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# A Taxonomy for Classifying Engineering Decision Problems and Support Systems

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David G. Ullman **E-mail**[Ullman](mailto:ullman@engr.oregonstate.edu)

Department of Mechanical Engineering

Oregon State University

Bruce D'Ambrosio

Department of Computer Science

Oregon State University

## ABSTRACT

The design of even the simplest product requires thousands of decisions. Yet very few of these decisions are supported with methods on paper or on computers. Is this because engineering design decisions don't need support or is it because techniques have yet to be developed that are usable on a wide basis? In considering this question a wide range of decision problem characteristics need to be addressed. In engineering design some decisions are made by individuals, others by teams - some are about the product and others about the processes that support the product - some are based on complete, consistent, quantitative data and others on sparse, conflicting, qualitative discussions. In order to address the reasons why so little support is used and the characteristics of potentially useful decision support tools, a taxonomy of decision characteristics is proposed<sup>(1)</sup>. This taxonomy is used to classify current techniques and to define the requirements for an ideal engineering design decision support system.

## 1. INTRODUCTION

There are thousands of decisions made in every design project. Many are made by individuals, others made by teams or committees. In any case, few are supported by formal methods or tools. This leads to one of two conclusions: Either there is no need for decision support (designers and design teams do very well without aid), or tools and methods have not yet been developed that give adequate decision support for the wide range of problems faced. Observation and limited results of formal studies lead to the conclusion that individual designers and, more importantly, teams of designers take too long to make decisions, frequently rehashing previous information, drop issues and fail to document rationale for later use. Thus, there is a need to explore

why current decision support systems are not more frequently used by designers. In this research, a classification scheme is developed to assist in understanding the existing methods and tools, and to define specifications for future decision support. To further understand the rationale for this paper, consider the following example.

The dialog below is a short segment of a design team meeting in which the discussion centers on selecting a material to use to manufacture a part. This problem is taken from actual practice and has been shortened and refined for this paper. It is typical of conversations that occur during the design of even the simplest product. Here Dave is the mechanical designer, Bill is a manufacturing engineer and Lucy is a sales/marketing representative. Lucy, as the manager of this project, needs to decide what to do.

*Dave: O.K. Our next problem has to do with the strike plate. This plate has to take the repeated impact of the latching mechanism. Currently I have it as part of the front panel which is made of 6065-T6 aluminum.*

*Bill: Isn't the impact going to really mess up the surface of this plate?*

*Dave: That's what I'm afraid of. So is Lucy.*

*Lucy: I told Dave that our customers wouldn't think much of our product if it looks like trash after only a short time in service. But, Dave tells me that it will add cost if the front panel and strike plate are two different parts. That's why we are having this meeting. Any ideas?*

*.....Silence.....*

*Dave: Well.... here are the options as I see them: I either put some coating on the plate, replace the plate with a harder material or redesign the whole interface.*

*Bill: That sounds like a pretty complete list. I can be of help on the first two options. We can put a polyethylene, polypropylene or nylon coat on the surface. As for replacing the Aluminum, I would suggest stainless steel.*

*Dave: Do you think we can get by with just a plastic coat on the surface? That sounds too easy.*

*Bill: I'm not sure, but I did it once before on a similar product and it worked well. A test piece could be made up and cycle tested.*

*Dave: Seems too soft to me?*

*Lucy: What about the stainless steel plate idea?*

*Bill: It should be hard enough to wear well.*

*Dave: I agree, but then I will have to find a way of connecting the plate to the rest of the aluminum panel. This presents some new problems such as transmitting the forces during impact and consideration for assembly. I think I should look at eliminating the plate by avoiding the impact.*

*Lucy: Can you do that?*

*Dave: I think so. I need to go back to some earlier decisions and see why we ended up with this problem in the first place. I am confident that, if given some time, I can avoid the problem altogether.*

Lucy: *Well guys, what do we do next to resolve this problem?*

There are many important points to notice about this simple dialog and they form the basis for a taxonomy that is refined throughout the remainder of the paper. The taxonomy's key classifications are in bold text. First, the problem that the team is trying to solve has a describable **structure**. It is characterized by completeness and quality of information describing the design space (i.e. alternatives and criteria for judging them), and the details on how a choice is made. Second, the problem **focus** changes from the product being designed to consideration of the tasks (i.e. the process) needed to support design decisions. Third, the resolution of this issue has a **range** of effects. A decision made on this issue may affect future issues and require reconsideration of decisions made past issues. Fourth and finally, Lucy is seeking **support** for deciding "what do we do next." The support she seeks can range from simply a good representation of the problem at hand to a full decision analysis with clear guidance as to what to do next. The four areas in bold will be refined and supported in Section 3, and used to classify the example in Section 4 and common decision support methods in Section 5. First, a simple decision problem model is developed as a basis for discussion.

## 2. THE STRUCTURE OF DECISION PROBLEMS

There are many types of problems solved during the design process. In reviewing the literature for this paper the authors found publications on decision making in five different sections of the library: operations research, optimization, artificial intelligence, psychology and business. Further, there are over 160 computer based decision support systems on the market [2]. In order to develop a common vocabulary which covers all these disciplines and tools is challenging. Since this paper is focused on those requiring a decision about which alternative to choose. A model based on IBIS (see Section 5) has been chosen. The terms in *italics* are key words based on the IBIS model and used throughout this paper.

1. In the example a number of interdependent design issues are discussed. A *Design Issue* is any question, problem or task identified by designers that needs to be resolved. The dialog begins with a potential problem with the product - "the strike plate... has to take the repeated impact of the latching mechanism" - and ends with a process or planning issue - "what do we do next." An issue may be the need to fulfill design requirements (i.e. specifications or constraints), the need to establish a value for some design object parameter, or the desire to determine the next part of the design problem to work on. Some important points about issues are: (1) they are often dependent on the resolution of other issues; (2) sub-issues arise (e.g. cycle testing the plastic coating); and (3) they can be focused on the product (the object being designed) or on the design process (e.g. what to do next) and these two types are often interwoven with each other as in the example above.

The same issue, revisited after gathering more information, may yield a different decision. In the example, an earlier set of decisions resulted in the current configuration. David even mentions going "back to some earlier decisions" and the resolution of the current issue may alter or even nullify some of these earlier decisions. Further, a process decision to reconvene in a couple of days after more information about some of the alternatives and criteria is gathered will probably be made. A refined decision can then be made at the next meeting. Thus, decision making is a *dynamic* activity.

Each issue has a set of *criteria* (i.e. constraints, specifications, requirements, needs) for evaluating alternatives that are potential solutions. These criteria may be a well developed set of equality and inequality

constraints. They may be refined requirements developed through a tool like Quality Function Deployment. They may be ad hoc (developed during the discussion as above) or they may be totally unstated.

2. For each issue a number of alternative solutions are proposed. An *alternative* (i.e. proposal, idea) is an option generated by an individual or a team for the resolution of a particular design issue. Alternatives range from all the possible values for a variable(s) to a set of discrete options having no apparent common variables. Some important points about alternatives are: (1) they are developed by various members of the design team; (2) they are often incompletely described and/or understood; (3) they are often dependent on the resolution of other issues or alternatives; (4) they will often introduce new sub-issues needed to develop sufficient information to evaluate or refine it; (5) they may be inconsistent with other alternatives used to solve another issue; (6) they may be at different levels of abstraction (e.g. some are vague ideas and others refined values for a component) and in a different language (e.g. text, sketches, physical objects). In the example Bill knows a lot about plastic coatings. This alternative is well known, but it is dependent on a new issue - develop and cycle test a sample - proposed by Bill to improve his knowledge. At another point Dave has only a rough, incomplete idea about the alternative for eliminating the front plate. To learn more about this alternative Dave will need to return to the earlier issues to reassess them and may need to address totally new issues.

Alternatives and criteria describe the *decision space* or, in terms of decision theory, the world. In the decision support methods described in Section 5, the decision space ranges from a matrix of the discrete alternatives versus the criteria for their evaluation (e.g. utility theory and Pugh's method), to the continuous area of potential variable values bounded by constraints (e.g. formal optimization).

3. In resolving an issue, *arguments* for and against the alternatives are given. Arguments require that alternatives be evaluated against the criteria. Evaluation requires comparisons that identify the relative merits or demerits of an alternative. These comparisons are made either between alternatives relative to a specific criterion or between an alternative and a criterion (see page 169 in [18] for a discussion). Some important points about arguments are: (1) they are made with varying levels of confidence, knowledge and abstraction; (2) they are posted by various members of the design team; (3) they may be inconsistent with each other; and (4) they will often introduce new sub-issues needed to develop sufficient information to complete the evaluation. In the example, some arguments given by team members were inconsistent (Dave and Bill did not agree on the plastic coat). Some arguments were incomplete (not everyone evaluated every alternative relative to every criterion) and they were made with various levels of team confidence. To refine the arguments sufficiently to support making a decision, Lucy must allocate scarce resources. Part of her decision is how much time and expertise to devote to increasing the completeness, confidence and consistency of the arguments.

The argument structure gives the rationale [19] for either supporting or opposing a particular alternative. This structure has two main parts, *preference* and *belief*, which are developed in the Section 3.

4. The decision on "what to do next" is a process decision based on information about both the product and the process. A *Decision* weighs the arguments supporting or opposing the alternatives for a particular issue. The effect of the decision is to either accept, reject, or modify each alternative, or to leave the issue pending while more information is gathered. The history of the design process is the chronological sequence of decisions that relate progress on the design project [8][9].

This model of the decision making, based on issues, criteria, alternatives, arguments and decisions helps in understanding the example dialog. It fits the structure of engineering decision making as shown in a number of studies [1][8][9][14][21][22]. Here it serves as a basic vocabulary for a taxonomy that is useful for classifying decision making problems and tools.

### 3. A TAXONOMY OF ENGINEERING DESIGN DECISION PROBLEMS

Based on the points raised above, Table 1 shows a taxonomy that can be used to classify types of problems, and the tools and techniques used to solve them.

<b>STRUCTURE</b>	DECISION SPACE	1. PROBLEM COMPLETENESS
		2. ABSTRACTION LEVEL
		3. DETERMINISM
	PREFERENCE MODEL	4. OBJECTIVE FUNCTION
		5. CONSISTENCY
		6. COMPARISON BASIS
	BELIEF MODEL	7. DIMENSION
		8. BELIEF COMPLETENESS
	<b>FOCUS</b>	9. PROBLEM FOCUS
	<b>RANGE</b>	10. RANGE OF INDEPENDENCE
	<b>SUPPORT</b>	11. LEVEL OF SUPPORT

**Table 1.** *Decision problem taxonomy*

The four key classifications, that were introduced after the example dialog, form the basis of this taxonomy. The **structure** of the decision problem is further decomposed into three sub-classes. The *decision space* is the set of all possible outcomes for the problem and the limits on them. This world of possibilities is defined by the alternatives (i.e. the variables) that are the potential solutions for the problem and the criteria or constraints that measure or limit the solution. In all decision problems these two pieces of information are central to the problem definition.

The *preference model* and the *belief model* characterize the structure of the arguments used to evaluate the alternatives. The preference model represents the goal of the problem or value of each potential outcome. In other words, preference is a model of what the decision maker(s) care about. This is often quantified by an objective, cost or utility function. The belief model is a representation of the likelihood of success for a particular solution to the problem. The belief model expresses what the decision maker(s) knows or accepts to be the basis for making the decision. This can be measured by the knowledge about the alternatives and the confidence in them satisfying the criteria.

The total taxonomy is composed of eleven numbered measures (see Table 1). Discussion of each of these includes an itemization of the possible values for each measure (underlined text) and an example from the dialog. Common decision support methods will be classified using these measures in Section 5 of this paper.

### **Decision Space Structure: 1. Problem Completeness**

In the decision space, information describing the alternatives and criteria may be complete or incomplete. If all the alternatives are known and all the criteria for evaluation can be itemized (i.e. fixed), then the problem is considered complete. In the example problem the alternatives and the criteria for their evaluation evolve as the discussion progresses. There is no confirmation that either is complete. The problem is open to new alternatives and criteria, as is the case in many design problems. In contrast however, most of the formalized decision support methods require complete information.

### **Decision Space Structure: 2. Abstraction**

In the decision space, the alternatives and criteria may be refined or abstract. Generally, refined information is quantitative, whereas abstract information is qualitative. In some decision problems, the Abstraction level of the information is mixed. It is well recognized that much early design information is qualitative and that the final manufacturing specifications are quantitative. In the example, the team's discussion is qualitative. Even though quantitative information exists about the hardness of materials, Dave and Bill do not bring it into the discussion. Rather, they use terms like "too soft" as appropriate. As the issue is further studied, quantitative information may become important (e.g. the results of Bill's cycle test).

### **Decision Space Structure: 3. Determinism**

The information used in the problem may be deterministic or distributed. While most analysis is performed on point-valued variables it has long been recognized that all design parameters are actually distributions [5][12]. Often the exact distribution of information is unknown.

### **Preference Model Structure: 4. Objective Function**

A key feature of all decision making methods is a mechanism for evaluating how well alternatives meets the criteria. This evaluation is quantified through an objective, utility or cost function, a measure of preference of one alternative relative to others. In many problems the objective function is based on the values for parameters that characterize the alternatives and the desire to maximize, minimize or find an internal optimum point for some parametric characteristic as in formal optimization. In other problems, the objective function is a weighted preference of criteria that call for judgement or satisficing rather than analysis. In the example, there is clearly no parameter being optimized, rather the team's decision will be based on their judgement of the information available.

### **Preference Model Structure: 5. Consistency**

When a team of designers is making design problem decisions, there may be many different viewpoints on the importance of criteria and the evaluation of alternatives, thus, preference models may vary within the team. If the problem is being solved by a single individual, a team with a unified view, or if a methodology can only represent a single viewpoint then the decision making problem is considered consistent. If, as in our example, there are conflicting viewpoints, then the preference model is inconsistent.

## Preference Model Structure: 6. Comparison Basis

The comparison basis is a measure of the type of comparison made in the evaluation of an alternative. An alternative is either compared absolutely to a criterion or relatively to another alternative. Relative comparisons are made along dimensions set by criteria. In the example, both types of comparisons are made. Dave, evaluating the concept of a plastic coat on the surface, makes an absolute comparison to a hardness criteria. If the issue is further refined, the choice between polyethylene, polypropylene and nylon will be a relative comparison among the hardness of the three materials plus a comparison along other measures set by other criteria.

## Belief Model: 7. Dimension

Some decision support methods allow the decision maker to express his/her belief or certainty in the information within the decision space. These methods generally use probability to quantify knowledge of the alternatives and criteria. Probability is also used to quantify confidence in an alternative's ability to meet the criteria. Knowledge is a measure of how much the evaluator knows about the alternative/criteria space. During design activities knowledge is generally increased by building prototypes, doing simulations (analytical and physical) or finding additional sources of information (e.g. books, experts, consultants). Confidence is a measure of how well the evaluator believes the alternative actually meets the criteria. Decision problems or methods are classed by the number of dimensions of information involved: none; one (confidence or knowledge); or two (knowledge and confidence). In the example, Bill's knowledge of plastic coatings is greater than Dave's and his confidence that this alternative meets the criteria is higher. In this case the team should have some confidence that plastics are a feasible option. Additionally, in the discussion, both Bill and Dave propose tasks to improve their knowledge about the alternatives. Dave's confidence in the alternative for "eliminating the plate by avoiding the impact" is tempered by his lack of knowledge about the idea. This lack is expressed in his response to Lucy's query with "I think so."

## Belief Model: 8. Belief Completeness

In most engineering decision making problems all the alternatives are not evaluated against all the criteria by everyone on the design team. This is especially true if the team is multi-disciplinary or if some team members have little knowledge about some of the criteria. Where item 1 above measured the completeness of the information representing the problem, this measure focuses on the completeness of the team evaluation of the information. In the example, if everyone on the team had given an evaluation of each alternative relative to each criteria then the belief model would be complete. Lucy gives no evaluation of the plastic coat idea, amongst others, and so the belief model is incomplete.

## Focus: 9. Problem Focus

The focus of each design issue is either on the product being designed or on one of the processes that support the design, manufacture or distribution of the product. The issue addressed in the dialog is focused on the product. A planning issue evolves during the dialog.

## Range: 10. Range of Issue Independence

Each design issue may be independent or dependent on other issues. The level of dependence affects the number of times an issue is reconsidered. There are three types of dependency considered here:

Type I: Independent Issues. A Type I decision is based on a single, independent issue. Arguments and alternatives related to the issue are based on unchanging information (i.e. a decision on an issue is made with constant (i.e. static) information). The implicit underlying model is that decision making proceeds monotonically. Each issue is resolved with a decision that is never retracted. Dependent issues must wait for decisions to be made in parent issues. Type I decisions can only occur in systems that can be decomposed into independent issues. This is an ideal situation and not usually the case in engineering decision making.

Type II: Dependent Issues. An issue in a Type II system is dependent on the resolution of other issues. Information about arguments and alternatives are shared by more than one issue. In order to reach a decision, an issue may be suspended while other issues are addressed. Additionally, issue dependence is important if decisions are retracted or changed as these changes affect other, dependent issues. Issue interdependence and retraction of previously made decisions are characteristic of most engineering design situations and is evident in the example: Dave faces the possibility of returning to an earlier decision because of a new criteria to minimize face plate marring. Lucy faces the problem that if the decision is made to put more effort into one issue there will be less resources available for work on other issues.

In reaching decisions for Type II situations, the alternatives for each issue and the dependency of arguments on those alternatives must be tracked. This is difficult for all but the simplest problem. Often, during the design process, this information is lost or the problem artificially simplified to make the problem Type I.

Type III: Interdependent Issues. Type III decision making concerns the composition and decomposition of issues. Where Type I and Type II decisions are limited in their range to a single issue, and simple "linear" relationships between issues, Type III focuses on the decompositions of issues into sub-issues and the subsequent composition of information derived in the sub-issues back into the higher level issue. In the example, the alternatives spawned new sub-issues. As the problem progresses, alternate sets of sub-issues may arise. The resolution of these sub-issues affects the resolution of the original issue. For Type III decisions, the representation of the design process must be rich enough to not only share data about the design object as in Type II tools, but to also represent the interdependencies of the issues. Specifically, the representation must relate how the resolution of an issue affects super-issues and how sub-issues are generated to resolve it. Another key feature of Type III decision making is that the issue decomposition is itself evolving as the design evolves, an extremely dynamic situation.

Most design work is of Type III. In a video taped study of a design session the issues associated with the development of a single physical part was explored [20]. Nineteen issues were visited 70 times, or 3.7 visits per issue. Each visit included new information which affected the alternatives considered, the criteria used and the decision made. The new information was a result of decisions made during the resolution of sub-issues and co-dependent issues.

### **Support: 11. Level of Support**

The level of support offered to the decision makers can be classified as either: representation, outcome determination, or decision analysis.

Level 1: Representation. The minimal amount of information to support decision making is the representation of the issues, alternatives, arguments and constraints on which the decision is based.

Level 2: Outcome Determination. In engineering, many decisions are made based on the result of analysis or simulation. In order to compare an alternative to a criteria the behavior must be determined either by mathematical analysis, development of a physical test or some other simulation of system. Thus, outcome determination gives information to support the evaluation needed to make a decision. Some decision support tools within commercial CAD programs are analysis tools with a strong user interface allowing rapid change of variable values (i.e. alternatives) so that iterative evaluations can be made easily.

Level 3: Decision Analysis. This level of support determines which alternative to choose in order to satisfy an issue. This is an extension of Level 2 in that information is needed about design preferences in order to make the decision. Level 3 tools are the most knowledge intensive. In order to actually make such a recommendation, the tool must not only know the distribution of possible outcomes, but also their utility.

#### 4. CLASSIFYING THE EXAMPLE DECISION PROBLEM

The classification outlined in the section above can be applied to both design problems and to decision support tools. In this section, as an example, the dialog in the introduction is measured using the categories listed in Table 1. Table 2 shows the eleven major measures of the taxonomy in the first column and values for classifying the example in the second column. In this table, as in others that follow, values that are shaded are discussed.

DECISION SPACE	1. PROBLEM COMPLETENESS	Incomplete
	2. ABSTRACTION LEVEL	Qualitative
	3. DETERMINISM	Undefined
PREFERENCE MODEL	4. OBJECTIVE FUNCTION	Judgement
	5. CONSISTENCY	Inconsistent
	6. COMPARISON BASIS	Absolute
BELIEF MODEL	7. DIMENSION	2; Knowledge and Confidence
	8. BELIEF COMPLETENESS	Incomplete
	9. PROBLEM FOCUS	Product
	10. RANGE OF INDEPENDENCE	Type III:: Interdependent
	11. LEVEL OF SUPPORT	Level 3: Decision Analysis

**Table 2.** *Example problem*

The issue in the example is how to reduce the potential damage of the latching mechanism as it impacts the strike plate. The alternatives and criteria for the team's evaluation evolve as the dialog unfolds. Since more alternatives and criteria may evolve, the decision space is incomplete. The discussion in the dialog is only about qualitative information. It is so abstract that is not clearly deterministic nor stochastic and is thus rated as undefined. The objective function is based on judgement. Since it is so informal, it is not clear if the basis

of judgement is consistent and so it is assumed inconsistent. Reading the dialog shows only absolute comparison to the criteria. The belief model is not articulated well, yet it is clear that the team members express both

knowledge and confidence on their evaluation of some of the alternatives. Lucy gives no arguments and Dave and Bill give incomplete arguments on most alternatives. The dialog, although focused on one issue, develops other interdependent issues. Finally, Lucy wants to know "what do we do next" - a request for a decision analysis.

Certainly not all decisions need the level of support demonstrated in this example. As is shown in the next section there are no tools currently available that can support Lucy in making a decision on this problem. However, there are many that are useful in more limited situations.

## 5. CLASSIFYING EXISTING DECISION SUPPORT SYSTEMS

There are many types of decision support tools available for use in engineering design. In this section a few of these tools will be classified using the taxonomy. This exercise will add insight into the usefulness and limitations of the various tools.

**IBIS:** The IBIS representation of decision making has been shown to be a good model of design problem solving [1][8][9]. IBIS allows the representation of the interdependent nature of issues, alternatives and arguments regardless of the type of data, its completeness or its consistency. In a software development project at NCR Corporation, researchers used IBIS based tools to represent the organization of issues, alternatives, arguments and decisions on a computer [21][22]. The entire project addressed 2260 issues and is by far the largest study of its type. Some of the results from this study are:

- \* IBIS provided a shared memory for the design team. The history of decisions made and recorded in the tools was easily reviewed and utilized by members of the design team and by management.
- \* IBIS helped the team detect design issues that had "fallen through the cracks." It was estimated the resulting savings were 3-6 times greater than the cost of using the tools.
- \* IBIS helped the team to more quickly understand the problem they were trying to solve.
- \* IBIS helped structure the information (issues, positions, and arguments) and helped establish and focus the agenda. Team meetings seemed more productive.
- \* IBIS supported communication with other levels of the organization. People not at a design team meeting easily discerned what was discussed -- not just what the final decision was.

The IBIS model allows for the representation of incomplete, dynamic information about interdependent issues associated with either the product or the process. Information is expressed informally, so that the design space can include quantitative or qualitative as well as deterministic or distributed data in support of the product or process. There is no formal structure to support belief or preference, however, these can be expressed informally as part of an argument. Although IBIS can model complex decision making information, it offers no automated support beyond the representation. This classification is shown in Table 3.

DECISION SPACE	1. PROBLEM COMPLETENESS	Incomplete
	2. ABSTRACTION LEVEL	Quantitative or qualitative
	3. DETERMINISM	Deterministic or distributed
PREFERENCE MODEL	4. OBJECTIVE FUNCTION	None
	5. CONSISTENCY	N/A
	6. COMPARISON BASIS	N/A
BELIEF MODEL	7. DIMENSION	None
	8. BELIEF COMPLETENESS	N/A
	9. PROBLEM FOCUS	Product or Process
	10. RANGE OF INDEPENDENCE	Type III: Interdependent
	11. LEVEL OF SUPPORT	Level 1: Representation

**Table 3.** *IBIS*

**Probabilistic Design:** Most engineering design analysis is deterministic. A single value representing the mean is calculated as part of the evaluation process. An extension of this traditional analysis is probabilistic design [5][12], a well refined technique for statistically analyzing the design of machine components. In this method, the equations that relate the variables (e.g. dimensions and material properties) in a problem deterministically are extended to relate their true, uncertain nature. Thus, each variable is represented by its probabilistic distribution.

As shown in Table 4, this method requires a complete and quantitative representation of the information in the decision space. The information represents the distribution of the variables that characterize the product. The distribution represents a form of confidence in the values of the variables. This does not support any form of preference model. The method is generally applied to the outcome determination of independent issues.

DECISION SPACE	1. PROBLEM COMPLETENESS	Complete
	2. ABSTRACTION LEVEL	Quantitative
	3. DETERMINISM	Distributed
PREFERENCE MODEL	4. OBJECTIVE FUNCTION	None
	5. CONSISTENCY	N/A
	6. COMPARISON BASIS	N/A
BELIEF MODEL	7. DIMENSION	Confidence
	8. BELIEF COMPLETENESS	N/A
	9. PROBLEM FOCUS	Product
	10. RANGE OF INDEPENDENCE	Type I: Independent
	11. LEVEL OF SUPPORT	Level 2: Outcome determination

**Table 4.** *Probabilistic design*

**Formal Optimization:** Formal optimization requires the design problem (i.e. the issue) to be expressed as a cost, objective or utility function to be minimized. Alternatives, characterized as sets of values satisfying this function must meet equality and inequality constraints (i.e. criteria). Arguments are given by the search algorithm and the decision is reaching the maximum or minimum value. This type of decision support tool, for both single issue and coupled systems, is classified in Table 5.

In design, most optimization is focused on variables that represent the behavior of the product being designed. These variables are quantitative and generally deterministic. In order to develop the cost function, a complete model of the system is necessary. The preference model searches for an optimum based on the absolute comparison of the variable values to the criteria. There must be a consistent view of this information and it must represent a single independent problem. There is no mechanism to represent belief in this method. Finally, the goal of optimization is to find the extreme value for the utility function, ergo there is decision analysis support.

Sobieski [13] and others have extended optimization across several interdependent issues. This type of optimization allows the decisions to be made on a number of dependent issues. For example, to optimize aero-space systems such as those with structures which need minimum weight, maximum strength and specific aerodynamic characteristics - three dependent issues each characterized by its own utility function must be satisfied.

DECISION SPACE	1. PROBLEM COMPLETENESS	Complete
	2. ABSTRACTION LEVEL	Quantitative
	3. DETERMINISM	Deterministic (generally)
PREFERENCE MODEL	4. OBJECTIVE FUNCTION	Optimum
	5. CONSISTENCY	Consistent
	6. COMPARISON BASIS	Absolute
BELIEF MODEL	7. DIMENSION	None
	8. BELIEF COMPLETENESS	N/A
	9. PROBLEM FOCUS	Product
	10. RANGE OF INDEPENDENCE	Type I: Independent Type II: Dependent
	11. LEVEL OF SUPPORT	Level 2: Decision Analysis

**Table 5.** *Formal optimization*

**CPM/PERT:** CPM/PERT methods are used to order a set of known tasks (i.e., issues). For each task, information about its dependency and precedence (i.e. constraints) is known with certainty and consistency. In CPM the alternatives are simply the various ordering of the issues. A similar method, called the precedence matrix method, exists for ordering sets of equations that represent the function of a device. Both of these techniques are fully developed in Steward [16]. Additionally, the CPM method is often extended through the use of PERT, which adds uncertainty to the CPM method by assuming a beta distribution for time estimates. The taxonomy in Table 6 covers all these methods.

DECISION SPACE	1. PROBLEM COMPLETENESS	Complete
	2. ABSTRACTION LEVEL	Quantitative
	3. DETERMINISM	Deterministic or Distributed
PREFERENCE MODEL	4. OBJECTIVE FUNCTION	Optimum
	5. CONSISTENCY	Consistent
	6. COMPARISON BASIS	Absolute
BELIEF MODEL	7. DIMENSION	None
	8. BELIEF COMPLETENESS	N/A
	9. PROBLEM FOCUS	Process (generally)

	10. RANGE OF INDEPENDENCE	Type II: Dependent
	11. LEVEL OF SUPPORT	Level 3: Decision Analysis

**Table 6.** CPM/PERT

CPM/PERT methods require complete, quantitative information in the decision space. Whereas most methods of this type require deterministic information, PERT supports distributions. In all cases, the goal is an optimum based on consistent data and is compared absolutely to the criteria constraining the problem. There is no belief support system for these methods. They usually support decision analysis of dependent issues (i.e. tasks) representing a process.

**Decision Support Systems and Decision Trees:** Decision Support Systems (DSS) and decision trees are widely used in business. DSSs are the outgrowth of management information systems (MIS) and are aimed at modeling the business processes. According to Hopple [6], they are "therefore targeted at top managers and executive decision-makers." There are many different DSS systems available and their development is still immature. Hopple lists 9 major families and over 50 different methods used in modeling. The literature contains very little information about DSSs for aiding decision makers dealing with ill-structured design problems. Little is known about ill-structured problems and so far computer decision aids have not been any more effective than delivery by traditional, paper and pencil means (e.g. Pugh's method)[3].

DECISION SPACE	1. PROBLEM COMPLETENESS	Complete
	2. ABSTRACTION LEVEL	Quantitative
	3. DETERMINISM	Distributed
PREFERENCE MODEL	4. OBJECTIVE FUNCTION	Optimum
	5. CONSISTENCY	Consistent
	6. COMPARISON BASIS	Absolute
BELIEF MODEL	7. DIMENSION	1, Knowledge
	8. BELIEF COMPLETENESS	Complete
	9. PROBLEM FOCUS	Process(primarily)
	10. RANGE OF INDEPENDENCE	Type II: Dependent
	11. LEVEL OF SUPPORT	Level 2: Decision Analysis

**Table 7.** Decision tree, Decision support system

Decision trees represent the relationships between issues and chance occurrences. From each issue node there are branches representing the various alternatives for resolving the issue. At each chance node there are branches representing the possible outcomes from events affecting the system over which there is no control. The probability of any of the branches from a chance node is a measure of the belief in the chance occurrence

[7]. The decision space is defined by all the possible outcomes, i.e. all the alternative/chance combinations. The values placed on each outcome by the decision makers, i.e. the worth of the outcome, define the preference model.

Decision support systems and decision trees support a belief model through which the expression of knowledge about chance occurrences affects the outcome of the system in dependent issues. This expression must be complete at each chance node to calculate the outcomes.

**Pugh's Method:** Pugh's method is a refined form of the decision matrix method [10][18]. Selection among itemized alternatives is accomplished by relative comparison to a set of criteria defined in the issue. Each alternative is weighed by its ability to meet each criteria. Belief is expressed through the expression of confidence in each alternative's ability to meet each criteria. This method is used to support judgements about qualitative information. It results in an abstract satisfaction expectation for each alternative. Pugh's method supports an individual decision maker and thus uses consistent information. The information must be deterministic and complete for the method to be useful.

DECISION SPACE	1. PROBLEM COMPLETENESS	Complete
	2. ABSTRACTION LEVEL	Qualitative
	3. DETERMINISM	Deterministic
PREFERENCE MODEL	4. OBJECTIVE FUNCTION	Judgement
	5. CONSISTENCY	Consistent
	6. COMPARISON BASIS	Relative
BELIEF MODEL	7. DIMENSION	1, Confidence
	8. BELIEF COMPLETENESS	complete
	9. PROBLEM FOCUS	Product or process
	10. RANGE OF INDEPENDENCE	Type I: Independent
	11. LEVEL OF SUPPORT	Level 2 Decision Analysis

**Table 8.** *Pugh's method*

**Utility Theory:** Utility theory allows decision makers to give formalized preference to a space defined by the alternatives and criteria. For example, in one method, each alternative/criteria pair is given a score reflecting how well the alternative meets the criteria. The scores for each alternative are combined with measures of each criterion's importance (i.e. weight) to give a total utility for the alternative. Utility is a measure of preference for one alternative relative to another. A good formalization of this method is given in Edwards [4].

Although utility theory allows a strong representation of preference, it has no model of belief. Thus, methods using this approach focus on ways of modeling the objective or utility function, have no formalized way to manage information concerning knowledge and confidence.

DECISION SPACE	1. PROBLEM COMPLETENESS	Complete
	2. ABSTRACTION LEVEL	Quantitative or qualitative
	3. DETERMINISM	Deterministic
PREFERENCE MODEL	4. OBJECTIVE FUNCTION	Judgement
	5. CONSISTENCY	Inconsistent is possible
	6. COMPARISON BASIS	Relative
BELIEF MODEL	7. DIMENSION	None
	8. BELIEF COMPLETENESS	N/A
	9. PROBLEM FOCUS	Product or Process
	10. RANGE OF INDEPENDENCE	Type I: Independent
	11. LEVEL OF SUPPORT	Level 2: Decision Analysis

**Table 9.** *Utility theory*

## 6. CONCLUSIONS

There are thousands of decisions made in every design project. Few are supported by formal methods or tools. This leads to one of two conclusions: Either there is no need for decision support (designers and design teams do very well without aid), or tools and methods have not yet been developed that give adequate decision support. From the results of the IBIS experiments combined with anecdotal evidence it is believed that individual designers and, more importantly, teams of designers do not make good design decisions. This is evidenced by the length of design meetings, the rehashing of previous information, the dropped issues and the lack of documented rationale for decisions. Thus, in this concluding section, the reasons for this lack of use and research directions to improve the quality of design decisions will be summarized. This section is organized parallel to the taxonomy, and reference to the example problem and Table 2 is suggested.

In reviewing the decision making literature from the different disciplines it is clear that all are solving problems that can be compared and contrasted using a structure composed of five information types - issue, criterion, alternative, argument and decision. Thus, the uniqueness or similarity of design problems and methods to those in other fields can be made with measures of these five. The taxonomy is an attempt to add such measures.

The taxonomy was developed by synthesizing terminology from disciplines which already have an established history of supporting decision making. Thus, the vocabulary in the taxonomy is difficult.

However, this effort at unifying the various view points serves as a basis for evaluating problems and decision support tools. It is suggested that before any tool is used on a design problem, the problem and the tool be evaluated against the eleven measures in the taxonomy.

In many design problems the decision space is incomplete - there are alternatives that have not been developed and some criteria are unknown or are only weakly understood. This is especially true in the early stages of the design process when critical decisions are made. Ideal design decision support would point the designer toward solutions possibly better than those in the set considered. It would also be able to assist criteria that are evolving, not fully refined or conflicting. Further, in many design problems, the alternatives and criteria are not all quantifiable. Thus, design decision support needs to accommodate information that is refined along with that which is abstract - qualitative. Finally, all design information, whether quantitative or qualitative, is distributed and not point-valued.

These characteristics of the decision space point to the need for tools and methods that can accommodate alternatives and criteria that are not well known, point-value variables. Pugh's method and IBIS move in that direction, but are almost too informal. Fuzzy methods attempt this, but are not widely accepted. Extensions of utility theory, optimization and other accepted methods to manage such information may be needed.

All decision support tools and methods are built around a preference model which relates how the alternatives are compared to the criteria. All of the methods or tools reviewed require a consistent preference model. However, most design problems are solved by teams of individuals possibly representing different view points. Each team member may have a different model of what is important and this preference needs to be easily reflected in any support tool.

All decisions are based on belief in how well the alternatives to meet criteria. Engineers are not accustomed to dealing with belief in a formal manner and thus tools commonly used are weak in support of any information that is not totally true. However, all decisions are made based on less-than-perfect knowledge and less-than-absolute confidence in the information. As a design is refined, tests are made and simulations run, knowledge increases and confidence in solutions evolve. There is challenge to develop decision support methods and tools that can support belief and its evolution.

To support engineering design there needs to be the realization that the product and process co-evolve. Thus support for decision making about the product must reflect the effect of the decision on the process (i.e. what to do next, time, cost, personnel commitments). Conversely, decisions about the process obviously affect the product.

Engineers decompose design problems into manageable sub-problems and work on these as independently as possible realizing that the decisions made on one may have ramifications on others. Managing this interdependence is difficult and often poorly done. The tools reviewed were limited in their support and need extension to give sufficient aid.

Finally, experiments with IBIS showed that even representation of the decision making process had benefit to designers. Thus, even the simplest aid in helping the design structure the decision space, preferences and beliefs seems to be of help. Of course, systems that give outcome or full decision analysis are even more

supportive. It is suggested that systems which currently offer representation or outcome analysis be pushed to offer more decision support. In these developments, attention to the previous ten measures of decision support is essential.

Like any classification system, the one presented in this paper is transitory. As new methods are developed and new insight gained, this scheme will change and evolve. As it is now, it adds structure to a diverse field that is little used in day-to-day engineering work, and explains that lack of use: existing tools do not address many of the core requirements for engineering decision support.

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Tables:

Table1: Decision Problem Taxonomy

Table 2: Example Problem

Table 3: IBIS

Table 4: Probabilistic Design

Table 5: Formal Optimization

Table 6: CPM/PERT

Table 7: Decision Tree, Decision Support Systems

Table 8: Pugh's Method

Table 9: Utility Theory

Bruce D'Ambrosio

Dr. D'Ambrosio received his Phd in Artificial Intelligence from the University of California at Berkeley in 1986. His current research is focused in developing decision-theoretic models of real-time monitoring, diagnosis, and assessment. Dr. D'Ambrosio is a member of AAAI and the ACM, is on the editorial board of Knowledge Engineering Review, the International Journal of Approximate Reasoning, and the Journal of Heuristics. He has served as both program and general chair for the Conference in Uncertainty in AI, and is organizer of the first Advanced Summer Institute on Probability in AI.

David G. Ullman

Dr. Ullman is a Professor of Mechanical Engineering Design at Oregon State University and a Professional Engineer in Oregon and New York. He has worked as design manager for a medical products OEM; holds two patents for current products one of which is licensed to major corporation. He is author of The Mechanical Design Process and The Failure Analysis Method. He contributed to Concurrent Engineering: The Product Development Environment for the 1990s. Dr. Ullman is the founder and first chairman of the ASME Design Theory and Methodology Committee and was chairman of the 1989 and 1990 Design Theory and Methodology Conferences. He is a fellow of the ASME. He holds a Masters in Aerospace Engineering from the University of Cincinnati and a PhD. in Mechanical Engineering from Ohio State University. He is currently involved in research aimed at understanding the mechanical design process and the development of design aids.

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