A STUDY AND CRITICAL REVIEW
OF DESIGN EVALUATION METHODOLOGIES

by

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(ABSTRACT)

Increased competition and the scarcity of resources has forced recognition of the significant potential of design to increase the effectiveness and efficiency of the resulting product, system, or structure. Moreover, the design process itself is undergoing a metamorphosis. Its largely sequential nature is giving way to greater concurrency and to the consideration earlier of downstream issues such as production, operation, and retirement.

A complete engineering design morphology, enhanced by a sound engineering design evaluation methodology, can enable the realization of systems that meet user needs more effectively and efficiently. Isolated groups are researching diverse ways to better integrate design evaluation within the engineering design process. The need is for increased communication between these research groups for mutual benefit.

A representative set of design evaluation methodologies is studied and critically reviewed in this thesis. This work is a step towards increased understanding between the different "schools of thought" and a baseline for further research.

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CHAPTER 1

DESIGN EVALUATION

Man's survival can be attributed to his ability to adapt the forces and laws of nature to his own use. This process is termed engineering[1]. More specifically, engineering design, according to Vidosic [1969], can be described as the development of a mechanism to transform a given input into a particular output, generally in the face of certain constraints and limitations[2].

1.1 Changing Nature of Design

Designs evolved slowly in the past with each revision incorporating a small change. Competition was limited to the market place on a commercial plane. Today, however, the pace of scientific discovery is very fast, a new body of knowledge develops rapidly and its use, more often than not, may dictate a complete break from past practice. The demands are for bolder, faster improvements; and as a result the technical risks faced by the designers are greater. So are the stakes. In other words, competition has shifted to the design office and the development laboratory, on a technological plane.

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[1] ABET has adopted the definition that "Engineering is the profession in which a knowledge of the mathematical and natural sciences gained by study, experience, and practice is applied with judgement to develop ways to utilize, economically, the materials and forces of nature for the benefit of mankind."

[2] According to Vidosic "Engineering design is the process that uses engineering tools - mathematics, graphics, language - and scientific principles to evolve a plan which when fully carried out will satisfy a human need.

The general nature of design problems have changed in modern times. The essential problem today is not how to span rivers but how to deal with river pollution, not how to build great cities but how to clean up slums. Rapidly depleting natural resources, increased international competition, increased social and environmental awareness, and ever stringent regulations and standards have highlighted the significance of a sound evaluation methodology for design.

The past two decades have been characterized by an increasing interest in research about engineering design. A review of the references at the end of this document gives credence to this observation. The design phase of the system life cycle is finally being recognized for the potential it offers in developing a truly efficient product, system, or structure that very closely tracks customer requirements and needs.

1.2 Engineering Design

The term design is often used from a very high level of abstraction. Design could be defined as any goal directed activity, subject to constraints, and performed by humans, or even as a plan by which certain goals may be achieved. Engineering design is, however, more specifically defined, taking care that it more closely relates to engineering concerns. It can be defined as a process performed by humans whereby information in the form of requirements is converted into a description of technical systems and other forms of abstractions, such as physical models and mock-ups so that these systems meet certain human needs. Moreover, this process is aided by technical and mathematical tools.

Von Flange [1959] describes engineering design as the primary function of engineering and identifies constraints and how they arise as the most significant factors in the evolution of a design. Some of these constraints and limitations are forced upon designers by the laws of nature, some result from the requirements and objectives of design, while others are self-imposed in the face of increased international competition, reduced resources, and increased social and environmental awareness. According to Vidosic [1969], some constraints are subtle and come to light only after a certain amount of work has been done. In other words, increased knowledge often leads a designer to become aware of new and increased number of constraints.

It can be argued that while a designing activity can be undertaken in the face of certain accepted bounds, the designer may be faced with additional constraints as the work progresses. The design activity must be flexible enough to incorporate these additional concerns. Moreover, because of this increased awareness the designer has a need and obligation to decide between competing design alternatives.

There is one major characteristic of engineering design that distinguishes it from design in most other domains. In domains like graphics or type design, the design activity actually culminates in the production of the object or artifact. In engineering design, however, the end product is typically not the object or artifact, but a set of specifications, descriptions, or some form of abstraction to aid in the manufacture of the object or artifact. From a broad perspective, any engineering design activity includes three general tasks of synthesis, analysis, and evaluation.

Synthesis can be defined as the process of assembling a set of candidate designs that seem to satisfy most of the significant specifications. Analysis is a process of ascertaining whether the identified candidate designs satisfy some of the other less obvious specifications and constraints. The result of the analysis could be a reduced number of candidate designs for further consideration. Evaluation on the other hand involves predicting the behavior of the candidate designs still under consideration. It involves derivation of the values of all relevant factors to determine the acceptability in terms of the stated objectives and specifications. This prediction and derivation also helps in decision making and selection of the preferred approach. It is the evaluation aspect of engineering design that is the focus of this work.

Even though most engineering design activities may be defined as above, there is a certain class of engineering problems that may involve a different approach. An example will be used to clarify this point. Very often, an engineering design problem could be defined as a "mature", for example, in bridge design. The design of bridges is an engineering design problem that has been worked on for centuries. So much so that a designer facing the same problem today is aided by the existence of a very substantial database of existing systems. In such a case, the process of synthesis as described above could be reduced to a classification problem. However, the process of evaluation and analysis still remain as relevant in order to adapt the design to the specific need.

1.3 Engineering Design Evaluation

As stated in the previous section, engineering design evaluation involves forecasting and prediction. This is necessary in order to model the expected system behavior. Moreover, since design evaluation can be considered as a form of decision making, it involves deriving values of the criteria chosen as a basis for selecting the preferred approach. Implicit here is the understanding that alternatives are not evaluated relative to any single criterion. Design evaluation must consider both economic and performance related issues according to Blanchard and Fabrycky [1990] (see Figure 1.1).

It is important to keep the role of engineering design and engineering design evaluation in the proper perspective. Both involve working with models. Inherent in the construction of these models are the assumptions necessary to represent the "real thing". These assumptions also help to keep the representations simple enough to allow easy manipulation, while capturing the significant and relevant properties of the system. Both, engineering design and the corresponding evaluations, involve making decisions in the face of incomplete knowledge. Fabrycky and Blanchard [1991] refer to this lack of knowledge in the initial stages of design and the tendency of the designer to commit a majority of the resources and configuration in the face of this ignorance and uncertainty (Figure 1.2).

An overall engineering design morphology and the experience and discipline of the designer can ensure a model or representation, in the face of incomplete and uncertain knowledge, that very closely tracks the "real thing". Present-day technologies like computer-aided design may help to further enhance the quality
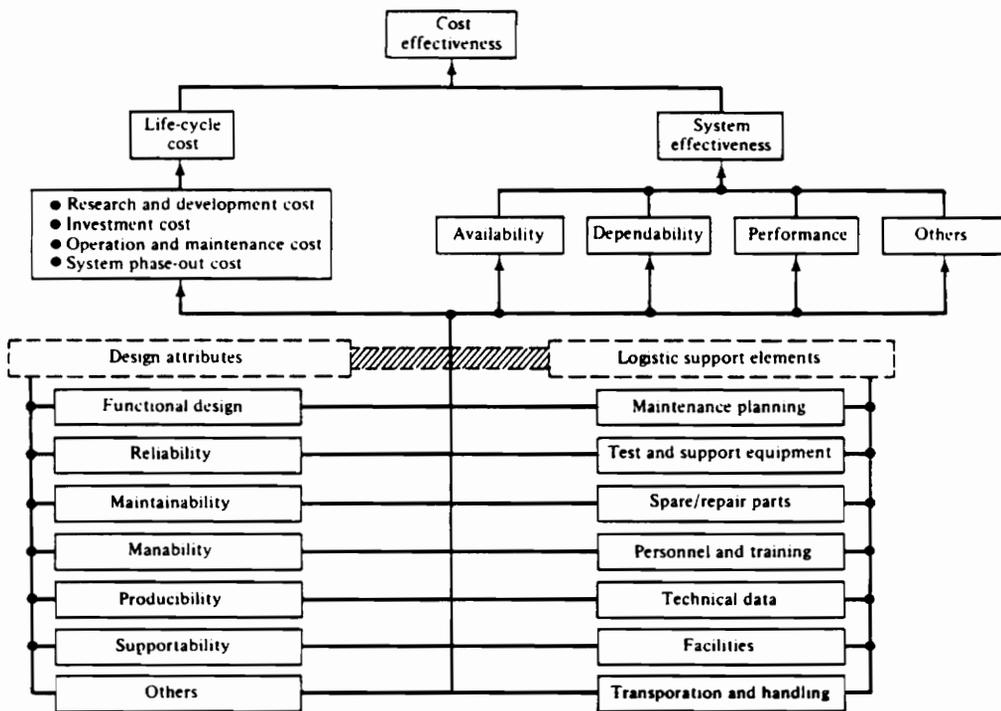
Figure 1.1. System cost effectiveness elements [Blanchard & Fabrycky 1990].
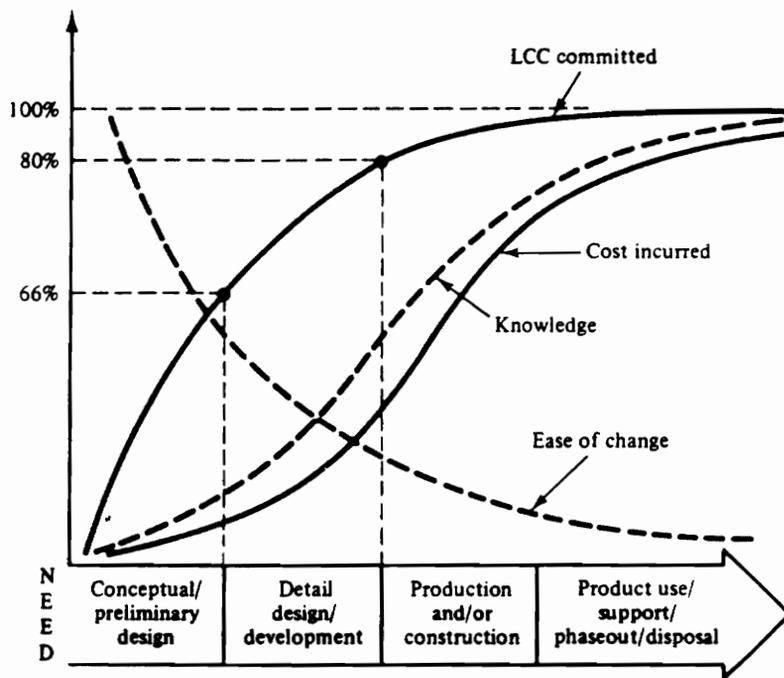
Figure 1.2. Life-cycle cost committed vs. knowledge [Fabrycky & Blanchard 1991].

of the models constructed. Nonetheless, a designer is working with models and the ultimate result of the engineering design activity is not the real system, but a technical description or a set of specifications which facilitate the actual fabrication of the desired entity. In other words, the result of engineering design, enhanced by a sound engineering design evaluation methodology, is an abstraction and does not in anyway guarantee an effective operational system.

System evaluation is a continuous process that evolves over the system life-cycle. This evolution and changing nature of design evaluation merits further consideration. Blanchard and Fabrycky [1990] refer to the evolutionary nature of system evaluation (Figure 1.3). In Figure 1.3, testing is considered to be a part of the overall system evaluation. Very often these two terms are used in place of each other. For the sake of the following discussion, design evaluation and testing are identified as the two primary activities of system evaluation. The roles of design evaluation and testing are contrasted to make explicit the changing nature of system evaluation over the life cycle.

It is proposed that design evaluation and testing represent the two extremes in the overall process of system evaluation, with a continuum in between. In the extreme case, design evaluation involves working with mathematical or analytical models while testing is performed on existing and operating systems. Figure 1.3 depicts the continuum between these two extremes. The earliest testing begins when the design evolves to the stage where physical mock-ups become possible. Later, when production models and prototypes become available, the process of testing becomes even more "real".
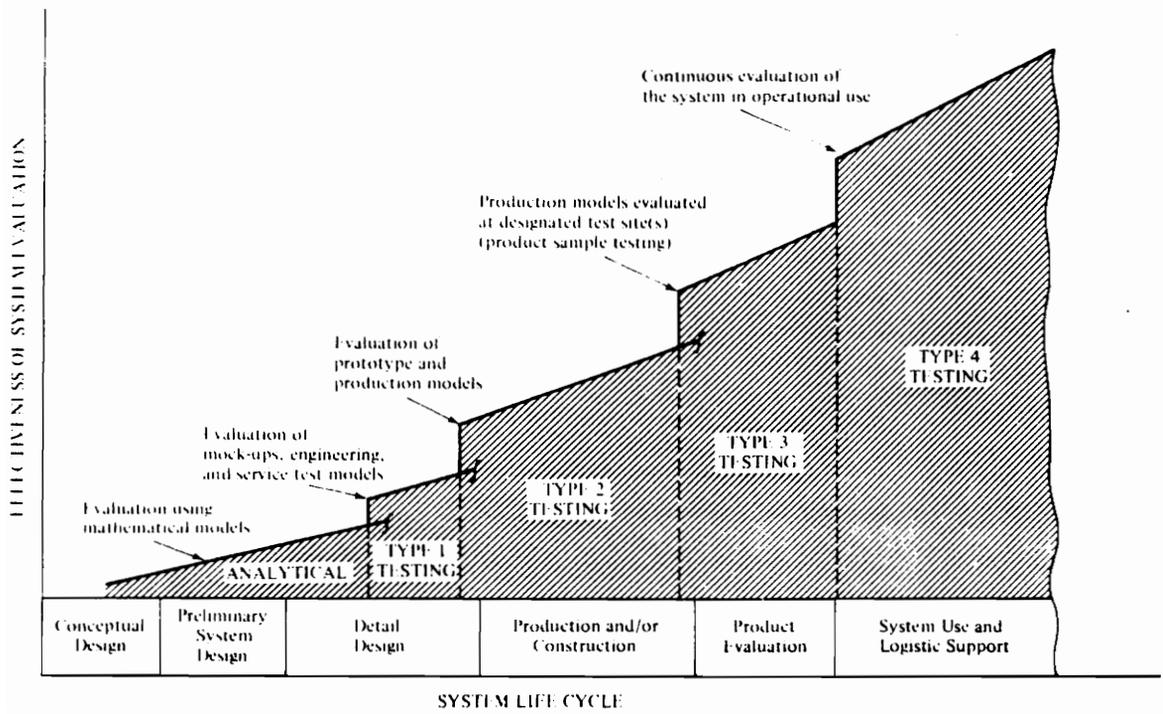
Figure 1.3. System evaluation [Blanchard and Fabrycky 1990].

With the above discussion in mind, it can be said that design evaluation depends primarily upon indirect experimentation, while testing evolves from indirect experimentation to phases where direct experimentation becomes possible. In terms of validity, testing is more effective than design evaluation. However, the ability to make changes or improvements in design (and the ultimate system) is greatly reduced. It is a more expensive during the testing phases. Testing in the later phases of the system life cycle is largely a process of verification. It could also be termed as a learning process that can contribute significantly to the designer's experience and thereby contribute to future design activities. To some extent it could be argued that design evaluation occures before the fact, whereas testing largely occurs after the fact. This work considers only design evaluation, or that phase of system evaluation where use is made of mathematical or analytical models or representations.

1.4 The Problem Setting

The engineering design environment is currently undergoing a metamorphosis. Greater concurrency is replacing the largely sequential nature of engineering design. Producibility and supportability considerations (including reliability and maintainability) are being integrated early on into the design process along with the more traditional concerns relating to performance, cost, and schedule.

Blanchard and Fabrycky [1990] propose the consideration of three concurrent life-cycles (Figure 1.4) for any design and development activity. These track the design of the product, the production system, and the support capability.

ACQUISITION PHASE ————————→|←——— UTILIZATION PHASE ——→|

| N E E D | Conceptual-Preliminary Design | Detail Design and Development | Production and/or Construction | Product Use, Phaseout, and Disposal |

Manufacturing Configuration Design   Manufacturing Operations

Product Support Configuration Design and Development   Product Support and Maintenance
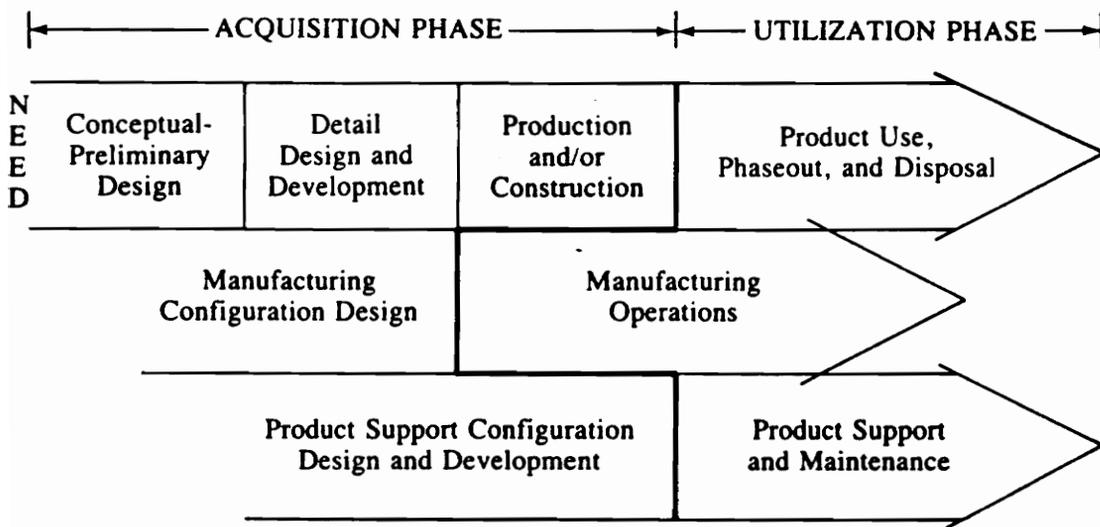
Figure 1.4. The three concurrent life-cycles [Blanchard & Fabrycky 1990].

The inclusion of producibility, supportability, and more recently disposability considerations along with prime mission performance in the evaluation process makes it more complete and life-cycle oriented. This makes the process of evaluating and selecting the "best" alternative more rigorous, with a greater number of competing requirements playing a role in this selection process.

There are different schools of thought on how to proceed with the process of design evaluation and the decision of selecting the "best" design. Vastly differing methodologies have been proposed. There is, however, a certain amount of agreement on the steps to be taken before evaluation can be done [Azarm, et. al., 1987]. These steps are:

a) A set of criteria needs to be established.

b) The criteria need to ranked in an order of increasing significance.

c) Constraints and limitations relative to the criteria need to be identified.

While the above steps are general enough, the specific activities involved in completing each one can and do differ for different methodologies. Although design evaluation is a significant process, it is but a step in the overall design activity and is greatly influenced by it.

Optimization is an important part of design evaluation, but it's involvement and nature is different in every methodology. Most references concentrate on the mathematical or analytical tools in the optimization process [Azarm, et. al., 1987]. This places the entire design process in a quantitative vein. Very often, the real life or actual conditions are excessively simplified or modified through assumptions to enable easy use of a quantitative model. Many mathematical optimization techniques exist, but their applicability to the engineering design

process is limited largely due to the qualitative nature of the design goals, requirements, and criteria. Moreover, tradeoff studies and sensitivity analyses that correspond to variations in the design parameters, variables, or features are often more important to the design process for real systems than the optimal solution itself.

The activities preceding optimization involve identification of the system parameters and variables, and selecting the criteria for evaluation, based on the system requirements and goals. These parameters and variables are used to form the evaluation function(s)[3] in accordance with the corresponding methodology. It is important that the evaluation function(s) be thorough enough to capture all the actual goals and requirements of the system being designed. All the parameters necessary to make the evaluation sound and robust must be represented. It is also important that the criteria for evaluation track the system goals faithfully.

1.5 Thesis Goal and Objectives

The goal of this thesis is to bring together, study, and contrast the diverse approaches to design evaluation. Four objectives were identified and completed. The first was to conduct a comprehensive literature review to identify a selected set of design evaluation methodologies. Each of the selected methodologies was studied in greater detail, and this fulfilled the second objective. The actual steps involved in the generation of the criterion or objective function(s) and the process

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[3] Some authors refer to the evaluation function as the objective function or the criterion function.

of evaluating design alternatives was then analyzed. Whenever possible, study of the evaluation methodology was preceded by a brief overview of it's evolution and of the design process of which it is a part. Thereafter, under the third objective, the methodologies were critically reviewed in a largely qualitative manner.

The following aspects of each methodology were considered:

a) The limitations of a methodology under certain conditions - For example, how well does the methodology respond to a primarily qualitative set of criteria? Very often, many of the goals, requirements, and criteria of a design activity are largely qualitative in nature.

b) The limitation of a methodology regarding its applicability to a narrow domain - Faced with a wide diversity and increasing complexity of designing activity, even in the same organization, generality in the approach to evaluating designs may be desirable.

c) The life-cycle completeness of the methodology - With the largely sequential nature of the designing activity giving way to a more concurrent approach, producibility, supportability, disposability, and other life-cycle issues need to be recognized during the design evaluation process.

d) The product completeness of the methodology - In other words, does the methodology remain relevant with the design process becoming increasingly detailed. Moreover, does the methodology react to design actions at the detailed level in a system and reflect the consequences or impacts at the overall system level.

e) The robustness of the methodology - For example, how well does the methodology account for uncontrollables like interest rates, inflation, labor rates, resource availability, etc.

f) The adaptability of the methodology to a computer environment.

g) The ease of use by the designer.

None of the methodologies studied made any reference to the desirability of a particular organizational structure to facilitate it's application. Realizing the relevance and importance of such issues the critical review in Chapter 5 provides a brief discussion of some concerns relative to organization styles and structures. Keeping in mind the diversity and complexity of the nature of systems being designed today, the critical review, which is the third phase of this work considers the application potential of the selected methodologies. Finally, in the fourth phase of this work, reference will be made to the current research efforts in the area of design evaluation.

1.6 Literature Review

The objective of the literature review was to select a set of design evaluation methodologies to satisfy the requirements of a taxonomy. Moreover, this set was to be studied and critically reviewed in the succeeding phases of this work. Because of a self imposed condition, only those methodologies were finally selected that are currently being actively researched. The seed papers for the three of the four methodologies selected have been published in 1987 or later [Dixon, et. al., 1989][Fabrycky 1991][Blanchard & Fabrycky 1990][Ostrofsky 1977] [Pedrycz & Knosala 1987]. Reference is made to earlier publications in some cases to clearly define the background and to follow the evolution of some of the methodologies.

The evaluation methodologies proposed by Ostrofsky, Fabrycky, and Dixon are themselves embedded in, and are integral parts of, rigorous design morphologies. The rigor of the design morphology results in the evaluation process being more comprehensive and complete. For this reason reference is made to the respective design morphologies in these three cases. In contrast, the design evaluation methodology proposed by Pedrycz and Knosala is not supported by any formal design morphology.

A fifth methodology proposed by Daschbach and Apgar [1987] was also considered and extensively studied. These authors suggest use of parametric models to estimate relative development, production, and operational costs of competing candidate systems during conceptual design. The basis of these parametric models are the empirical relationships that exist between cost parameters, e.g. dollars or labor hours, and selected physical or performance parameters, e.g. product size, quality, complexity, power, and BTUs. These empirical relationships are known as cost estimating relationships or CERs. Parametric models are typically computerized and analyst interactive, and are aggregates of these cost estimating relationships.

Daschbach and Apgar's [1987] approach was later dropped and not included in the list of methodologies to be studied in greater detail and critically reviewed. The approach involves the relative evaluation of candidate systems on purely economic terms and fails to consider the performance aspect of design. Evaluation is done on the basis of a single criterion, cost, and so the methodology falls short of being a complete design evaluation methodology (see Figure 1.1).

Case studies will not be offered to validate the proposed methodologies. However, the interested reader will be referred to some published case studies which further clarify the applicability of some of the selected methodologies. References are also made during the course of this work to supporting articles and publications even though they may not contribute directly to the methodology being studied. One of the objectives of this work is to bring together the issues being currently researched in the area of design evaluation. Extensive referencing will help achieve that goal. As such, the references are not limited to the methodologies being studied herein.

CHAPTER 2

OSTROFSKY'S CRITERION FUNCTION AND
FABRYCKY'S DESIGN DEPENDENT PARAMETER APPROACH

This chapter focuses on two design evaluation methodologies embedded within the framework of two different design morphologies. The first was set forth by Asimow [1964] and later extended by Ostrofsky [1977]. The second is being developed by Fabrycky [Blanchard & Fabrycky 1990] in the Systems Engineering Design Laboratory at Virginia Polytechnic Institute and State University.

2.1 Design Morphology

Webster's New International Dictionary defines morphology as the branch of biology that deals with the form and structure of animals or plants. Extending the definition, design morphology refers to the form and structure of the design process required to meet an established need through the effective and efficient utilization of resources.

The design morphologies addressed in this chapter recognize that requirements and limitations of the production and utilization phases drive activities of the primary design phases. For the morphology to be capable of facilitating desired results, knowledge of these requirements and constraints is necessary in the design phases. The morphology provides only the necessary framework. Knowledge of the involved disciplines remains as the basic building block.

Both the morphologies recognize the iterative nature of design. Knowledge is being continuously accumulated beginning with the recognition and analysis of the need and ending with the ultimate process of retiring the system. Unfortunately, decisions must be made to drive the process towards achieving the necessary conclusions, in the face of incomplete knowledge and within time constraints. Because of this incompleteness of knowledge during front end design phases, reexamination of the decisions taken is needed at subsequent points in time.

This process of reexamination, and often decision change, reflects the iterative process of design. However, this restructuring will cause a ripple effect in the subsequent phases of the development cycle and must be followed through. Asimow's [1964] policy of least commitment helps reduce the need for restructuring and consequently the ripple effect. The objective of the policy being to permit maximum flexibility at each step, no irreversible decision should be made until it absolutely must be.

2.2 Ostrofsky's Criterion Function Method

Ostrofsky's methodology for evaluating design alternatives has it's roots in the work originally done by Asimow [1964]. Asimow [1964] notes that the design, development, and implementation of new systems involving very complex equipment occurred, for the first time, on a recurring basis during the period of the Second World War. The inexperience in working with such systems lead to a number of expensive and abortive trials. Approximately fifteen years thereafter, Asimow delineated his design philosophy and morphology. It was a recognition

of the need to improve and make effective the designing of large-scale systems. This morphology attempts to emerge with an orderly sequence of decisions which should be addressed in order to emerge with an effective set of plans for the objective in mind.

A philosophy of design was offered by Asimow [1964] in an attempt to make explicit some of the principles and concepts that are of the greatest generality. The objective being to mold these principles and concepts into a discipline of design. It was he who first expressed the need to establish an element to take care of the evaluative function by setting forth a general critique that provides a way of measuring the validity and value of results in a specific application. Consequently, Asimow's philosophy of design, relative to the view set forth here, comprise three major parts; a set of consistent principles and their logical derivatives, an operational discipline which leads to action, and finally a critical feedback apparatus which measures the advantages, detects the shortcomings, and illuminates the directions of improvement (see Figure 2.1). While each design problem has it's own peculiarities, there is a general pattern that is, by and large, common to all design problems. Asimow translated this pattern into a series of major phases (see Figure 2.2). According to him, generally, a new phase is not begun until the preceding one has been completed. However, final details of the previous phase may sometimes be addressed in the next phase.

Keeping in mind the objectives of this study, attention will be focussed on the Primary Design-Planning Phases only. The primary design phases, which include the activities of feasibility study relative to the identified need, the preliminary design, and detailed design, are broken down further to show the steps involved
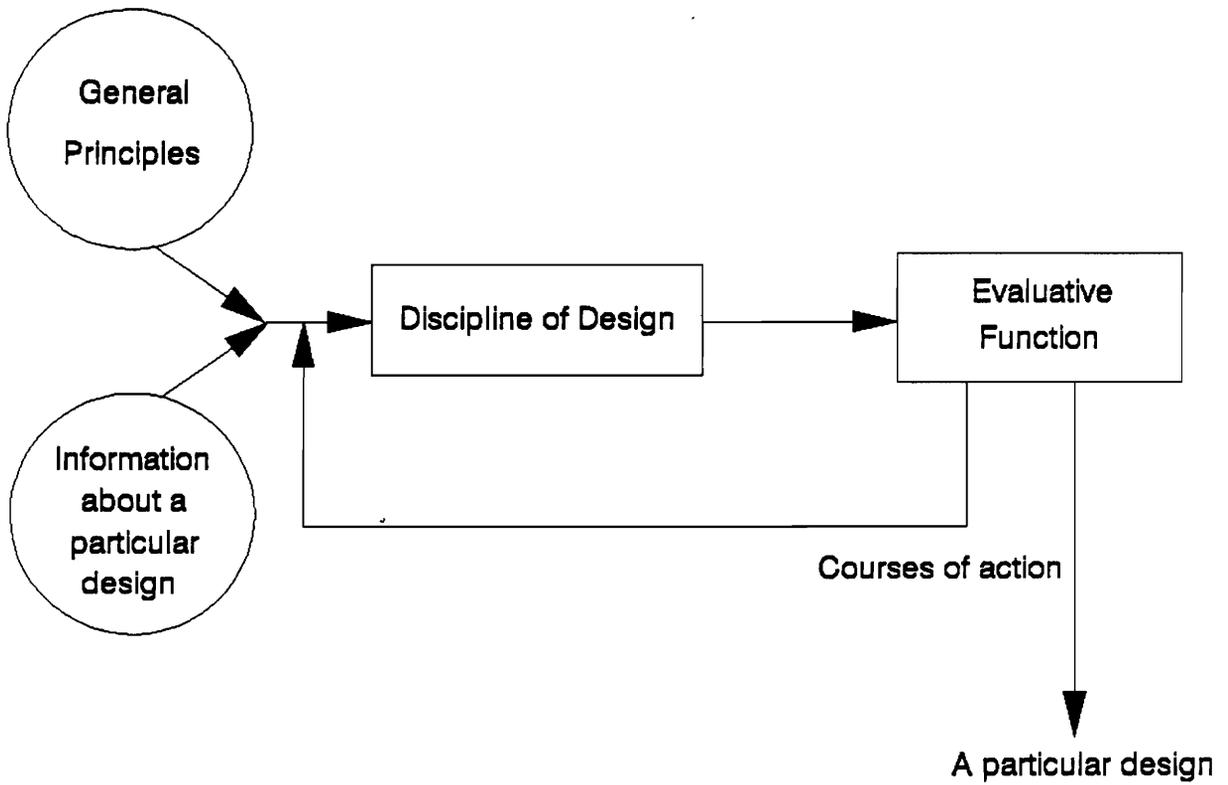
Figure 2.1. Asimow's philosophy of design [Asimow 1964].

and the interconnections to be considered [Ostrofsky 1977]. Figure 2.3 shows the detailed steps involved during the preliminary design phase.

All subsequent steps are influenced by the feasibility study. It helps accomplish several of the initial objectives, including the synthesis of solutions, in the form of competing candidate systems, and the screening of these candidate systems. The result is a set of alternatives acknowledged to be feasible. This feasible set of candidate systems is next compared and evaluated with greater rigor. If no useful solutions emerge, the design problem is termed "not feasible". In other words, the completed feasibility study results in a comprehensive needs analysis, an identification of the design problem, and a set of feasible solutions.

During the preliminary design phase the goal is to choose the best alternative from the set of feasible alternatives. "Best" must be defined relative to the criteria explicitly delineated. According to Ostrofsky [1977] these criteria, unless directly measurable, must be related to parameters and other attributes of the alternatives. Relations between the parameters and criteria must be established. Criteria must be ranked on a relative importance basis. Performance levels must be assigned to each criteria for the respective alternative approaches, and the "best" alternative must then be selected.

The objective being to make strong indications to the designer of the adequacy of his selection. The selected alternative is then further tested and predictions made concerning its performance in the production-consumption stages of the life-cycle. Rate of obsolescence, technical deterioration, and socioeconomic conditions such as competition and state-of-the-art must be evaluated.
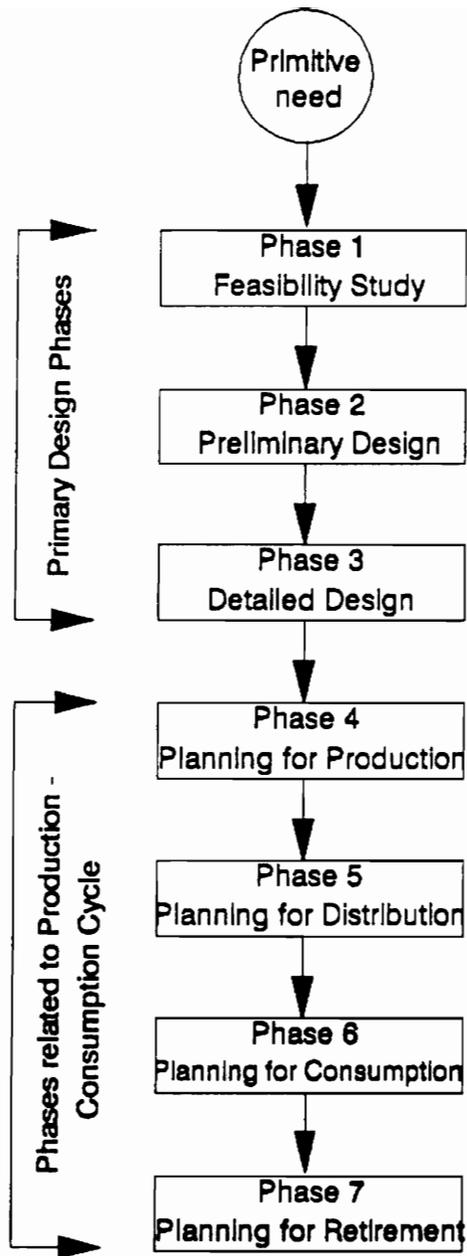
Figure 2.2. The phases of a complete project [Asimow 1964].
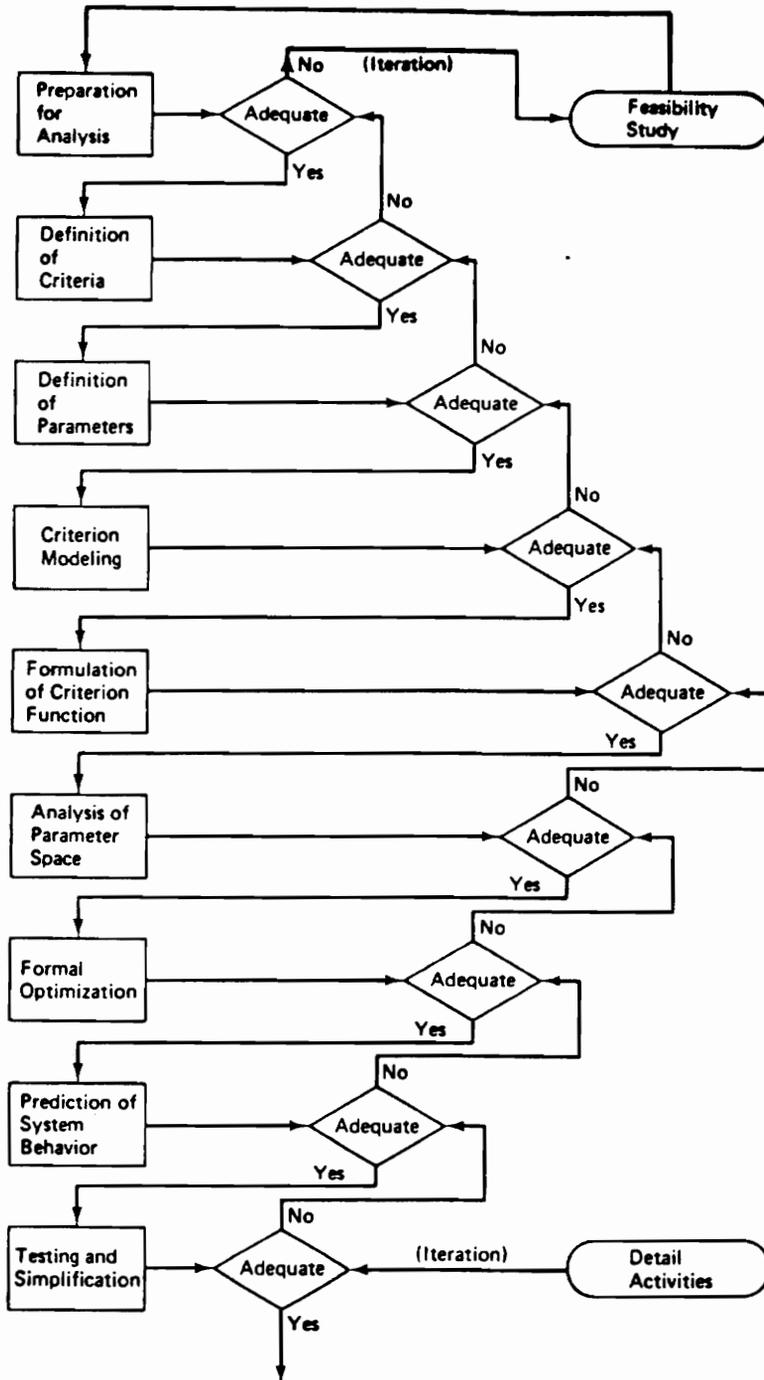
Figure 2.3. Activities during the preliminary design phase [Ostrofsky 1977].

Ostrofsky [1977] adopted the basic morphology offered by Asimow, but extended it further with an emphasis on the evaluative function.

2.2.1 The process of problem formulation

The objective of problem formulation is to bound the needs and requirements of the production-consumption phases and to identify the constraints. It follows the need analysis and problem recognition. Each phase of the production-consumption cycle is studied and as many descriptors as is practical are identified in a matrix. Descriptors in this context can be defined as those outputs from each phase of the life cycle that are desired, constraints, and other concerns. These descriptors can be simple one-word items or activities, or they can be narrative and detailed in order to convey the designer's ideas. In completing the matrix, an overall subjective image of the system is created, greatly reducing the odds of not considering a significant factor.

The matrix created is two dimensional, consideration is given to the different phases in the system life cycle on one axis, and the descriptors, characterized as inputs or outputs, on the other. The inputs are further broken down into intended inputs and environmental inputs. The outputs are broken down into desired outputs and undesired outputs (Figure 2.4). Ostrofsky suggests that the designer first focus on the outputs.

The desired outputs are descriptors which would be reflected if the system successfully met all intended objectives. Every system is inevitably associated with some undesirable characteristics which, if accurately anticipated, can be

minimized with regard to their effects on the outcome. As an example, for some systems increased weight may be an undesired characteristic. These undesired characteristics are referred to as undesired outputs in the matrix. Care must be taken not to induce redundancy into the matrix. For example, a desired output may be light weight, and if that is so, then heavy weight in the undesired column has the same effect and does not contribute meaningfully.

Environmental inputs on the other hand are those characteristics that are available for use or which otherwise influence design. These could refer to the existing facilities, equipment, and available personnel. Intended inputs for the different phases can normally be derived by focusing on what is needed to start the process in a certain phase with the objective of arriving at the desired output. These intended inputs supplement the environmental inputs to enable the desired outputs and to contain the undesired outputs.

2.2.2 Synthesis of solutions

After constructing the matrix during problem formulation, the next step is to identify the sequence or set of functions which, when accomplished, will meet the needs of the production-consumption cycle. The functions identified may be performed by the operator, a piece of hardware, or a software module. While there is no "best" way of doing this, it does imply some knowledge of the problem. Relationships between elements of the different functions must be identified. Next, similar functional activities are grouped together to form conceptual subsystems. This process of grouping can be continued down further to form assemblies below subsystems and so on.
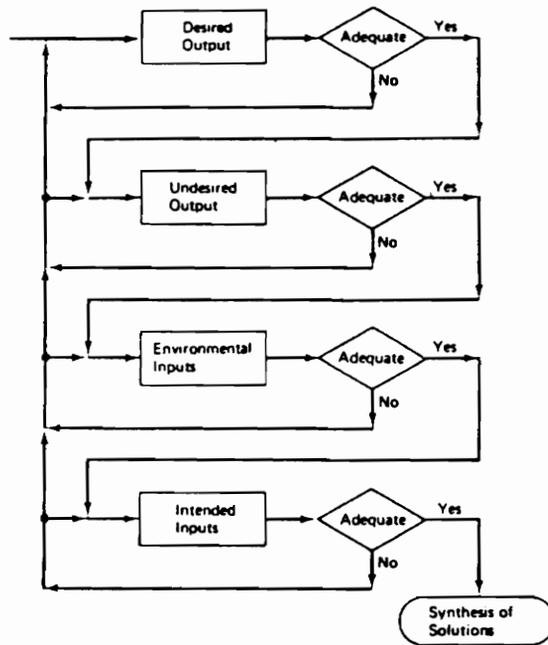
Identification and formulation of the problem.

	INPUTS		OUTPUTS	
	Intended	Environmental	Desired	Undesired
Production				
Distribution				
Consumption-Operation				
Retirement				

Figure 2.4. Activity analysis for problem formulation [Ostrofsky 1977].

To perform the above task and to further synthesize alternative candidate systems, the designer must first identify the concept or concepts to be used in addressing the system level problem. A concept here is defined as a basic approach to the solution of the design problem, using a well defined physical phenomenon. For large scale systems it possible to have subconcepts as well, that is, alternative approaches to some basic concept which relates to a larger concept but which may require a different grouping of subsystems. Alternative candidate systems are synthesized by considering all possible combinations of different subsystems that result from combinations of lower element possibilities. The approach allows the consideration of an exhaustive set of possibilities based upon the manner in which the subsystems and the lower level elements are defined.

2.2.3 Preliminary screening of candidate systems

All the candidate systems identified are next screened for feasibility. This study is conducted with the limited knowledge at hand, and as such, keeping with the principle of least commitment only those alternative candidate systems are dropped which are definitely infeasible. This infeasibility can be because of lack of physical realizability and/or economic worthwhileness, etc.

In the analysis that follows, an optimum candidate system is defined as the candidate system which is theoretically the most favorable for the criteria defined. Whereas, an optimal candidate system is the one which is the most favorable for the criteria and belongs to the set of candidates defined.

2.2.4 Definition of the criteria

The criteria which will form the basis for evaluating the alternative candidate systems are identified from the input-output matrix that was put together in the problem formulation stage. Once identified, it is important to assign relative importance to the different criteria (Table 1). The weighting given to each criterion has a value between 0 and 1. Moreover, the sum of the weighting factors assigned to all the criteria equals 1.

2.2.5 Definition of parameters

More often than not, direct measurement of the criteria identified for evaluating a certain system is not possible. This results in the need for evaluating the candidate systems in terms that relate the evaluation to the criteria established. The elements, which are directly measurable and can be combined somehow to provide a meaningful measure of a criteria, and which at the same time are characteristics of the candidate systems, are defined as the design parameters. It is made explicit at this stage that there is no mechanical way to link the parameters to the criteria, it depends on the intuitive comprehension of the interactions and interrelations that exist.

An understanding is needed of the relationships between criteria and parameters as well as between candidate systems and parameters. Figure 2.5 provides a sketch of the relationships among criteria constituents. While parameters provide a majority of the input to the quantitative evaluation by the criterion, often there are elements that contribute significantly to a criterion but which cannot be

Table 2.1. Criteria and relative weights [Ostrofsky 1977].

Criterion, x_i	Weight, a_i
x_1	a_1
x_2	a_2
x_3	a_3
.	.
.	.
.	.
x_n	a_n

$$\sum_i^n a_i = 1.0, \qquad 1.0 \geq a_i \geq 0$$

measured directly. These elements have to modelled from other parameters which can be defined for the candidate systems. Finally, there may exist elements that impact the value of a criterion significantly, but cannot be measured with the resources at hand. If significant enough, studies and tests must be conducted to adequately estimate their values. After listing the elements and parameters needed for a meaningful evaluation of the alternatives, Ostrofsky suggests that they be checked for consistency, completeness, and compactness.

2.2.6 Criterion modelling

At this point the designer has a set of feasible candidate systems along with an identified set of criteria and the parameters and other elements that link the criteria to the candidate systems. The "best" candidate system is the one rated as having superior performance relative to the criteria. A cardinal scale is established, from which a unique value results for every candidate system[4]. This helps in not only identifying the "best" candidate system, but also establishes a ranking for all the other alternatives being considered.

The criterion function is constructed from a combination of the criteria and their respective weighting values. A particular set of parameters, $\{y_k\}$, relates to the set of criteria defined for the evaluation. In other words, the set $\{y_k\}$ relates to every criterion, although each y_k may have a different functional relationship with each x_i, and, indeed, a particular y_k may not relate to some of the x_i, where $\{x_i\}$ is the set of all the criteria being considered (Figure 2.6).

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[4] A cardinal scale is one in which the interval between two successive candidate systems has a consistent unit value, independent of their relative performance values.
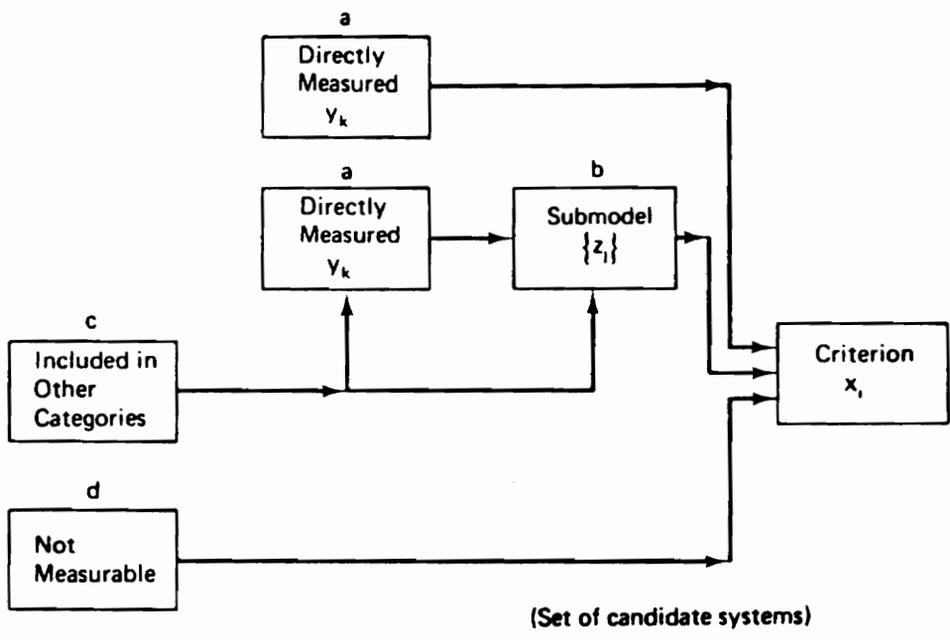
Figure 2.5. Constituents of a criteria for a set of candidate systems [Ostrofsky 1977].

At times, when the parameters do not relate directly to a certain criteria, the designer has to formulate submodels. These submodels are identified as z_i, and they relate to the y_k just like the x_i. Submodels also relate to x_i, and help form the link between the parameters and criteria. In other words, the submodels mark an insertion of another level of functional relationship between the x_i and y_k, make relating the two more accurate.

Each criterion can be viewed as a function of a certain set of parameters, $\{y_k\}$. The set $\{y_k\}$ has different parameters as members for different criteria. The next step is to establish relationships among the parameters and a criterion. It is accepted here that the accuracy of this relationship is dependent on the knowledge available from past experience, mathematical capability, literature review in this area, and the extent of the current investigation and testing. The effectiveness of the overall prediction and selection of the best alternative candidate system will depend on the accuracy of this mathematical modelling.

As described above, submodels are attributes of a criterion which serves as the link between the criterion, x_i, and the parameters, y_k. An attribute may be of importance to a criterion meaning, but it may be too complex to be measured by only one parameter. In the above case, a submodel relates to the parameters exactly as a criterion might relate during the structure of the model. Once structured, the submodel then relates to the criterion as the parameter did in the description given above.
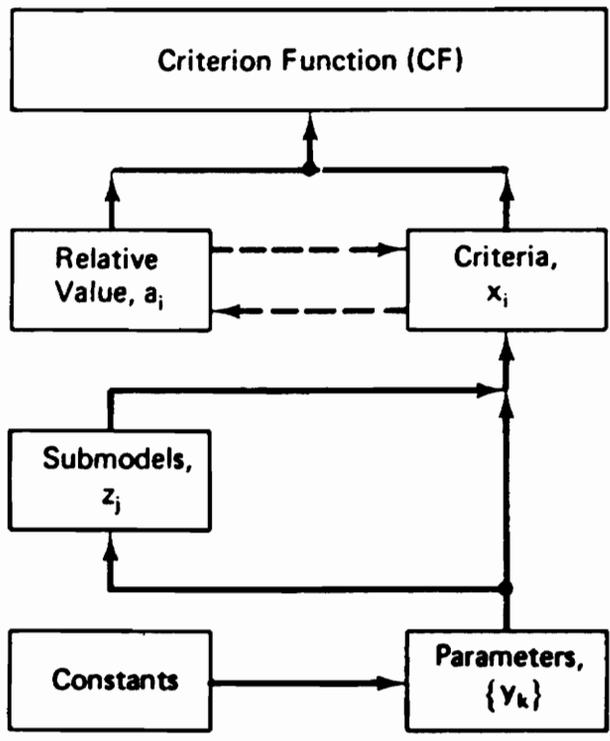
Figure 2.6. Criterion function constituents [Ostrofsky 1977].

Functionally,

$$x_i = f_i\{z_j\} \tag{2.1}$$

or, the ith criterion is a function of the submodels relating to it. When parameters relate directly to the criterion, they can be considered as sub-models themselves. Further,

$$z_j = g_j\{y_k\} \tag{2.2}$$

and by substituting,

$$x_i = f_i\{z_j\}$$
$$= f_i\{g_j\{y_k\}\} \tag{2.3}$$

The above equation then states that the ith criterion is a function of the set of submodels, $\{z_j\}$, which themselves are functions of the set of parameters, $\{y_k\}$. A designer can establish additional levels of models in this manner until the accuracy and completeness of the modeling is adequate.

2.2.7 Formulation of the criterion functions

After having modelled all the criteria, x_i, the next step is to decide on the range of acceptable values for each parameter, y_k. Candidate systems with parameter values beyond this identified range will then be considered technically infeasible. Next, as shown in Table 2.2, the range of acceptable values for the submodels must be made explicit. The above exercise will help construct a table of acceptable range of values for the corresponding set of criteria.

At this point the designer can synthesize a function to include all the criteria. This function will yield a single value on a cardinal scale for each candidate system being studied. On examining the different criteria that make up this function, the designer will have to handle the different units that characterize the different criteria. For example, x_1 may be measured in inches, and x_2 in pounds. The designer has to relate the sensitivity of the unit value of x_1 with the unit value of x_2.

While a rigorous approach is possible, a simplifying assumption helps convey the concept. For each criterion, performance is identified as a fraction of the allowable range for that criterion, for example:

$$X_i = \frac{x_i - x_{i\,min}}{x_{i\,max} - x_{i\,min}} \tag{2.4}$$

Since $x_{i\,max} - x_{i\,min}$ in the denominator defines the range for x_i and the distance of the performance of the candidate system x_i from $x_{i\,min}$ in the numerator, the resulting fraction will represent the performance of the candidate system's ith criterion and the equation will be unique for each criterion of every candidate system. Therefore, a unitless fraction results. When this fraction is given its relative importance, a_i, the product $X_i a_i$ then represents the weighted value or the relative value of the ith criterion. These may then be added to give:

$$CF_\bullet = \sum_i a_i X_i \tag{2.5}$$

or multiplied to give:

$$CF_\bullet = \prod_i a_i X_i \tag{2.6}$$

Table 2.2. Range of submodels and criteria [Ostrofsky 1977].

RANGE OF SUBMODELS

x_i	z_{ij}	z_{ij} min	z_{ij} max
x_1	z_{11}	z_{11} min	z_{11} max
	z_{12}	z_{12} min	z_{12} max
	.	.	.
	.	.	.
	.	.	.
	z_{1n}	z_{1n} min	z_{1n} max
x_2	z_{21}	z_{21} min	z_{21} max
	z_{22}	z_{22} min	z_{22} max
	.	.	.
	.	.	.
	.	.	.
	z_{2n}	z_{2n} min	z_{2n} max
.	.	.	.
.	.	.	.
. $_j$	.	.	.
x_p	z_{p1}	z_{p1} min	z_{p1} max
	z_{p2}	z_{p2} min	z_{p2} max
	.	.	.
	.	.	.
	.	.	.
	z_{pn}	z_{pn} min	z_{pn} max

RANGE OF CRITERIA, x_i

	x_i	x_i min	x_i max
x_1	Criterion 1	x_1 min	x_1 max
x_2	Criterion 2	x_2 min	x_2 max
.	.	.	.
.	.	.	.
x_p	Criterion p	x_p min	x_p max

one since CF_α will always have a value between 0 and 1, while the second equation results in very small numbers. Substituting Equation 2.4 into Equation 2.5, gives:

$$CF_a = \sum_{i=1}^{a} a_i \left(\frac{x_i - x_{i\,min}}{x_{i\,max} - x_{i\,min}} \right) \tag{2.7}$$

and from Equation 2.1, $x_i = f_i\{z_j\}$:

$$CF_a = \sum_{i=1}^{a} \sum_{j=1}^{m} a_i \left(\frac{f_i\{z_j\} - x_{i\,min}}{x_{i\,max} - x_{i\,min}} \right) \tag{2.8}$$

and from Equation 2.3, $x_i = f_i\{g_j\{y_k\}\}$

$$CF_a = \sum_{i=1}^{a} \sum_{j=1}^{m} \sum_{k=1}^{f} \left(\frac{f_i\{g_j\{y_k\}\} - x_{i\,min}}{x_{i\,max} - x_{i\,min}} \right) \tag{2.9}$$

Equation 2.9 represents the criterion function value for the candidate system, and is equal to the sum of the weighted criteria when defined in terms of the submodels and the design parameters. This is then the single quantitative function which can be used to evaluate the performance of every candidate system in the set that warrants consideration.

Before the different candidate systems can be equivalently compared and the best from amongst them selected, the criterion function corresponding to each of them must first be optimized. For each candidate system, there is a feasible range of values for each Y_k. The optimization problem thus gets reduced to optimizing over the set of design parameters, such that the value of the criterion

function is maximized or minimized, as the case may be.

2.2.8 Multiple criterion computation methods

The descriptions in the earlier sections were focussed on making explicit the main steps in the design evaluation methodology as proposed by Ostrofsky. Assumptions were used. Mathematical rigor was sacrificed in an attempt to simplify and make clear the process itself. While the concepts, the main steps and their sequence, and the objectives remain the same, Ostrofsky has proposed a total of eight different, mathematically rigorous models. These eight different models work under eight different broad situations, but the primary steps in the overall process remain the same.

The criteria identified can be of two types, independent or dependent. An independent criterion being one that has no interaction or impact on any of theother selected criteria, whereas a dependent criteria is one that has any number of interactions with the other criteria. The relative weights of these criteria on the other hand can be of four types, constant, interval, variable, and variable with discontinuities as shown in Table 2.3. This table graphically refers to the nature of the relationships between the criteria and relative weights. Combination of the different criteria types with the different relative weights types give a total of eight combinations. Each of these eight cases is associated with varying degrees of complexity. A study of each of these combinations is considered beyond the scope of this work.

Table 2.3. Various relationships between criteria and the weights.

	INDEPENDENT	WITH INTERACTION	GRAPHIC REPRESENTATION OF RELATIVE WEIGHTS
CONSTANT	1	5	
INTERVAL	2	6	
VARIABLE	3	7	
VARIABLE WITH DISCONT.	4	8	
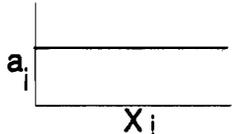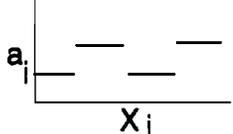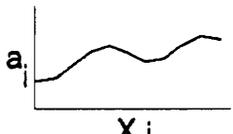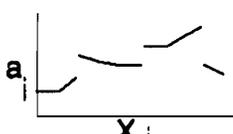
2.3 Fabrycky's Design Dependent Parameter Approach

The design dependent parameter (DPP) approach evolved from an idea proposed by Churchman, Ackoff, and Arnoff in 1957 [Churchman, et. al., 1957]. These authors proposed a model structure for operations that expresses system effectiveness as a function of a set of variables at least one of which is subject to control. The general form of the model was given to be:

$$E = f(x_i, y_j)$$

where,

E = system effectiveness

x_i = variables under direct control

y_j = variables not subject to direct control

The above formulation was the baseline. Fabrycky [Fabrycky, et. al., 1984] proposed that an effectiveness function is a mathematical statement formally linking a measure of effectiveness with variables under direct control of the decision maker, and variables not under direct control, in the face of constraints expressed as functions of the controllable and uncontrollable variables and a set of constraint constants. The set of controllable variables was designated as X, the set of uncontrollables was designated as Y, and the set of constraints constants as B:

$$E = f(X,Y) \; ; \; g(X,Y) > / = / < B$$

Both formulations presented above addressed the problem of decision making in

the domain of operations. The second formulation of the effectiveness function was modified and applied to inventory operations by Banks and Fabrycky [1987]. To handle the most general inventory system reflecting multi-items and multi-source, the set of controllable variables was split up into a set of source dependent parameters, e.g. procurement lead time, replenishment rate, item cost, procurement cost , and a set of source independent parameters, e.g. demand, inventory holding cost, and shortage cost. The set of controllable variables became the set of policy variables, e.g. the procurement level, and the procurement quantity for each item. The function is then:

$$E = f(X, Y_d, Y_i) \; ; \; g(X, Y_d, Y_i) > / = / < C$$

The above modification was effected primarily to handle inventory operations. It was extended further to address design [Blanchard & Fabrycky 1990][Fabrycky 1991]. While the structure of the formulation did not change, the terminology did. While E remained the effectiveness measure, X became the set of design variables, e.g. number of deployed units, retirement age, repair channels; Y_d became the set of design dependent parameters, e.g. weight, reliability, maintainability, producibility, design life; and Y_i became the set of design independent parameters, e.g. cost of money, labor rates, material cost per unit, shortage penalty cost. It provides a framework for the evaluation of design alternatives in a concurrent life-cycle engineering environment . The design evaluation function (DEF) is embedded in a computer-aided life-cycle engineering morphology (CACED), which in turn is embedded in a comprehensive life-cycle engineering methodology [Blanchard & Fabrycky 1990].

2.3.1 Life-cycle engineering methodology

In their life-cycle engineering methodology, Blanchard and Fabrycky [1990] propose that there are in effect three life-cycles that the designer has to consider (Figure 1.3). It is acknowledged that the design and development of the product, the process, and the support capability in a coordinated manner is not easy to accomplish, but is necessary to maintain a competitive edge. The entire process will be facilitated by the developments in computer networking which will make possible the timely acquisition, assimilation, and use of design information.

The broad activities that make up the overall systems engineering process are illustrated in Figure 2.7. The entire process is driven primarily by the identified and analyzed need. A requirements analysis helps translate the need into an engineering problem statement with specific objectives identified, e.g. a minimum system reliability, a minimum system availability, maximum weight, maximum space occupied, etc. The designer's attention until recently has been focussed on the prime mission requirements and prime mission equipment performance. Consideration of the system support capability is also necessary for an integrated development effort, this is initially accomplished by defining the system maintenance concept. This helps delineate the anticipated levels of maintenance support, the basic responsibilities for support, general overall repair policies, the major elements of logistic support, the effectiveness requirements relative to the system support capability, such as test equipment reliability, facility utilization rate, and personnel efficiency.

As mentioned above, the functional requirements analysis and the maintenance

concept help identify the system requirements both from the operational point of view and the maintenance point of view. This activity is followed by a preliminary systems analysis. The system requirements identified are translated into a problem statement, the objectives are clarified, and the design and development problem is suitably bounded. Moreover, criteria for evaluating candidate systems are identified. The criteria selected should reflect the concerns of the problem statement. This preliminary analysis is followed by advanced system planning. The purpose being to separate the technical requirements from the management requirements. The technical requirements lead to the system specifications (Type A), whereas the management requirements lead to the Systems Engineering Management Plan (SEMP).

The next significant activity is the proposed system's functional analysis. Here a function is defined as a specific or discrete action required to achieve a given objective. This action could be accomplished through the use of hardware, software, firmware, personnel, or any combination thereof.

The process of functional analysis is accomplished through the development of functional flow diagrams. The primary purpose is to structure the system requirements in functional terms. It helps identify the basic system organization, and the significant functional interfaces. The functional flow diagrams are employed as a mechanism for portraying system design requirements in a pictorial manner, illustrating series and parallel relationships, the hierarchy of system functions, and functional interfaces. These diagrams are broken down to the level necessary to establish the needs of the system (Figure 2.8). The functional flow diagrams must represent the functions necessary to portray the
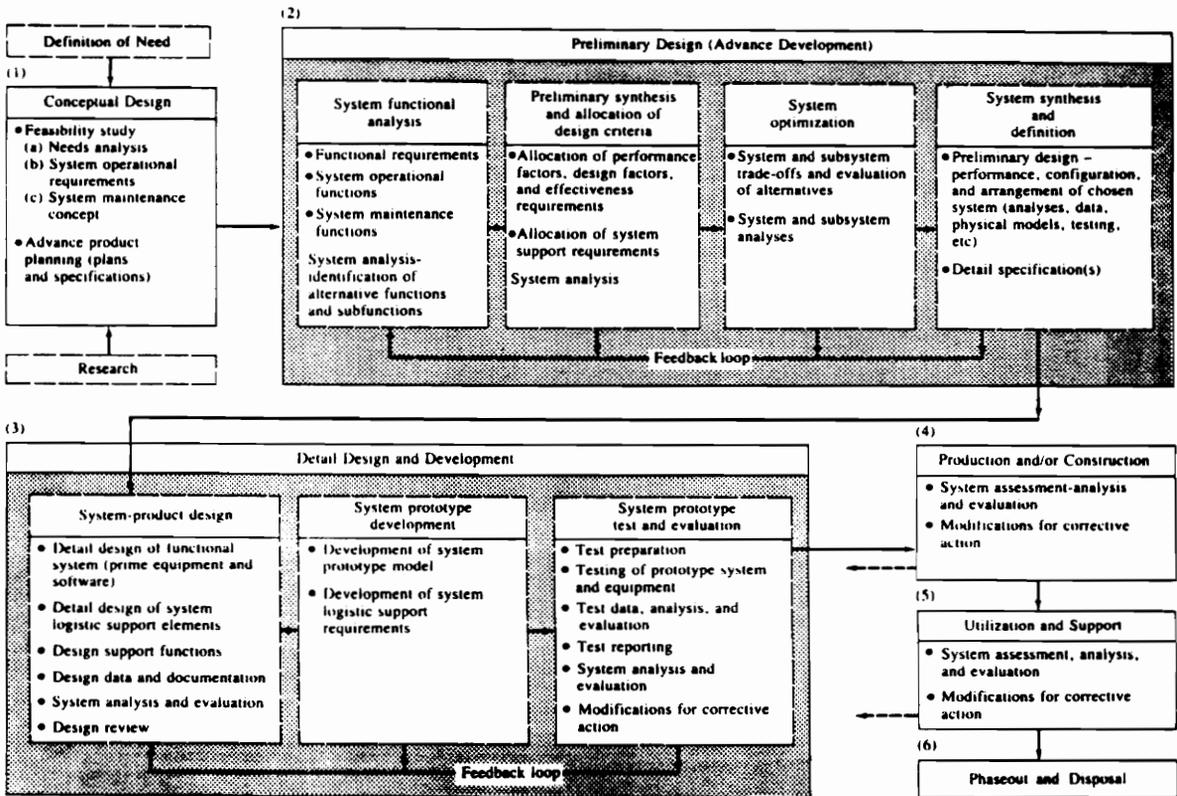
Figure 2.7. The systems engineering process [Blanchard & Fabrycky 1990].

desired system utilization and operation. Also represented must be the functions that make up system maintenance, i.e. activities necessary to make the system operational again in case of failure, which could result in system shutdown or performance degradation.

Functional analysis constitutes the process of translating the system operational and support requirements into specific qualitative and quantitative design requirements. On completion of the functional flow diagrams, similar functions are grouped together to form conceptual sub-systems, assemblies, modules, and sub-modules, etc. This serves as a baseline for the allocation of system requirements and detail design.

Allocation refers to the process of distribution, allotment, or apportionment of top-level requirements to lower indenture levels of the system. The allocation of system level requirements helps establish boundaries and constraints for detail system design. Allocation also helps identify the evaluation criteria for the sub-systems and other elements that constitute the overall system. This is necessary for design teams working independently on different elements of the overall system. They will otherwise establish their own goals, and the results when combined may not comply with the overall system requirements. The engineer may envision any number of design configurations which conform to the constraints and boundaries established, and which will help satisfy the specified requirements.

After identifying the different alternatives, the next step involves performing trade-offs and evaluating the identified alternatives. The system parameters selected as
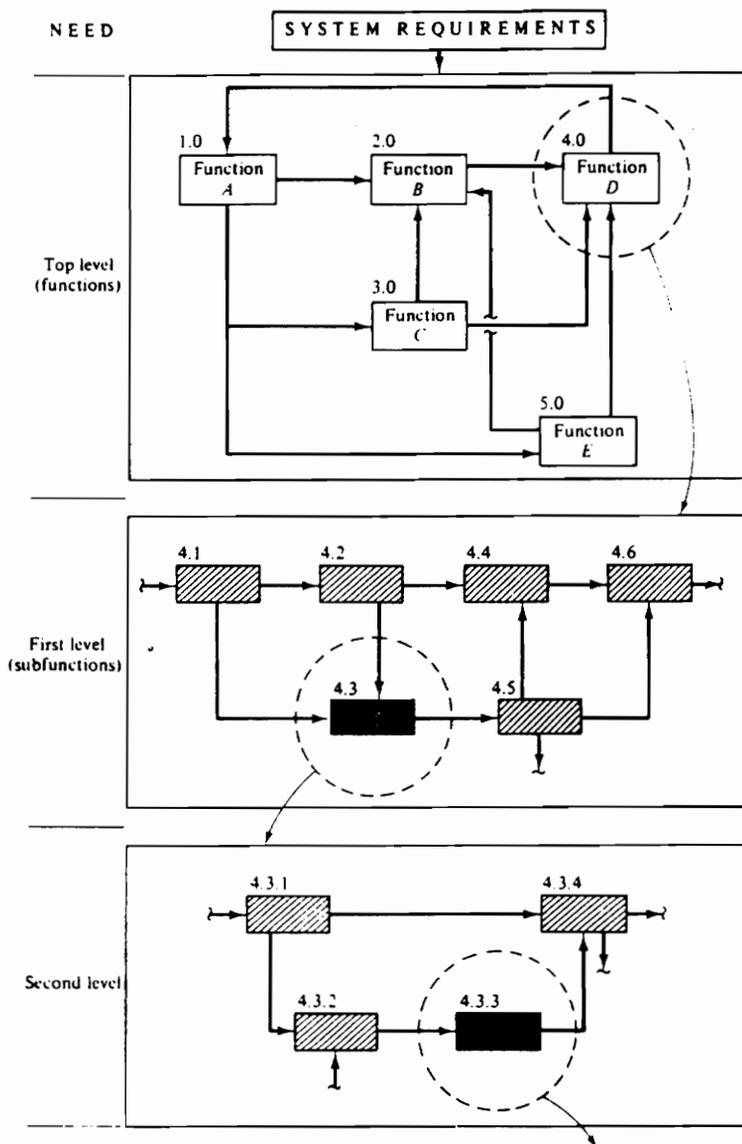
Figure 2.8. System functional indenture levels [Blanchard & Fabrycky 1990].

the evaluation criteria should reflect compatibility with the problem statement and the original need. The parameters selected at the system level are of the highest order and get decomposed into parameters of a lower order when associated with sub-systems and elements that make up the system. These lower order parameters can in fact be combined in various ways to give a measure for the next higher order parameters as shown in Figure 2.9. Depending on the degree of relevance and/or importance, these parameters can have weighting factors associated with them.

The evaluation is further facilitated by the use of appropriate mathematical models. This makes it possible to deal with the problem as an entity and allows consideration of all major parameters of the problem on a simultaneous basis. Moreover, it is also necessary to construct a matrix showing parameter relationships, each parameter being analyzed with respect to every other parameter to determine the magnitude of relationship. Model input-output factors and parameter feedback relationships must be established. The model is constructed by combining the various factors and then testing for validity.

Finally, before selecting the preferred approach, the designer is advised to do a sensitivity analysis to test the robustness of the decision. The above activity was to identify the most attractive system level configuration. Thereafter, it is necessary to progress through further definition leading to the realization of hardware, software, etc., and items of support.

If the activities preceding this stage were accomplished faithfully, the elements that make up the overall system have associated with them allocated

requirements that now become their design goals. This will help realize sub-systems and lower elements that are compatible with each other. Moreover, the functional analysis helped identify the significant interfaces within the system and these can be addressed during the process of designing the lower elements.

2.3.2 Computer-aided concurrent engineering design

It is imperative to adopt a concurrent approach to design. This is dependent upon and facilitated by the presence of a proposed computer-aided workstation environment (CACED). This environment is presented as a morphology for computer-aided concurrent engineering design. The multi-disciplinary team has the responsibility of analyzing and updating the algorithms and tools incorporated into the computer-aided process. The computer-aided concurrent engineering design (CACED) morphology provides a framework to make that possible [Blanchard & Fabrycky 1990][Fabrycky 1990][Fabrycky 1989]. Refer to Figure 2.10 for a schematic of the morphology. The numbered blocks are described as follows:

Block 1. The human element of the CACED system (an individual or a team) links with a set of CAD/CAE design tools via a human computer interface (HCI).

Block 2. The CAD/CAE design generator provides the framework and facilitates the process by which the designer(s) creates a design and determines its features.

Block 3. Design features (conceptual, preliminary, or detailed) are passed to estimators/predictors where design dependent parameter (Y_d) values are determined by estimation and prediction.
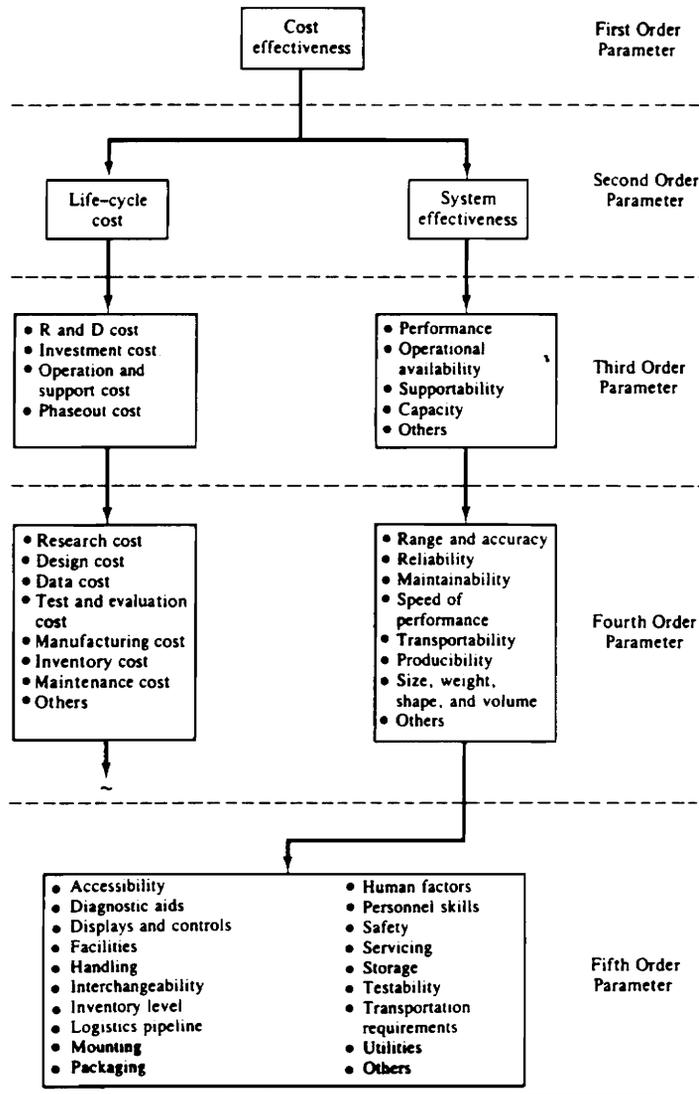
Figure 2.9. Order of evaluation parameters [Blanchard & Fabrycky 1990].

Block 4. An evaluator(s) provides the designer(s), via a human computer interface, an evaluation (E) of the design at its current iteration (or state of development).

Block 5. A data base of economic and physical factors is maintained as a source of and to facilitate the forecasting of design independent parameters (Y_i)(e.g., interest rates, labor rates, material costs, etc.) and physical properties (e.g., MIL-HBK-217) as a source of inputs to the estimation/prediction of design dependent parameters.

The first consideration at the preliminary design stage is the selection of a technology that has the potential to help achieve the proposed system objective. Once the decision relative to the technology is finalized, the designer(s) have a set of controllable design features to work with. These design features are linked to each other by virtue of the underlying relationships resulting from the basic sciences that influence the chosen technology. Moreover, these design features, either singly or in combination, yield a number of intermediate performance measures. These measures may be further employed to yield measures for system effectiveness and life-cycle cost for the proposed system design, and consequently for the system cost effectiveness.

Cost effectiveness, as shown in Figure 1.1, is defined as a measure of the system in terms of mission fulfillment or system effectiveness and total life-cycle cost. It can be expressed in various terms, depending upon specific mission or system parameters that one wishes to evaluate.
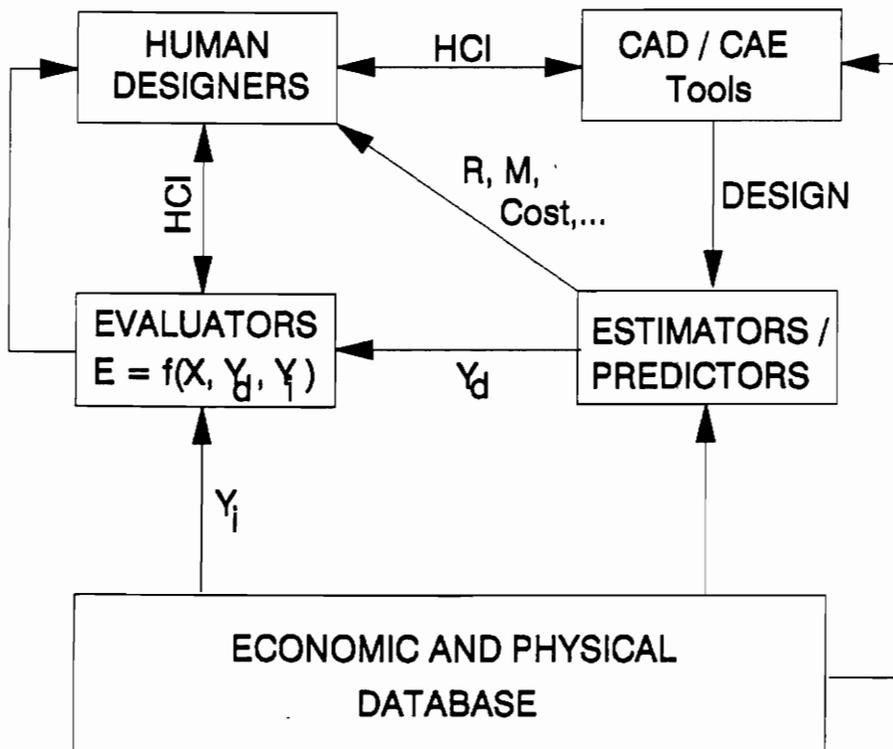
Figure 2.10. Computer-aided concurrent engineering design morphology [Blanchard & Fabrycky 1990].

It is acknowledged that true cost effectiveness is impossible to measure given the numerous factors that influence the design of a system and that cannot be realistically quantified. Use of specific cost-effectiveness Figures of Merit (FOM) [Blanchard & Fabrycky 1990] is recommended, such as:

$$FOM = \frac{availability}{life\text{-}cycle\ cost}$$

$$FOM = \frac{system\ capacity}{life\text{-}cycle\ cost}$$

2.3.3 Design evaluation

Essential to the selection of the best alternative is the activity in Block 4: design evaluation. The key to design evaluation is the derivation of comparable performance and life-cycle cost measures. Comparability, over a number of candidate systems or design iterations, requires metrics for equivalence in performance terms and in economic terms as depicted in Figure 1.1.

2.3.4 The design evaluation function

It is proposed that the design evaluation function be developed to address and separately determine performance effectiveness and equivalent life-cycle cost. The function is a mathematical means of linking design with operations such that optimal achievement of acquisition and utilization is made possible. Constraints exist on both the parameter set Y_d, and the design variable set X. Accordingly, optimization is to be accomplished in the face of both sets of constraints.

It is important to realize that the set of alternatives is determined by sets of values for the design dependent parameters. The sets of design dependent parameters values that satisfy all constraints relative to the parameter set constitute the feasible set of alternative candidate systems[5]. For each feasible set of design dependent values, Y_d, optimal values of the design variables, X, are determined. The result is an optimal value for E, one for each set of design dependent variable values. This permits direct comparison of the competing candidate systems. Critical is the availability of a means of altering design dependent parameters in real time and in the face of the design independent parameters, leading to the optimal comparison of design alternatives. The hard linkage among design considerations is provided in this process by estimators and predictors of cost elements and RM&S performance measures on the basis of the design features. The results of the estimators/predictors and then the evaluator is conveyed to the designer through a graphical display, the design evaluation display (Figure 2.11).

2.3.5 A design evaluator shell

As the designer(s) works his or her way through a number of design alternatives by generating a different set of design dependent parameters each time, a design evaluator, is activated. The REPS is such an evaluator [Blanchard & Fabrycky 1990][Altenhof, et. al., 1990], but there are others. The schema for this evaluator is shown in Figure 2.12. A finite homogeneous population of repairable units designed, deployed, and then maintained in operation to meet a certain demand

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[5] It is critical to note here that design iterations which result in a change of design dependent parameter values represent different candidate systems. Each of these candidate systems must be optimized in the face of design variables and the corresponding constraints before comparisons can be made.
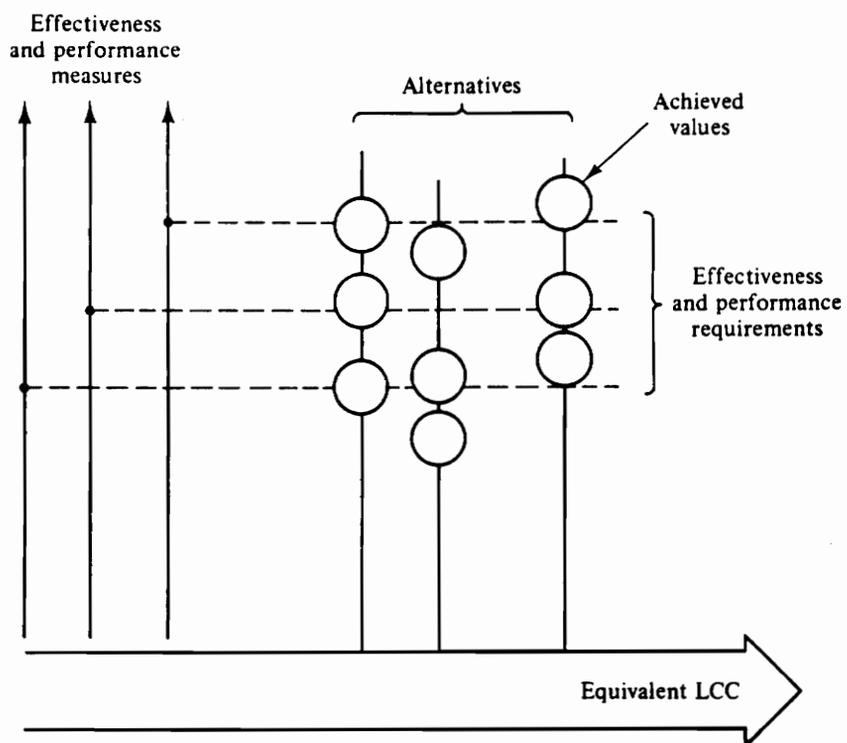
Figure 2.11. Design evaluation display [Fabrycky & Blanchard 1991].
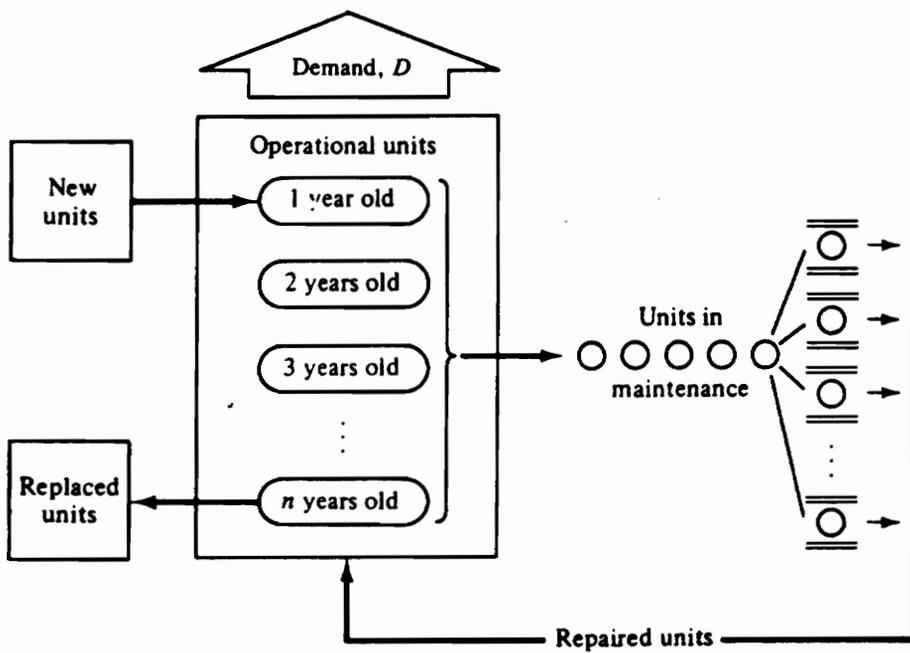
Figure 2.12. The repairable equipment population system (REPS) schematic [Blanchard & Fabrycky 1990].

is addressed. During operation, these units fail, are repaired at one of the repair channels and returned to service. On reaching the retirement age, these units are replaced with new ones. The objective of the model is to determine the optimal population size, the replacement age of the deployed units, and the number of repair channels, in the face of design independent parameters so that the expected equivalent annual life-cycle cost is minimized. REPS outputs the optimal expected equivalent annual life-cycle cost (EALCC); an evaluation measure.

As the designer perturbs system design features values of the design dependent parameter set may change. The model reports to the designer the degree to which change in the identified features impact the overall evaluation measure E, and the other design dependent parameters. The design evaluation display is used to convey this information. While REPS is a general evaluator that addresses the case of a homogeneous population of repairable equipments, it can be embedded within a more domain specific model [Altenhof, et. al., 1990]. Specific design features can then be related to the various design dependent parameters identified. Each design feature is given the order from the highest to the lowest directional derivative along with the sign of that derivative. This facilitates the activity of searching for the better design alternative.

CHAPTER 3

DIXON'S REDESIGN STRATEGY

This chapter will focus on research by Dixon, et. al. [1989] towards generating computer-based models of design processes in the Mechanical Automation Laboratory at the University of Massachusetts. Dixon's research will be reviewed from the viewpoint of how trial designs are evaluated, and how the results of evaluation are used for redesign.

3.1 Computer Modelling of the Design Process

The primary thrust of the above research is towards modelling the design process on the computer [Dixon, et. al., 1989][Dixon 1987]. According to Dixon, a computer model of the design process need not necessarily track the way a human may attempt all or part of the same task, it is simply a description of how the computer performs the specified task. The three main reasons that make such computer-based models valuable are:

(a) they make explicit the knowledge and strategies needed for a certain design task.

(b) they enable experimentation with the knowledge and strategies that contribute to the development of design theory.

(c) they can lead to the development of software which may facilitate the design process [Dixon & Simmons 1985].

Under this broad research area, the evaluation of trial designs and their redesign

is conducted and discussed in the context of computer-based models of design processes, with a focus on the configuration and parametric design stages. While the generation of initial designs is an important aspect of design problem solving, the research attention is focussed on what happens after the initial design is generated; that is, on evaluation and redesign. Here redesign refers to the next design iteration.

An explicit distinction is made between analysis and evaluation. The process of analysis provides data for the process of evaluation. Evaluation of the results of analysis, in turn, provides the information on the basis of which effective redesign of trial designs can be undertaken. If the analysis and evaluation of a design cannot be performed for a given factor, it cannot be improved relative to that factor. Moreover, if evaluation is possible only for a dimensioned version of a design, then redesign is not possible during the conceptual and preliminary design stages. And the computer models shall be reduced to a single-concept design strategy, similar to that observed in human designers.

According to Marples [Marples 1961], evidence runs counter to the popular notion of a designer as a man "bursting with ideas". Because of his knowledge and experience, a designer "knows" how to accomplish certain functions and prefers that to novelty. This is because of the emphasis on reliability and delivery time. Only when none of the initial ideas are feasible, does a designer thinks of new ways [Ullman, et. al., 1987]. In other words innovation is imposed upon him, not sought by him. Moreover, the new combinations of known principles, materials, manufacturing processes, and geometric shapes and the innovative capacity are limited by the number of elements he can call to mind. Marples

observes that the mystique of creativity often consists of dogged exploration and hard thinking. This is where modelling the design process on the computer can be very helpful in generating alternatives and then coupling them with evaluation and redesign.

3.2 Designing with Features

According to Dixon [Dixon, et. al., 1989], designing with features facilitates design evaluation in the early stages of design. A feature is defined as an entity with both form and function. The term function here is interpreted as any reason or reasons that the form is included in design. The reason can link a feature to the system operation, to manufacturability, or to any other life-cycle issue. Moreover, function is always implicit in evaluation. It a design evaluates well, then its function will have been fulfilled well. In other words, the methods of evaluation are operational expressions of function.

The central thrust of Dixon's research being to develop computer based design process models, the objective is to obtain a features' representation of in-progress designs so that CAD tools can provide automatic manufacturability evaluation. Intelligent mechanical computer-aided design systems will need to reason about the topology and geometry of designed artifacts. This reasoning is done in terms of features, a feature being any geometric form or entity that is used in reasoning in one or more design or manufacturing activities (i.e. fit, function, manufacturability evaluation, analysis interfacing, inspectability, serviceability, etc.) [Dixon, et. al., 1989].

Existing CAD systems do not provide the representations necessary for reasoning about various manufacturing and operations related activities. Most provide a boundary representation or a constructive solid geometry representation. To serve the geometric reasoning needs of intelligent CAD systems, representations in terms of features are needed. Emphasis is on designing with features from the outset, rather than extracting features from existing CSG or boundary representations.

Figure 3.1 displays the architecture of a design-with features system. The features used by the designer are called design-with features and they are available in a Design-With Features Library. As the designer builds an artifact, using add, modify, and delete operations, a primary representation of that artifact is automatically created in terms of the design-with features. The architecture shown is the basis for research under way at the University of Amherst.

A monitor insures that the operations requested and performed are allowable and understandable to the CAD system. The designer will not be allowed to combine features in ways that the system cannot interpret. The completeness and sophistication of the design-with-features implementation will dictate the extent to which the designers will feel constrained and limited. While the impacts of this limitation are still being researched, it is justified to an extend by the resulting standardization, which in turn will lead to improved manufacturability and product quality.

It is being reasoned that the features representation of designs may have another significant advantage over conventional representations. This approach may be
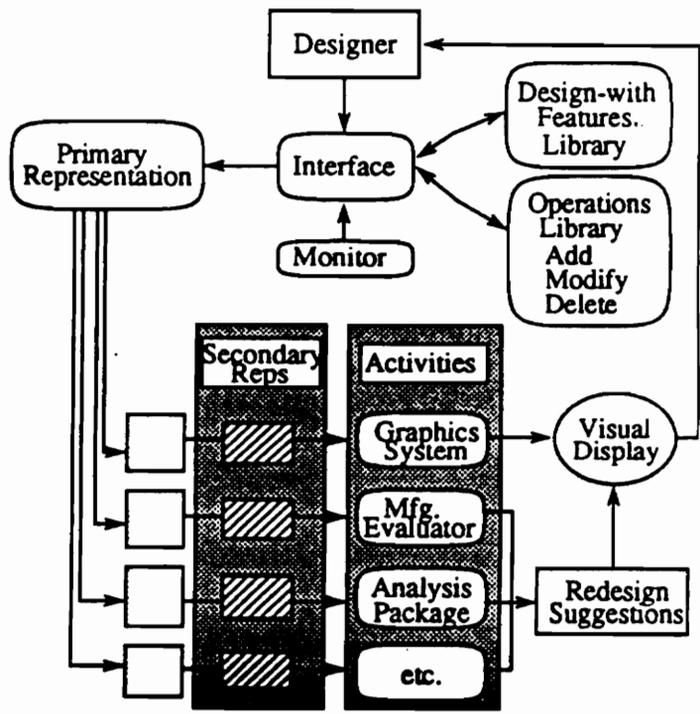
Figure 3.1. A design-with-features system architecture [Dixon, et. al., 1989].

able to capture certain types of designer functional intent. One of the severe limitations of existing CAD tools is their inability to capture the intended function of a feature or a group of features. The system, therefore, has no general basis for managing constraints later, when changes are made. A designer is required to attend to all the details associated with a design change. A CAD system with the designer's intentions included in the representations of the in-progress design is likely to help remedy this situation to some extent.

A detailed study of the origin and evolution of features representation is considered beyond the scope of this work. The reader is referred to [Vagul & Dixon 1985] and [Stiny 1989] for a more comprehensive study regarding features.

3.3 The Design-With Features Concept

According to Rinderle [Rinderle 1987], a product, specifically a mechanical device, can be described in three different ways. A list of specifications or requirements is used to describe a device at the stage of product conception. This is the functional description. A second description is through the use of engineering drawings which focus on the geometric information, tolerancing, and material types. This is a description of the form. A third representation of the product is through a process plan. The process plan is the listing of all operations necessary to fabricate the product.

There are at least three descriptions of the product; a functional imperative, a description of the form, and a prescription for fabrication. It is the relationships among function, form, and fabrication which are the essence of mechanical

design. A design is complete when all of the above descriptions have been specified. Although these specifications are generally completed in sequence, according to Rinderle, designers continuously consider the interaction among these representations. It is the relations among these three descriptions which influence the complexity of the design process, and the reliability, adjustability, maintainability, and flexibility of the system.

Designing with features help couple together specifications relative to the form and function of mechanical component being designed. This results in the advantages mentioned in the previous section.

3.4 Mechanical Design Problems

Dixon's methodology for evaluation of designs for redesign based upon the design-with-features concept is limited to the detail design of mechanical components and assemblies. It is argued that a prerequisite for development of scientific theories and principles of engineering design is the existence of a taxonomy of design problems [Dixon, et. al., 1988]. The taxonomy suggested by Dixon defines the problem in terms of six initial and final stages of knowledge. These six states are: perceived need, function, physical phenomena, embodiment, artifact type, and artifact instance. A basic problem type is then identified by specifying the initial and final knowledge states, e.g. an initial state of knowledge of artifact type and a final state of artifact instance defines a parametric design problem. Other problem types include functional, phenomenological, embodiment, attribute, preliminary, conceptual, and feasibility.

One reason for the design process being largely unsupported by formal theory is it's existence only at a very high level of abstraction. At operating levels, there are many design processes. The different design processes result from the existence of numerous design problems, numerous design people, and numerous design environments. Dixon's taxonomy does not consider the design people and the design environments, it considers only design problems. Moreover, only those design problems are considered that fall in the narrow domain of mechanical components and assemblies.

In deriving this taxonomy, it is assumed that a design problem consists of both an initial state and a final desired state of knowledge type (Figure 3.2). The initial state of knowledge can be of six types. The final state is also defined by the existence of six mutually exclusive types of final knowledge states. For a more comprehensive and in-depth explanation of each of these states, and the subclassification of these states. Refer to [Dixon, et. al., 1988].

Keeping the above classification of design problems in mind, discussion will be limited to the evaluation and redesign of parametric and configuration design problem types. A parametric design problem being one in which the artifact type represents the initial state of the knowledge and the artifact instance represents the final state of the knowledge.

Conversely, the term configuration while being the subject of some uncertainty, has been given an operational definition by Dixon. Design problems of the configuration type are represented, in part, by a structure in which the slots are the attributes of the design. While parametric design concerns finding values for
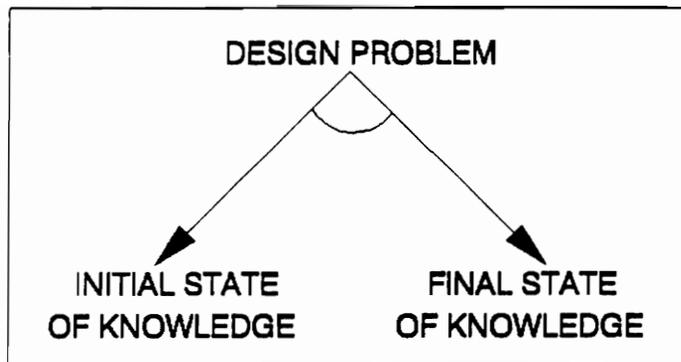
MAJOR PROBLEM TYPE	INITIAL STATE OF KNOWLEDGE	FINAL STATE OF KNOWLEDGE
FUNCTIONAL	Perceived Need	Function
PHENOMENOLOGICAL	Function	Phenomena
ATTRIBUTE	Embodiment	Artifact Type
EMBODIMENT	Phenomena	Embodiment
PARAMETRIC	Artifact Type	Artifact Instance

Figure 3.2. Design problem taxonomy [Dixon, et. al., 1988].

the attributes to be placed in the slots, the slots themselves are the elements of the configuration. Dixon considers a configuration change to have been made whenever the slots themselves are modified; that is, when attributes are added, deleted, or changed in meaning. Implicit in this is that if the arrangement or connectiveness of the attributes is changed, the attributes will also change creating a configuration change.

3.5 Design Process Models

In the area of computer-based models, development is being directed to certain design problem types as identified in the taxonomy. Moreover, the design processes are argued to be significantly different depending on whether the artifact being developed is a component part or an assembly. The models being developed reflect these differences. Most of the work has been done in the area of parametric design problem and to a lesser extent in the area of configuration design.

In the domain of parametric design problems, for component part design, the model being used is termed iterative redesign and the schema is shown in figure 3.3 [Dixon, et. al., 1989]. The activities of evaluation and redesign play a significant role. This model formed the basis for the development of two programs called Dominic I (Figure 3.4) and Dominic II (Figure 3.5) [Dixon, et. al., 1986][Duffey & Dixon 1988][Orelup 1987]. While Dominic I is said to perform designs in four narrow mechanical design domains, Dominic II is slightly more general and research is under way to make these programs more domain independent. Moreover, Dominic II represents an improvement because of the

implementation of a performance monitor, a redesign strategy selector, and a library of redesign strategies [Howe, et. al., 1986][Irani, et. al., 1989]. Figure 3.6 represents a modified iterative redesign model as being applied to configuration design.

For assembly design, the model used is called iterative respecification. It assumes that a large, complex problem has been decomposed into separate but interdependent subproblems as shown in Figure 3.7. Here the leaf nodes are component design problems solvable by iterative redesign. The other nodes are referred to as system manager nodes, and are modeled by iterative respecification as shown in Figure 3.7. A more comprehensive description of the process models in considered beyond the scope of this work. The iterative redesign model and the iterative respecification model implemented in the Dominic programs are discussed below for the parametric design of component parts and assemblies respectively.

3.6 Evaluation and Redesign in Parametric Design for Component Parts

Usage of the iterative redesign model for the parametric design of components involves a strict problem formulation. Certain terms need to be defined before theprocess can be understood fully. First, problem specification parameters are those entities whose values define a specific problem within a narrow domain. Second, design variables are those factors whose values the designer can select and control by design decisions. The number of design variables impact the size of the design space to be explored for the optimal design. The maximum and minimum limits for these must be stated in clear terms.
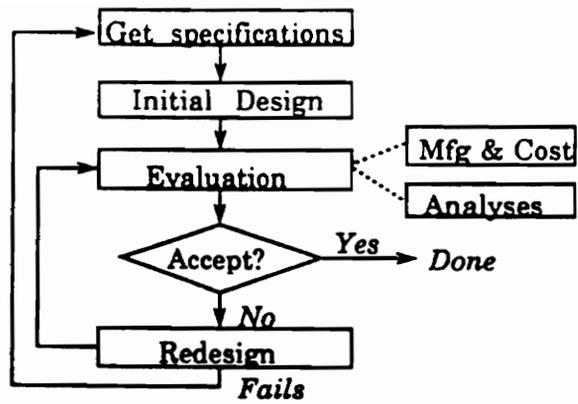
Figure 3.3. The iterative redesign model schema [Dixon 1987].
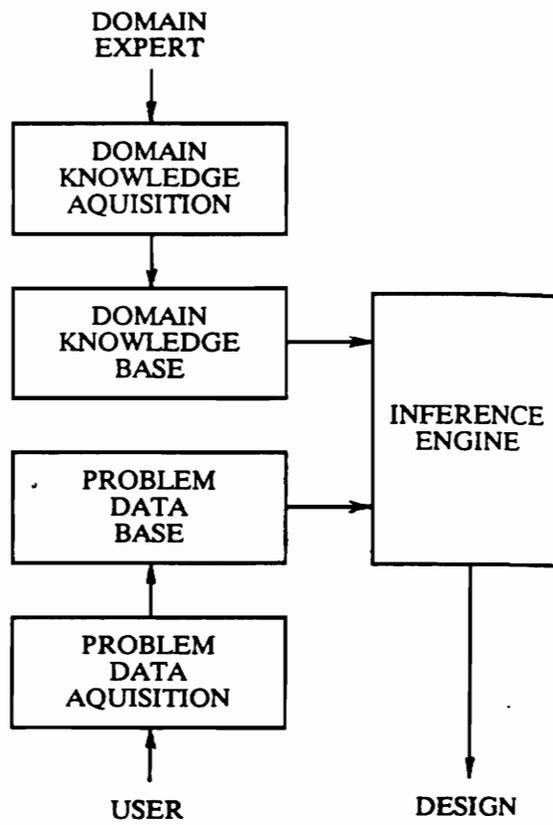
Figure 3.4. Architecture of Dominic I [Dixon, et. al., 1986].
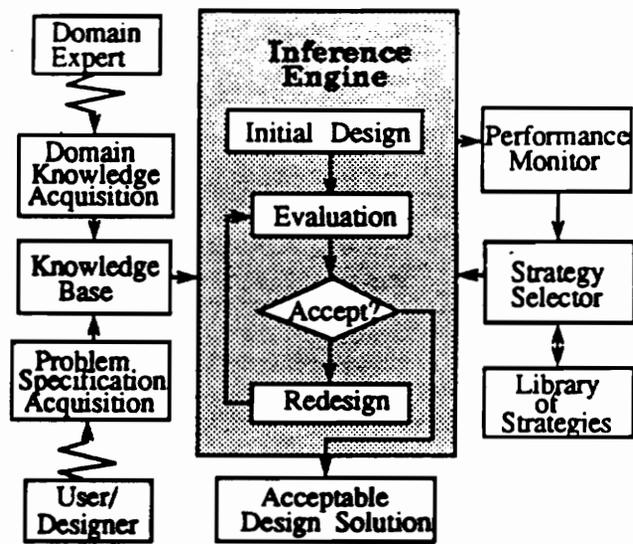
Figure 3.5. Architecture of Dominic II [Orelup 1987].
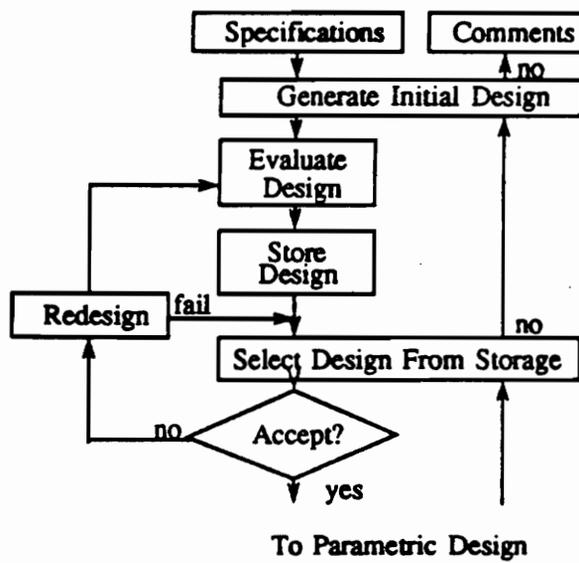
Figure 3.6 Iterative redesign schema for configuration design [Dixon, et. al., 1989].
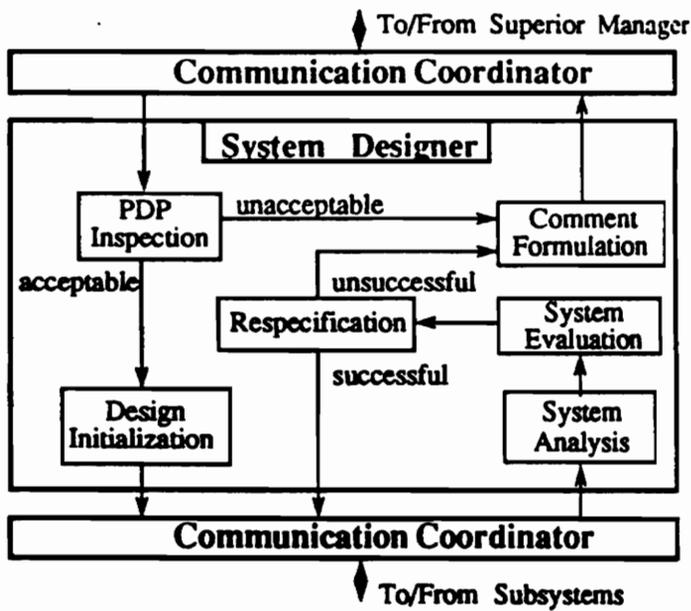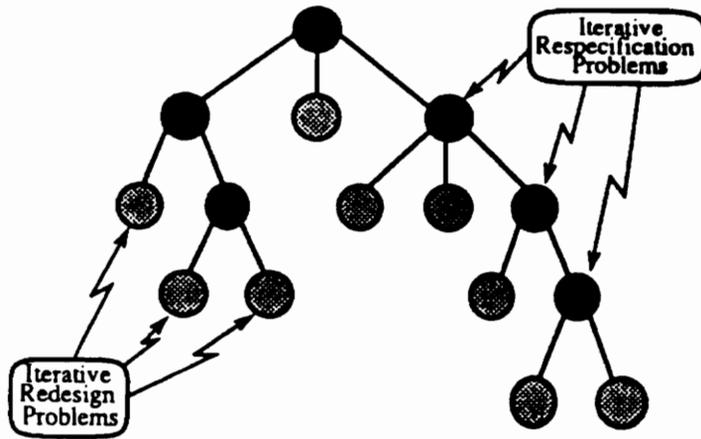
Figure 3.7 Iterative respecification schema [Dixon 1987].

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Third, performance parameters are measures of the merit of a design on separate or individual factors; overall merit includes consideration of multiple performance parameters. These parameters form the basis for the evaluation. In the Dominic programs for example, these parameters are assigned priority categories of high, moderate, or low. Design requirements are required relationships among design variables and possibly problem specification parameters. Constraints are expressed as inviolable relationships among design variables or among design variables and problem specification parameters. Dependencies are relationships between individual performance parameters and individual design variables.

According to Dixon, the easiest evaluation situation is when the design variables, performance parameters, and constraints are all numeric, and when analysis procedures exist that will produce quantitative values. Numerous means exist to enable evaluation of such problems. Classical optimization methods can be applied most effectively, it the overall merit of the design can be reduced to a single criterion function measure, and if the performance parameters can be expressed as clearly delineated constraints. These methods are very powerful, but since not many real engineering problems can be formulated as required by these methods, several methods for practical knowledge-based interfaces from real design problems to optimization methods are being developed.

A considerable amount of work has been done in multi-objective optimization, but with application primarily to decision analysis in operations research and management science. Less work has been done with an application focus on engineering design and systems development.

Dixon's research is directed to cases when the performance parameter satisfaction boundaries are necessarily inexact or "fuzzy". In some cases, even the design variable limits may be fuzzy. Classical optimization techniques do not necessarily address these situations, which involve trading off satisfaction on one or more performance parameters of differing importance against satisfaction on one or more others. Use is made of goal programming techniques and the fuzzy set theory. In the design process models, fuzzy performance satisfaction relationships are used. According to Dixon, the knowledge needed to establish the satisfaction ranges is available from experienced designer's and that a linear approximation of the fuzzy boundary is quite satisfactory. The use of continuous numerical satisfaction values, say 0 to 1, is said to be impractical, instead the satisfaction ranges is divided into sub-ranges of excellent, good, fair, poor, and unacceptable. The relative importance of performance parameters, as mentioned before, is also handled by assigning fuzzy importance levels like high, moderate, and low. And finally the overall merit of a design is evaluated from a table similar to the one shown in Figure 3.8.

Each time an evaluation is performed, the results are used to construct and maintain a dependency table, which is simply a record of the current value of an approximate relationship between each of the design variables and each of the performance parameters [Orelup 1987]. This table helps in the search for the optimal solution to the design at hand. Initial entries to a dependency table in the Dominic programs are provided by "experts". The initial information can be in terms of high, moderate, and low. Moreover, the each dependency is also

Overall Merit	Priority		
	High	Moderate	Low
Excellent	= excellent	≥ good	≥ fair
Good	≥ good	≥ fair	≥ poor
Fair	≥ fair	≥ poor	≥ poor
Poor	≥ poor	≥ poor	≥ poor
Unacceptable	unacceptable	unacceptable	unacceptable

Figure 3.8. Table for computing overall merit [Dixon, et. al., 1989].

designated as being either positive or negative. These dependency values are used to relate performance parameters and design variables as shown below:

$$\frac{x\text{-new}}{x\text{-old}} = \frac{y\text{-new}^d}{y\text{-old}^d}$$

where:

x-new = new value for the selected design variable

x-old = old value of this design variable

y-new = desired new value for the selected performance parameter

y-old = old value of this performance parameter

d = dependency value

Thus a dependency of d = +1 indicates a positive linear relationship, whereas a value = -1.45 indicates a more strongly negative relationship. The form of this equation makes possible a relatively simple transformation from qualitative and intuitive judgements about dependencies in a domain to an intuitively satisfying numerical value. After each iteration during the course of the design process, the dependency table is updated towards a more accurate set of values. It is accepted by Dixon that these values indicate local information about dependencies in the neighborhood of the last design tried, and that the values are not globally valid for most cases.

The Dominic programs implement a hill climbing algorithm, which is similar to standard optimization methods. The major difference lies in the formulation of the problem. Optimization techniques require the user to formulate problems in terms of quantitative mathematical functions, whereas Dominic's formulation is more

akin to a very low level design language; that is, Dominic accepts inputs in terms that relate more naturally to the physical design problem or domain.

3.7 Evaluation and Redesign in Parametric Design for Assemblies

Just as in the case of the iterative redesign model for components (Figure 3.3), the iterative respecification model (Figure 3.7) also involves a very strict problem formulation. Every system manager (all nodes are system managers except the leaf nodes) receives problem specification parameters from the system manager above, and develops and passes problem specification parameters to the system managers or component design modules below. Component design variables are under the control of the component design modules. System design variables are however not determined by any sub-system or component below a system manager, but must be selected by the system manager module itself.

Starting at the bottom of the decomposition tree (Figure 3.7), component design modules pass selected evaluation data up to the system managers above. They do not, however, pass an evaluation of each of their performance parameters, only the overall evaluation of the design they have settled on is passed upward. Moreover, they communicate to the system manager comments on the changes in the problem specification parameters which they have been assigned, and which would help them produce a better design. For each problem specification parameter, the comments include a requested direction for change and the magnitude, along with a priority level.

System managers also pass up to the system managers above the same

information as the component design modules. In addition to receiving this data, each system manager performs analyses as needed to obtain an evaluation of the system as a whole using the designs received from below. This is again done in the same way as described for the component parts. At this stage, a system manager has the following items available:

a) the overall evaluations of each of the sub-systems or components below.

b) comments on the current set of specifications from each module below,

c) an evaluation for each of its own system evaluation parameters,

d) an overall evaluation level for the system, and

e) a history relating the problem specification parameters it assigns and the system design variables that it selects to these evaluation levels.

With this information, the system manager modules reallocate resources and make the necessary changes to improve the design.

CHAPTER 4

PEDRYCZ AND KNOSALA'S FUZZY SET APPROACH

Knosala and Pedrycz [1987] have proposed a method of ranking and rating alternatives that are generated during the course of any designing activity. It is assumed that the information available is of three kinds: deterministic, probabilistic, and fuzzy. They also propose a method of presenting the evaluated alternatives in a graphical manner that facilitates decision making.

4.1 The Approach to Design Evaluation

It is argued by Pedrycz and Knosala, that traditional optimization techniques are highly formal and structured. Decision making in the engineering design environment however has to deal with certain intuitive and fuzzy situations [Baas & Kwakernaak 1977]. It is difficult to suggest a formal tool that can best handle a situation of this nature. Any method proposed should address the different natures of information available, and in the most general case handle data being both deterministic as well as nondeterministic, i.e. probabilisitic and fuzzy. The method presented by Pedrycz and Knosala addresses the most general case.

Since this methodology is not embedded within an overall design morphology, it is assumed by the authors that a finite set of feasible alternatives exists. Let this set be denoted by:

$$A = \{A1, A2, A3, \dots , An\}$$

Alternatives A1, A2, ..., An will be evaluated with respect to a set of criteria, each having it's own grade of importance. The obtained evaluation can exist in one of the following forms:

    a) as crisp data, i.e. a real number on a certain scale.

    b) as a fuzzy set defined in a unit interval.

    c) as a random variable specified with the aid of one of its well known

        characteristics, e.g. distribution function, density function, moments, etc.

Denote by A_{ij}^{I}, A_{ij}^{II}, and A_{ij}^{III}, the partial evaluation expressed by one of these above forms. More specifically, it expresses an evaluation of the ith alternative with respect to the jth criterion. So when these three notations are linked, for the first form, A_{ij}^{I} stands for a real number, for the second form, A_{ij}^{II} stands for a membership function viewed as A_{ij}^{II}: $[0,1]$ -> $[0,1]$. Relative to the third form, A_{ij}^{III} is viewed as a random variable $A_{ij}^{III}(x,w)$, $x \in [0,1]$ specified for example by its probability function.

At this stage attention is focussed on the problem of determining the membership function of the fuzzy sets. A method proposed by Saaty [1980] is utilized. The essence of the process is to perform a pairwise comparison of the alternatives identified. To each pair of alternatives (say the ith and the jth) one assigns a number from a scale (usually consisting of 7 +- 2 scale levels). It reflects a relative preference of the ith alternative with respect to the jth one. The more the ith alternative is preferred over the jth one, the higher is the number obtained. In the extreme case, if A_i is completely preferred when comparing to A_j, then this number is equal to the highest element in the scale. The results of this pairwise comparison are summarized in a matrix form,

$$R = [\, r_{ij} \,], \quad \text{where } i, j = 1, 2, ..., n.$$

The matrix form also satisfies two additional properties: $r_{ij} = 1$, and $r_{ij} = 1/r_{ji}$, which is the reciprocal property. It has been pointed out that the membership function describing ranking of the alternatives with respect to the given criterion corresponds to the eigenvector generated by the greatest eigenvalue of the matrix, R. In the method discussed here, Pedrycz and Knosala consider a triangle like membership function of $A_{ij}^{''}$, in other words they get three characteristic points in the [0, 1] interval. Denote them by α, β, and m respectively. stands for a lower limit, expresses the upper limit, while m is a modal value of the membership function. In this situation, when faced with an expert, his evaluation of the ith alternative may only be approximate, so instead he or she specifies the most pessimistic (lower limit) and the most optimistic (upper limit) values. The most expectable value from the experts point of view corresponds to the modal value. Instead of dealing with a single expert, a set of experts specify the three values of the estimation of preferability of the ith alternative. In this manner, upper limit, lower limit, and modal values of the membership function for the preferability of the alternatives is obtained. Therefore,

$$V_{ijmin} = \min v_{ij} (k)$$
$$V_{ijmax} = \max v_{ij} (k)$$
$$V_{ijmodal} = \sum_{k=1}^{K} v_{ij} (k) / K$$

where "k" stands for an index expressing values coming from the k-th expert, and k = 1, 2, ..., K.

Figure 4.1 displays the three possible shapes of the membership functions

derived in such a fashion. The authors also point out that the partial evaluation A_{ij} is viewed as a particular case of fuzzy values. In order to get a homogeneous and complete evaluation of any given alternative, it is necessary to make a consistent representation of the factor of uncertainty, in other words, fuzziness and probability. All the probabilistic statements must be transformed into the language of fuzzy sets or vice versa.

4.2 Determination of the Importance of Criteria

It is pointed out that while the weights assigned to the criteria may have a crisp numerical character, or a linguistic nature. The linguistic nature is however more suited to the fuzzy set theory being utilized by the authors. This allows conversion of linguistic statements such as very important criterion, and more or less important criterion into relevant membership functions defined in the unit interval. For this study, A and D assumed seven different linguistic labels describing the importance of the criteria. The weights of the criteria are treated as fuzzy sets W_j: $[0,1] \rightarrow [0,1]$, $j = 1, 2, ..., m$. The process of constructing the matrices is slightly different than before. At first, one chooses a criterion that is viewed as being important, and thereafter evaluations are performed for the remaining criteria in the problem.

For two criteria, one being "important" and the other "very important", numbers are assigned from [0,1]; these numbers are modified with a step equal to (0.1). The better the two numbers reflect description of the criteria by a given expert, the more they satisfy the expert. This pair of numbers that completely reflects difference between the criteria is ranked at the highest rate reaching the highest
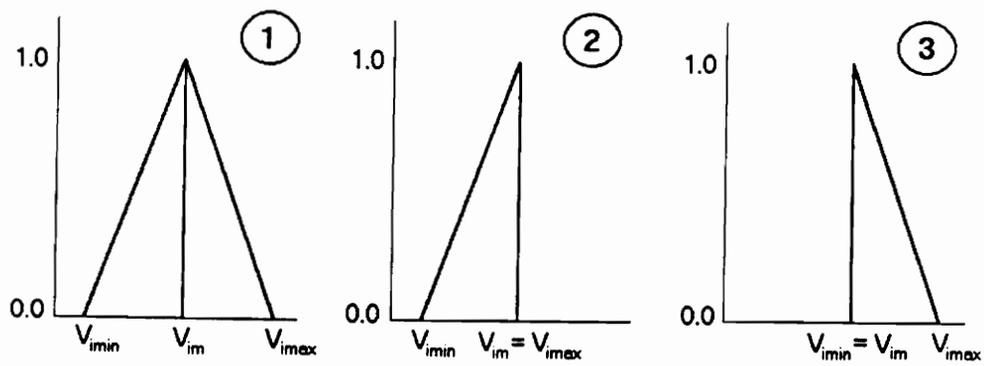
Figure 4.1   Possible shapes of the membership function [Pedrycz & Knosala 1987].

number in the scale attached. A pair of the same numbers attached to two diverse criteria is ranked at a very low level. Thus the elements in diagonal of the formed matrix are set to 1.0. An inverse of these two numbers provides an inverse of the evaluation. Figure 4.2 reflects an example of membership functions for three linguistic labels, important, less important, and very important. An interpretation of these membership functions thus becomes obvious. For each element of the unit interval, $z \in [0,1]$, the corresponding value of the membership function $W_k(z)$ expresses to which extent "z" fits the k-th linguistic category W_k.

4.3 Aggregation of the Partial Evaluations of the Alternatives

An aggregation of the partial evaluations of the alternatives is performed by taking into account the relative importance or weightage of the relevant criteria. This aggregation is expressed as:

$$Z_i = F(A_{i1}, A_{i2}, ..., A_{im}, W_1, W_2, ..., W_m), i = 1, 2, ..., n.$$

where Z_i stands for the fuzzy set defined in $[0,1]$ and F denotes an aggregating function. It is common to treat the above function as linear. Then, in accordance with the extension principle, the membership function of Z_i is calculated by:

$$Z_i(z) = sup[min(A_{i1}(a_1), A_{i2}(a_2), ..., A_{im}(a_m), W_1(w_1), W_2(w_2), ..., W_m(w_m))]$$

In this case, the supremum is taken over all the elements $a_1, a_2, ..., a_m, w_1, w_2, ..., w_m$, such that they satisfy the following relationship:
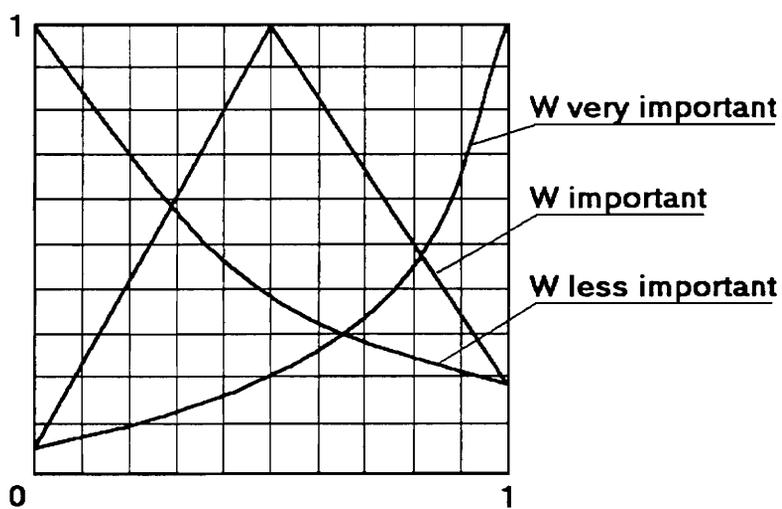
Figure 4.2. Membership functions for three linguistic categories [Pedrycz & Knosala 1987].

$$z = F(a_1, a_2, ..., a_m, w_1, w_2, ..., w_m)$$

In such a situation, when limiting the equation to a linear form, in other words, an additive aggregating function, the above formula converts into:

$$Z = \sum_{j=1}^{m} a_j w_j \bigg/ \sum_{j=1}^{m} w_j$$

where z, a_j, $w_j \in [0,1]$. Next, according to A and D, it is plausible to replace the fuzzy sets by their pointwise representation and simultaneously generate an index of interactivity among them. This is done using the following formulae:

A weighted mean, expressing pointwise view on the alternatives:

$$Z_i \Rightarrow T_i = \int_0^1 z . Z_i(z) \, dz \bigg/ \int_0^1 Z_i(z) \, dz$$

An interaction index z_i, z_j defined as:

$$b_{ij} = \int_0^1 \left(Z_i \cap Z_j \right) z . dz = \int_0^1 \min \left(Z_i(z), Z_j(z) \right) dz$$

The above equation helps visualize how the fuzzy sets Z_i and Z_j intersect. If on the other hand, no overlap exists between them, then the interaction is equal to zero. Figure 4.3 displays a graph of preferences of the alternatives, that has been built using the formulae given above. It helps visualize relationships existing between the alternatives being discussed.
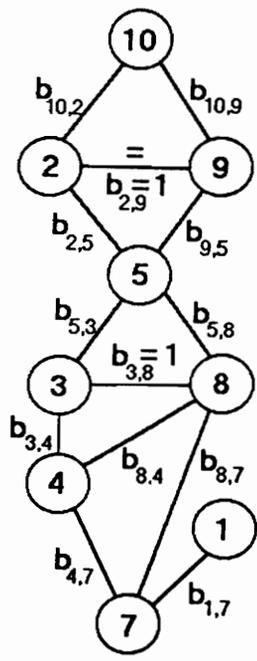
Figure 4.3 Graph of the preferences of the alternatives [Pedrycz & Knosala 1987].

CHAPTER 5

CRITICAL REVIEW OF THE EVALUATION METHODOLOGIES

The goal of this thesis was to focus on design evaluation, a specific aspect of engineering design. Its intent was to study the state-of-the-art in this area. In this chapter, the methodologies will be critically reviewed. Two issues played an important role in the selection of these methodologies. First, only those methodologies were selected that are not limited in their application potential to a narrow problem domain. And secondly, the final selection represents most of the current and diverse approaches to the subject of design evaluation.

5.1 Nature of Scientific Research

According to the dictionary definition [Websters 1989], the term *science* stands for accumulated systematized knowledge, especially when it relates to the physical world, and the term *theory* represents the general principles drawn from a body of facts. According to Eder and Hubka [1989], the term "Design Science" has long been accepted as describing a body of knowledge about the goals, processes, procedures, techniques, and objectives of engineering design, including a theory of engineering design. The existing but isolated islands of knowledge in the domain of engineering design are slowly being drawn together into a cohesive whole. This work is intended to be a contribution in that direction.

Research in the engineering domain, like in any other field, is following two parallel paths. First, the speculative, reflective, and to some extent philosophical way of

postulating hypotheses, formulating theories, modelling, and subsequent testing. And second, the classical experimental, empirical way of observing, describing, abstracting, modelling, generalizing, and formulating hypothesis and theories. The empirical way usually includes elements of self-observation, as well as impartial observation of experimental subjects. While neither of the two routes can be self-sufficient, they must be (and to some extent are being) coordinated for consistency and plausibility.

5.2 Design Evaluation - Diverse Approaches

Ostrofsky's work has been largely of a theoretical and philosophical nature, on the other hand the design dependent parameter approach, while being theoretical, depends upon empirical curve fitting and parametric cost estimations. Dixon's primary research thrust has been to observe human designers and emulate their behavior and hopefully their expertise through computer-based models. The process suggested by Pedrycz and Knosala is also largely theoretical.

Of the four evaluation methodologies studied, three, namely, Dixon's evaluation for redesign, Ostrofsky's methodology for design and development, and Fabrycky's design dependent parameter approach, are embedded within an overall engineering design morphology. Pedrycz and Knosala's fuzzy set approach is typical of processes that can be used once the alternatives have been identified, although it is not part of an overall and complete process of engineering design.

Each of these methodologies have a common goal and objective; to help

designers identify the best of the available and feasible alternatives. The approach is each case is, sometimes slightly and sometimes radically, different. While the diverse and varied approaches signal healthy research in this area and are desired, there needs to be some understanding in the research community on the language and terminology used to support this work. The advantages could be significant. A common language can further communication between the different "schools of thought", and generally benefit research in the area.

The four methodologies having been presented in some detail, this chapter will focus on an analysis and review of the same. Certain similarities and differences will be highlighted. The terms used by different authors will be defined and brought together upon a common platform as a first step towards a "common language". The developments in the optimization community to further help the process of design evaluation will be summarized, as also the optimization techniques currently being used in the four approaches. Certain management related concerns will also be highlighted. Moreover, each of the methodologies will be analyzed with respect to the following concerns:

  a) The limitations of a methodology under certain conditions. For example, how well does it respond to a primarily qualitative set of criteria? As stated earlier, very often, many of the goals, requirements, and criteria of a design activity are largely qualitative in nature.

  b) The limitation of a methodology in that it's application potential is too domain specific. Faced with a wide diversity and increasing complexity of the designing activity, even in the same organization, generality in the approach to evaluating designs may be desirable.

  c) The life-cycle completeness of a methodology. With the largely sequential

nature of the designing activity giving way to a more concurrent approach, considerations like producibility, supportability, and disposibility need to be addressed during the early design phases.

d) While there is a desirability for the methodology to be life-cycle complete, it should also be product complete. In other words, does the methodology remain relevant and compatible as the design process becomes increasingly detailed.

e) The robustness of the methodology. For example, how well does it consider uncontrollables like interest rates, inflation, labor rates, labor availability, etc.

f) The adaptability of the methodology to a computer-aided environment.

5.3. The Diverse Terminology used in Design and Design Evaluation

The different terms used by the authors of the methodologies being studied will be defined in this section. To proceed with the definitions in a systematic manner, the sequence and structure as shown in Table 5.1, and keyed to the letters, will be maintained in the following paragraphs. Moreover, while the similarities and differences implicit in definitions are obvious, whenever possible the definitions will be strenghtened with examples.

a) Parameters. Webster's dictionary defines this term as a set of physical properties whose values determine the characteristics or behavior of something. This general term has been modified in a host of different ways by the various authors.

Table 5.1. Diverse terminology used in design research.

	Ostrofsky	Fabrycky	Dixon	Pedrycz & Knosala
A) PARAMETERS				
Problem Specification / Definition Parameters			X	
Performance Parameters			X	
Design Parameters	X			
Design Dependent Parameters		X		
Design Independent Parameters		X		
B) DESIGN VARIABLES		X	X	
C) FUNCTION				
Criterion Function	X			
Objective Function			X	
Evaluation Function		X		
Membership Function				X
D) COST EFFECTIVENESS		X		X
E) SYSTEM EFFECTIVENESS		X		
F) DATABASES		X	X	
G) INFERENCE ENGINE			X	
H) RELATIVE WEIGHTS	X	X	X	X
I) DESIGN PHASES	X	X		
J) DESIGN FEATURES			X	
K) INPUT-OUTPUT MATRIX	X			
L) DEPENDENCY TABLE			X	

Dixon defines two kinds of parameters, problem specification or definition parameters and performance parameters. Problem specification or definition parameters are those parameters whose values define a specific problem in a domain. For example, in the domain of standard V-belt design, the specification parameters are the horsepower to be transmitted, center distance limits, drive speed, desired load, and desired life of the system. On the other hand, performance parameters are those factors by which the quality of a design is judged. Examples are the stress or deflection of a beam, weight and reliability of an airplane, etc.

Ostrofsky uses the term design parameter. Very often the criteria identified for evaluating a system under development are such that their direct measurement for the various candidate systems is not possible. This generates the need for methods that allow the evaluation of the candidate systems in terms that relate the evaluation to the criteria established. These terms or elements that are usually directly measurable and which can be combined to provide a meaningful measure of a criterion, and which at the same time are characteristics of the candidate systems are called design parameters. Moreover, the establishment of the design parameters depends upon the understanding of the nature and characteristics of the candidate systems under review. Examples of parameters are total volume, weight, number of moving parts, operating time, assembly time, etc.

Fabrycky defines two different classes of parameters in his methodology, design dependent parameters and design independent parameters. The design independent set consists of those factors that are beyond the control of the designer, but which affect the overall effectiveness of all candidate systems and

can significantly alter their desirability. Examples include interest rate, inflation rate, labor rate, labor availability, and demand. On the other hand, the design dependent parameter set represents those factors whose values are under control of the designer and are further impacted by the speciality disciplines being brought to bear in the development process. Moreover, every instance of the design dependent parameter set represents a possible candidate system. Examples of design dependent parameters include reliability, maintainability, time to altitude, throughput, transmitted load, etc.

It is important to point out a similarity in Ostrofsky's and Fabrycky's approach towards establishing parameters and their values. Both propose a hierarchy of parameters (Figure 2.5 and Figure 2.9). The higher order parameters if not directly measurable are broken down into lower order parameters until direct measurement is possible for the purpose of evaluation. Both use this approach to link parameters to criteria.

b) Design variables. Dixon uses the term design variables but defines it differently for the component and system levels. At the component level, design variables are the set of factors that completely and unambiguously define a component. They are factors whose values the designer can select and control by design decisions. Moreover, the number of design variables determines the size of the design space that must be explored. For example, in the heat sink domain, fin thickness, fin spacing, and fin height are design variables. On the other hand, at the system level, the design variables are factors that are not chosen by any of the sub-systems but are a part of the system design. They affect the problem specification parameters of the sub-systems. For example, in a

system composed of posts and beams, the number of posts is a system design variable.

Fabrycky also uses the term design variables, but his definition is radically different from that of Dixon. Once a set of feasible candidate systems has been generated, each of the candidate systems is optimized over the set of design variables before being compared with each other. Here, it must be restated that the sets of values of the design dependent parameters represent instances of possible candidate systems (refer footnote #5 on page 53). Moreover, a candidate system is termed feasible if none of the requirements are being violated. Unlike design dependent parameters, different values of the design variables do not represent different candidate systems. They merely represent a set of factors over which each set of design dependent parameters or each candidate system must be optimized before being evaluated with respect to the other candidate systems under consideration.

c) Function. With the goal being design evaluation, the objective of each of the methodologies is to model the system or product under development such that all the significant and not so significant factors have been considered. The four methodologies presented exhibit four considerably diverse ways to model system characteristics. The result of this modelling is a criterion function in Ostrofsky's approach, an objective function in Dixon's approach, an evaluation function in Fabrycky's approach, and a set of membership functions in Pedrycz and Knosala's approach.

In the first three approaches, the criterion, objective, and evaluation functions

represent essentially the same thing. These are three different names as preferred by three different authors to refer to that final function which is the result of all the modelling and which represents the essence of the system's or product's characteristics.

Ostrofsky uses the term criterion because his ultimate function consists of the selected criteria, which in turn may consist of the various parameters. Dixon uses the term objective, which is also the term used in classical optimization to represent the overall objective of the analysis or modelling effort. Fabrycky on the other hand uses the term evaluation in order to refer to the process under way, i.e. design evaluation. Pedrycz and Knosala use the term membership function, because their approach calls an for a pairwise comparison of the various candidate systems and the fuzzy representation of the aggregated partial evaluations of each of the candidate system over the interval [0, 1].

d) Effectiveness. Only Fabrycky and Blanchard use this term. They identify two levels of effectiveness, system effectiveness and cost effectiveness as shown in Figure 1.1. System effectiveness, as the term implies, refers to the effectiveness of the system or product under development with respect to the various criteria identified, like reliability, maintainability, and other performance related factors like time to altitude, capacity, etc. Cost effectiveness on the other hand relates system effectiveness with the resources expended and committed or life-cycle cost. Fabrycky and Blanchard while acknowledging that overall cost effectiveness may be very difficult if not impossible to ascertain, suggest that the designer employ various cost effectiveness figures of merit as described in Section 2.3.2.

e) Databases. Fabrycky and Dixon explicitly suggest the use of databases to facilitate the process of design and design evaluation. Refer to Figures 2.10, 3.1, 3.4, and 3.5. Fabrycky incorporates an economic and physical database within the computer-aided concurrent engineering morphology, along with another database linked to the CAD tool to archive various design iterations or candidate systems. Dixon, because of the thrust of his research efforts are to model the design process on the computer via an expert system, makes use of a domain knowledge base which in turn acquires knowledge from an expert in that domain. Along with this domain knowledge base, Dixon maintains a library of the various features that are to be used to construct the form of the artifacts, and a library of operations like add, modify, and delete, that can be used on the various features.

f) Inference engine. This term is explicitly used only by Dixon and suggests that his research involves artificial intelligence. The inference engine works on a set of strategies with the objective of improving the current design. The inference engine decides which performance parameters need to be worked on further, by how much do the selected performance parameters have to be changed in order to meet the requirements, which design variables are related to the selected performance parameters, and by how much should these be changed, and in case the selected design variables are related to other performance parameters, how does any change in these variables affect those other performance parameters. Use is made here of the dependency table which will be described later in this section. Presently, the inference engines in the Dominic models work on one performance parameter and one design variable at a time. Dixon acknowledges the limitation and proposes this to be an area that needs further research effort.

While not making use of the inferencing and expert system approach, block 4 of the computer-aided concurrent engineering morphology proposed by Fabrycky (Figure 2.10), conveys to the designer not only the overall evaluation measure, E, but also the deviations, both positive and negative, of the design dependent parameters. It is, however, up to the designer to ascertain the changes necessary to make up for any serious and negative deviations. The design evaluation display (DED) is used to convey this information (Figure 2.12). There is potential here to make use of an inferencing approach similar to the one being used presently by Dixon, in order to make suggestions to the designer.

g) Relative weights. All four methodologies being studied make use of the concept of relative weights. There are clearly two approaches to making use of this concept. Using deterministic and numerical values for the weights, or using the fuzzy approach to assigning weights to the various criteria. These approaches, as being used by the different authors, will be discussed in a following section.

h) Design phases. As mentioned earlier, three of the methodologies being studied are embedded within an overall design morphology. These morphologies, to be complete, must address the entire life-cycle. Ostrofsky and Fabrycky use the term phases to segment the various stages in design, development, and operations.

Ostrofsky, along with Asimow, divide the system or project design and development activity into the primary design phases and phases related to the production and consumption cycle. The primary design phases consist of the

feasibility study, the preliminary design, and the detailed design. The phases related to the production and consumption cycle consists of planning for production, planning for distribution, planning for consumption, and planning for retirement (Figure 2.2). Fabrycky, along with Blanchard, broadly divide the system life-cycle into the acquisition and utilization phases. The acquisition phase consists of all design, production, and distribution related activities, and the utilization phase consists of all the operations, support, and retirement or disposal related activities (Figure 2.7).

Dixon does not use the concept of phases. In order to convey the difference in the activities as the design evolves he uses the concept design problems (Refer to Section 3.2 and Figure 3.2). A design problem is defined by the initial state of the knowledge and the desired final state of the knowledge. Thus, as discussed in Section 3.2, a parametric design problem is one in which the artifact type represents the initial state of the knowledge, and the artifact instance represents the desired final state of the knowledge. Comparing this with the phases concept, the parametric design problem falls in the detailed design phase according to both Ostrofsky and Fabrycky. Moreover, it is towards this design problem that most of Dixon's research efforts are directed.

i) **Design features.** This is a term used only by Dixon. It is described as a geometric form or entity that is used in reasoning about one or more design or manufacturing related activities (Refer Section 3.1 and 3.2). In terms of computer-aided design, a feature can be a significant portion of a part, an entire part with respect to the assembly, or even an assembly with respect to the system, depending on the current point of view. The important concept being that the

feature, and not the part can be treated as a graphical unit to analyze it's performance or contribution to the product. Dixon is however dealing with features at the artifact level. The Dominic models incorporate a design-with features library and an operations library which facilitates and guides the creation of forms by the designer.

j) Input-output matrix. This is a concept used by Ostrofsky (Refer to Section 2.2.1 and Figure 2.4). The construction of this matrix impacts the selection of the criteria. It is at this stage that the designer must exercise discipline in order to consider uncontrollable external factors that may impact the ultimate desirability of the candidate systems, and to make the subsequent evaluations life-cycle complete.

k) Dependency table. This is a concept used by Dixon. The dependency table is a matrix relating each design variable to each performance parameter. This table is used by the inference engine as described earlier. The initial entries to the matrix are done by a domain expert, and may be subsequently changed or adjusted by the model.

5.4 Comparison of the Selected Methodologies

Having discussed the diversity in the terminology used by the various authors, the selected methodologies will be compared with respect to some of the points indicated at the beginning of Section 5.1 and in Chapter one. Table 5.2 indicates the nature of the following comparisons which follow.

Table 5.2. Comparison of the selected methodologies.

	Ostrofsky	Fabrycky	Dixon	Pedrycz & Knosala
RELATIVE IMPORTANCE	NUMERICAL VALUE	NUMERICAL VALUE	FUZZY	FUZZY
OPTIMIZATION	YES	YES	YES	NO
Optimal Design	X			
Optimum Design	X			
MANAGEMENT OF DESIGN FUNCTION	ADDRESSED	ADDRESSED	NOT ADDRESSED	NOT ADDRESSED
APPLICATION DOMAIN	GENERAL	GENERAL	MECHANICAL COMPONENTS & SUB-ASSEMBLIES	GENERAL
LIFE-CYCLE COMPLETENESS	YES	YES	RESTRICTED	OPPORTUNITY EXISTS
PRODUCT COMPLETENESS	YES	YES	YES	OPPORTUNITY EXISTS
ADAPTABILITY TO COMPUTER	DIFFICULT	YES	YES	YES
ROBUSTNESS	OPPORTUNITY EXITS	YES	NO	OPPORTUNITY EXITS
DESIGN MORPHOLOGY	EMBEDDED WITHIN	EMBEDDED WITHIN	EMBEDDED WITHIN	NO
TESTING	ADDRESSED	ADDRESSED	NOT ADDRESSED	NOT ADDRESSED

5.4.1 Relative importance of the criteria

The significance of the process of assigning relative importance or weights to the criteria selected while evaluating designs is universally accepted. The difference however lies in the approach for doing so. There are two clear "schools of thought". Ostrofsky contends that the deterministic assignment of weights to the criteria is not only possible but the best way to go. He argues that even the most qualitative criterion can be modelled in terms of parameters that are measurable and quantitative. A substantial amount of research has been done by him on the nature and characteristics of weights relative to the values of the criteria. He proposes that weights assigned to criteria may be constant over the entire range of values of the criteria, or may assume different values in certain intervals, or may be continuously variable over the entire range of values for the criteria, and finally may be continuously variable with discontinuities over the range (Table 2.3). Models have been developed to reflect these different characteristics. Fabrycky also explores the use of numerical weights in [Midkiff & Fabrycky 1991].

Dixon and Pedrycz & Knosala on the other hand argue for fuzzy relationships in the assignment of relative importance of the selected criteria. An attempt to quantitatively model a highly qualitative criteria may require excessive assumptions which in turn may result in the loss of a certain amount of information or "truth". According to Dixon, the knowledge to establish satisfaction ranges is available from experienced designers, and that the linear approximation of the fuzzy boundary is quite satisfactory.

5.4.2 The role of optimization in design

The design process consists of need analysis, conception, organization, analysis, evaluation, feedback and refinement. Explicit in the overall process is the evaluation, test and selection of the "best" design from a set of feasible alternative designs. This is the main role and objective of optimization in the design process. According to Azarm [Azarm, et. al., 1987], an optimized design can be defined as the best feasible rational design. In order to be best, a desired objective function should be minimized or maximized. In order to be feasible, a set of requirements should be satisfied, and to be rational, all the required information and knowledge about what is to be optimized should be known so as to facilitate the development of an appropriate model.

At this stage it is important to note that there exist numerous and well tested optimization methods which can be applied. A limitation in most existing models, however, is the strict nature of the problem formulation required. Moreover, most of the available optimization techniques are unable to handle qualitative data. Dixon argues that not many real engineering problems are formulated as required by the traditional optimization techniques. However, research is under way for developing methods for practical knowledge-based interfaces from real design problems to optimization methods [Dixon & Simmons 1985][Kamal, et. al., 1987].

In the most general case, the design optimization model involves a set of variables that constitute an objective function which needs to be either maximized or minimized, and a set of constraints expressed in terms of the variables that must be satisfied for a design alternative to be termed feasible. The objective

function should be expressed in terms of the design variables, i.e., F(x), and the constraints expressed by functional relations such as h(x) = 0, and or g(x) < = 0. From a modelling point of view, the functions F, h, and g may be given explicit algebraic expressions of the design vector x. Often these are derived directly from basic equations and laws of engineering science. However, basic engineering principles are not always capable of describing the problem completely, so use of empirical or experimental data must be made to establish relationships through curve fitting of data or other means. In the general case, more than one objective function may exist, and moreover the objectives may be competing and may require some compromise.

To address the above problem, significant progress has been achieved in the domain of multi-objective optimization, with some application to engineering design [Balachandran & Gero 1987][Dlesk & Liebman 1983][Papalambros 1987][Parkinson, et. al., 1984][Stadler 1984]. Another area of development in the field of optimization is the ability to decompose a big problem into sub-problems that lend themselves to easier optimization. Sobieski has developed a method for optimizing large problems by decomposing the problem into smaller subproblems arranged into a tree hierarchy [Sobieski, et. al., 1982]. Similar work in the domain of multi-level optimization has been done and is amply documented.

But as a final word, the process and method of optimization finally selected depends upon the nature of problem formulation. More important in this study was the framework being used by the authors in arriving at the objective function. The formulation of the objective function is of primary importance. It must reflect completely and truly the characteristics desired in the system being developed.

Evaluation and the optimization process used to support the selection of the "best" candidate system is only as good as the problem formulation.

5.4.3 Management of the design function

A design engineer in the real world faces responsibility for the technical progress of the organization. This responsibility manifests itself in the products that are conceived, designed, tested, and finally approved through the various engineering design groups. Moreover, the product must meet user requirements and be safe during operation in the field. To achieve these results the engineer uses the design morphology most suited or compatible with the organization of which he or she is part. Embedded within this morphology will be the design evaluation methodology, again the selection of this depends upon the past experience of the decision makers, the compatibility of the methodology with the overall morphology, and the organization itself.

Effective use of any of the morphologies or design evaluation methodologies studied during the course of the work, not only depends upon understanding it, but also upon the effectiveness of its management. In other words, beyond the engineering related, substantially technical responsibilities, the engineering design manager must also be a competent manager of people, budgets, and time. He or she must understand his staff and learn what motivates them, how they respond to challenges and stress. The success of any methodology not only depends upon it's theoretical or empirical trueness for success, but also, and sometimes more so, upon the people who utilize it.

Of the four methodologies studied only Fabrycky and Ostrofsky follow up the technical framework for design dependent approach and the criterion function approach, and the overall design morphology with a discussion of the engineering management function, and it's impact upon the success of the approach. Blanchard and Fabrycky suggest that early system design and planning can be translated into a set of technical requirements and management requirements. The relationships that exist between these two sets of requirements are shown in Figure 5.1. The systems engineering management plan (SEMP) addresses activities and procedures necessary to accomplish and achieve the stated objectives. The SEMP serves to integrate the activities of the various engineering related activities that play a role in systems development. Figure 5.2 makes explicit the scope of the systems engineering management plan. Organization of the various activities listed becomes the other significant activity and concerns the identification of the activities that need to be accomplished, the grouping of the activities identified, and staffing the structure with the appropriate personnel skills to perform the various functions. It is argued that the establishment of the organizational structure for a system project is impacted by the objectives, the characteristics of the system, the tasks identified, the schedule and budget requirements. According to Bronikowski [Bronikowski 1986], organizational structures are significantly impacted by company strategy. This strategy in very general terms could be one of the following:

    a) First in the field

    b) Fast follow

    c) High-volume, low-cost producer

    d) Customer needs producer

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                    │      PROGRAM REQUIREMENTS        │
                    └─ ─ ─ ─ ─ ─ ─ ─ ─ │ ─ ─ ─ ─ ─ ─ ─┘
                    ┌─────────────────────────────────┐
                    │  PROGRAM MANAGEMENT PLAN (PMP)   │
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PROGRAM TECHNICAL REQUIREMENTS

PROGRAM MANAGEMENT REQUIREMENTS

SYSTEM SPECIFICATION (TYPE A SPECIFICATION)

SYSTEM ENGINEERING MANAGEMENT PLAN (SEMP)

RELATED PROGRAM MANAGEMENT PLANS

DEVELOPMENT SPECIFICATION (TYPE B SPECIFICATION)

PRODUCT SPECIFICATION (TYPE C SPECIFICATION)

PROCESS SPECIFICATION (TYPE D SPECIFICATION)

MATERIAL SPECIFICATION (TYPE E SPECIFICATION)

INDIVIDUAL PROGRAM PLANS

- FUNCTIONAL DESIGN PLAN.
- RELIABILITY PROGRAM PLAN.
- MAINTAINABILITY PROGRAM PLAN.
- HUMAN FACTORS PROGRAM PLAN.
- SYSTEM SAFETY PROGRAM PLAN.
- INTEGRATED LOGISTIC SUPPORT PLAN (ILSP).
- LOGISTIC SUPPORT ANALYSIS PLAN (LSAP).
- PRODUCIBILITY PLAN.
- SUPPLIER ENGINEERING PLAN(S).

- CONFIGURATION MANAGEMENT PLAN
- TEST AND EVALUATION MASTER PLAN (TEMP).
- MANUFACTURING PROGRAM PLAN.
- TOTAL QUALITY MANAGEMENT PLAN (TQM).

Figure 5.1. Relationship between program technical and program management requirements [Blanchard & Fabrycky 1990].

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                           ┌─────────────────────┐
                           │ SYSTEM ENGINEERING  │
                           │  MANAGEMENT PLAN    │
                           │       (SEMP)        │
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PART I	PART II	PART III
TECHNICAL PROGRAM PLANNING, IMPLEMENTATION AND CONTROL	SYSTEM ENGINEERING PROCESS	ENGINEERING SPECIALTY INTEGRATION

Describes the technical program tasks that must be plannned and implemented in the fulfillment of system engineering management objectives.

Describes the system engineering process as it applies to the definition of system requirements and the development of those requirements into a final product configuration.

Describes the system requirements in the various engineering specialty areas and the integration of these specialty areas into the overall "mainstream" engineering design and development effort.

INCLUDES

- Program requirements (statement of work).
- Organization.
- Supplier or subcontractor requirements (contracting).
- Program interfaces.
- Work breakdown structure (WBS).
- Scheduling.
- Technical performance measurement (TPM).
- Cost estimating/reporting.
- Program monitoring/control.
- Risk management.

INCLUDES

- Identification of need.
- Feasibility analysis.
- Operational requirements.
- System maintenance concept.
- Functional analysis.
- Requirements allocation.
- System analysis and trade-offs (optimization).
- System design.
- System test and evaluation.

INCLUDES

- Reliability engineering.
- Maintainability engineering.
- Human factors engineering.
- Safety engineering.
- Value/cost engineering.
- Logistics engineering.
- Components engineering.
- Producibility.
- Quality engineering.
- Other engineering and design-related disciplines.

Figure 5.2. The scope of the system engineering management plan [Blanchard & Fabrycky 1990].

Moreover, the structure of an initially defined organization may need to change over the course of the system life-cycle in order to address the concerns of each phase more effectively. Design is dynamic, and the organization should adapt to the changing environment.

Numerous publications exist that address the engineering design function in an organization[Dean & Susman1989][Steward 1981][Steward 1981a][Thomas 1977]. There is, however, need for further research on this issue considering the metamorphosis that the design process is undergoing today, from becoming a primarily sequential process to a more concurrent activity.

5.4.4 Application potential of the evaluation

Three of the four methodologies studied are extremely general in their problem formulation. A framework exists in each to address design problems independent of the problem domain. As stated earlier, the increasing complexity and diversity of design problems make this problem domain independence a very attractive feature.

Dixon's research has been predominantly influenced by the objective of trying to generate computer-based engineering design process models. Because of the nature of the research, and the features based approach, the applicability of the methodology proposed by him is limited to the domain of mechanical engineering based problems. Moreover, the research to date been even more domain specific than that. The models have as yet addressed only the parametric and configuration design problem types, as defined by him. Dixon argues however,

that the research strategy is to work in a variety of specific problem domains, work with a set of relatively simple cases that involve the research issues intimately, and then to move on to more complex and general cases.

Here it must be stated that the different methodologies studied are still being researched and are by no means mature. They are in different stages of development depending upon the research strategy adopted by their proponents.

5.4.5 Life-cycle completeness of the evaluation

The competition that exists today on a global scale, along with the need to make the most of the scarce resources available to the organization, almost demands a high degree of cost effectiveness. To achieve this overall cost effectiveness, the designer must consider and address all issues that impact it throughout the life-cycle of the product or system under development.

Each of the methodologies studied address the life-cycle issues to varying degrees, and in their own different ways. In the paragraphs that follow this will be made clear. At this point it is important to mention that the most important factor in the consideration of issues that impact system effectiveness in the later stages of the life-cycle is the discipline and the desire to do so by the designer or the design team. The different methodologies offer frameworks that facilitate the work of the design team from this perspective, assuming there is the will to do so.

The most significant phase in the approach proposed by Ostrofsky when life-cycle issues pertaining to the production, utilization, and disposal phases can be

made integral to the process of evaluation and selection is the generation of the input and output matrix. During the process of filling up the matrix (Figure 2.4), the environmental and intended inputs, and the desired and undesired outputs should reflect the issues that the designer needs to address during the various phases of the life-cycle. At this stage, it is the responsibility of the designer to consider factors and issues that not only address the technical aspects of the system relative to the performance of the prime mission, but also factors that broaden the problem to address the ensuing phases of production and utilization.

The effort expended in generating the above matrix helps bound the problem. Moreover, this matrix of inputs and outputs becomes the foundation for the identification of the criteria to be used in the evaluation and selection process that follows. According to Ostrofsky, if the input-output matrix is inadequate, it should be revised to properly reflect the needs of the project and the production and utilization phases, before any further meaningful progress is possible.

The fuzzy set approach has been proposed as a very general process, without the benefit of being embedded in any one particular design morphology. The approach has been proposed without the authors making explicit the nature of the variables to be considered or the significance of addressing life-cycle issues. However, as stated above, this approach is general enough and leave it to the user to incorporate and consider issues that will make the overall evaluation life-cycle complete to the extent intended.

The identification and selection of the design dependent parameters and the design independent parameters impact the extent to which design evaluation is life-cycle complete in the case of the approach proposed by Fabrycky. Once

again the framework exists, but it is up to the designer to make the most effective use of it. The design dependent parameters address the system characteristics as impacted by the various speciality engineering disciplines being brought to bear in the development process. Hopefully the characteristics identified reflect the needs, requirements, and also the constraints of the production and utilization phases. A note here on the constraints, these can be of two types, technology related, and or resource and facilities related. On the other hand, the design independent parameters help address the environmental characteristics which will impact the effectiveness and hence the desirability of the selected candidate system. These environmental characteristics are argued to be beyond the control of the designer and include factors like, labor availability, labor rates, inflation and interest rates.

Dixon's evaluation, because of the features driven approach proposed, is to some extent restrictive. As stated earlier, a feature is defined as an entity with both form and function, and the entire design is driven by features representation. Again, it is argued that function is always implicit in evaluation, and that evaluations are operational expressions of functions. Because the entire evaluation is features driven, it is limited to the performance aspects and manufacturing aspects of the artifact under development. Factors external to the system or artifact under development which can very significantly affect and alter the effectiveness of the overall system are not being considered at this stage of the research.

5.4.6 Product completeness of the evaluation

The importance of addressing all life-cycle issues during the evaluation was made

clear during the discussion in the previous section. For the methodology to be complete and entirely compatible it should also be product complete. In other words, as design evolves from the preliminary stage to the detailed stage, the information available, the objectives, the requirements, etc. become more specific. Hopefully, the specific and detailed requirements of the detailed design phase still track the overall system requirements and objectives. The methodology should be able to handle this transition of emphasis and remain relevant to the entire process.

Of the four methodologies studied, the ones proposed by Ostrofsky and Fabrykcy make explicit this process of transition to a more specific environment while keeping the overall objectives in mind. This is done by merely repeating the same process at the detailed levels, with the requirements at the lower levels being governed and allocated from the levels above. The fuzzy set approach once again does not talk of this process but is general enough to be applied accordingly. Dixon's research on the other hand is at this stage focussed on the detailed artifacts to begin with. In keeping with the research strategy proposed by him, efforts are underway towards making the features based evaluations relevant at higher levels.

5.4.7 Adaptability to a computer-aided environment

All four being studied are embedded within a computer environment to varying degrees. In fact, Dixon's primary research objective is the development of computer-based design process models. The features based representation of artifact designs is driven by the objective of taking full advantage of the computing

potential existing today. Dominic I and Dominic II are two of the computer-based design process models discussed in chapter 3. Fabrycky's design dependent parameter approach to design evaluation is also embedded within an overall computer aided concurrent engineering morphology (Figure 2.10). Evaluation occupies block 4 of the morphology, and the results of the evaluation are fed back to the designer, who generates the designs using the computer-aided design tools across a human-computer interface. The fuzzy set approach has also been modelled on the computer.

Ostrofsky's methodology is the most mature of the four studied, and is the most complex to model and implement on the computer due to the theoretical rigor involved in modelling even the most qualitative criteria in a quantitative manner. Moreover, the approach towards having deterministic relative weights assigned to the various criteria has resulting in the need to model the behavior of these weights over the range of values of the corresponding criteria. This is discussed in detail in the earlier section on relative importance and weights.

5.4.8 Robustness of the methodologies

The robustness of any methodology depends not only by how completely it addresses factors that are internal to and integral with the design process, e.g. factors that address the total life-cycle, and factors that address the increasing details as design evolves, but also on how well, if at all, it addresses factors that are external to the overall process of design. These factors that are external to the design process are very frequently beyond the control of the designer or the designing team, e.g. interest and inflation rates, labor availability, labor rates,

technological advancement, etc.. Nevertheless, these factors can very significantly impact the desirability of any of the candidate systems under review.

While the above factors are uncontrollable, they should be included in the system design evaluations, and further analyzed to investigate the extent of impact their variance can have on the candidates being reviewed. This analysis will contribute to the designer's confidence during the decision making, it will also expose the robustness of the selected approach in the face of these external factors, and could very well result in a decision reversal.

In the four methodologies identified, opportunities exist to include these external and uncontrollable factors in the evaluation process in at least three cases, with the exception of Dixon's approach as it stands today. However, it is again upto the responsible designer to take these factors into consideration. Fabrycky is the only author who makes explicit the consideration of these factors through the identification of the design independent parameters early in the design process. It is suggested that the designer before finalizing the decision analyze the robustness of the selected approach by making use of sensitivity analysis type studies. In the case of Ostrofsky's approach, an opportunity exists to identify these factors during the development of the input-output matrix. He also suggests the use of sensitivity studies to analyze the selected approach for increased confidence.

5.4.9 Consideration of testing

As was discussed in Chapter 1, testing is a part of the overall system evaluation

and serves the important purpose of verification of the characteristics of the system being developed. According to Ostrofsky [1987], the process of testing increases the information base upon which performance estimates are made for operations. It is used to expose shortcomings that escaped notice till this advanced stage in the development process. The extent of testing is a function of the severity of the problems that need resolution and the resources available. The gains that can result from testing are given due consideration in the morphologies proposed by Ostrofsky, and by Blanchard and Fabrycky.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The engineering design methodologies studied and reviewed in the previous chapters are currently in varying stages of development. A section is this chapter will be devoted to the research currently underway and being planned for the future by the authors of the different methodologies. The lessons learned and conclusions drawn as a result of undertaking this work will also be summarized.

6.1 Summary of the Critical Review

In Chapter One it was demonstrated that this work could be divided into four main activities. The first resulted in a significant literature review and ultimately in the selection of the four methodologies. Chapters Two, Three, and Four contain presentations of the selected methodologies, and represent the second activity. A critical review of the methodologies presented was undertaken in chapter Five, which was the objective of the third activity.

One of the most significant results of the critical review was to make explicit some of the fundamental differences in the engineering design research community which could hinder communication between the isolated research groups. There is a strong need for the different "schools of thought" to agree to a "common language", in terms of the terminology used. The intent of the proposed standardization or commonness is not to restrict in any way the work being done by the different groups. Clarified terminology could go a long way in promoting

better understanding and communication between the people involved. In the long run it could reduce duplication of efforts and give everyone the benefit of lessons learned.

The review also pointed out the efforts underway in the optimization community to adapt this discipline to the requirements of the design activity in various stages of evolution. To date almost all the optimization models being developed seem geared to the production and operations stage of the life cycle. As is obvious from Figure 1.2, the potential and opportunity to make effective and efficient improvements is the greatest during the design phases. Significant commitment to resource allocation and configuration occurs during these stages. While good work in underway to improve the production and operation phases, this in no way can make up for the lost opportunities of the design phases. The potential offered, and finally recognized, and the flexibility to make changes during the nascent stages of development must finally be tapped in order to remain effective and to produce products that command respect in the face of limited resources and stiff global competition.

The qualitative nature of many requirements and constraints in design and the criteria selected for evaluation of candidate systems has resulted in renewed interest in the field of fuzzy sets and systems. Dixon makes use of this concept in defining the relative weights of the selected criteria as also some of the constraints. Pedrycz and Knosala use this concept for plotting preferences in making decisions about alternatives.

Only Dixon and his group of research associates are making use of artificial

intelligence concepts to help guide the designer toward a better design. The changing nature of design, from a sequential process to a largely concurrent activity, was discussed in Chapter 1. The multidisciplinary nature of design results in the designer or the design team having to access knowledge from a diverse range of engineering and other knowledge domains. Such an environment can benefit substantially from use of knowledge-based expert systems that can aid the designer in the search through the problem space. This can significantly reduce the development time. Definite opportunities to make use of this technology exist in the design dependent approach being pursued by Fabrycky and his associates in the Systems Engineering Design Laboratory at Virginia Polytechnic Institute and State University.

The management role in assuring an efficient design function needs to be researched further in light of the metamorphosis underway in the engineering design community. Faced with making decisions and committing resources and configuration (while not having enough information available) is prompting researchers to consider factors that impact effectiveness during production and operations in the design phases.

6.2 Review of the Current Research Activities

As was obvious from the critical review of Chapter Five, all four evaluation methodologies have potential for further improvement. There is a realization of the potential in the design phases for increasing the effectiveness of the ultimate product or system. There is a need for greater analysis during early design.

A renewed interest in making the final product of design more robust and resilient in the face of noise during the production and operation phases has lead to research efforts at both the University of Massachusetts at Amherst and Virginia Polytechnic Institute and State University at Blacksburg to try and bring to bear some of Taguchi's ideas during the primary design phases. The objective is the ability to "know" more about the system and to have greater control over the behavior of the final product. Research is also underway at Virginia Polytechnic Institute and State Univeristy in the domain of organizational structures with the objective to identify organizational and management factors and functions that will help foster increasing concurrency in design.

Dixon's group is presently involved in broadening the application scope of the Dominic models discussed in Chapter Three. Work is also being done to incorporate more sophisticated strategies within the inference engine of the Dominic models. Ostrofsky's research efforts, on the other hand, are concentrated towards modelling the varied nature of the criteria and the corresponding the relative weights.

6.3 Conclusions

The primary goal of this thesis was to take a step towards a pulling together of the various findings of groups of researchers working in the domain of engineering design. A critical review made explicit the diverse approaches being explored. The common objective is to guide the designer to better designs and then to help in the selection of the "best" approach; best relative to the criteria selected and in

the face of the constraints identified. Each group can benefit and learn from work done by others. Greater communication and interaction between these groups is necessary before this can happen. Bringing together in one document the nature and objectives of the four methodologies should aid in this communication.

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