization problem is formulated. A detailed discussion of direct and inverse design & optimization problems is offered in *Design and Synthesis Optimization of Energy Systems*, to which the reader is referred.

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Biographical Sketch

Enrico Sciubba (born July 11, 1949) is a Professor in the Department of Mechanical and Aeronautical Engineering of the University of Roma 1 "La Sapienza", in Roma, Italy. He received M.Eng. Degree in Mechanical Engineering from University of Roma in 1972. After working for two years (1973-75) as a Research Engineer in the Research & Development Division of BMW, Munich (Germany), he returned to the University of Roma as a Senior Researcher (1975-1978). He then enrolled in the Graduate School of Mechanical Engineering, majoring in Thermal and Fluid Sciences, at Rutgers University, Piscataway, NJ, USA, where he was granted a Ph.D. degree in 1981. He joined the Department of Mechanical Engineering of the Catholic University of America, in Washington DC, USA, as an Assistant Professor in 1981, and worked there until 1986, when he returned to the University of Roma 1 first as a Lecturer, then as an Associate and finally Full Professor. He holds the Chair of Turbomachinery, and lectures on Energy Systems as well, both at the undergraduate and graduate level. In 1999 Dr. Sciubba was elected a Fellow of the American Society of Mechanical Engineers. In 2000, he received an Honorary Doctoral title from the University Dunarea de Jos of Galati (Romania). His research is related to CFD of Turbomachinery, to Exergy Analysis, and to Artificial Intelligence applications in the design of Energy Systems. His publications include more than 40 archival papers, over 150 articles in international conferences, one book on Turbomachinery (in Italian) and one on Artificial Intelligence (in English).