A DECISION-BASED PERSPECTIVE

for the

DESIGN OF METHODS

for

SYSTEMS DESIGN

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MOTIVATION

By system definition we mean the establishment of a construct which characterizes the needs and requirements of a system for a particular application. The importance of system definition and concept design in the development of new, major engineering systems cannot be overemphasized. A popular representation that has been used to illustrate this importance with respect to life cycle cost is reproduced below. As can be seen design freedom or management leverage rapidly decreases once a project is underway. In other words, the freedom to make modifications to a concept becomes increasingly expensive as one gets further into the project. In effect, a significant amount of the life cycle costs have been committed at the time when relatively little knowledge about the object of design has been generated. Usually, this occurs by the end of the conceptual and preliminary design phases.

We believe that the design research community --- the theorists, the academics and engineers in industry --- must all contribute to the common goal of striving to develop a recognized science of design. In an ultimate sense, the purpose of developing the science of design is to ensure that our manufacturing industries can become more effective as well as efficient and that the designers, manufacturers and maintainers of our products will be working in an environment where their subdisciplines are considered simply as parts of the continuous technological spectrum which spans what we have come to call life cycle engineering.

Our recent work and research interests suggest that there is a viewpoint of design research - three-faceted and tightly organized within itself - which should be considered. The issues we include in our view of design research do not exist separately but as a single interactive entity. They are

1 Meta-design - the way in which we define and partition a problem using generic discipline-independent modeling techniques.
2 Computer-based design supports holistic or systems thinking.
3 Adaptive Action Learning - a way of learning through doing.

We believe this tripartite view of design research is unique and is essentially congruent with the principal elements required to establish the philosophy and practice of the science of design which, when accepted and used in industry and academe, will ensure the continued growth and improved productivity of our industries.
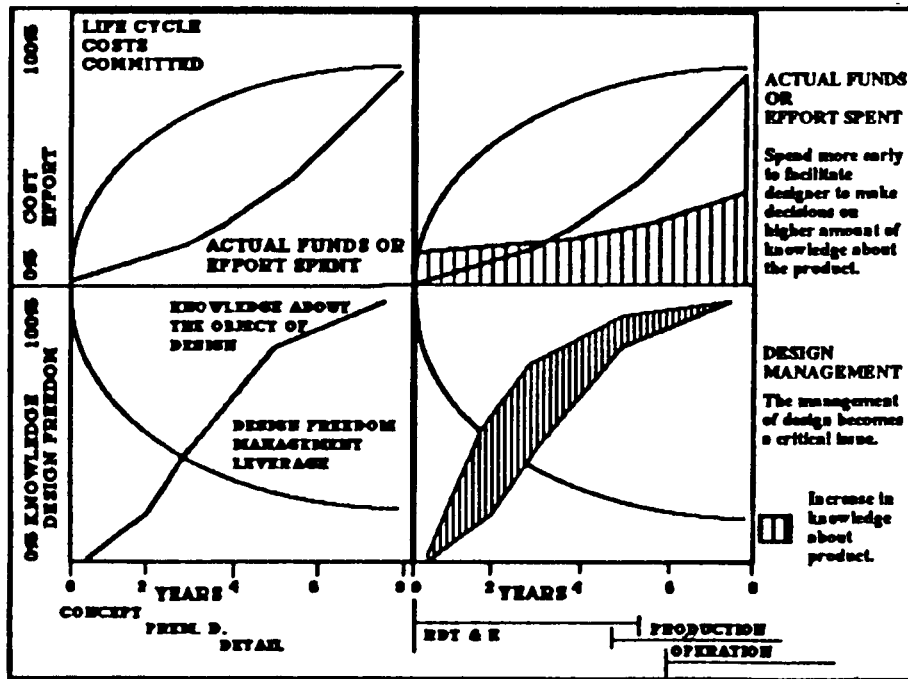
ORGANIZATION OF MATERIAL

"Everyone designs who devises courses of action aimed at changing existing situations into preferred ones." Simon [1, p 129].

The preceding definition is not discipline specific. It can be used as the basis for categorizing the activities of groups of individuals in other science-based disciplines than engineering, for example, management science, systems science, economics and the social and behavioral sciences. The members of the groups are designers in the context of Simon's definition. They design artifacts and machines (engineers), industrial organizations (managers), including their communication and information networks (behavioral scientists and experts in information science) and accounting information systems (accountants, managers and experts in information science). We subscribe to Simon's definition of a designer. In this paper our comments are directed principally towards engineering design, but are not limited to it. The organization of the material is given below.

DEFINITIONS

  Decision-Based Design
  Heterarchy and Hierarchy
  System

THE DECISION SUPPORT PROBLEM TECHNIQUE: CONCEPTUAL MODELS

  Short Term Goal: Design that can be Produced and Maintained
  Long Term Goal: Design, Manufacture and Maintenance as a Continuous Process

DECISION-BASED DESIGN

  Meta-Design, Computer-Based Design and Adaptive Action Learning
  The Characteristics of Decisions
  Decision Activities to Decision Entities
  Types of Design

THE DECISION SUPPORT PROBLEM TECHNIQUE: STATUS

  Designing for Concept and Designing for Manufacture
  Designing for Concept: A Scenario
  Status: Software, Decision Hierarchies and Applications

ISSUES THAT NEED TO BE CONSIDERED TO FOSTER DEVELOPMENT

DECISION-BASED DESIGN

Decision-Based Design [2,3] is a term we have introduced to provide a new focus from which design methods can be developed. In the context of Decision-Based Design, we assert that the principal role of an engineer is to make decisions associated with the design of an artifact. This seemingly limited role ascribed to engineers is useful to provide a starting point for developing design methods based on paradigms that spring from the perspective of decisions made by designers (who may use computers) as opposed to design that is assisted by or based on the use of computers, optimization methods (computer-aided design optimization) or methods that evolve from specific analysis tools such as finite element analysis. In other words, we do not consider Decision-Based Design as a subset or superset of Computer-Aided Design or Computer-Based Design. We see it in another role. Many design approaches were developed originally for purposes and uses now considered outmoded. Their continued use by designers is contingent largely upon custom, tradition and familiarity, and the innate conservatism of most engineers. Enter Decision-Based Design; considering design as a decision-based process offers designers a new and different perspective for viewing established approaches and provides them with the basis for extending and developing anew these established tools of the trade.
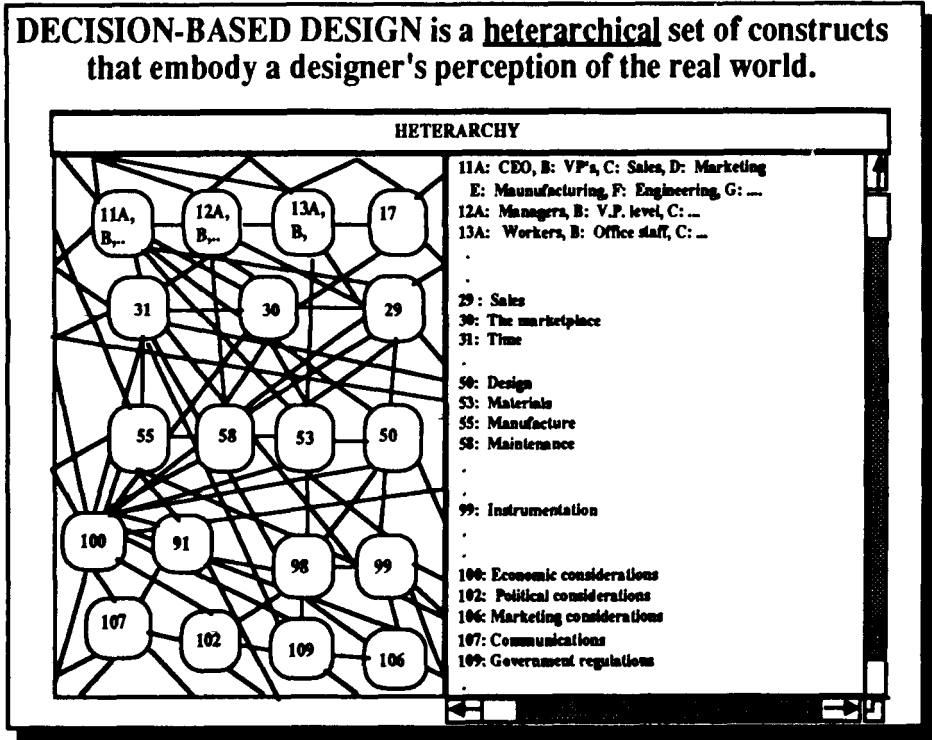
The implementation of DBD can take many forms. One implementation of Decision-Based Design is the Decision Support Problem Technique [4,5].

- **A new term** - to provide a new focus from which to develop methods that support
    - systems thinking, and
    - the making of decisions by designers of engineering systems.

- **Principal** role of engineer in DBD is to make decisions associated with the design of an artifact.

- **Starting point** for developing design methods based on paradigms that spring from the perspective of decisions made by designers (with or without computers).

- DBD has as its content a **heterarchical** set of constructs that embody a researcher's perception of the design environment and the real world.
    - definition of "system"
    - types of design: original, adaptive and variant
    - open and closed environments
    - the nature of decisions and the type of decision activities.

- There is NO SINGLE unique TECHNIQUE or METHOD for the implementation of DBD. The development of a major class of design technique or method will be a result of a researcher selecting a subset of constructs and establishing a **hierarchy** between them.

DECISION-BASED DESIGN: DEFINITION

We define Decision-Based Design as a heterarchical set of constructs that embody a developer's perceptions of the design environment and the real world.
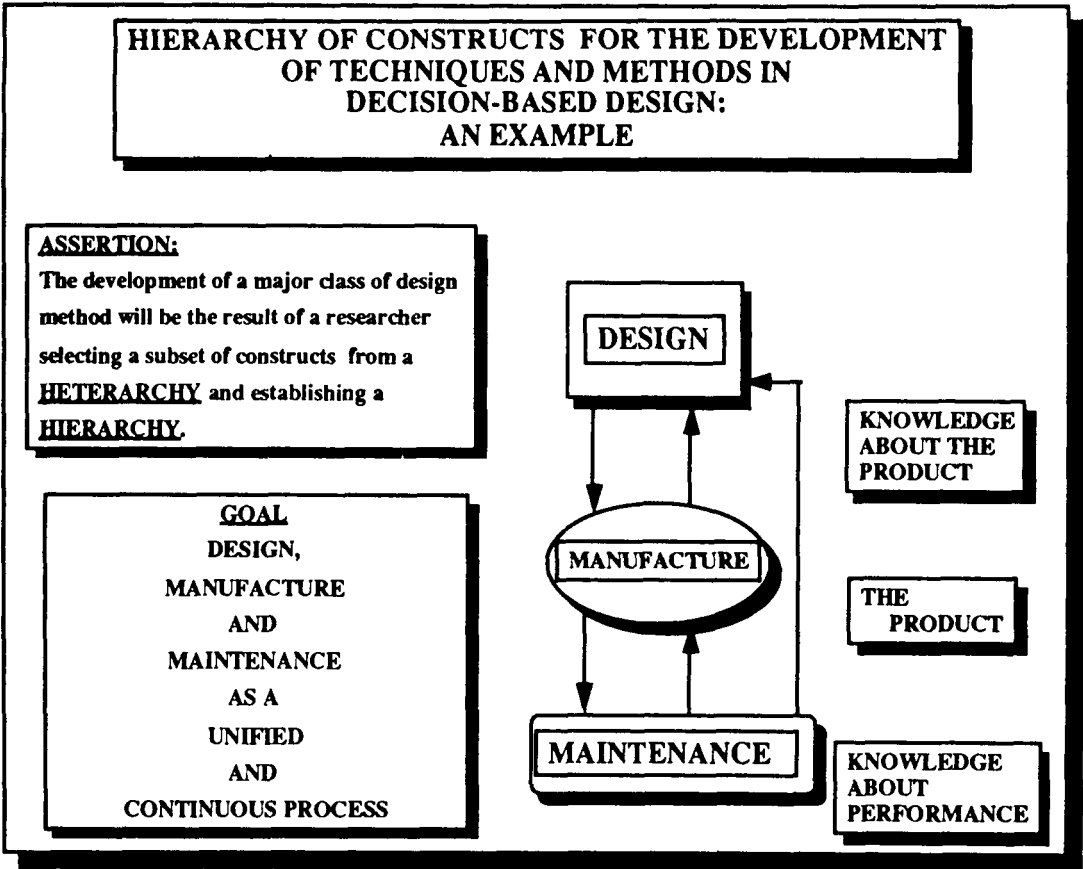
The heterarchical constructs associated with a product's life-cycle are the product's market, the product (the design must meet or exceed the criteria related to the product's function, meeting its market, its capability for being manufactured in serial and, when it reaches its market, that it be free of unreasonable dangers), its manufacture (tooling and assembly), its maintenance and its subsequent retirement. A portion of the heterarchical set of constructs for a product's life-cycle are shown below. The relationships between the constructs are not ordered and hence not directed.

DECISION-BASED DESIGN is a heterarchical set of constructs that embody a designer's perception of the real world.

HETERARCHY

11A: CEO, B: VP's, C: Sales, D: Marketing
E: Maunufacturing, F: Engineering, G: ...
12A: Managers, B: V.P. level, C: ...
13A: Workers, B: Office staff, C: ...

29: Sales
30: The marketplace
31: Time

50: Design
53: Materials
55: Manufacture
58: Maintenance

99: Instrumentation

100: Economic considerations
102: Political considerations
106: Marketing considerations
107: Communications
109: Government regulations

DECISION-BASED DESIGN: HIERARCHY

Different hierarchies can result from the same heterarchy. A heterarchy is transformed into a hierarchy once the **goal** for the transformation is identified and the subsystems that can contribute to the achievement of the goals are selected and placed in the hierarchy.

HIERARCHY OF CONSTRUCTS FOR THE DEVELOPMENT OF TECHNIQUES AND METHODS IN DECISION-BASED DESIGN: AN EXAMPLE

ASSERTION:

The development of a major class of design method will be the result of a researcher selecting a subset of constructs from a HETERARCHY and establishing a HIERARCHY.

GOAL
DESIGN,
MANUFACTURE
AND
MAINTENANCE
AS A
UNIFIED
AND
CONTINUOUS PROCESS

DESIGN

MANUFACTURE

MAINTENANCE

KNOWLEDGE ABOUT THE PRODUCT
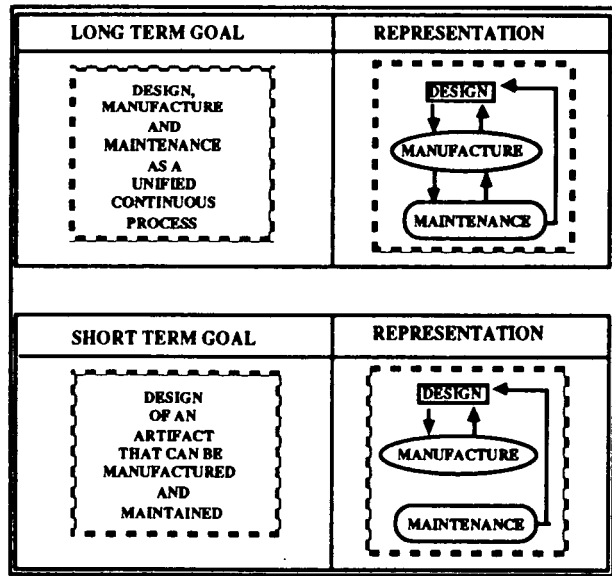
THE PRODUCT

KNOWLEDGE ABOUT PERFORMANCE

THE DECISION SUPPORT PROBLEM TECHNIQUE: GOALS AND REPRESENTATION

The implementation of Decision-Based Design can take many forms. A comprehensive approach called the Decision Support Problem Technique [3,4,5] is being developed and implemented at the University of Houston to provide support for human judgment.

Different hierarchies can result from the same heterarchy. A heterarchy is transformed into a hierarchy once the goal for the transformation is identified. In the long term our goal is to unify the processes of design, manufacture and maintenance.

In the short term our goal, for the UH Decision Support Problem Technique, is to develop processes and tools to support the making of decisions associated with the design of an artifact that can be produced and maintained. In the long term we would like to develop the capability to design, manufacture and maintain as a unified continuous process. Note that the representations for the two cases are different.
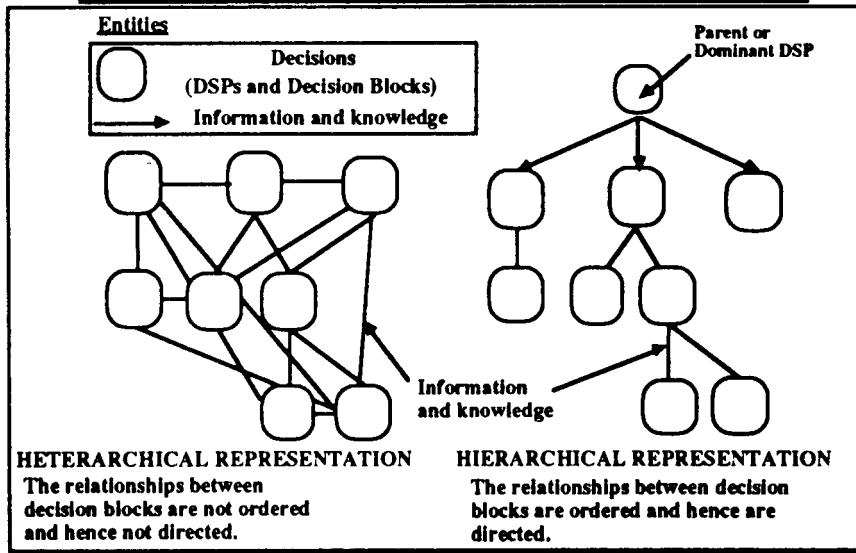
We define the term system to mean a **grouping of associated entities which is characterized by a mental construct.** The terms in this definition were selected for the specific meanings and associations they can convey. The term **grouping** conveys the impression that an act of forming and arranging is involved. **Associated** is used to indicate that there is an association among or that relationships may exist between the entities in a grouping without indicating the precise natures of the association or relationships. The **entities** could be any thing with an essential nature that can be conceptualized, including other systems, concepts, ideas, symbols, and objects in the real world. The term **characterized** is meant to convey that the characterization of the grouping is unique and that it is coupled to the grouping and mental construct which have been selected. Only with both can a mental image of the system be created. A **construct** is "a complex idea resulting from a synthesis of simpler ideas". The redundant qualifier **mental** serves to highlight the involvement of the human mind in the process of creating a construct. This definition is, as will become evident from the following sections, of primary importance for the development of methods rooted in Decision-Based Design.

SYSTEM a grouping of associated entities which is characterized by a mental construct.

THE PROCESS OF DECISION MAKING AS A SYSTEM

Entities

Decisions
(DSPs and Decision Blocks)

Information and knowledge

Parent or Dominant DSP

Information and knowledge

HETERARCHICAL REPRESENTATION
The relationships between decision blocks are not ordered and hence not directed.

HIERARCHICAL REPRESENTATION
The relationships between decision blocks are ordered and hence are directed.

CONCEPTUAL MODEL
# DESIGN THAT CAN BE MANUFACTURED AND MAINTAINED

A process, according to our earlier definition, can be modeled as a system. In the DSP Technique unification of process is sought through the harmonious 'hierarchical' integration of

- **DESIGN** - a process of converting information that characterizes the needs and requirements for a product into knowledge about a prototype of the product,

- **MANUFACTURING** - a process in which the knowledge about a prototypical version of the product is converted into replicates of the product, and

- **MAINTENANCE** - a process in which information that characterizes the performance of a product in terms of its function and its effects on its environment is monitored and analyzed in order to

  - maximize the performance/cost ratio (thereby enhancing customer satisfaction)

  - gain knowledge for design modifications (thereby increasing industrial competiveness).

This hierarchical construct of design for the life-cycle provides the conceptual model of design (see below) for which the Decision Support Problem Technique is being developed. It is clear that the conceptual model can be modeled in its entirety using the entities of DSPs and information/knowledge.

A conceptual model representing the short term goal for the Decision Support Problem Technique is shown below.
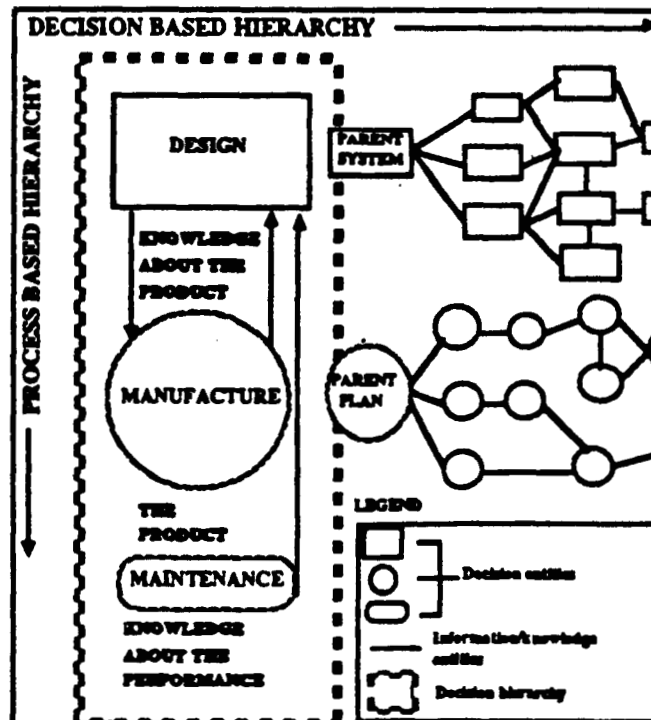
CONCEPTUAL MODEL
UNIFIED DESIGN, MANUFACTURE AND MAINTENANCE

Continued from previous page.

The relation between the processes of design, manufacturing and maintenance is below and in the next slide. Within the checkered box, the three processes contain knowledge about the interaction between them. This establishes a process-based hierarchy in the creation of an artifact. Outside the checkered box, the rectangles, circles and ovals are used to represent collections of related decisions within design, manufacturing and maintenance, respectively. These decisions correspond to systems and subsystems when dealing with design and plans and subplans when dealing with manufacturing and maintenance. The interaction between the DSPs within each of the processes is represented by the lines connecting the rectangles, circles and ovals. The lines represent the passing of information and knowledge. The patterns of the networks shown are possible hierarchical representations of the decision process in design, manufacturing and maintenance . These hierarchies are based on the types of decisions made in each process. Hence they are called decision-based hierarchies which engineers recognize today as being common to the three linked processes of design, manufacturing and maintenance.

A conceptual model representing the long term goal for the Decision Support Problem Technique is shown below.
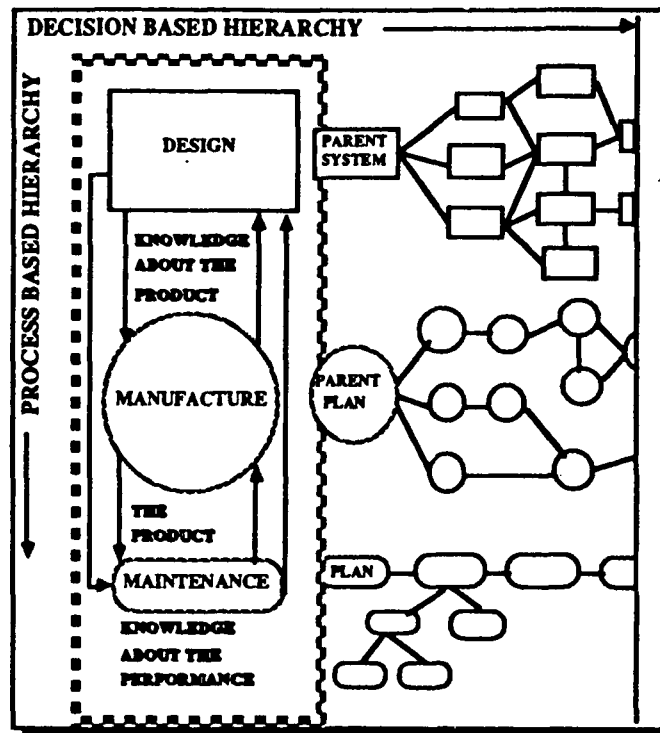
DECISION-BASED DESIGN: SOME OBSERVATIONS

The design of most real-life engineering systems is characterized by the following descriptive sentences:

- The problems are multi-leveled, multi-dimensional and multi- disciplinary in nature.
- Most of the problems are loosely defined and open; virtually none of which has a singular, unique solution, but all of which must be solved. The solutions are less than optimal and are called satisficing solutions.
- There are multiple measures of merit for judging the "goodness" of the design, all of which may not be equally important.
- All the information required may not be available.
- Some information may be hard, that is, based on scientific principles and some information may be soft, being based on the designer's judgment and experience. The design environment is invariably fuzzy.
- Design is the process of converting information that characterizes the needs and requirements of a system into knowledge about the system itself.

The design of a complex engineering system involves partitioning of the system into smaller manageable parts which in turn require the formulation and solution of a series of problems involving decisions to be made by the designer.

A Decision-Based Design Technique is based on the following assertions:

- Design involves a series of decisions, some of which may be made sequentially and others that must be made concurrently.

- Design involves hierarchical decision making, and the interaction between these decisions must be taken into account.

- Design productivity can be increased through the use of analysis, visualization and synthesis in complementary roles, and by augmenting the recognized capability of computers in analysis to include the use of expert systems with limited (at present) capability in synthesis.

- Symbols are processed to support human decisions:
  - Analog/signals
  - Numbers
  - Graphs/Pictures/Drawings
  - Words

A technique that supports human decision making, ideally,

- must be process-based and discipline-independent,
- must be suitable for solving open problems that are characteristic of a fuzzy environment, and
- must facilitate self-learning.

META-DESIGN, COMPUTER-BASED DESIGN AND ACTION LEARNING

Central to the development of Decision-Based Design are the following major areas of research:

1   Meta-Design: This consists of two parts, namely, partitioning and planning. Partitioning deals with the way in which we define and partition a problem using a generic discipline-independent modeling technique. Planning involves the way in which we organize the expertise of individuals, the information (and knowledge) embodied in databases, and computers.

2   Computer-based Design: The use of discipline-independent processes to facilitate the generation domain-dependent information and knowledge that are needed to negotiate satisficing solutions to problems.

3   Adaptive Action Learning: A way of learning through doing.

Meta-design: Meta-design consists of two parts, namely, partitioning and planning.

Partitioning: In each of the areas of overlap in a multidisciplinary program engineers and scientists from one discipline bring with them the intellectual baggage of the technical culture in which they have been trained. They work as, say, engineers who have knowledge of the problems and methods in another area, but they tend to abide in their discipline and use its approaches and methods without changing their mindset. Recently, as designers move towards each other and seek out common ground, they have redefined their problems and in the process defined a meta-level on which to approach them. This meta-level represents the common ground on which, say, engineers and managers can meet . These meta-engineers and meta-managers operate at a level where the commonalties and only the commonalties of their disciplines exist; thus they are of this common ground with a mutually understood mindset and not simply (as in the case of a multidisciplinary approach to a problem) engineers and managers working in the overlapping areas of each others disciplines with the mindset from which they come.

Planning: The process of planning decisions is crucial for effective implementation of Decision-Based Design. The decisions themselves are not made in this phase; rather, the decisions that need to be made, to convert information that characterizes the needs and requirements for a product into knowledge about a prototype of a product that can be manufactured and maintained, are placed in a decision plan. This plan is created with the knowledge of what will be needed in implementing a designer's tasks and their relationships one to another and on the knowledge gained from meta-engineering, the design organization and its resources, the time scale and the anticipated costs.

Computer-based Design: The pervasive influence of computer-based thinking has spread to every part of every science-based discipline like a benign virus, creating an environment that has encouraged the parallel growth of systems thinking and an appreciation of the practical limits of analysis-based science in design. These events have encouraged designers to look afield for new paradigms and new approaches and methods. The computer-based approach we espouse is captured in its essence in some later discussions here and elsewhere [2,6,7]. In a sense it is the antithesis of computer-aided design; in detail at least for us a term which is used to characterize methods of automating calculations and visualization essentially without interaction by the designer. Our computer-based approach to design requires the constant interaction between two entities - a human designer and a computer.

Adaptive Action Learning: The focus of effort at present in Decision-Based Design is to increase the knowledge about the object of design early on and to develop computer tools for supporting human decision making in the very early stages of project initiation. In our opinion, the development of design theory will improve design practice only under certain conditions. We offer for consideration one condition that we feel is of paramount importance. Unlike the practitioners in other fields of science, academics in design must be concerned with the pedagogical aspects of how design skills (associated with both theory and practice) can be passed on to their students. We believe that, in the long term, only that portion of theory that can be taught (or as we prefer to say learned) to a large number of students will influence design practice. We have found that what we call "adaptive action learning" with its emphasis on the synergistic effects associated with teamwork [4,7] is an essential ingredient in our research and in assuring that our students do, in fact, understand the approach, methods and design philosophy we espouse. Over two thousand years ago, Confucius is quoted as having said,

"Tell me, and I will forget.

Show me, and I will remember.

Let me do it, and I will understand."

This captures our feeling and belief that only through a hands-on learning process coupled with participation in a goal-oriented design process can our students truly become the designers we want them to be.

Central to the development of Decision-Based Design are the following major areas of research:

META-DESIGN
Partitioning deals with the way in which we define and partition a problem, using a generic discipline-independent modeling technique.

Planning involves the way in which we organize the expertise of individuals, the information (and knowledge) embodied in databases, and computers.

COMPUTER-BASED DESIGN
The use of discipline-independent processes to facilitate the generation domain-dependent information and knowledge that are needed to negotiate satisficing solutions to problems. Our computer-based approach supports systems thinking and requires the constant interaction between two entities - a human designer and a computer.

ADAPTIVE ACTION LEARNING
Confucius is quoted as having said,
   "Tell me, and I will forget.
    Show me, and I will remember.
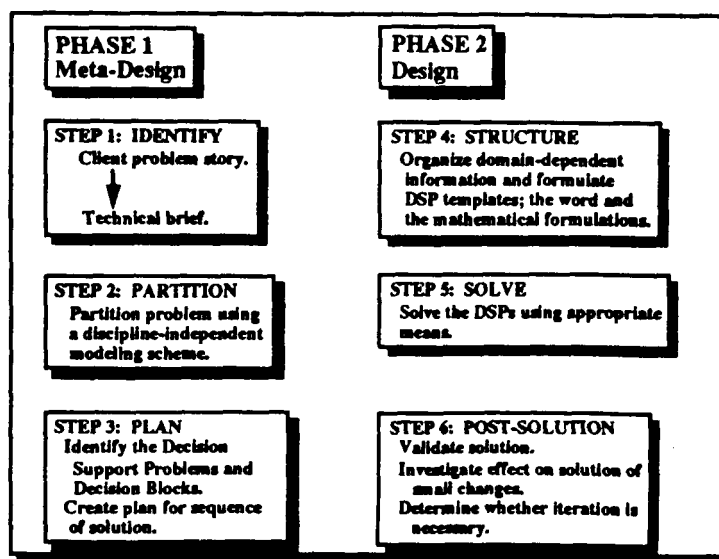   Let me do it, and I will understand."

THE DECISION SUPPORT PROBLEM TECHNIQUE PROCESS

The principal role of any Decision-Based Design process is to convert information that characterizes the needs and requirements for a product into knowledge about the product itself. The DSP Technique facilitates the conversion of information for the product into knowledge about the product that can be used for its manufacture. In the DSP Technique identification, decomposition, organization and synthesis are used:

- to **identify** the <u>information</u> that characterizes the needs and requirements for the design and is necessary for the process of design,
- to **partition** and decompose a design problem into appropriate Decision Support Problems,
- to **organize** the domain dependent information in a form suitable for solution, and
- to **synthesize** the component solutions into one "system" solution and thereby gain <u>knowledge</u> about the <u>product</u> being designed.

In the DSP Technique the process, for converting information into knowledge, consists of two phases (meta-design and design) and six steps as shown below. These steps are valid for any stage in the design process and the DSP Technique can be used for designing systems and components.

Our efforts to date have been directed to developing the second phase, namely, design. In the process we have identified various decision hierarchies (see later) and developed software to solve them (see later). These developments, we believe, are of value to industry and are appropriate for use in a classroom.since Decision Support Problems can be formulated and solved as an activity in any other design scheme; particularly if designing for concept is involved.
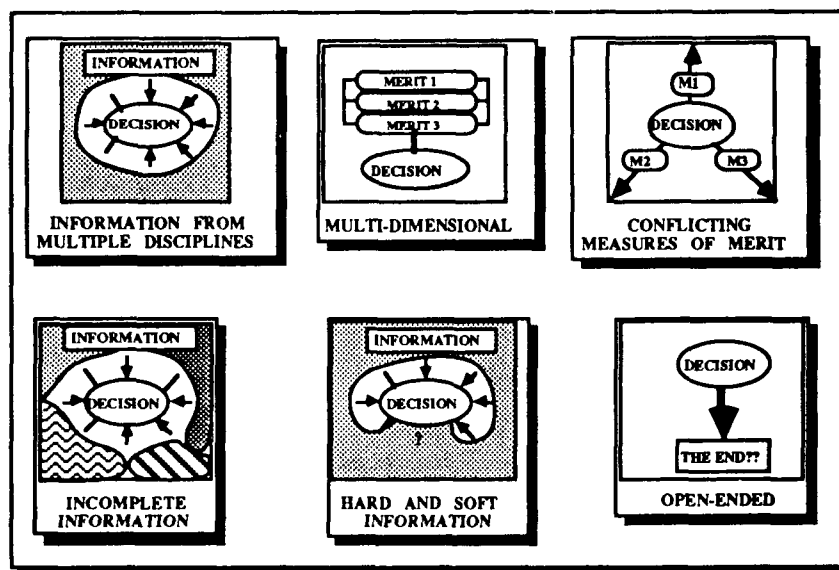

PHASE 1
Meta-Design

PHASE 2
Design

STEP 1: IDENTIFY
Client problem story.

↓

Technical brief.

STEP 4: STRUCTURE
Organize domain-dependent information and formulate DSP templates; the word and the mathematical formulations.

STEP 2: PARTITION
Partition problem using a discipline-independent modeling scheme.

STEP 5: SOLVE
Solve the DSPs using appropriate means.

STEP 3: PLAN
Identify the Decision Support Problems and Decision Blocks. Create plan for sequence of solution.

STEP 6: POST-SOLUTION
Validate solution. Investigate effect on solution of small changes. Determine whether iteration is necessary.

CHARACTERISTICS OF DECISIONS

In engineering a designer often walks a fine line between developing and maintaining a model that is amenable to solution and one whose results yield information and knowledge that is usable in practice. In engineering, decisions involving design are characterized by the following descriptive sentences:

- Decisions involve information that comes from different sources and disciplines.

- Decisions are governed by multiple measures of merit and performance.

- The measures of merit may not be of equal importance to the final decision and may conflict with each other.

- All of the information for making an adequate decision may not be available to a designer.

- Some of the information may be hard (based on scientific principles), some may be soft (based on the perceptive judgment of the designer) and some may be partially soft (empirical in nature).

- The problem for which the decision is being made is open.

These characteristics dictate the mathematical form of the DSPs and govern the type of solution algorithms appropriate for solving them. For example, these characteristics virtually rule out the use of traditional single objective optimization in Decision-Based Design.

| INFORMATION FROM MULTIPLE DISCIPLINES | MULTI-DIMENSIONAL | CONFLICTING MEASURES OF MERIT |
| INCOMPLETE INFORMATION | HARD AND SOFT INFORMATION | OPEN-ENDED |

DECISION ACTIVITIES TO DECISION ENTITIES

An abstract, conceptual statement about the relationship between decisions as people discuss them and how they could be structured for computer-based solution is made in in the figure below [2,8]. The Decision Support Problems and Decision Blocks are also shown in the Figure. The transformation of decision activities into decision blocks is based on the inherent characteristics of decisions in engineering design. The transformation of DSPs into DBs depends on the type, separability and order in which the decisions have to be made to effect a solution. As is evident from the figure the process of this transformation is modeled using the decision and knowledge/information entities described earlier. Further, the transformation process complies with our earlier definition of system. The set of Decision Support Problems shown in the figure is incomplete.

PRELIMINARY SELECTION
The selection of the top-of-the-heap concepts for further development.

SELECTION
The indication of a preference based on multiple attributes for one amongst several feasible alternatives.

COMPROMISE
The improvement of an alternative through modification.

HIERARCHICAL
Decisions, within a decision entity in which both selection and compromise occur.
Decisions, between decision entities, which involve subplan interaction and compromise.

CONDITIONAL
Decisions in which the risk and uncertainty of the outcome are taken into account.

HEURISTIC
Decisions which are made on the basis of a knowledge base of facts and rules of thumb.
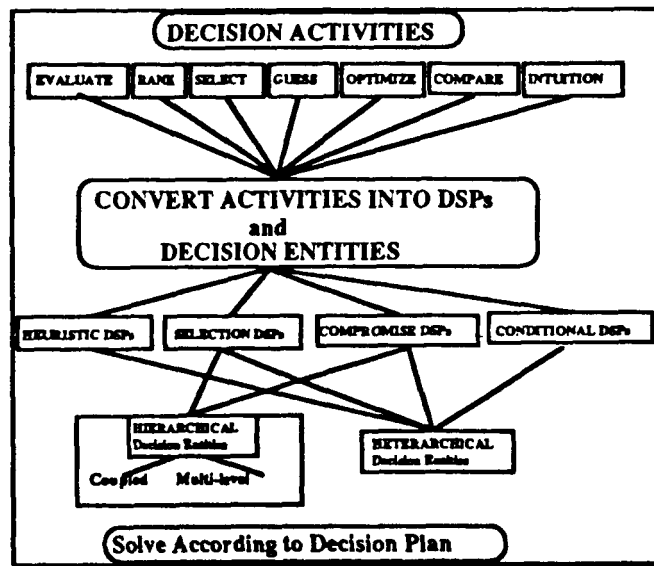
TYPES OF DESIGNS

- **Original Design** - The design specification for the system may require the system to perform the same, similar or a new function altogether. An original solution principle is defined for a desired system and used to create the knowledge and information so that it can be manufactured and maintained.

- **Adaptive Design** - An original design is adapted to meet a modified set of specifications. The solution principle, in the main, remains the same but the product will be sufficiently different so that it can meet the changed specifications.

- **Variant Design** - The size and/or arrangement of parts or subsystems of the chosen system are fine-tuned, say, to meet a set of specifications more cheaply; the specifications and solution principle remain the same.

ORIGINAL DESIGN

ADAPTIVE DESIGN

VARIANT DESIGN

ORIGINAL SPECIFICATIONS

DIFFERENT/MODIFIED SPECIFICATIONS

FINE-TUNED
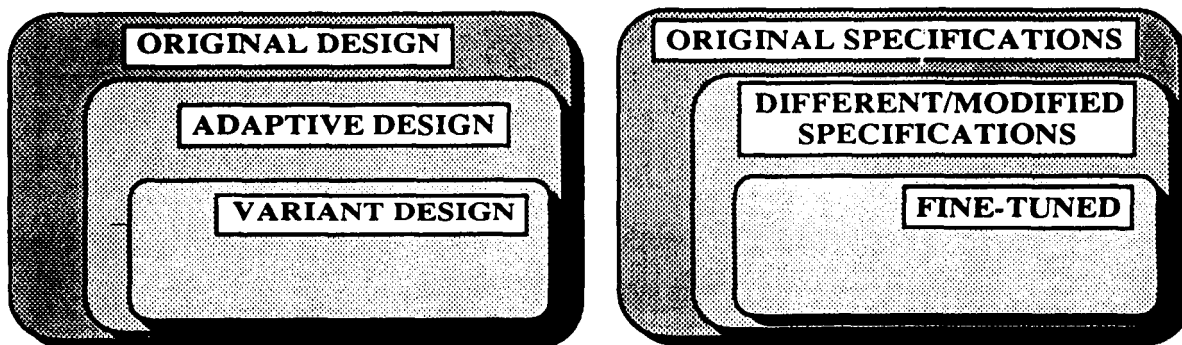
CHARACTERISTICS OF DESIGN GUIDANCE SYSTEM

IT MUST BE COMPATIBLE WITH ALL THREE TYPES OF DESIGN.

ELEMENTS OF IT MUST BE USABLE INTERCHANGEABLY.

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DESIGNING FOR CONCEPT

According to our definition, the principal role of any design process is to convert information that characterizes the needs and requirements for a product into knowledge about the product itself. Further, it is safe to assume that because of the complexity of the product (an engineering system) the conversion of information into knowledge will have to be accomplished in stages. In the traditional design process names have been given to the stages such as feasibility, conceptual, preliminary and detail. The names and the number of stages, from the standpoint of the information necessary for making decisions in each of the stages, are not important. What is important is that

- the types of decisions being made (e.g., selection and compromise) are the same in all stages, and

- the amount of hard information increases as the knowledge about the product increases.

It appears to us that, in Decision-Based Design, the ratio of soft to hard information available is a key factor in determining the nature of the support that a human designer needs as he/she negotiates a solution to a design problem. Our current efforts are focused on understanding what is needed and developing the tools to support human decision making in the early stage of a project. We assert that it is possible, based on the ratio of hard to soft information that is available, to make a distinction between designing for concept and designing for manufacture (see below). Based on this distinction it is possible to categorize computer-based aids into two categories, namely, tools that provide support for human decision making and tools for automation.
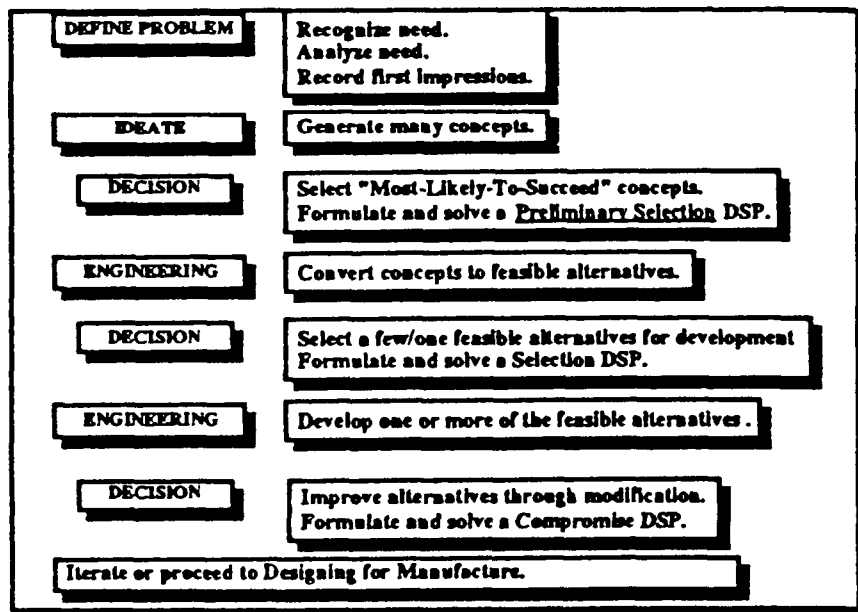
DESIGNING FOR CONCEPT AND MANUFACTURE: A DECISION-BASED PERSPECTIVE
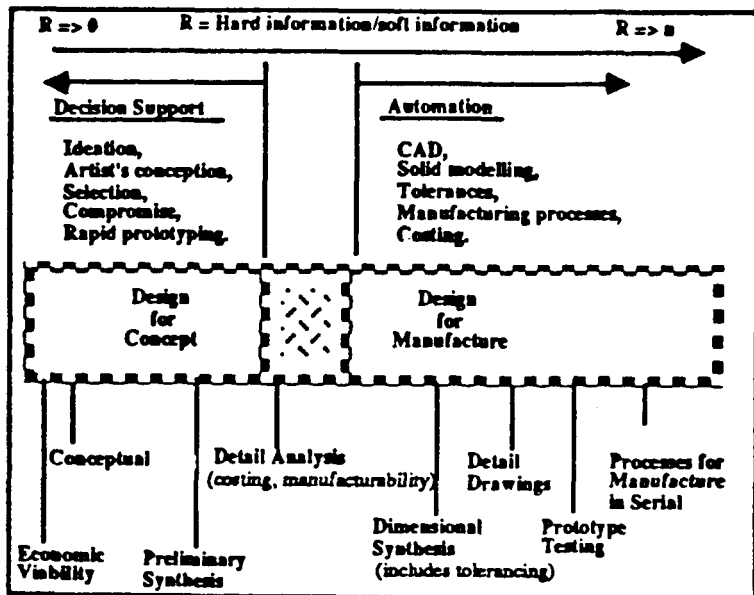
DESIGNING FOR CONCEPT: A SCENARIO

In designing for concept we seek to cast a wide net, that is, generate many concepts and then systematically home-in on a concept that meets its functional specifications and can be produced and maintained. In other words we are involved in the process of converting information that characterizes the needs and requirements for a product into specific knowledge that can be used in designing for manufacture. In designing for manufacture we attempt to ensure that the product can be manufactured cost-effectively. Of course we recognize that in practice iteration will occur and this, for convenience, has not been illustrated in the figure.

A schematic of designing for concept is shown below. Let us assume that the process is underway and the problem definition is available. This permits ideation that results in the identification of alternative ways (concepts) of achieving the objectives embodied in the problem definition. Ideally, a large number of concepts should be generated. At this stage most of the information will be soft and there should be many concepts. We envisage a **preliminary selection DSP** being formulated and solved to identify the more promising "top-of-the-heap" or "most-likely-to-succeed" concepts. In preliminary selection we start with concepts, the end product of ideation. We evaluate the concepts based on criteria. The criteria are quantified using experience-based judgment (or soft information) only. The solution to the preliminary selection DSP involves the rank ordering of concepts. Therefore one cannot automatically infer, from the rankings, by how much one concept is preferred to another and hence it is injudicious to use this approach to identify the "best concept". At this stage we expect engineering analysis to be used to convert as many of the top-of-the-heap concepts one can afford into feasible alternatives. These alternatives will be characterized by both hard and soft information. We envisage a **selection DSP** being formulated and solved to identify one or two alternatives that should be further developed. In selection we start with feasible alternatives. We evaluate the feasible alternatives based on attributes (using both hard and soft information). We solve the selection DSP to identify the best alternative. The solution to the selection DSP involves the ordering of alternatives. One can infer from the ranking by how much one alternative is preferred to another and therefore the best alternative is known. Further development involves improvement through modification and we believe that the **compromise DSP** is appropriate for this task. Iteration is necessary and is not precluded from the scenario just presented.

DEFINE PROBLEM	Recognize need. Analyze need. Record first impressions.
IDEATE	Generate many concepts.
DECISION	Select "Most-Likely-To-Succeed" concepts. Formulate and solve a Preliminary Selection DSP.
ENGINEERING	Convert concepts to feasible alternatives.
DECISION	Select a few/one feasible alternatives for development Formulate and solve a Selection DSP.
ENGINEERING	Develop one or more of the feasible alternatives.
DECISION	Improve alternatives through modification. Formulate and solve a Compromise DSP.

Iterate or proceed to Designing for Manufacture.

THE DSIDES SOFTWARE

The software for the Decision Support Problem Technique continues to be developed by the Systems Design Laboratory at the university of Houston. The software is called DSIDES (Decision Support In the Design of Engineering Systems). At this time, we provide no computer-based support for the planning and structuring steps of the DSP Technique. An experimental system for partitioning is available [2].

Software to solve preliminary selection and selection DSPs in an interactive and extremely user-friendly environment has been written in PASCAL for the Apple Macintosh computers. This software is called MacDSIDES. A version for the IBM PC/AT is also available. The algorithm used is summarized in [9,10,11]. This software has been used, in industry, in two major projects involving designing for concept.

Software to solve the compromise DSPs is called DSIDES and has been written in FORTRAN 77. DSIDES can also be used to solve selection and hierarchical DSPs. To date, ship design has been the largest single application of the compromise DSP formulation [12,13,14]. Applications involving the design of damage tolerant structural [15,16] and mechanical systems [17,18,19], the design of aircraft [11,20], mechanisms [17,21], a solar-thermal-powered agricultural-water pumping system [22,23], design using composite materials [24,25] and data compression [22]. DSPs have been developed for hierarchical design; selection- compromise [13,26,27], compromise-compromise [28] and selection-selection [10]. An overview of DSIDES (its function and structure) is presented in [6]. The compromise DSP is solved using a unique optimization scheme called Adaptive Linear Programming. This scheme is described in references [29,30].

Current projects include the development of templates for designing thermal energy systems [22] templates to study the interaction between design and manufacturing [24,25] and the conceptual design of automobile tires [31]. Other projects include the incorporation of intelligence into the DSIDES software, the development of a method for data compression and the development of the capability to design lubricants using information obtained from condition monitoring.

The software for the Decision Support Problem Technique is called:

Decision	D
Support	S
In the	I
Design of	D
Engineering	E
Systems	S

MacDSIDES: Macintosh Plus, SE and II (PC-DSIDES end of summer)

PSELECT   Preliminary Selection
  Identify top-of-the-heap concepts
  Use information that is "soft" only.

SELECT   Selection
  Identify the most appropriate alternative for further development
  Use both "hard and "soft" information

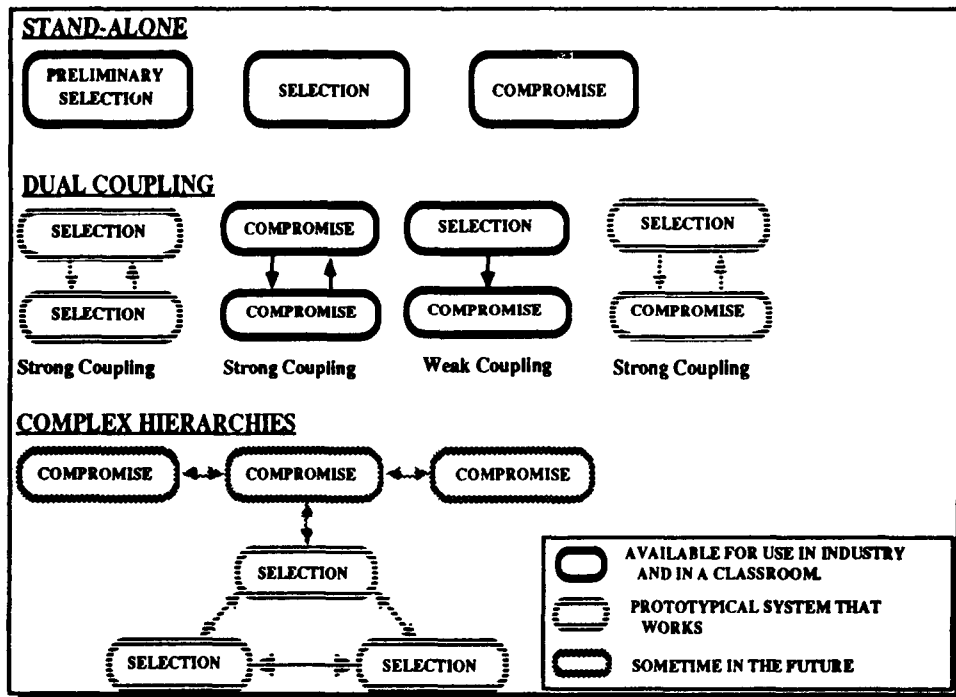DSIDES: Mini-computers

SELECT   As above
SLIPML   Compromise
  Improve alternative through modification - multiobjective optimization.
SLIPML   Coupled
  Hierarchical problems involving both Selection and Compromise

DECISION HIERARCHIES

Some decision-based hierarchies and their status of development (and availability for use in industry and in the classroom) are shown below. One construct may be of particular importance to this audience and is briefly described. A coupled selection-selection DSP arises whenever we have a system that can be decomposed into several inter-dependent subsystems that have to be selected by the designer. It is always present in "Catalog Design" a procedure in which a system is assembled by selecting standard components from catalogs of available components. The performance of the overall system depends on all of the components, which are dependent on each other. It is not appropriate to select any component without taking into account the effect it has on the other components and the performance of the system as a whole. Further information is provided in reference [10]. The same construct is also appropriate for use in identifying an initial layout in the early stages in designing for concept.

STAND-ALONE

| PRELIMINARY SELECTION | SELECTION | COMPROMISE |

DUAL COUPLING

SELECTION	COMPROMISE	SELECTION	SELECTION
SELECTION	COMPROMISE	COMPROMISE	COMPROMISE
Strong Coupling	Strong Coupling	Weak Coupling	Strong Coupling

COMPLEX HIERARCHIES

| COMPROMISE | COMPROMISE | COMPROMISE |

SELECTION

| SELECTION | SELECTION |

AVAILABLE FOR USE IN INDUSTRY AND IN A CLASSROOM.

PROTOTYPICAL SYSTEM THAT WORKS

SOMETIME IN THE FUTURE

CLOSURE

In a recent paper [32], Dixon (who is currently the Director of the NSF Design Theory and Methodology Program) offered his viewpoint of engineering design as he sees it today --- no longer only an art and not yet a recognized science. He raises four issues which comprise his view of the status of engineering design science today, namely,

(a) that researchers in design theory constitute a single goal-directed research community

(b) that the development of design theory is essentially still in a pre-theory stage

(c) that the goal of the design research community should be the development of a formal scientific theory or theories of design that will enable the generation of hypotheses for testing by traditional scientific methods

(d) that the development of design theory will improve design practice

We are in agreement with the sense of his observations. In another paper [33] we offer an interpretative commentary on their scope and impact. We start by presenting a historical perspective of the centuries-long evolution of design from a wholly intuitive art to the beginnings of becoming a rational science. We comment on Dixon's four observations in the context of this view of the origins and present state of design and offer a fifth perspective which takes into account the discipline-specific origins of design in several fields and is focussed forward in time. In this new view, we introduce the notion of meta-design. Finally, we offer our views on the process of identifying research activities worthy of support in today's yeasty environment of change-just-over the horizon. Some of these views are summarized below.

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1 DEVELOPMENT OF DESIGN METHODS THAT ARE BASED A HOLISTIC, SYSTEMATIC VIEWPOINT OF DECISION MAKING, NAMELY, DECISION-BASED DESIGN IS RECOMMENDED.

2 THERE ARE MANY DIFFERENT WAYS OF IMPLEMENTING DECISION-BASED DESIGN. OUR APPROACH IS CALLED THE DECISION SUPPORT PROBLEM TECHNIQUE.

3 FOR LONG TERM COST-EFFECTIVENESS RESEARCH IN THIS AREA SHOULD:

• SUPPORT THE DEVELOPMENT OF A DOMAIN INDEPENDENT PROCESS AND THE DEVELOPMENT OF DOMAIN DEPENDENT INFORMATION.

• BE OF A KIND THAT MAKES CONTACT AT SOME LEVEL WITH THE PRACTICAL WORLD.

• PROVIDE FOR GAINING INSIGHT AND UNDERSTANDING THAT COULD BE USED FOR INCREASING DESIGN PRODUCTIVITY.

• CONTRIBUTE TO OUR UNDERSTANDING OF THE PROCESS OF DESIGN.

• INCLUDE SOME MEANS TO FACILITATE AN EVALUATION OF THE EFFECTIVENESS OF THE DEVELOPMENT.

• CONTAIN A COMPONENT THAT IS TEACHABLE AND/OR LEARNABLE.

CLOSURE continued

There is much that remains to be done and as we have learned to say, since we came to Texas - *y'all come! There is so much to do!*

4 SOME SPECIFIC RESEARCH ISSUES

- THE DEVELOPMENT OF A TAXONOMY AND CONCEPTUAL MODELS FOR PROCESSES IN DESIGN IS CRUCIAL. FOR EXAMPLE, DESIGN FOR MANUFACTURE, DESIGN FOR THE LIFE-CYLE, HETRARCHY AND HIERARCHY, PARTITIONING, PLANNING, ETC.

- THE DEVELOPMENT OF THE CAPABILITY TO MODEL SYSTEM) BEHAVIOR IS CRUCIAL.

- THE DEVELOPMENT OF THE CAPABILITY TO MODEL FEATURES ASSOCIATED WITH REAL-WORLD DECISIONS IS IMPORTANT.

- EVENT-BASED DESIGN GUIDANCE SYSTEMS WILL BE NEEDED.

- INTELLIGENT DATA REDUCTION SCHEMES AND REPRESENTATION SCHEMES FOR USE IN DESIGN GUIDANCE SYSTEMS WILL BE NEEDED.

- DESIGN OF A COMPUTER ENVIRONMENT TO SUPPORT THESE ACTIVITIES IS NECESSARY.

5 IN AN AGE CHARACTERIZED BY RAPID CHANGES IN TECHNOLOGY AND AN ABUNDANCE OF INFORMATION ANY SIGNIFICANT INCREASE IN PRODUCTIVITY WILL, TO A LARGE MEASURE, DEPEND ON THE EDUCATION THE ENGINEERS HAVE RECEIVED. WE WILL GAIN MOST FROM THOSE WHO HAVE, AS PART OF THEIR EDUCATION PROCESS, BEEN GIVEN THE OPPORTUNITY TO LEARN HOW TO COPE WITH CHANGE.

REFERENCES

1 H.A. Simon, *Sciences of the Artificial*, 2nd Edition, MIT Press, 1982.

2 J.A. Shupe, J.K. Allen, D. Muster and F. Mistree, *Decision-Based Design: Some Concepts and Research Issues*, Expert Systems: Design and Management of Manufacturing Systems, A. Kusiak (ed.), Society of Manufacturing Engineers, June 1988.

3 J.A. Shupe, *Decision-Based Design: Taxonomy and Implementation*, Ph.D. Dissertation, Department of Mechanical Engineering, University of Houston, May 1988.

4 D. Muster and F. Mistree, *The Decision Support Problem Technique in Engineering Design*, The International Journal of Applied Engineering Education, Vol. 4, No. 1, 1988, pp. 23-33.

5 F. Mistree, H.M. Karandikar, J.A. Shupe and E. Bascaran, *Computer-based Design Synthesis: An Approach to Problem Solving*, Systems Design Laboratory Report, Department of Mechanical Engineering, University of Houston, August 1988.

6 S.Z. Kamal, H.M. Karandikar, F. Mistree and D. Muster, *Knowledge Representation for Discipline-Independent Decision Making*, Expert Systems in Computer-aided Design, J.S. Gero (ed.), Elsevier Science Publications, 1987, pp. 289-321.

7 F. Mistree and D. Muster, *Mechanical Design: An Undergraduate Curriculum for Design in the Systems Age*, 1984 ASEE Annual Conference Proceedings, Salt Lake City, Utah, June 1984, pp. 818-826.

8 F. Mistree and D. Muster, *Designing for Concept: A Method that Works*, Proceedings International Workshop on Engineering Design and Manufacturing Management, The University of Melbourne, Melbourne, Australia, November 21-23, 1988.

9 N. Kuppuraju, P. Ittimakin and F. Mistree, *Design through Selection: A Method that Works*, Design Studies, Vol. 6, No. 2, 1985, pp. 91-106.

10 E. Bascaran, R.B. Bannerot and F. Mistree, *Hierarchical Selection Decision Support Problems in Conceptual Design*, Systems Design Laboratory Report, Department of Mechanical Engineering, University of Houston, June 1988.

11 F. Mistree, S. Marinopolous, D. Jackson.and J.A. Shupe, *The Design of Aircraft using the Decision Support Problem Technique*, NASA Contractor Report 4134, April 1988.

12 T.D. Lyon and F. Mistree, *A Computer-based Method for the Preliminary Design of Ships*, Journal of Ship Research, Vol. 29, No. 4., December 1985, pp. 251-269.

13 W.F. Smith and F. Mistree, *The Influence of Hierarchical Decisions on Ship Design*, Marine Technology, Vol. 24, No. 2, April 1987, pp. 131-142.

14 W.F. Smith, T.D. Lyon and B. Robson, *AUSEVAL - A Systems Approach for the Preliminary Design of Naval Ships*, Proceedings Bicentennial Maritime Symposium, Sydney Australia, Jan. 18-20, 1988, pp. 1-29

15 J.A. Shupe and F. Mistree, *Compromise: An Effective Approach for the Design of Damage Tolerant Structural Systems*, Computers and Structures, Vol. 27, No. 3, pp. 407-415, 1987.

16 J.A. Shupe, F. Mistree and O.F. Hughes, *A Conceptual Basis for the Design of Damage Tolerant Structural Systems*, Recent Experiences in Multidisciplinary Analysis and Optimization, NASA CP 2327, April 1984, pp. 907-942.

17 S. Mudali, *Dimensional Synthesis of Mechanical Linkages using Compromise Decision Support Problems*, M.S. Thesis, Department of Mechanical Engineering, University of Houston, October 1987.

REFERENCES continued

18 N. Nguyen and F. Mistree, *A Computer-based Method for the Rational Design of Horizontal Pressure Vessels*, ASME Journal of Mechanism, Transmissions and Automation in Design, Vol. 108, June 1986, pp. 203-210.

19 A. Jivan and F. Mistree, *A Computer-based Method for Designing Statically Loaded Helical Compression Springs*, ASME 11th Design Automation Conference, Cincinnati, Ohio, September 10-13. ASME Paper Number 85-DET-75.

20 S. Marinopolous, D. Jackson, J. Shupe and F. Mistree, *Compromise: An Effective Approach for Conceptual Aircraft Design*, Paper No. AIAA-87-2965.

21 Q-J. Zhou, *The Compromise Decision Support Problem: A Fuzzy Formulation*, M.S. Thesis, Department of Mechanical Engineering, University of Houston, May 1988.

22 E. Bascaran, F. Mistree and R.B. Bannerot, *Compromise: An Effective Approach for Solving Multi-objective Thermal Design Problems*, Engineering Optimization, Vol. 12, No. 3, pp. 175-189, 1987.

23 E. Bascaran, R.B. Bannerot and F. Mistree, *The Conceptual Development of a Method for Solving Multi-objective Hierarchical Thermal Design Problems*, 1987 National Heat Transfer Conference, Pittsburgh, August 1987. Paper No. 87-HT-62.

24 H.M. Karandikar, W.J. Fuchs, F. Mistree and H. Eschenauer, *Compromise: An Effective Approach for Designing Composite Conical Shell Structures*, Proceedings 1988 Design Automation Conference, September 1988.

25 F. Mistree, W.J. Fuchs, H.M. Karandikar, R. Srinivasan, *Design of Composite Material Systems using the Decision Support Problem Technique*, Systems Design Laboratory Report, Department of Mechanical Engineering, Houston, October 1987, 157 pages.

26 N. Kuppuraju, S. Ganesan, F. Mistree and J.S. Sobieski, *Hierarchical Decision Making in System Design*, Engineering Optimization, Vol. 8, March 1985, pp. 223-252.

27 J.A. Shupe, F. Mistree and J.S. Sobieski, *Compromise: An Effective Approach for Design of Hierarchical Structural Systems*, Computers and Structures, Vol. 26, No. 6, pp. 1027-1037, 1987.

28 W.F. Smith, *The Development of AUSEVAL: An Automated Ship Evaluation System*, M.S. Thesis, Department of Mechanical Engineering, University of Houston, December 1985.

29 F. Mistree and O.F. Hughes, *Adaptive Linear Programming: An Algorithm for Solving Multi-objective Decision Support Problem*, Systems Design Laboratory Report, University of Houston, November 1986.

30 F. Mistree, O.F. Hughes and H.B. Phuoc, *An Optimization Method for the Design of Large, Highly Constrained, Complex Systems*, Engineering Optimization, Vol. 5, No. 3, Aug./Sept., 1981, pp. 141-144.

31 N. Bhattacharya, R.P. Reddy, L. Velez, V. Tsikkinis, L. Koszegi, *A Decision Support Problem Template for the Preliminary Design of Automobile Tires*, Systems Design Laboratory Report, Department of Mechanical Engineering, University of Houston, May 1988.

32 J.R. Dixon, *On Research Methodology Towards A Scientific Theory of Engineering Design*, Artificial Intelligence for Engineering Design, Analysis and Manufacturing, Vol. 1, No. 3, June 1988.

33 D. Muster and F. Mistree, *Engineering Design as it Moves from an Art to a Science*, Proceedings NSF Grantee Workshop on Design Theory and Methodology, Rensselaer Polytechnic Institue, Troy, New York, June 3-5, 1988.