AN ABSTRACT OF THE THESIS OF

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An Engineering Decision Support System, EDSS, was developed using Bayesian mathematics which incorporates knowledge and confidence components observed in alternative-criterion pair decision making. The separation of knowledge and confidence has been previously unaccounted for in decision-making methods. EDSS provides decision support to individuals or teams which must make choices between alternatives using alternative-criterion pair evaluations. Further, EDSS was instanciated into computer software.

The EDSS decision support system was statistically tested using two variables, mechanical experience of the participants and the use of a decision method, at two different levels and in a replicated factorial experiment. The experiment consisted of teams of subjects solving a simple mechanical design problem. Data from the experiment was collected for eighteen different metrics in four categories. This research reports on each of eighteen metrics using the hypothesis that the use of EDSS will show improvements in, or positive impact on, the following four categories: the decision making productivity of idea processing, the decision-making process, the perception of the decisions made by the decision makers, and the ease of use of a computer decision support tool.

Statistical results of the experiment showed that EDSS successfully matched ad-hoc and Pugh's decision matrix performance for sixteen of the eighteen metrics and statistically exceeded the remaining two. These two metrics are, the conduction of more evaluations of alternative-criterion pairs ,and increased problem understanding.

This research also shows that a new alternative-criterion pair evaluation method has been successfully created that provides for:

- A separation of knowledge and confidence in the Belief Model of decision making.
- Decision results without complete evaluation of all alternative-criterion pairs.
- Aggregation of preferences from team members.
- A convenient means for investigating decision improvements.

An Engineering Decision Support System (EDSS) with Alternative-Criterion Pair Evaluations

by

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Derald Herling, Author

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF APPENDIX FIGURES

LIST OF EQUATIONS

An Engineering Decision Support System (EDSS) with Alternative-Criterion Pair Evaluations

1. INTRODUCTION

This research has developed a new alternative-criterion pair decision-support method. This method incorporates two distinct components not previously used in alternative-criterion pair decision methods. These components were repeatedly observed in video protocols of engineering decision making using the evaluations of alternative-criterion pairs as the decision method. The first component uses two pieces of information, a person's knowledge level and confidence belief, to specify a satisfaction level for the alternative-criterion pair being evaluated. The second component provides decision results for a condition where less than a complete set of all alternative-criterion pairs has been evaluated.

A decision-support method is a regular, orderly, definite procedure that aids or helps decision makers in determining the best possible alternative or solution to an issue or problem. In support of this activity, this new method uses both the knowledge level and confidence belief usually found when video protocols of mechanical design decision activities are analyzed. The method also quantifies and consolidates, at any level of completeness, the set of evaluation information provided by the individuals or team members into a usable decision result. This consolidation into a common collaborative environment is possible in an office or across a global network. After consolidation, numerical results are provided for each alternative evaluated. These results provide support for final alternative selection used by the members. The Engineering Decision Support System, EDSS, is the name of the decision-support method and the computer program that instanciates this method.

EDSS as a decision method and computer program was tested using a replicated factorial experiment. Hypothesis testing and statistical validation of this new decision-support method was conducted using data taken from an experiment. The experiment required teams to solve a simple mechanical design problem by selecting a *best* solution. Data sources from the experiment includes video tapes, audio tapes, computer files, drawings, written notes and diagrams, and a formal questionnaire. Results from the experiment and the testing of the hypothesis, that the use of EDSS shows improvements in or positive impact on decision making, address four general categories with eighteen specific metrics.

This introductory chapter explains the motivation and objectives that guided this research. Using a taxonomy, Chapter 2 details the background review conducted on methods that apply to alternative-criterion pair decision making. The alternative-criterion pair evaluation decision problem structure is explained in this chapter. This structure includes the decision space, preference and belief models used to address the alternative-criterion pair evaluation. Additionally, Chapter 2 investigates some available computer decision support tools. Chapter 3 explains the information structure and representation of the evaluation activity as used by EDSS. The three models used within EDSS, cognitive, decision, and mathematical, are detailed in Chapter 4. Instanciation of the decision-support method in a PC Windows® software program is shown in Chapter 5. The experimental procedure, the design of the evaluation metrics, and the experiment variables are found in Chapter 6. The experiment, the design problem, data collection, and post-session reflections are described in Chapter 7. Chapter 8 is an extensive chapter, detailing the results of the experiment for the eighteen metrics. Qualitative comments about the decision making performance of the different groups are found in Chapter 9. Chapter 10 discusses and compares the results of using EDSS with other studies and alternative selection methods. Final conclusions and discussions are detailed in Chapter 11. Finally, recommendations for future research are treated in Chapter 12.

This research is motivated by the desire to provide a decision-support method that matches the structure and kind of information in alternative-criterion pair evaluation observed in engineering conceptual design activities. Additional motivation exists to provide improvements and new capabilities to decision-making activities which evaluate alternative-criterion pairs. The primary objective for this research is to confirm, through valid testing, that the motivations were appropriate, correct, and obtained.

Motivation for a new decision method that matches observations about observed information centers around alternative-criterion pair evaluations. Chapters 3 and 4 explain in detail this specific kind of decision problem and the structure of the information that it contains. Most importantly, in evaluating an alternative-criterion pair, this new decision method allows users to specify a two dimensional belief model: individual knowledge level about the pair, and a user's confidence belief that the alternative satisfies the criterion. This method also allows for decision results even when the evaluation activities are less than complete. This kind of evaluation is prevalent and commonly observed in the concept or idea evaluation phase of technical or engineering design activities (Olson 1992). This phase mostly occurs in the early stages of product design, but may also occur at any point along the time line of the technical product or project when many concepts and ideas are being considered as solutions to a design problem. This decision method is also useful in other areas that are not strictly technical, if alternative-criterion pairs are the basis of the evaluation or decision making scheme.

The alternative-criterion pair evaluation activity, whenever it occurs, can benefit from improvements. In quest of improvement, many books are sold, articles written, conferences attended, and workshops conducted that promise to help engineering designers do a better job in less time. This suggests that the engineering community is also very interested in strategies or systems that will facilitate decision making. Examination of the present set of decision methods that are commonly used for technical issues or evaluation of alternative-criterion pairs reveals that each method requires the user and the information to conform to its specific method requirements (see Chapter 2 for a detailed discussion). One example of how EDSS provides a more appropriate and useful decision method is that it does not require a complete evaluation of all alternatives with all criteria before valid decision results are available.

Another improvement motivation behind this research is to empower technical decision makers, who have various levels of specific experience-based knowledge, to use quantified knowledge to produce better decisions. EDSS matches the observed style of technical alternative evaluation more accurately than other methods. EDSS has the further advantage of a convenient software format.

Additional motivation for development of EDSS comes from the desire to use a more developed understanding of the kinds and types of information that people solving technical problems or engineers use and express during the preliminary or concept selection phases of design activities (Stauffer, 1987; Ullman, 1995). This information and representation form a structure which is fully explained in Chapter 2. Part of this increased understanding is a desire to more accurately differentiate criterion statements and understand their impact on decisions. This also is fully explained in Chapter 4. This work proposes a structure for stating criteria statements used in alternative-criterion pair evaluations.

Documentation of decisions is becoming increasingly important in many areas. In certain business areas, such as forest management, formal decision documentation is required (Anderson, 1995). Another example within the government, "The Department of Defense Military Standards: Software Development and Documentation (MIL-STD-498)," requires that system-wide design decisions be recorded in a manner that can be retrieved and viewed. It has been repeatedly expressed that decision makers quickly forget the rationale behind decisions (Herling, 1996). EDSS provides documentation which allows the rationale to be open for review.

A final motivation for this work is a desire for a decision method that has its genesis in the technical or engineering disciplines, where the predominant decision method is pair-wise evaluation of alternatives and criteria, rather than from the research in psychology, social science, business, or operations research. In May 1996, a World Wide Web search for titles related to engineering decision analysis or decision making (these terms are used interchangeably in the literature and in this work) produced only common business subject listings. No engineering or technical titles were found. A search of the web site of Amazon.com of Seattle, Washington (reportedly the world's largest book store) using their books-in-print search also produced nothing specific to the engineering decision analysis field.

Based on the motivations above, an objective statement was formulated for this research, that is, prove that decision performance can be improved with the use of EDSS. As an encapsulation of that primary objective, it is hypothesized that use of EDSS improves alternative-criterion decision performance. This hypothesis must be tested in an objective way. An experiment was designed that reproduced the decision activities observed in video protocols and a set of metrics that could be measured and used for hypothesis testing was devised. These metrics and the hypothesis are used to validate the motivations for this research. The metrics used for the test are explained in Chapters 6.

In summary, the overall objective for this research is to provide an effective and appropriate alternative-criterion pair decision-support method which improves decision performance and which technical decision makers find useful.

2. BACKGROUND REVIEW

This chapter reviews decision methods and software using the taxonomy of Ullman (1995). A decision method is any theory of choice used to select an item from among many candidates and a taxonomy is a classification system. Section 2.1 explains that taxonomy. Section 2.2 focuses on those methods that are considered appropriate for use with alternative-criterion pair evaluations commonly observed in technical or engineering decision making. Alternative-criterion pairs are an atomic unit of the evaluation activity in this research. The alternative is a candidate for solving the problem. The criterion statement is one of many requirements that the alternatives endeavors to satisfy if the alternative is to be selected as a solution to the problem being solved. Sections 2.3 and 2.4 review some other decision methods from computer science, business, and other areas. Sections 2.5, 2.6, and 2.7 review some decision software packages targeted for technical or engineering, general, and problem specific areas. The final section 2.8 is a conclusion.

2.1 Taxonomy

The taxonomy used for this chapter is shown in Table 1. The decision methods selected below, because of their relevance to the decision making activities that motivated this research, were evaluated in terms of the eleven attributes specified in the taxonomy. Those attributes which are being defined as superior in terms of the decision activity that motivated this research are in bold type. The attributes defined as superior were defined based on conceptual design evaluation protocols (Cross, 1996; Ullman, 1995; Stauffer, 1991).

The decision activity and the method used to select a final solution to the problem in this research have a discernable structure which was commonly observed in the above mentioned video protocols, has a focus, a specific range of independence, and additionally, some definable level of support. In concert with the above, an alternative-criterion pair evaluation decision method that meets the motivations behind this research is characterized by those attributes in bold print in Table 1. These key attributes or characteristics for the decision problem type addressed in this research and the attributes that motivated creation of a superior decision method for these problems are explained below.

STRUCTURE	DECISION SPACE	1. Problem Completeness	Complete or **Incomplete**
		2. Quality	**Quantitative and Qualitative**
		3. Determinism	Deterministic and **Distributed**
	PREFERENCE MODEL	4. Objective Function	**Judgement and Optimum**
		5. Consistency	Consistent or **Inconsistent**
		6. Comparison Basis	**Absolute and Relative**
	BELIEF MODEL	7. Dimension	One or **Two - Knowledge and Confidence**
		8. Belief Completeness	Complete or **Incomplete**
FOCUS		9. Problem Focus	**Product and Process**
RANGE		10. Range of Independence	Type I: Independent Issues; Type II: Dependent Issues; **Type III: Inter-dependent Issues**

Table 1a. Background Review Taxonomy (Ullman, 1995)

SUPPORT	11. Level of Support	Level 1-Representation; Level 2-Outcome Determination; **Level 3-Decision Analysis**

Table 1b. Background Review Taxonomy (Ullman, 1995)

Under the *Structure* heading of the taxonomy, there are three subdivisions, which form the next column to the right of *Structure*. The first subdivision is *Decision Space*, the second is *Preference Model*, and the third is *Belief Model*.

The *Decision Space* defines the boundary that contains the set of information about prospective solutions from which some theory of choice is used to select a single solution that solves the problem or issue (Figure 1). An issue is a semantic statement about a problem being solved. Problem solving activity begins establishing or creating this space and its resulting boundary. Problem solving is the activity of searching through an unbounded space and selecting prospective solutions to be included within the bounded decision space. Both this research and other design activity videos establish that this decision space or its boundary is not static (Cross, 1996). The space expands or contracts as the problem solving activity includes or excludes information about each selected prospective solution. Within this boundary is semantic information or graphical or physical forms which convey information which is used in selecting a final or best alternative.

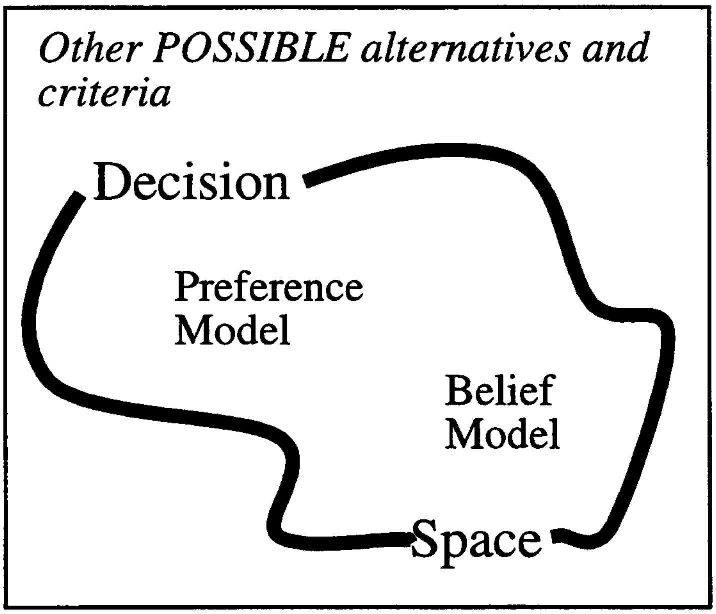

Figure 1. The Decision Space

The concept of a space that contains information as a set and has a boundary can be useful in visualizing decision activities. The *Decision Space* has three attributes which are explained below: *Problem Completeness*, *Quality*, and *Determinism.*

2.1.1 Decision Space - Problem Completeness

Problem Completeness combined with *Decision Space* indicates whether the method requires *Complete* or *Incomplete* evaluation or how many alternative-criterion pair evaluations must be conducted before the method provides decision results. If the decision method requires a complete evaluation of *all* alternative-criterion pairs before any decision results are available, then it is defined as *Decision Space - Problem Completeness*: *Complete*. If decision results are available using less than the complete set of all alternative-criterion pairs evaluations, then the method is defined as *Decision Space*

- *Problem Completeness*: *Incomplete*. In the protocols most decisions were made based on incomplete evaluation, so Incompleteness defines the first attribute for a decision method that matches the research motivation.

2.1.2 Decision Space - Quality

Quality indicates whether the method requires *Quantitative* or *Qualitative* information. Quality of information is a term used to quantify where the information would be placed along a continuum ranging from concrete to abstract. High-quality information is concrete, specific, measurable, or defined. In contrast, low-quality information is abstract, unspecific, or undefined. It can be subjective in nature. The quality of information used in the decision space falls anywhere on the spectrum of high quality (concrete) to low quality (abstract). The method sought for this research would be able to accommodate both information qualities, therefore both are in bold print.

2.1.3 Decision Space - Determinism

Determinism indicates whether the method requires *Deterministic* or *Distributed* information. The information or numbers used as variables in the decision problem, and provided to the decision method, may be either single-valued (deterministic) or multi-valued (distributed). Review of the literature on decision and design problems reveals that the information or variables are stated almost exclusively in a deterministic manner. The only known exceptions are in texts that address probabilistic design where design data is treated as having both a mean value and a variance (Hagen, 1984). A superior decision method accommodates distributed information as well as deterministic, so *Distributed* is in bold print.

2.1.4 Preference Model - Objective Function

The second part of the decision method *Structure* is the *Preference Model,* which defines how the information within the *Decision Space* is organized, by assigning value to the various solutions proposed and the criteria statements used in determining the *best* answer to the problem. Criteria are the semantic statements of the specifications or requirements that the alternative attempt to satisfy in an issue. The three parts of the *Preference Model* are the *Preference Model - Objective Function, - Consistency,* and - *Comparison Basis.*

The *Objective Function* is the rationale the decision method uses in establishing preferences. This is a key part in a decision making method. The two extremes are *Judgement* valued, where the information in the *Decision Space* is abstract, and *Optimum* valued, where the information is concrete. The *Objective Function* is used to order or rank what is being evaluated. While for the vast majority of conceptual design problems using an alternative-criterion evaluation the *Objective Function* is *Judgment* valued, the optimal decision making method should allow both *Judgment* and *Optimum Objective Functions,* so both are shown as bold print.

2.1.5 Preference Model - Consistency

Consistency describes whether the decision method requires the same set of preferences between decision makers or allows for different preferences when using the *Objective Function* in the *Decision Space.* A method which requires that all evaluators of the alternative-criterion pairs have the same set of preferences is *Preference Model - Consistency - Consistent.* If the method allows decision makers to have different sets of preferences, it is *Inconsistent.* An example of a decision method with a *Consistent* set of preferences is a method that is used by a single decision maker or in a group where complete agreement by all participants exists for the preferences specified. In video protocols of group design sessions, at a time much beyond the problem understanding phase, team members express comments such as, "Oh, that's what it means," which identify inconsistent preference models. This phenomena of inconsistency during decision activities suggests that the most accommodating decision method is one which allows for *Inconsistency*.

2.1.6 Preference Model - Comparison Basis

Comparison Basis defines whether decision makers evaluate alternative-criterion pairs in an *Absolute* or a *Relative* manner. An *Absolute* comparison considers only one alternative and one criterion as if this evaluation were the only evaluation required. The result of this evaluation is a semantic or numerical statement about how the alternative satisfies the criterion. Absolute evaluations do not refer to any other alternative or criterion. In contrast, a *Relative* comparison requires an evaluation that proceeds from some previously evaluated alternative-criterion pair. Decision makers used both *Absolute* and *Relative* comparisons in their decision making, so a universal decision method should accommodate both.

2.1.7 Belief Model - Dimension

Belief Model is the cognitive aspect of the decision method. It is the final part in the decision method *Structure* and has two parts, *Dimension* and *Belief Completeness*.

Belief Model - Dimension for a decision method is either one or two dimensional. The two *Dimensions* observed in decision making activities are *Knowledge* and *Confidence*. In the context of alternative-criterion pair evaluations, examples from the above videos demonstrate the use of *Knowledge* and *Confidence* dimensions. In this research, *Knowledge* is defined as an individual's personal or first-hand experience about a specific alternative relative to a specific criterion. The knowledge level about a specific alternative is independent of whether or not the alternative is believed by the individual to be successful in meeting a given criterion. It specifies factual background that an individual has about the alternative. It has a basis in experience or extrapolation from experiences that are very similar.

Confidence quantifies the level of surety or assurance of a propositional assertion made that an alternative satisfies a criterion. A propositional assertion is a statement that is taken to be true, and which is verifiable. A propositional statement from this research would be, "the alternative of a ball and cup satisfies the criteria of an alpha angle of +/- 15 degrees." To use a betting analogy, confidence determines how large a bet to place on whether the alternative satisfies the criterion. This aspect of the argumentation allows quantifying of the likelihood of success. Confidence also represents the individual's degree of belief or certainty, based on past encounters with similar alternatives and criteria (Bacchus, 1990). For example, in one experiment in this research, a team member mentioned that he had previously used a certain device and was confident that the device would also work for the application that was being discussed. In this context, confidence can be contrasted with a statistical probability value based on sampling of an unlimited number of persons with the same experience. Another way of viewing confidence as used here is that an unlimited number of decision makers having the same knowledge level and same set of previous experiences, would quantify their confidence with the same value. Or, it can represent the mean value of an unlimited number of decision makers who have the same knowledge level but do not have the exact same set of previous experiences as a basis for quantifying their confidence. This curve is assumed to be statistically normally distributed. Confidence can also be thought of as an assignment of a probability to a single event. It may also be considered as the mean value of experimental results if the decision maker could conduct unlimited experimental assessments.

Literature review and this research indicate that the two dimensions, knowledge and confidence, correctly define the belief model used in the evaluation of alternative-criterion pairs. It appears from reading the decision literature that many decision methods combine both of these into what is commonly termed an evaluation. In the decision making that motivates this research and for a superior alternative-criterion pair decision method, the distinction between knowledge and confidence is significant.

2.1.8 Belief Model - Belief Completeness

Belief Completeness defines how many of the maximum possible decision-making evaluations have been done. A condition of *Belief Incompleteness* is when fewer than all the alternatives are evaluated with all the criteria. For example, with a N alternative and M criterion decision problem, an NxM matrix exists. If a subset of the NxM matrix is evaluated, then this is labeled an *Incomplete* belief structure. In video protocols of individuals and teams solving design problems, including those in this research, team members always evaluate less than the complete NxM matrix. This incomplete condition was observed across different teams and differing problems. Final decisions are made in spite of belief incompleteness. It appears that there is some undefined or unarticulated 'belief completeness threshold' that must be reached during the evaluation phase. Below this critical threshold no final decision can be reached, but once this threshold has been passed, team members decide to accept one of the alternatives as a final solution, to gather other information, or even to postpone the decision until some later time. All of these responses to the thresholds were observed in this research. This research does not address the nature of this threshold. Clearly, if a decision method can provide a final decision using incomplete belief, the most demanding condition, it can also provide a final decision with complete belief.

2.1.9 Problem Focus

Problem Focus, the second of the four major categories listed in the far left column of Table 1, is intended to address whether the decision method is appropriate for product design problems or a process problem. An all-inclusive decision-support method that satisfies the objectives of this research should be able to provide for evaluation of problems from both of these areas.

2.1.10 Range of Independence

The third major category, *Range - of Independence*, specifies the dependency of the problem being addressed by the decision method. Videos of design activities show that decision methods must be suitable of the complete range from independent problems to interdependent problems. If independent problems are the simplest decision problems, then the most useful decision-support method would be one that can provide decision support for interdependent problems.

2.1.11 Level of Support

The final category of the taxonomy of Table 1 concerns the *Level of Support* the decision method provides to the user. Level I is minimal support and Level III is support that determines which alternative to select. Decision makers that choose the decision method addressed by this research, most assuredly would choose Level III, which is therefore in bold.

2.2 Technical or Engineering Decision Analysis Methods

This section reviews literature of decision methods that closely match the motivation of this research, specifically, methods used in concept-selection activities in the design phase of mechanical engineering using alternative-criterion pair evaluations. Again, decision analysis and decision making are both used to describe the selection of a single alternative from a group of possible solutions to a problem or issue. The sixteen methods discussed below are not intended to be exhaustive, but they are a fairly complete representation of methods which are suitable for selecting a *best* alternative from a list or set of candidates.

To begin the background review some general comments and history on decision methods follow. Winterfeldt (1986), in one of the classical texts on decision analysis, presents eleven decision problem examples. These problems can be grouped into the following general categories.

1. Decision based on diagnostics - a key characteristic is reaching a decision based on examination of an artifact.
2. Decision based on prediction - a key characteristic is basing a decision on prediction of a single consequence or event based on the probability of multiple influences.
3. Decision based on assessing risks for various actions - a key characteristic is selection of a course of action based on assessing risks for each path.
4. Decision based on evaluation of alternatives - a key characteristic is selection of a single alternative from a set of alternatives.
5. Decision based on using value tree or prioritizing - a key characteristic is the need to assign priority values to limbs of a tree structure or list.

Decision making using alternative-criterion pair evaluations fits the evaluation problem category above. Many of the methods reviewed in this chapter were first formalized over a decade ago. Additionally, decision making and problem solving theory came from academic areas such as economic, social science, and other nontechnical problem areas (Simon, 1986). Within today's engineering environment, methods that were developed decades ago in unrelated nontechnical academic areas need to be evaluated for appropriateness and usefulness. The lack of separate categories for technical or engineering decision methods in Winterfeldt's listing implies one or more of the following conclusions: technical or engineering decision making is unstudied, technical or engineering decision making is unimportant as a theoretic field of study, methods that were developed for non-engineering areas are applicable to technical decision making without modifications, or those in the engineering areas have borrowed methods without rigorously evaluating their applicability. A fresh look at the present group of decision methods using the taxonomy of Table 1 is warranted. Tables 2a and 2b summarize the decision methods reviewed in Sections 2.2, 2.3, and 2.4. The far left column lists the method reviewed, and columns labeled 1 to 11 correspond to the taxonomy of Table 1. The additional column "Auth" identifies methods reviewed by Ullman (1995) with a "U" or as part of this research with an "H". In the following review, decision methods are listed in alphabetical order.

	STRUCTURE											
	DECISION SPACE			PREFERENCE MODEL			BELIEF MODEL					
	1 PC	2 Q	3 D	4 OF	5 C	6 CB	7 D	8 BC	9 PF	10 RoI	11 LoS	Auth
Analytic Hierarchy Process						x					x	H
Bayesian Belief Network	x		x		x	x	x	x			x	H
CPM/PERT methods			x									U
Decision trees			x						x		x	U
Dempster-Shafer	x	x			x		x	x			x	H
Dominic method											x	H
Feasibility judgement	x										x	H
Methodology for the Evaluation of Design Alternatives (MEDA)											x	H
Fuzzy sets		x	x			x	x				x	H
Go/no-go screening	x										x	H
Issue Based Information System (IBIS)	x	x	x							x		U
Method of Imprecision (MoI)			x								x	H
Optimization											x	U
Pair wise comparison											x	H
Probability Calculus		x	x			x	x				x	H
Probabilistic design											x	U

Table 2a. Taxonomy of Decision Methods

	STRUCTURE											
	DECISION SPACE			PREFERENCE MODEL			BELIEF MODEL					
	1 P C	2 Q	3 D	4 O F	5 C	6 C B	7 D	8 B C	9 P F	10 R o I	11 L o S	A u t h
Pugh's method											x	U
Utility theory											x	U
Conjoint analysis									x			H
Computer Science Artificial Intelligence											x	H
Computer Science Expert Systems											x	H

Table 2b. Taxonomy of Decision Methods

2.2.1 Analytic Hierarchy Process

The taxonomical categorization of the Analytic Hierarchy Process is found in Table 2a. This method applies to the Winterfeldt (1986) evaluation problems listed above. The Analytic Hierarchy Process decision making method arranges the factors that are important to making a decision into a hierarchy with a structure that descends from an overall goal down to sub-criteria (Saaty, 1990). Those factors that the Analytic Hierarchy Process uses in the decision process are goals, attributes, issues, and participants. This hierarchy is not modeled after a traditional decision tree but is merely used as a graphical representation. The Analytic Hierarchy Process can be used with both relative and absolute comparison methods, and uses pair-wise comparison to establish the hierarchy of the criteria for both methods. This activity establishes a preference model. The method indicates the three principle parts of a problem: goal, criteria, and alternatives. For the relative comparison, each alternative is compared pair-wise with all other alternatives, but for the absolute comparison, each alternative is rated against the criteria and a linear additive aggregation is conducted. Categories that match the ones found in bold in Table 1 are marked with an 'x; in Table 2a. Of the eleven categories, only two are found in bold in Table 1. The conclusion is that the Analytic Hierarchy Process rates poorly in satisfying the motivations of this research. Consistent with this conclusion, the problem example used by Saaty (1990), who is associated with a business school, is how to select a house. Unfortunately this is not a technical or engineering problem. Nevertheless, this decision method does have some potential for application to technical design problems or evaluation problems listed by Winterfeldt.

2.2.2 Bayesian Belief Networks

The taxonomical categorization of the Bayesian Belief Networks is found in Table 2a. This method can apply to many of the problems listed above. A Bayesian Network can be described as a network with nodes. An example of this node arrangement would be a map of a country in Europe where the network was the railroad lines that connect the cities. The nodes describe events probabilistically. Baye's equation allows the calculation of the probability of an event when the knowledge of a previous event is specified (Butler, 1995). The connections between nodes exists due to a causal chain of events just like the connection between cities requires the event of traveling on the railroad tracks (Charniak, 1991). The cause of the second node is due to the occurrence of the first node. With the train example, it can be said that one arrived at the second town because one traveled through the first town. One attribute of Bayesian Network nodes is that one starts with a knowledge of prior probabilities of all root nodes (nodes without predecessors) and uses the conditional probabilities of all non-root nodes. Another important attribute is that, contrasted with normal probability theory found in a complete tree structure, all joint probabilities need not be calculated, only those that are directly causative. An example of application of Bayesian decision making is the testing of IC circuits, from the diagnostic category given above. In this application of Bayesian methods the testing occurs only on the network that has causal connection (Middlestat, 1994). Categories that match the ones found in bold in Table 1 are marked with an 'x' in Table 2a. Of the eleven categories, seven are found in bold in Table 1. The conclusion is that Bayesian Belief Networks rates high in satisfying the motivations of this research. This is especially true in the taxonomy section of *Structure*. Butler (1995) mentions that Bayesian Belief Networks have been used for preliminary design decision making corresponding to the evaluation problem category of Winterfeldt (1986) listed above.

2.2.3 CPM/PERT Methods

The taxonomical categorization of CPM/PERT methods is found in Table 2a. This method applies to the Winterfeldt (1986) prediction problems listed above. The CPM/PERT are a standard method for scheduling events, tasks, or activities (Marks, 1978). The primary use of CPM/PERT is in large project resource allocations contrasted with selection of an single alternative based on a list of criteria. Decision support provided by these methods is used to select which events, tasks, or activity path should be taken based upon time or resource considerations. Of the eleven categories in Table 2a only one 'x' is found. The conclusion is that CPM/PERT rates poorly in satisfying the motivations of this research. It should be noted that CPM/PERT methods have an important attribute not readily found in other decision methods: *Problem Focus* - which is *Process* oriented.

2.2.4 Decision Trees

The taxonomical categorization of Decision Trees is found in Table 2a. A Decision tree is a classic method that identifies the options and possible outcomes of proceeding along a series of linked activities or choices (Hiam, 1990). The problem is structured in a tree configuration with nodes identified as option points. Probabilities are assigned to the nodes for use in calculating the outcome. Methods other than probabilities can be used for node branching such as “yes-no.” Decision trees are not suitable for ill-structured or ill-defined problems. An ill-structured problem is one that has abstract information, or in which the problem requirements are vague. Decision Trees demand that all the branch information or data be specified. Decision Trees have three of the eleven attributes found in bold in Table 1. The conclusion from the above is that this method is not appropriate for alternative-criterion pair evaluation problems that have motivated this research. One of the important features found in this method that is bolded in Table 1 is the *Decision Space - Determinism - Distributed.* The ability to accommodate information that is more than deterministic is highly desirable in a decision method that motivated this research.

2.2.5 Dempster-Shafer

The taxonomical categorization of Dempster-Shafer is found in Table 2a. This method bases decisions on evaluation of alternatives. As a method that intends to model human decision making, an alternative has a certain probability based on evidence and accompanying it is an ignorance factor assigned which must sum to unity (1.0). The basis of this method is the collection of evidence that supports a decision (Shafer, 1976). The alternative that has the largest plausibility value would by default be the best alternative choice. In the article by Butler (1995) this method is included as useful for preliminary design. Unfortunately the example presented by Butler is not a concept selection decision analysis problem. Possibly one of the most interesting aspects of this method is the fact that as more evidence is collected in support of an alternative the higher the plausibility value becomes. Of the eleven categories in Table 2a, six match those found as bold print in Table 1. Unfortunately this method has one critical shortcoming which prevents it from being suitable for the decision making important for this work, that being it does not provide for direct evaluation of alternative-criterion pairs.

2.2.6 Dominic Method

The taxonomical categorization of Dominic Method is found in Table 2a. This method fits in the group of decisions based on the evaluation of alternatives mentioned above. This method is very similar to Pugh's decision matrix, see below, but is more complex (Dixon, 1995). The added complexity comes from the two evaluation terms used for alternative-criterion pairs. The Dominic method uses words rather than Pugh's plus and minus values as its method of determining which alternative to choose. The first word category is a performance rating of the alternative-criterion pair and the second is for importance or priority of the criteria. As found with Pugh's method in section 2.2.17, this method has only one attribute found in bold Table 1. The conclusion is that although this method is used for alternative selection it rates poorly in satisfying the motivations of this research.

2.2.7 Feasibility Judgement

The taxonomical categorization of Feasibility Judgement is found in Table 2a. This method also fits in the group of decisions based on evaluation of alternatives mentioned above. This concept evaluation technique is very rudimentary with only three possible results from evaluation of alternatives: the alternative is not feasible, it is feasible with some qualifying conditions, and it is worth considering (Ullman, 1992). This method utilizes a single evaluator's judgement based on his or her experiences. No ability is provided with this method to specify criteria. All the criteria are aggregated as the feasibility judgement is conducted for each alternative. The method should be considered a very unrefined decision method. This method has two categories from those that are bolded in Table 1. Another limitation of this decision method is that its use is restricted to a single evaluator. The conclusion based on the above is that this method is not suitable, as it does not satisfy the motivations behind this research.

2.2.8 Methodology for the Evaluation of Design Alternatives (MEDA)

The taxonomical categorization of MEDA is found in Table 2a. This method also is in the group of decision methods based on evaluation of alternatives. The intent of this method is to provide a functional relationship for revealing design worth which can be used in attribute tradeoffs and final alternative selection (Thurston, 1991). The two critical steps in using this method are the determination of functions that define the performance characteristics of the design, and the step that determines the function which describes the worth of a design based on combining multiple performance attributes. If these functions cannot be specified this method cannot be used for alternative evaluation. This method is very similar to standard utility theory, explained in more detail below, with its final overall value that is a function of a set of performance levels of attributes. Of the eleven categories this method has only one which is found as bold in Table 1. One of the major disadvantages is that this method requires total belief completeness. The conclusion is that this method is useful for alternative selection but requires extensive development of the functional relationships.

2.2.9 Fuzzy Sets

The taxonomical categorization of Fuzzy Sets is found in Table 2a. Fuzzy set mathematics can be used for choosing an alternative from a proposed set of alternatives (Wood, 1990). This method models the uncertainty found in an attribute and assigns a functional relationship to it. Assignment of a functional relationship allows for its manipulation with other attribute functions. A coupling of attribute value information is required so that final alternative selection is possible. Without these parametrics the method cannot be used for decision analysis (Butler, 1995). Of the eleven categories, Fuzzy sets has five from Table 1. This method has an intensive computational requirement. For the twenty criteria listed for the design example in Verma (1995), there are three functions specified for each criterion used for each alternative. This seems to be computationally excessive for a method that is used to select a best alternative at the concept phase. The conclusion based on the above is that this decision method is a poor match for the motivations of this research.

2.2.10 Go/no-go Screening

The taxonomical categorization of Go/no-go Screening is found in Table 2a. This method also provides for decisions based on evaluation of alternatives. Of all the methods for decision analysis this is one of the most subjective and a method that is only judgement based (Ullman, 1992). Go/no-go screening evaluation is conducted by asking a criterion based question about the concept being evaluated. The answer is either a go or no-go response. No numerical results are produced from this evaluation, only a go or no-go outcome. This is a single evaluator method. Of the eleven categories only two match those on Table 1. The greatest strength of this method is the minimal information requirement for the group of alternatives being evaluated. Evaluations can be conducted quickly. The greatest weakness is the highly subjective foundation that the evaluation comes from. This decision method rates poorly in satisfying the motivation of this research.

2.2.11 Issue Based Information System (IBIS)

The taxonomical categorization of IBIS is found in Table 2a. An Issue Based Information System (IBIS) is a hypertext design rationale recording tool (Conklin, 1989). This method was designed to support the design process, but not provide direct decisions based on some method. It includes the ability to record issues, alternatives, arguments, and decisions on a computer. One of its strongest aspects is its ability to keep track of issues and alert the users of issues that have not been resolved (Yakemovic, 1989). The method does not calculate any results that are used for evaluation of alternatives. It provides a recording device for information that is used in an external evaluation method. It has been included here because of its application to the evaluation phase of the design process. IBIS's greatest strengths are that the *Decision Space* attributes match those in Table 1 as does *Range*. Unfortunately, it is not a formal evaluation method and only allows *Level of Support* at Level 1 - Representation. Based on the above this method does not satisfy the motivations of this research.

2.2.12 Method of Imprecision (MoI)

The taxonomical categorization of MoI is found in Table 2a. This method is in the group of methods that evaluates alternatives. Developed at Caltech's Engineering Design Research Laboratory, MoI is intended to provide a methodology for representation and manipulation of design imprecision in the early stages of engineering design (Otto, 1993). As with Fuzzy Sets and Probability Calculus, this method deals with imprecision of the design parameters. The method is represented as useable "at the concept stage" but in fact this term is meant to mean "preliminary phases of engineering design, where the designer is most unsure of the final dimensions..." (Antonsson, 1995). This method has application in the preliminary design phase of engineering design when parameters for the design are well defined but specific dimensions have not been established. Of the eleven categories that are bold from Table 1 only two match, making it a poor match for a decision method that matches the motivation of this research..

2.2.13 Optimization

The taxonomical categorization of Optimization is found in Table 2a. This method also is an evaluation of alternative decision method. The primary characteristic of this decision method is that the problem must be expressed as a closed form mathematical formula (Vanderplaats, 1984). Either a single maximum or minimum result is produced from the calculations, which is provided to the user as the final decision. Criteria statements must be translated into constraint equations and the list of alternatives is from the set of parameter values that are constraint feasible. The final or best alternative is that which the method determines from the internal math calculations. This method is intended for use with problems that are completely defined with equations for the problem parameters. This method has only one category from the Table 1 that is marked with an 'x' in Table 2a. The conclusion is that this method is not recommended as one that satisfies the motivations of this research.

2.2.14 Pair-Wise Comparison

This is a subset of Pugh's method explained in section 2.2.17.

2.2.15 Probability Calculus

The taxonomical categorization of Probability Calculus is found in Table 2a. Probability calculus mathematics can be used for choosing an alternative from a proposed set of alternatives. This method is analogous to Fuzzy Sets (Wood, 1990) reviewed above. It uses probability calculus in representing and manipulating uncertainty in selecting from among alternatives. This uncertainty in choosing among alternatives is what Wood (1990) defines as design imprecision. Their objective is "to provide methods and tools for the decision-making aspects of preliminary engineering design" (Wood, 1990). The example that the authors state makes it clear that the preliminary engineering design that they are focusing their method on is not preliminary concept alternative selection as defined in this research, but rather parameter design after the overall concept has been determined. They state, "At the preliminary stage, the designer is not certain what values used for each design parameter." Their example is uncertainty for dimensions of teeth pitch, radii, etc. and in another example a beam which does not have a selected shape. In both of these examples the authors have a highly refined concept that they consider 'preliminary.' They do admit that "most of our research and examples have used parametric descriptions of design...nothing in principle limits the technique to these areas" (Wood, 1990). This is not the type of decision making that motivates this research. As with Fuzzy Sets, this method has five 'x' in Table 2a from items in Table 1. This method also has an intensive computational requirement which means that it is not a simple decision method. As an example, in substitution for the functions that describe the desirability of the preference there is a probability density function. This, like the Fuzzy Sets, seems to be computational excessive for a method that is used to select a best alternative at the concept phase and is therefore poorly suited for a decision method that matches the motivation of this research.

2.2.16 Probabilistic Design

The taxonomical categorization of Probabilistic Design is found in Table 2a. This method is an important extension from the formal optimization method. The characteristics that differentiate probabilistic design from optimization is the stochastic treatment of design variables in the problem (Haugen, 1980). All of the same comments that apply to optimization, see above, apply to the probabilistic design decision method. As with optimization, this method is intended for use with problems that are completely defined with equations for the problem parameters with the probability density function of each parameter. This method, as is optimization, is restricted to use with problems that have all the parameters functionally defined. As with Optimization, Table 3b has only one category from the Table 1 marked with an 'x' in Table 2a. This method does not comply with the motivations of this research.

2.2.17 Pugh's Method

The taxonomical categorization of Pugh's method is found in Table 2b. This decision method is one of the most popular and often quoted methods found in the recently published group of engineering product design books. It is used for alternative selection. It is also known as a decision matrix (Pugh, 1991). The method establishes a matrix with alternatives listed down one side and evaluation criteria listed cross the top. The matrix is a completion of many pair-wise comparisons of alternatives with criteria statements. One alternative is selected as a datum and comparison with successive alternatives for each criteria is conducted. The validity of a number of important assumptions that are implicit with the use of Pugh's method should be understood. Their veracity can impact the results. These assumptions are: for any given participant, his or her knowledge level for an alternative-criterion pair is equal with all other participants, and that all the criteria are satisfied to some degree or level for each alternative listed.

Only one category from Table 1 is marked in Table 2b. Even though this is a very popular decision method it does a very poor job in satisfying the motivations of this research.

2.2.18 Utility Theory

The taxonomical categorization of Utility theory is found in Table 2b. This method combines decision making attributes from a number of the categories listed from Winterfeldt (1986). For any given problem, utility theory produces a preference list of the alternatives. It requires a person to elicit information from participants and begins with a value function to formalize the preferences (Keeney, 1993). The key aspect of Utility theory is that construction of a utility function demands that the participant establish pair-wise tradeoff preferences. For a given criteria and two alternatives, the participant must determine at what threshold he or she considers both alternatives to be equal in preference. The result is an ordinal ranking of alternatives for the criteria under consideration. Utility theory has only one category in Table 2b that matches those found in Table 1. This method, as with others that require a great deal of computational work, seems to preclude its wide spread acceptance as a method that is viable for the concept evaluation decision method that motivates this research.

2.3 Computer Science Decision Analysis

Computer science organizes and processes data. The decision making required is one of selecting the best type of data structure into which the data is organized. Once the structure is selected the most effective algorithms are generally known and matched to the data structure. The process of selecting the best type of data structure is presently done using experience and past examples of similar problems (Sedgewick, 1988). Review of a few computer science decision methods are included here to give a balanced perspective on decision methods.

2.3.1 Algorithms

The common computer science data structures are arrays, linked lists, stacks, queues, and trees. With the selection of a data structure, based upon the characteristics of the information, the choice of an algorithm that reduces either storage space requirements and or execution time is generally stipulated. This choice is made based on experience and use of similar examples (Sedgewick, 1988). No taxonomy review was conducted for this decision method, see methods below.

2.3.2 Artificial Intelligence

The taxonomical categorization of Artificial Intelligence decision method is found in Table 2b. This decision method most closely matches one based on diagnostics. Two key ingredients found in artificial intelligence problems is that the problem has a data structure and uses an algorithm for deciding on a solution to the problem (Rich, 1991). As with the discussion on algorithms above, the data structure and the algorithms are inexorably linked. The decision analysis that is performed is then restricted to the confines of what the algorithms execute. Decision analysis in this area is very refined in that the information and data structure are tightly coupled with no opportunity for modification or deviations, and the results or output is also precisely prescribed by the algorithm used. There is only one category from Table 1 that is found in Table 2b. The conclusion is that this decision making method does not satisfy the motivations of this research.

2.3.3 Expert Systems

The taxonomical categorization of Expert Systems is found in Table 2b. The application of expert systems in design is found in configuring objects subject to constraints (Waterman, 1986). As with artificial intelligence problems the design problem structure must conform to what the expert system can accept, problems that are outside of this structure cannot be solved with expert system techniques. The same comments that were given above apply to Expert Systems.

2.4 Other Decision Analysis Fields

The only other decision making area that is related to evaluation of alternative-criterion pairs that motivates this research is business. There are many methods and tools that are used for business decision making or what is commonly called in the business area as decision analysis. The spectrum goes from financial, leadership, operations, sales, to general decision making (Hiam, 1990). A review of books in the library shelves at Oregon State University, which has a business school, reveal that most of the decision methods are primarily qualitative, judgement based methods, spread sheet, or linear programing-based what-if calculations procedures.

2.4.1 Conjoint Analysis

The taxonomical categorization of Conjoint analysis is found in Table 2b. Since the early 1970's (Green, 1990) conjoint analysis has been used by marketing researchers to estimate the impact of characteristics of products or services on customer preferences (Cattin, 1982). One of the key principles of conjoint analysis is the overall preference for a product or service that is composed of the scores of components for the product or service (Green, 1975). This is akin to selecting the best alternative from a group of alternatives where the alternatives have a set of characteristics or attributes. Cattin (1982) lists "new product/concept identification" which was the most stated reason for use of conjoint analysis. Of the eleven categories, conjoint analysis has one that matches Table 1. Three important aspects to conjoint analysis should be noted as applies to evaluation of alternative-criterion pairs decision making. First, conjoint analysis provides decision-making information for either a product or process. Marketing use of this method work equally effectively for either. Second, this is one of the few methods that provides expert coaching via a quantitative data about which attributes of the alternatives the customer prefers most. This attribute is more fully explained in Chapter 13 where new features that have been added to EDSS are explained. This expert coaching data is provided from the computer program that is used to record the rank ordering of the evaluation and uses a utility algorithm. One final aspect of this method is that it is limited to alternatives that are completely defined. The example in Green (1975) is a product where three different alternatives are provided for customer evaluation. Clearly this method is not suitable for evaluation of alternatives that are ill-defined and therefore it is not suited for meeting the motivations of this research.

2.4.2 Executive Decision Making Tools

A pocket book (Hiam, 1990) lists 101 decision methods for the chief executive officer. The areas that are presented range from financial, leadership, marketing, to general decision making areas. Closer examination of the individual methods yields the conclusion that the vast majority of these methods are very subjective and qualitative in spite of the fact that some of these methods are used by large well known corporations. No attempt is made to categorize any of these methods using Table 1.

2.4.3 Medical Decision Making

In medical decision making, dealing with patients, the *best* alternative to select cannot be simply defined. Decision problems of this type match those based on diagnostics or assessing risk for various actions. Decision making methods in medicine, where a patient's life or health is the problem, are predominatly characterized as decision tree problem. Each branch, a course of action, has a probability assigned based on the medical personnel's experience or information. Decision-making processes, generally conducted by a single evaluator, for the patient can lie on a spectrum between optimizing the medical outcome to providing a satisfactory outcome. Of all decision methods reviewed, this area is unique with tremendous ethical criteria (Burtztajn, 1981, Walton, 1985). The Journal of Medical Decision Making is devoted to this special decision field. The decision methods in this field contain heuristics which are contrary to the motivations of this research.

2.4.4 Public Policy

This Category of decision problems predominatly uses multiattribute utility theory for decision making. Utility theory is reviewed in section 2.2.18.

2.4.5 Operations Research

The Operations Research and Management Science Society publishes a special review of decision analysis application methods. Corner (1991) has published a literature review for 1970-1989. This article classifies those articles into application areas and subareas. The decision making methods are decision trees, value functions, utility functions, probabilistic analysis, pairwise comparisons, hierarchical decision analysis, optimization methods which have been reviewed above.

2.4.6 Consulting Firms

There are a number of consulting firms that specialize in decision analysis. See Winterfeldt (1986) for a listing.

2.5 Technical or Engineering Specific Decision Support Software

According to the criteria outlined in bold in Table 1, this section reviews those software packages that aid in decision making during evaluation of alternative-criterion pairs. Software packages that may aid in problem structuring, such as Quality Functional Deployment (QFD), are not intended to be decision making packages, and under this definition are mentioned for completeness but are not reviewed. Specialized engineering analysis software packages are not included. Although they are used for assisting in making design decisions, they are highly specialized and are generally intended to provide parametric study of highly refined products or processes. An example of this special category is the analysis software that is used for computational fluid dynamic, it allows engineers to change individual parameters as they design or improve the next generation of pumps (Valenti, 1996). These analysis packages have the product or design completely defined and limit the decision making to choosing between different variations of the present configuration. This same kind of decision aiding can be found in software that analyzes processes, such as the CPM/PERT software described above. These analysis packages cannot assist in decision making if the alternatives are abstract. This reviews that follow include those software packages that are considered appropriate for decision making activities that match the motivations and assumptions described in Chapter 1 and the taxonomy of Table 1.

The following review of software packages is not intended to be an exhaustive compilation of what may be available. Emphasis was placed on programs that are consider by this author as useful for the decision making that motivates this research and that were available for review. Nagel (1993) listed 89 software packages, but unfortunately none of these titles are technical or engineering specific, nor are there any engineering and or technical company names listed for these packages. Reviewing these package titles and their company names indicates that most of them are designed for business or operations research. It should be noted that the general packages listed below are not included in Nagel's list which indicates that this software area, as would be expected, is rapidly developing. However, a May 1996 web search for engineering decision support, or engineering decision analysis or software, still failed to produce companies that address this technical area. Additionally as a decision support tool, the following software review does not include packages that involve retrieval of information which the decision makers then use as a basis for making a decision, such as a company data base. This type of decision support is not in concert with the motivations of this research.

2.5.1 Decision Matrix

This decision method is Pugh's method adapted to a spreadsheet format. The taxonomy categorization of the Decision Matrix is found in Table 3. This method has been reviewed above under Pugh's method. As software the alternatives and criteria are the rows and columns of the spreadsheet. This format provides the alternative-criterion pairing found in decision making activities this research addresses. Any common spread sheet program can be programmed for this method in a matter of minutes. This decision method is commercially available, see DecideRight® below.

2.5.2 MOOSE

The computer program MOOSE (Methodology Of Organizing Specifications in Engineering) is a methodology that organizes information from the Product Definition Phase (PDP) that is used in the conceptual design phase (Gershenson, 1994). The taxonomy categorization of this method is found in Table 3. This method is not strictly a decision method nor is it commercially available. It structures the information that is used in the conceptual design phase evaluations. It has been included here for two reasons. First, it provides aid to engineering decision makers by structuring technical problems. Secondly, it is a software package that was developed by a team of researchers that has a good understanding of the mechanical design process (Gershenson, 1994; Stauffer, 1987). This method provides five of the eleven categories of Table 1. The three most unique aspects of this method is that it allows for problem incompleteness, inconsistent preference modeling, and incomplete belief. The major shortcoming is that it is not a strict decision method and only allows a level of support that is problem representation, therefore does not satisfy the motivations of this research.

	STRUCTURE											
	DECISION SPACE			PREFERENCE MODEL			BELIEF MODEL					
	1 P C	2 Q	3 D	4 O F	5 C	6 C B	7 D	8 B C	9 P F	10 R o I	11 L o S	A u t h
Decision Matrix									x			H
MOOSE	x	x			x			x	x			H

Table 3. Taxonomy of Technical Decision Software

2.6 General Decision Support Software Packages

Several general or non-technical/engineering decision software packages are reviewed to produce a more complete review. Those packages that are reviewed give a basic understanding of the decision support software that is available commercially. Conjoint analysis software is not included in this review since this method has been discussed above and was not actually available for hands-on review.

As with Winterfeldt (1986) and the grouping of decision problems which gives a more 'global' understanding, Nagel (1993) lists the following common types of decision software:

1. Decision tree software for use when the problem is defined as having quantified risk assessment nodes.
2. Linear programming to address problems that require decisions about allocations of resources such as time or people.
3. Statistical packages for future prediction.
4. Spreadsheet software where alternatives and criteria are entered in a matrix.

5. Artificial or rule based domain specific software.
6. Multiple criteria decision making software.
7. Subject specific decision software.
8. Brainstorming or idea generating software where no specific decision or outcome is produced.

It should be noted that the above list of eight common software areas does not have a one to one correspondence to the list comprised from Winterfeldt (1986). It is postulated that this condition exists because of a lack of research into the specific requirements of the different decision methods that is must be provided for in software instanciation. This motivation of this research has produced a decision method and its instanciation that does not commit this error.

The following software conforms to the area defined above as multiple criteria decision software, the motivation of this research, but are predominately displayed in a spreadsheet format.

2.6.1 Bayesian Decision Support System ®(OPA)

This software is a quantitative/qualitative risk analysis software intended to support the information processing environment. The taxonomy categorization is found in Table 4. This software, based on Bayesian decision methods reviewed above, is highly restrictive in its application, which is risk analysis. It appears to be even more restrictive than the Bayesian method previously described. Because of the software's high cost, the package was not available for reviewed. This review is based on limited written sales material. Since this software was examined based on written material only, it is impossible to assess how appropriate this package would be for this research. One important limitation that was determined for this software is that it assumes that all users have equal knowledge levels. From the literature evaluation there are three of the eleven categories that match those found in Table 1. The conclusion from this review is this package does not satisfy the motivations of this research.

	STRUCTURE											
	DECISION SPACE			PREFERENCE MODEL			BELIEF MODEL					
	1 PC	2 Q	3 D	4 OF	5 C	6 CB	7 D	8 BC	9 PF	10 RoI	11 LoS	Auth
Bayesian Decision Support System ®(OPA)		x							x		x	H
Best Choice 3 ®	x	x			x						x	H
Criterium DecisionPlus®	x	x									x	H
DecideRight ®											x	H
DPL ®												H
Decision Pad ®												H

Table 4. Taxonomy of General Decision Software

2.6.2 Best Choice 3 ®

The taxonomy categorization if found in Table 4. The instanciation of this method is a mix of both spreadsheet software and multiple criteria decision making. The program is a pair wise comparison method which requires the user to select one criterion and evaluate two alternatives. This process is repeated for each criterion. This technique comes from research in management science. It prompts the user to compare alternative pairs and gives a numerical result back to the user that is like a utility measurement. A review of the product appears in PC Magazine (February, 1990). Each pair-wise comparison is very similar to Pugh's decision matrix (--, -, 0, +, ++) for each pairwise comparison. Criteria weights can be defined. Use of multiple participants with weights is possible. None of the examples quoted are technical or engineering. This software provides a number of the desired attributes found in bold print on Table 1. Table 4 shows four of the eleven attributes marked with an 'x'. One major limitation of this software is the requirement of belief completeness or the requirement that the user must conduct a complete evaluation on all alternatives using a selected criteria. This assumes that the user has an appropriate knowledge level to do so. Another important limitation of this software is that it assumes that all users have equal knowledge levels, while appropriate technical software must provide for two dimensions under the belief model. Based on these factors, the use of this software for decision making that motivated this research is not recommended.

2.6.3 Criterium DecisionPlus ®

The taxonomy evaluation of this software is found in Table 4. Two different multi-criteria analysis with uncertainty analysis models are provided with this software. A tradeoff report is provided which provides three methods for rating alternatives: full pair-wise comparison, partial pair-wise comparison, or a direct method. In addition the Analytic Hierarchial Process (Saaty, 1990) and SMART method (Winterfeldt, 1986) are available for weighing alternatives against criteria. One important feature of this software that is absent in nearly every other software package is the expert coaching or tradeoff report. One important limitation of this software is that it assumes that all users have equal knowledge levels. It is the conclusion that the use of this software is not recommended.

2.6.4 DecideRight ®

This software is a single user, alternative-criteria pair evaluation matrix decision-making tool based on Pugh's decision matrix. Evaluation of alternative-criterion pairs using nontechnical words such as, "Good, Fair, and Poor" is used. One important limitation of this software is that it assumes that all users have equal knowledge levels while an appropriate technical software must provide for two dimensions under the belief model. As with previous comments on Pugh's method, this software is not recommended.

2.6.5 DPL ®

The taxonomy categorization is found in Table 4. DPL claims to be a combination of a decision tree and an influence diagram. It also allows the user to modify a standard utility function. It allows for sensitivity analysis and building of a value model. It is a single user software. One important limitation of this software is that it assumes that all users have equal knowledge levels. The conclusion that the use of this software is not recommended and is based primarily on the requirement that the problem be described in a tree structure. This structure does not conform to the problem structure that motivated this research.

2.6.6 Decision Pad ®

See Table 4 for the taxonomy categorization of this method. The method uses a multivariate utility analysis decision matrix. Decision Pad® literature reports that the user can choose different preprogramed templates which are special problem types like employee evaluation. Criteria and alternatives are displayed in a matrix or worksheet format. Criteria weights can be used. Sensitivity analysis is possible with a worst-best possible score. Multiple evaluators are also possible. One important limitation of this software is that it assumes that all users have equal knowledge levels. Based on the above, it is the conclusion that the use of this software for decision making that motivates this research is not recommended.

2.7 Problem Specific Decision Support Software

In contrast to the two software areas reviewed above, there is a category of decision software that should be labeled as problem or domain specific. This software is targeted towards providing specific and rather narrow domain application decision support. Two examples are discussed below to reveal the nature of this software.

2.7.1 Conjoint Analysis

Conjoint analysis is a marketing method that was explained above. The software package aids researchers in deciding which attributes of a product are most desirable. It is very similar to alternative selection described in this research. The primary feature of this method is that the alternatives are completely known and the final decision is restricted to which attributes of the product are most desirable. From the review literature (Wittink, 1989; Cattin, 1982) it appears that there is no preferred software package used by the majority of marketing firms to conduct and calculate conjoint analysis. No taxonomy categorization is provided. The major limitation of this software has been discussed.

2.7.2 Judged Utility Decision Generator (JUDGE)

This decision software is used for numerical evaluation of military targets. JUDGE (Winterfeldt, 1986) is an example of operations research software. The program elicits numerical values for potential targets and provides decision aid for final target selection. The description provided did not give enough information about this software to allow taxonomy categorization. Even with the limited description provided it does not seem appropriate for decision making in this research.

2.8 Conclusions

It can be concluded after reviewing the above decision methods, Section 2.2, 2.3, 2.4, that none of these methods provide decision methods that motivated this research. They fail to have more than a few of the attributes found in Table 1. The best match of these requirements is with the Bayesian Belief Networks.

From the limited review of software packages above, Section 2.5, 2.6, 2.7, it can be concluded that there has not been any commercial development of software decision methods that addresses the motivations of this research. These decision makers are forced to use single-decision software packages that are missing important characteristics or use multiple packages with overlapping capabilities. As a last resort they can create a dedicated program for their local use. The complex experiences of programming EDSS in this research suggests that it is entirely likely that except for research projects at universities, there has been no industrial programming for technical or engineering decision making as it is not considered financially worthwhile.

The next chapter describes the representation of the structure of information used for EDSS.

3. DECISION PROBLEM INFORMATION STRUCTURE FOR USE IN EDSS

This chapter explains the terms used in the EDSS decision method. The alternative-criterion pair evaluation activity that motivated this research was found to have a small but distinct vocabulary. The six words that comprise that vocabulary are explained in sections 3.1 through 3.6.

It should be stated again - this research distinguishes between the creative, brain-storming idea generation phase called problem solving and the phase which is used to represent decision making. This research does not study how individuals generate unique alternatives or ideas, or how they establish problem criteria or requirements.

3.1 Issues

An issue is a semantic statement about a problem being solved, and is used interchangeably with "problem statement." EDSS provides decision support for Type I: Independent Issues under *Range of Independence* of Table 1. Single independent issues are issues which do not depend on previous issue solutions and whose outcome does not impact other issues. An example of a problem that could be considered independent is one without a cost criterion or requirement. It should be quickly seen that the solution is independent in this one requirement only (cost), not independent in all requirements. Any solution, regardless of cost, is acceptable. The solution becomes an interdependent solution when a new requirement is added to the existing list of requirements.

Interdependent issues or problems can be converted to independent ones by moving the criterion or requirement that is causing the interdependence into the independent list of criteria. It is postulated but not proven with this research that all interdependent problems can be compressed into one independent problem by including all the interdependent criteria from previous levels, creating a super issue statement as an umbrella under which all requirements are listed. Solving this single super issue obviously can be overwhelming. This single super issue can be understood if one considers a car. The list of requirements for this super issue most assuredly would be volumes in length. More prudent management of such a large issue is accomplished by restructuring the problem into smaller subassemblies with much smaller requirement lists. Exactly how larger issues are broken into more manageable subissues is not a subject of this research. After the issue statement has been defined the next important term is the list of alternatives that is proposed as a solution for the issue.

3.2 Alternatives

Alternatives are the set of proposals which have the potential to solve or resolve the issue under consideration. Only those alternatives inside the *Decision Space* of Figure 1 are evaluated by the decision maker. The alternative set may be represented semantically, graphically, or physically. The alternatives combine with the criteria, explained below, to form alternative-criterion pairs.

3.3 Criteria

Criteria are the semantic statements of the specifications or requirements of an issue that the alternatives attempts to satisfy. The criterion statements may be given or specified in the problem statement, or derived through previous design choices. For example, the first source of criteria statements for a new product design issue is the customer requirement list. Engineers and technical problem solvers are taught that criterion statements, which are used for evaluation of alternatives, must always be definitive. The specifications, given or derived, determine the criteria used in the decision activity evaluations (Andreasen, 1995).

The syntax of criterion statements has not been systemically treated except to define general taxonomy types (Hinrichs, 1992). Also, Edwards (1994) referred to criteria in a structural manner. Refinement of criteria statements through the establishment of mathematical axioms/principles is required if a decision method is to fulfill the research objectives stated in Chapter 1. This work proposes to establish a refinement on the Edwards and Hinrichs taxonomical structures. The proposal is the use of propositional syntax for criterion statements, Equation 1, which produces a Boolean response. The syntax shows that criterion statements which are propositionally stated allow for simple Boolean responses. Either the alternative satisfies the criterion, a yes response, or the alternative does not satisfy the criterion, a no response. The proposed refinement can also be used to clarify customer requirements of the popular Quality Functional Deployment (American Supplier Inst., 1987) problem formulation. The refinement permits consistent mathematical treatment of criterion statements during the evaluation activity. It begins with a propositional statement or assertion to which further mathematical modification can be applied. Bayes' rule (Scheafer, 1995) provides for this mathematical modification. The statement "Is Satisfying" can be modified grammatically to produce, "does satisfy," "satisfies," or "will satisfy." Those criterion statements that use this connecting verb syntax are called Boolean - simple. The syntax is stated in the grammatical active voice.

*Alternative ...X... : **Is Satisfying** : Criterion ...Y...*

Equation 1. Propositional Alternative-Criterion Statement Syntax

Again, a Boolean response to the criterion statement is one that allows only a yes or no answer to the question of whether or not the alternative "Is Satisfying" the criterion. Equation 2 shows an example from the experiment problem of this research, explained in Chapter 7, of both possibilities for this propositional Boolean condition using the yes or no response.

Response - Affirmative: **Yes** it is possible to manufacture Alternative1 (drawings 4 and 5) using the machine tools in the shop of Rogers Hall Response - Negative: **No** it is not possible to manufacture Alternative1 (drawings 4 and 5) using the machine tools in the shop of Measured criterion statements have a syntax that are structured with quantified measurement within the statement Rogers Hall

Equation 2. Propositional Statement with Boolean Response

The propositional Boolean criteria syntax can also be applied to an additional criterion statement type known as a measured criterion statement. Measured criterion statements have a syntax that includes a quantified measurement within the statement. This criterion type is called Boolean - with measured qualifiers. Like criterion statements that do not have quantified measurements within the statement, Boolean - simple, measured criterion statements are also taken as propositionally true statements. An example of the measured criterion statement is: "more miles per gallon is better" or "the alternative with the least of attribute X is best."

3.4 Criteria Weights

Criteria weights are the preferences assigned to criteria by individuals based on their viewpoints, which may come from different rationales or causes. Preferences also help engineers restructure problems to facilitate solution, as by reducing large issues to smaller ones. This structuring is well documented (Keeney, 1993). This activity has an added benefit of requiring that the problem solver determine the relative importance of various criteria. This yields a preference model for the criteria or problem requirements in the decision problem. This preference is not to be confused with alternative preference outcome, which is the result of the decision making process.

This research demonstrated that individual members of a decision making group do not necessarily have the same criteria preferences. The three members of one of the research teams using EDSS to evaluate alternatives weighted the criteria as shown in Table 5 below. This example shows minimal variation among members for the same criterion but does demonstrates that each person's preferences may range as much as a factor or two.

Criteria	Person 1 (criterion weight)	Person 2	Person 3
Carry the weight of optical device	.24	.25	.25
Swivel joint is alpha and beta direction	.22	.25	.25
Both swivel axis intersect at a point	.20	.20	.25
Easy to manufacture	.17	.15	.13
Long life	.17	.15	.13

Table 5.Normalized Criteria Weights for Each Person

3.5 Knowledge Level

Knowledge is defined as an individual's personal experience about a specific alternative relative to a specific criterion. It is what is factually known or understood and taken as true by the decision maker. Technical knowledge is a measurement of one's knowledge, ranging from a condition of unknowledgeable to expert level knowledge, as in technical subject areas that form the motivations of this research. It is associated with a specific domain or area of understanding. Knowledge level is the first of two important types of information required from the user of EDSS in decision support. The second, explained below, is confidence level. The relationship between them corresponds to that between alternatives and criteria. A person's knowledge level is concrete and testable. For example, if people were asked about their knowledge level on ball and socket joints used to support square tubes similar to the swivel joint problem, the answer might fall anywhere between 'unknowledgeable' to 'expert.' An objective test could quantify and verify the knowledge level. Notice that, as mentioned previously, one's knowledge level is very specific to a field. This allows for the use of an individual's specified knowledge level with the qualitative confidence factor (explained below) in decision making. The quantifiable and explicit use of a person's knowledge level in the decision making that motivated this research has not been previously accounted for in a decision method. Rather, the many decision methods show that only one component, commonly called a belief, is elicited from the user during evaluation of alternatives. Although this component is never explicitly clarified, it appears to include both a knowledge factor and a confidence factor. Examples of this implicit condition found in the literature follow the pattern, "It is my opinion that alternative A satisfies criterion B." These statements are subjective and are not subject to objective verification by testing or other means. The use of a quantified knowledge level opens up a completely new set of possibilities for decision method mathematics.

If knowledge is objective, "the fact of knowing a thing, state, etc...; familiarity gain by experience" (Oxford, 1971), it is not synonymous with judgment. The dictionary defines judgment as similar to opinion or belief. These words - judgment, opinion, and belief - imply some level of authority, but this authority is not quantified, nor is it required to be qualified as a means of understanding the significance of the judgment or opinion. Subjective definitions of the knowledge level of decision makers must be replaced with definitive definitions.

The importance of knowledge levels in decision making is illustrated by the search for a second medical opinion when a patient is contemplating specialized surgery. A patient only seeks another opinion from recognized medical experts in the field of the patient's ailment. Under these circumstances, the first question a patient asks is whether the expert is knowledgeable about the relevant disease or condition.

Use of experts, people knowledgeable about a given subject, in technical decision making is not new. Matheson (1968) asked three experts, all assumed to be qualified at the same expert knowledge level, in the field of technology to specify the expected lifetime of a new material. Each person returned similar lifetimes. Implicit within the problem was the fact that others with less than expert knowledge were not asked for their opinions. Since use of a complete team of experts from the same specialized area is not available to solve every problem, accommodations for different knowledge levels must be possible within the decision method.

In an article on decision support, Chelsea White (1990) supported this concept saying, "Our experience has lead us to recognize the following difficulties in applying the DA [decision analysis] paradigm. First,. . . in which experts express their knowledge, yet such statements rarely translate into precise values . . ." The fact that EDSS addresses this difficulty and allows translation of knowledge into specific knowledge values, distinguishes it from other decision making methods. In addition to quantifying the level of knowledge, it is valuable to quantify a person's confidence level, which is explained below.

3.6 Confidence Level

Confidence is subjective, or judgement based, and it is paired with knowledge during alternative-criterion pair evaluations, as the second dimension of the belief model found in the taxonomy of Table 1 (Ullman, 1995). Confidence quantifies the level of surety about a propositional assertion made that an alternative satisfies a criterion. To use a betting analogy, confidence defines how large a wager to place on the alternative's success in meeting the criterion. This aspect of the argumentation or evaluative decision making allows quantification of the likelihood of success and represents the individual's degree of belief or certainty (Bacchus, 1990). While knowledge is verifiable through testing, confidence is not. When evaluating an alternative-criterion pair, statements about confidence level are separable from those about knowledge level.

The six words explained above are foundational to the explanation in the next chapter of the models used in EDSS. This and subsequent chapters build on each other as shown in Figure 2 below.

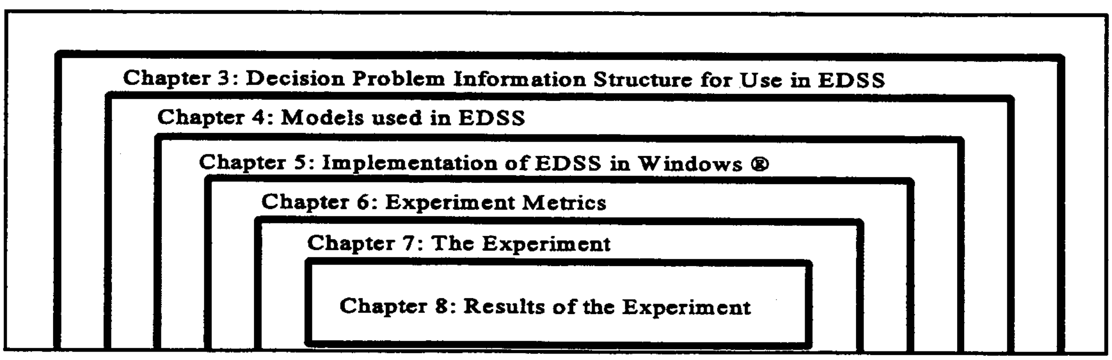

Figure 2. Chapter Structure

4. MODELS USED IN EDSS

This chapter explains the three models that are the foundations of EDSS. These are the cognitive model (how people access and process information used in problem solving), the decision model (how people use the information in arriving at a final decision), and the mathematical model (the formulas used in the decision model).

4.1 Cognitive Model

The cognitive model used here that provides the problem-solving performance needed in technical decision making is the information processing model (Newell, 1972). Information processing is a theory describing human problem solving. In this model the problem-solving activity is portrayed as accomplishing a task in contrast with problem solving that is related to personal behavior or is emotionally motivated. The theory's processing characteristics include using a person's long term memory, short term memory, and the external world. The information processing model is represented in two ways. It is either, "A sequence of mental processes or operations performed on information in a subjects memory" (Mayer, 1992), or, "A sequence of internal states or changes in information that progresses towards the goal" (Mayer, 1992). The verbal expressions that identify information processing in the work of Stauffer (1987), were repeatedly observed on videos of all teams in this research. For example, team members said, "I have used joints like this before..." or "This is just like..." These examples conform to the information processing cognitive model and indicate that the participants have and use factual information and experiences inside the decision space (see Figure 3). This figure shows that a decision maker uses information processing to move previous factual information and experiences from the area represented as *The rest of the universe*, into the *Decision Space* for use in decision making. This factual information and experiences are associated with alternatives that become possible solutions to the issue being addressed.

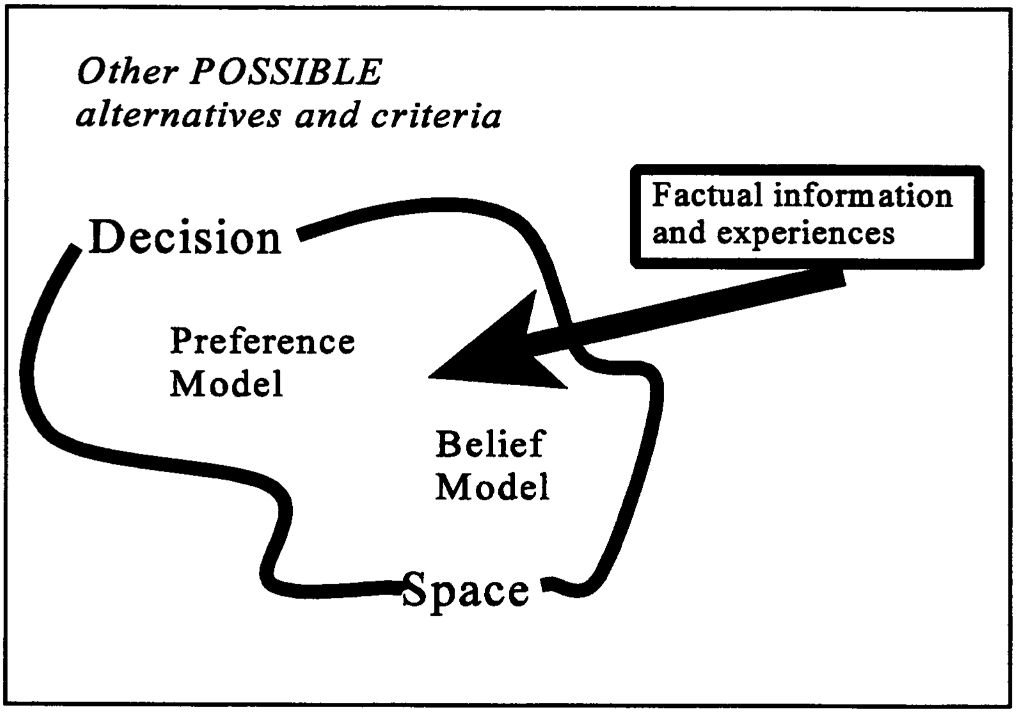

Figure 3. Information Processing During Decision Making

4.2 Decision Model

The decision model used here is a theory of choice using evaluation techniques. Once alternatives have been brought into the decision space, selecting an alternative as a solution to the issue requires choice based on evaluations. Evaluation activities use the factual information and experiences that accompany each alternative. Evaluation is the design process step which proceeds selection or, "choosing between a number of alternative possibilities for further action" (Eekels, 1990). Two important subjects that are part of the evaluation processing are discussed below. The first is how the decision maker actually goes about evaluation of the many alternatives using the criteria statements, and the second is how the decision makers deals with the principle of decision uncertainty.

Figure 4 shows the data network representation of Nagy (1990) that provides additional graphical representation of the cognitive model used in mechanical design. In this research the constraint is the criterion statement, the design object is the alternative, the argument is the evaluation of the alternative-criterion pair, and the decision the final alternative selection.

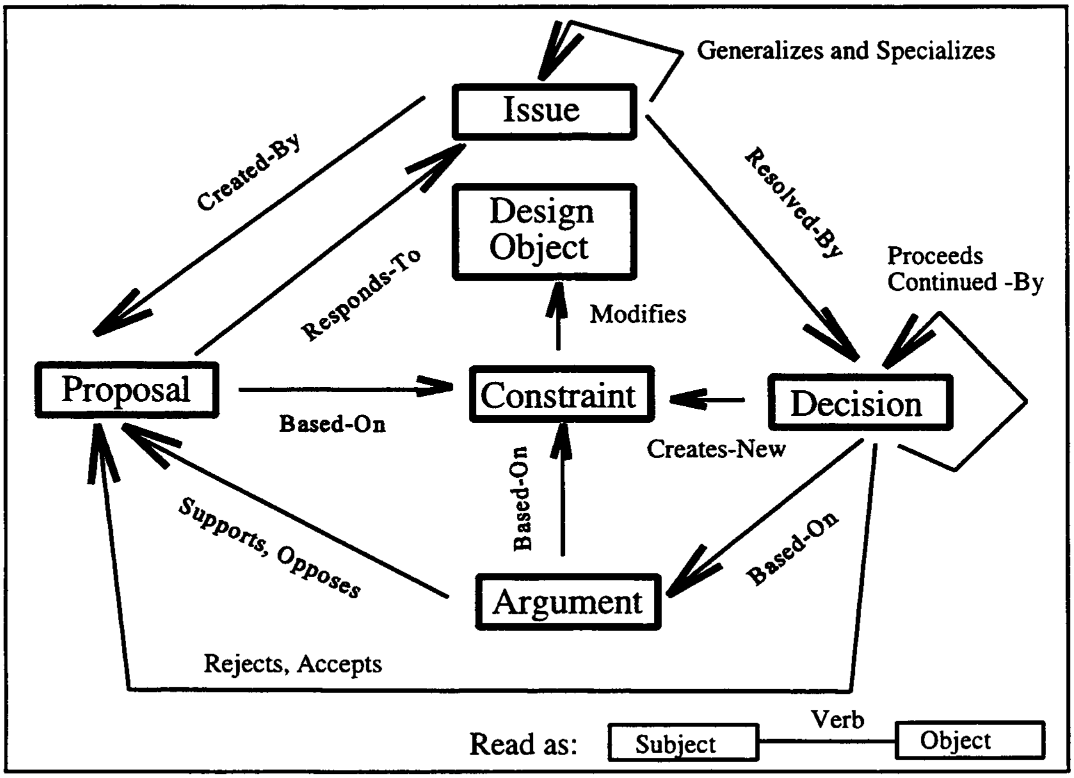

Figure 4. Data Element Network (Nagy, 1990)

4.2.1 Evaluation Using the Alternative-Criterion Pair

In this research and others (Dwarakanath, 1995; Stauffer, 1987), decision makers were observed conducting evaluations using alternatives and criteria in grouped, alternative-criterion pairs (see Figure 5 below). EDSS uses this same pair structure as a primary feature of the EDSS decision method.

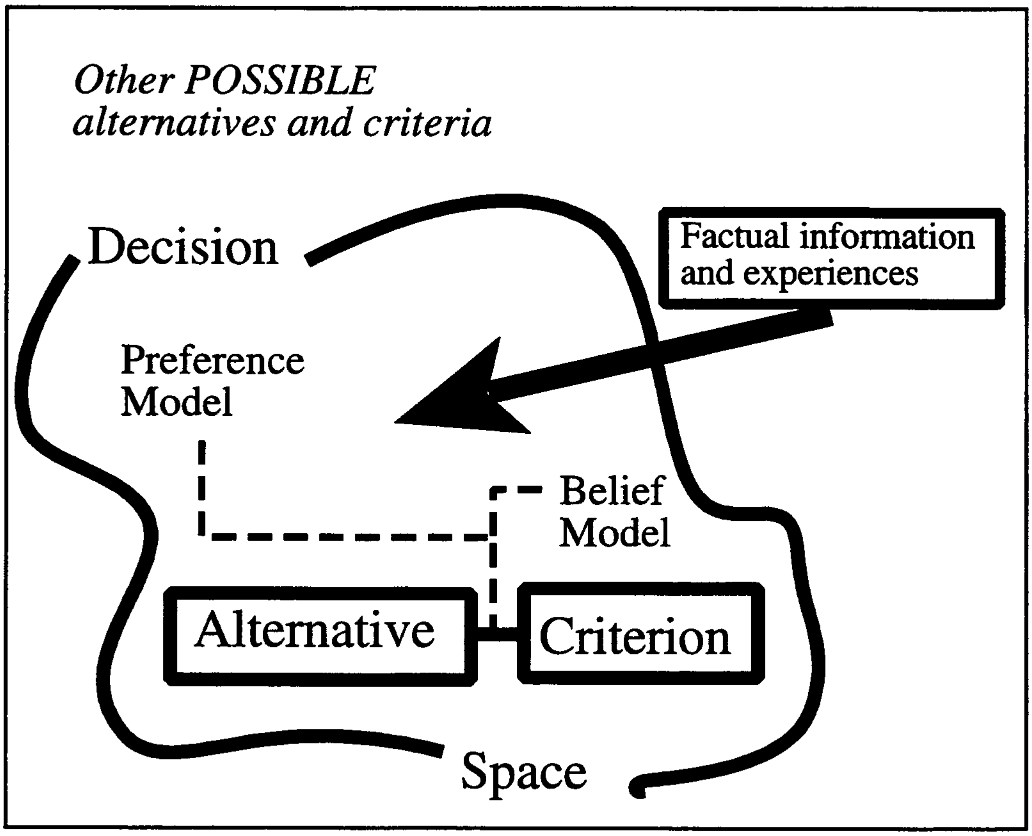

Figure 5. Evaluation using Alternative-Criterion Pairs

When using criteria statements for evaluation of alternatives, a consistent application of an evaluation scheme must be assured. It can be considered equivalent to the use of a datum plane in geometry. The use of a propositional alternative-criterion statement syntax explained in the previous chapter assures this consistency. The Boolean response from this syntax provides a simple datum. An example of a propositional criterion statement from the experiment used in this research is that "the [final solution] swivel joint must have an alpha angle within the range of plus or minus fifteen degrees." This statement can be worded in the active affirmative voice which makes it easy to evaluate. Using the propositional alternative-criterion statement syntax of Equation 1, the simple question of, "does the alternative that I am considering satisfy the alpha angle requirement or does the alternative that I am considering not satisfy the alpha angle requirement," can provide a simple yes or no Boolean response.

A unique advantage occurs when propositionally stated criteria statements with Boolean responses are used in evaluations. With these statements the only consideration is the answer to the question of whether or not the alternative satisfies the criterion. This feature eliminates possible confusion that can occur when using criterion statements that are worded using an increasing objective function and in the same decision activity using a decreasing objective function for other criterion. This combining of contrasting objective functions has been observed. The only way a consistent decision result is possible in this situation is if some implicit criterion transformation takes place. Propositional Boolean criteria statements used in EDSS do not have this conflict.

4.2.2 Decision Making with a Condition of Uncertainty

Classical decision analysis defines decision making under a condition of uncertainty as a lack of ability, by the decision maker, to known what the exact outcome will be from selecting a choice or course of action. A simple example for decision making under a condition of uncertainty is purchase of stock on the stock market. Fulfillment of the expected outcome is not known at the time of stock purchase. This example illustrates a simple Boolean condition equivalent to the Boolean response for criterion statements explained previously.

All decision models, and the analysis that accompanies them, have some uncertainty in both the data and the model. EDSS uses a Bayesian approach to decision analysis, rather than a classical approach to decision analysis. The Bayesian position asserts that any uncertainty relates to information about the issues or event rather than uncertainty about whether the issue or event itself will occur. Applying this position to the problems addressed in the research, given the set of possible alternatives, it is almost certain that one of the alternatives will produce a solution to the issue under consideration.

This condition of the unknown is the uncertainty that accompanies decision making. If decision makers always knew the outcome of their choices, there would be no uncertainty associated with the decision. Evaluation of alternative-criterion pairs using a propositional assertion allows only two outcomes. Either the alternative does satisfy the criterion statement or the alternative does not. This simple Boolean outcome is elegant and provides a powerful foundation for the mathematical model explained next.

4.3 Mathematical Model

This section describes the mathematical model used to calculate EDSS decision results using the cognitive and decision models explained above. In the most simple terms, EDSS elicits an individual's knowledge level and confidence belief for an alternative-criterion pair and calculates a numerical result. This numerical result comes from a function called the Satisfaction Value, SatValue.

The EDSS Satisfaction Value function is the first known method to combine knowledge level and confidence belief into what is classically defined as a decision analysis value function. Classical decision analysis value functions are used for assigning a numerical value to a specific alternative using a criterion or assigning a numerical value to an alternative using criteria. For a single alternative, it has or is assigned an attribute value, represented in Equation 3 as x_1 with the subscript indicating criterion 1. The value is normalized to values 0.0 and 1.0. This zero to one value range is assigned by the decision maker using some normalizing scheme. This normalizing scheme can range from subjective to objective. Two typical schemes which normalize attribute values are using the extreme attribute value equated to 1.0, and normalizing all others accordingly or setting some value as the extreme attribute value equated to 1.0. As would be expected with multiple alternatives for the same criterion, a functional assignment based on the attribute level is shown in Figure 6. This one-to-one mapping of the alternative attribute value and a corresponding ordinate value can be as simple as a one to one mapping in a table format. For a problem with criteria there is a function for each criterion.

$$Value_{alternative\ i}[0.0,1.0] = f[v_i(x_i)]_{criterion\ j}$$

Equation 3. General Value Function

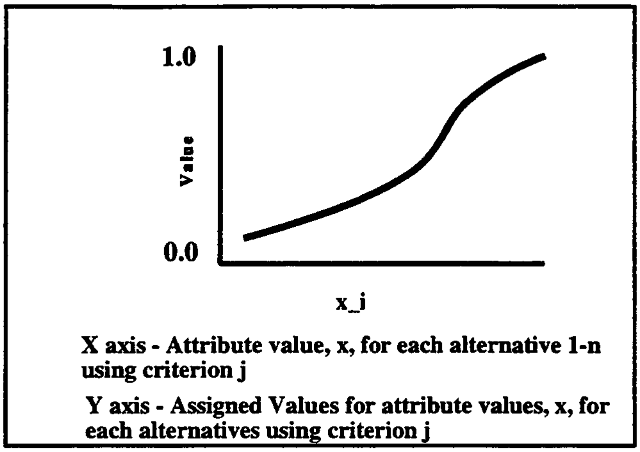

Figure 6. Value Function for Alternatives 1-n, using a Criterion

From classic decision theory (Keeny, 1993, Winterfeldt, 1986) a value function for the alternative using all the criteria, subscript 1 to n, is aggregated into a single value for the alternative as shown in Equation 4. Aggregation methods are not discussed here but in a simplest manner can be combined linearly.

$$Value_{alternative\ i} = f[v_1(x_1), v_2(x_2), \ldots v_n(x_n)]$$

Equation 4. Value Function for Many Criteria

For criteria with numerical attribute values for the alternative, this functional treatment seems understandable. Anchoring of the first alternative with a measurable attribute value is straightforward. As an example, in the case of the problem used in this research, if exact fabrication costs were available for each alternative the teams were evaluating, then the highest fabrication cost alternative would be assigned some value close to 0.0 and in turn each of the other alternatives would be assigned some value greater than this lowest value assigned, up to the least expensive fabricated alternative. Accordingly the alternative with the least fabrication cost would have the highest value. This produces a functional relationship between the fabrication cost and an evaluator's value assignment. In EDSS this value function is the Satisfaction Value, SatValue, which was created as part of this research. The Satisfaction Value calculation used in EDSS, with an alternative, Alt, criterion, Cri, participant, knowledge, K, confidence, C, is given in Equation 5.

$$SatValue = \frac{[CK+(1-C)(1-K)]}{[CK+(1-C)(1-K)]+[C(1-K)+(1-C)K]}$$

Equation 5. Satisfaction Value for Single Alternative, Criterion, and Participant

Values for the Satisfaction Value function range from 0.5 to 1.0 for knowledge and 0.0 to 1.0 for confidence. The range for knowledge begins at 0.5 due to the Boolean yes-no response discussed above. As a beginning position, one where an evaluator has no knowledge, there is a 50-50 or 0.5-0.5 probability that the alternative will satisfy the criterion. The standard Bayesian premise allows revision of prior information with new information. Equation 5 is the foundation of the EDSS mathematics which accomplishes this revision of a no knowledge prior probability value of 0.5. The range for confidence can be equated with 0.0 which is 100% confidence that the alternative will not satisfy the criterion and 1.0 as 100% confidence that the alternative will completely satisfy the criterion. Using these values produces a three dimensional surface for the Satisfaction Value contour plot shown in Figure 7 and surface plot shown in Figure 8.

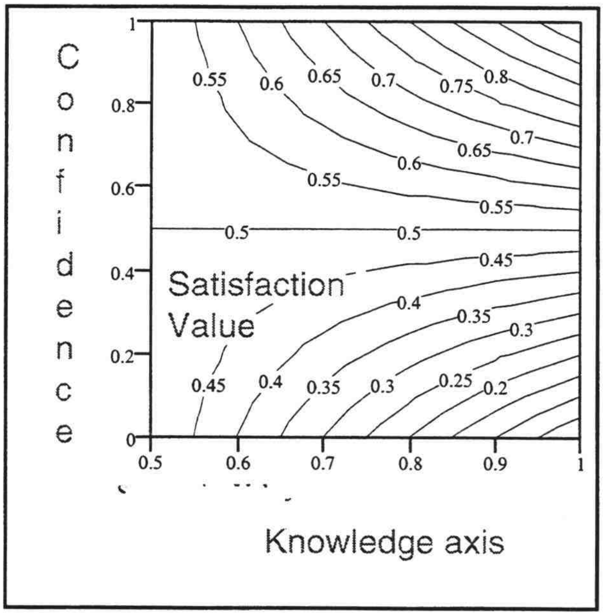

Figure 7. Satisfaction Value Contour Plot

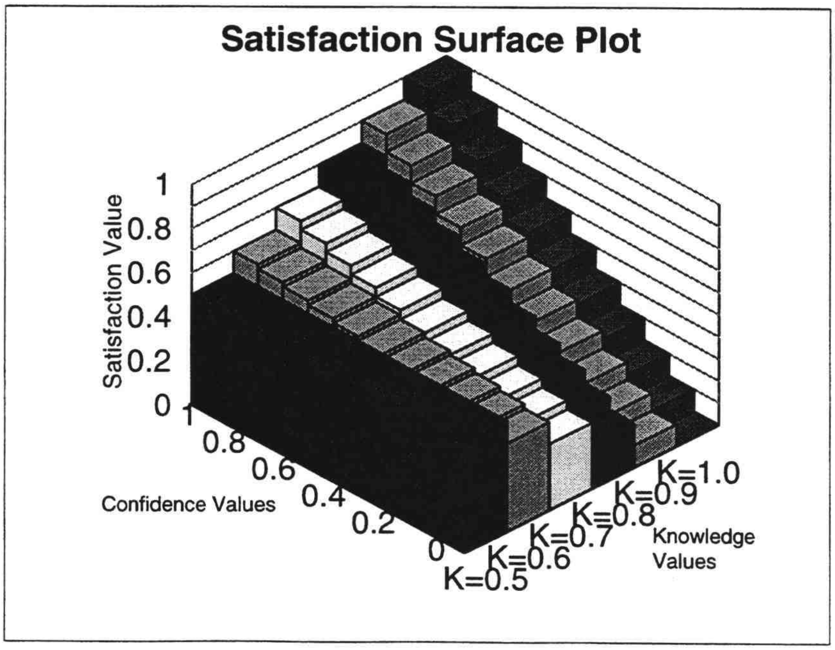

Figure 8. Satisfaction Value Surface Plot

For simplicity in using the decision method, common words were selected to represent knowledge levels and confidence beliefs. From Ullman (1994), the knowledge and confidence values used in the Satisfaction Value had discrete values assigned to these common words. As an example, an amateur knowledge level is assigned a value of 0.78 and a likely confidence belief was assigned a value of 0.73.

To illustrate the SatValue(Alt_i Cri_j) for a single participant, K = amateur (0.78) and C = likely (0.73) yields a SatValue = 0.63. This same formula can be applied to any number of criteria for a single alternative. For aggregation, a single participant, of all criteria for a single alternative Formula 6, below, is used. The aggregation is linearly additive. The weight of each criterion for a participant is normalized with their sum equaling 1.0, $\sum$NCri = 1.0.

$$SatValue(Alt_i) = \sum_{Criteria} (NCri) \frac{[CK+(1-C)(1-K)]}{[CK+(1-C)(1-K)]+[C(1-K)+(1-C)K]}$$

Equation 6. Satisfaction Value for an Alternative Across all Criteria for a Single Participant

In the relatively simple example below (see Table 6) the Satisfaction Value, SatValue, for this alternative is 0.56. This value is only slightly better than a decision maker admitting neutrality, 0.5-0.5 probability, about this alternative. A knowledge level of 0.5 means that the decision maker has no knowledge and the outcome that the alternative will satisfy the criterion is a 0.5-0.5 probability. It could satisfy the alternative and it could not satisfy the criterion. The contour plot, Figure 7, indicates that if a decision maker has no knowledge, a knowledge level of 0.5, then confidence belief will have no effect on the value of the Satisfaction Value. Neutrality is having no knowledge about the alternatives ability to either satisfy or fail to satisfy the criterion. This example has only three criteria, which the single participant has evaluated. The participant has assigned a preference to each of the criteria, thus expressing *Belief Completeness*.

Criteria #	Knowledge	Confidence	Criteria weight value	NCri
One	Experienced	Likely	1	0.17
Two	Informed	Potential	3	0.5
Three	Weak	Questionable	2	0.33

Table 6. Normalized Criteria Weights for One Participant

As an example, diagraming of the Satisfaction Value for a complete decision, three participants with two alternatives and criteria, is shown in Figure 9. This diagram uses a node diagram for the Satisfaction Value of any alternative 1...n . Each Satisfaction Value for an alternative is a parent node that is independent from any other parent node. The child nodes can have any combination of 1...m participants who record data at the Knowledge and Confidence nodes. There is no requirement that all criteria nodes be populated with Knowledge and Confidence data. These alternative-criteria nodes are the children nodes of the Satisfaction Value for the specific alternative.

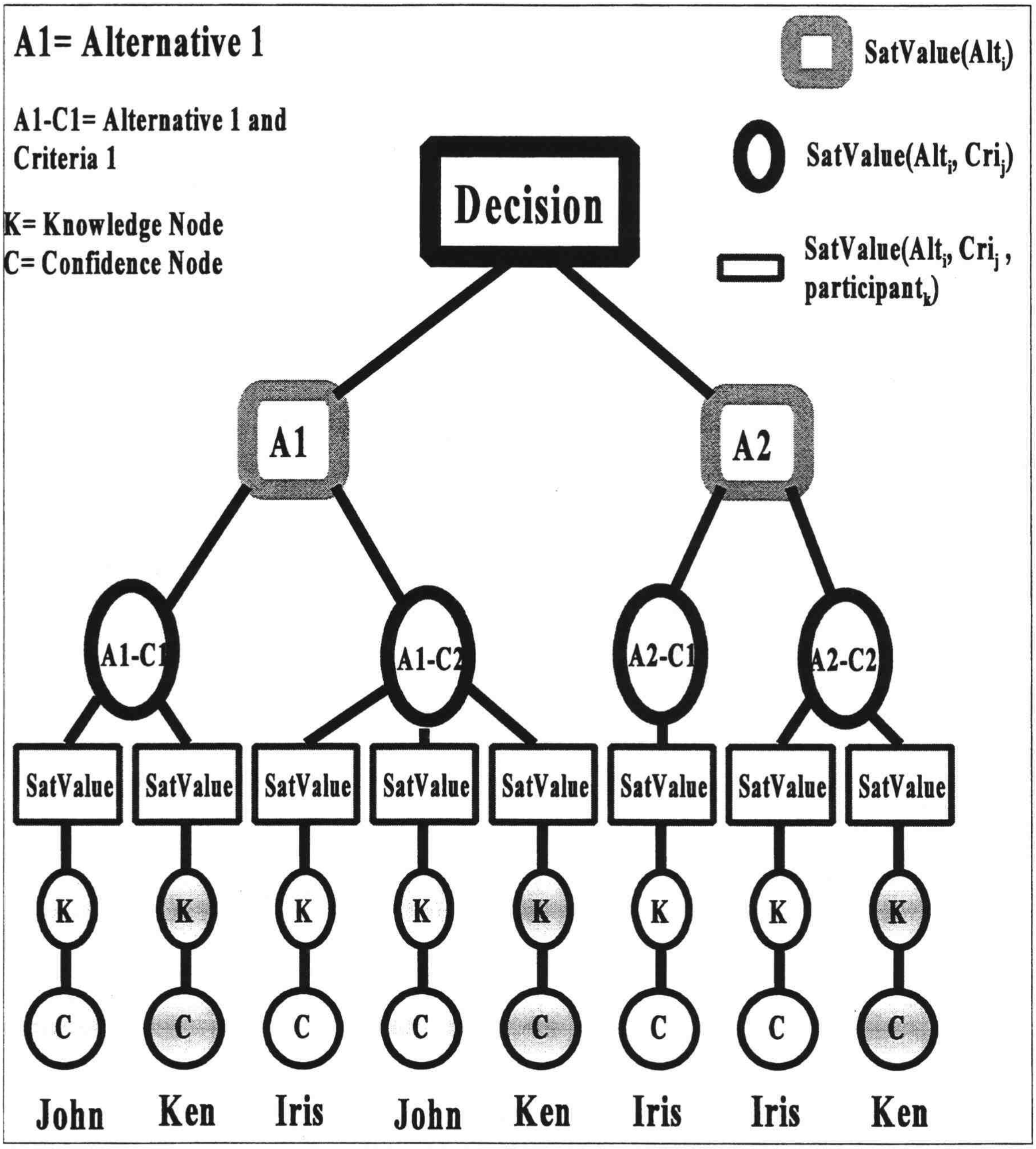

Figure 9. Node Diagram of EDSS Decision Method

Equation 7, also developed as part of this research, begins at the leaf node of this node structure as a method of combining participants evaluations of a specific alternative and criterion. Equation 7 is used for the four nodes, A1-C1, A1-C2, A2-C1, and A2-C2. This also is a Bayesian mathematical position of revising prior information with new data. The leaf node is shown in Figure 9 as the Confidence nodes for the participants. When using the EDSS decision method the movement of the decision maker through the tree structure begins at the leaf or bottom node and proceeds upward towards the parent node which will be the final decision. Although it has been previously stated that evaluation of alternative-criterion pairs is not structured after a tree configuration, Figure 9 does use the tree diagram with nodes to show the construction of EDSS mathematics model. The two paramount differences between decision analysis with its tree structure and Figure 9 is direction of movement on the diagram, and the contents of the parent and leaf nodes. In decision methods that stipulate decision trees as the method, the movement by the decision maker is from the parent node, top-most node, to the leaf node, which is the final alternative selected as a result of the decision-making process. With EDSS the movement and the leaf nodes are essentially reversed. The movement is from the leaf node, a condition of what is known and believed about an alternative-criterion pair, up the structure to the parent node, which is to be the final decision result.

Equation 7 provides the numerical value for the Satisfaction Value node shown in Figure 9, for a single alternative paired with a criterion using knowledge and confidence evaluation values from participants.

$$SatValue(Alt_i - Cri_j) = \frac{\prod_{Participant} [CK+(1-C)(1-K)]}{\prod_{Participant} [CK+(1-C)(1-K)] + \prod_{Participant} [C(1-K)+(1-C)K]}$$

Equation 7. Satisfaction Value for a Single Alternative and Criterion for all Participants with Knowledge and Confidence

4.3.1 Aggregation Function

From the use of Equation 7, a listing of all alternative Satisfaction Values is possible, from which a final alternative is selected. Aggregation functions provide the methods for combining the final decision making information. If there is a single evaluator using a decision method, there is no need for aggregation methods. Aggregation functions and methods are needed when teams of evaluators must combine their information. The classical nontechnical decision method for aggregating information from more than one source is through the use of a consolidation evaluator. The job of this consolidating evaluator is to assess all the information and choose some method or scheme to compress this information into a single scalar value. The choice of method and scheme is determined by the consolidating evaluator. EDSS uses a linear additive consolidation. The justification for a linear additive method rests with the use of a value function for the Satisfaction Value. The Satisfaction Value for each alternative-criterion pair is a strict numerical value; no conversion or transformation into any other function or number is required.

Linear additive consolidation of each alternative Satisfaction Value across all criteria is shown in Equation 8. Equation 8 provides the calculation for the value of the alternative, A1 and A2 in Figure 9. The V(NCri) value in Equation 8 is the normalized (to 1.0) criteria weight using all participants' criteria weight values.

$$SatValue(Alt_i) = \sum_{Criteria} V(NCri) SatValue_{each\ criterion}$$

Equation 8. Satisfaction Value for Single Alternative for all Criteria

When teams are used for making a decision, EDSS consolidates information from each participant and combines it using Equation 8. The final step in the use of the EDSS decision-making process is presenting the user with a single scalar Satisfaction Value for each alternative using the criteria preferences and Equation 8.

4.3.2 Limit Analysis of the Satisfaction Value Calculations

As part of testing any new mathematical method, the function must provide reasonable and believable results at limiting conditions. Limit analysis was conducted on the Satisfaction Value calculation for those conditions that can be defined as extreme values for knowledge, confidence, and participant numbers. In all cases the results were reasonable and believable.

4.3.3 Axioms for EDSS the Model

There are a few axioms and conditions that are implicit with the EDSS method, and are listed below. As with mathematical axioms, proof is self-evident and not required.

1. Criteria weights express the participant's preferences and remain constant across all alternatives.
2. Participants can accurately specify their knowledge and confidence for alternative-criterion pairs.
3. A participant may use either qualitative or quantitative information that shows a strength of preferences.

4. For the propositional Boolean treatment of criteria statements - the fact that the alternative satisfies the criterion is independent of the fact that it will not satisfy the criterion.

5. For propositional Boolean treatment of criteria statements - the probability P, P(alternative A satisfies criterion B) + P(alternative A WILL NOT satisfy criterion B) = 1.

6. For any unique alternative the Satisfaction Value for criterion is linearly additive and independent.

5. IMPLEMENTATION OF THE ENGINEERING DECISION SUPPORT SYSTEM IN WINDOWS®

This chapter introduces the Engineering Decision Support System, EDSS, computer program. The EDSS decision support method was programmed using the Clarion® software with a Windows® user interface. This chapter explains the various screens in the program. Information or data input required from the user for each screen is explained in a tutorial fashion. The screens in this chapter display data from an experiment explained in Chapter 7. The EDSS version shown in this chapter, which was used by the teams in the Chapter 7 experiment, was version 0.21. There have been many expansions and improvements made to the EDSS program since this early version and the latest version is explained in Chapter 13, "EDSS version 0.45."

The implementation of EDSS as a PC software program uses as a foundation a conventional relational data base. The information required from the user, its storage, and the information provided back to the user, is stored by EDSS in a file and record format that is standard to relational data bases. EDSS is a multi-user program that operates on a conventional network such as Novell® if standard record locking-out techniques available with all data bases have been disabled.

This chapter assumes that the EDSS user is familiar with standard Windows® techniques. No specific mouse or keystroke commands are explained. It should be noted that EDSS is still in beta testing and the program, as it is explained below and in chapter 13, is not intended to represent a commercial quality software. Since the software is a beta version, no extensive design of computer interface methods or screens was attempted, except that general human factors principles served as a guide (Sanders, 1993). It is also assumed that all users act in a completely professional and honest manner, entering and modifying only their own information. A web version of the program is available, although not nearly as complete as the PC version, at http://www.cs.orst.edu/~dambrosi/edss/info.html.

5.1 Data Input

After proceeding past the opening EDSS screen, the user may retrieve or enter information selectively by using the buttons which are below the menu bar at the top of the open screen. The next sections follow in serial fashion, but this should not be interpreted as a strict program requirement.

The sample screens shown in this chapter (Figures 10-16) are taken from one of the teams that used EDSS for their decision support method in the experimental problem of the design of the simple mechanical swivel joint. The experiment is explained in more detail in Chapter 7.

The use of EDSS makes some fundamental assumptions, which are listed below, about the user and his or her entering of data into the program.

1. The participant does not bias any data input for the purpose of influencing the outcome.
2. Knowledge and confidence values specified by the participant are truthful and unbiased.
3. Criteria weights express the participant's preferences and remain constant across all alternatives.
4. The participant can accurately specify his or her knowledge and confidence for alternative-criterion pairs.
5. The participant shows preferences that can be based on either qualitative or quantitative information.

5.1.1 Issues Screen

This is the first screen (Figure 10) the program presents to the user after the opening screen . An issue (see Section 3.1) is the primary index or entry point into the information or data base held by EDSS. Figure 10 displays the issue which was the problem statement for teams in this research, "Design Swivel Joint of a wall mounted mech...." Access to this screen is available at any time from the Issues button below the menu bar. Within the Issues screen accessing or entering information is possible by using one of two paths. Existing issues stored in the data base may be retrieved using the drop down menu arrow to the right of the Issue: text area. A previously entered issue may be selected by highlighting its title using standard Windows® methods. The other option open to the user is to add a new issue.

Clicking on the Add button brings up a screen which allows the user to record the title of the new issue, the participant who created or added the issue to the data base, and any notes the participant wishes to record. These data areas are self evident. Additionally, attachment of an issue drawing file is possible if the file name and path are specified in the area labeled.

Modifications to previously entered issues are possible. The change and delete buttons allow modification of wording or deletion of the issue from the data base. Deletion results in complete eradication of the issue from EDSS. For practical considerations with this version, the number of issues stored should be limited to an upper value of between 25 and 50.

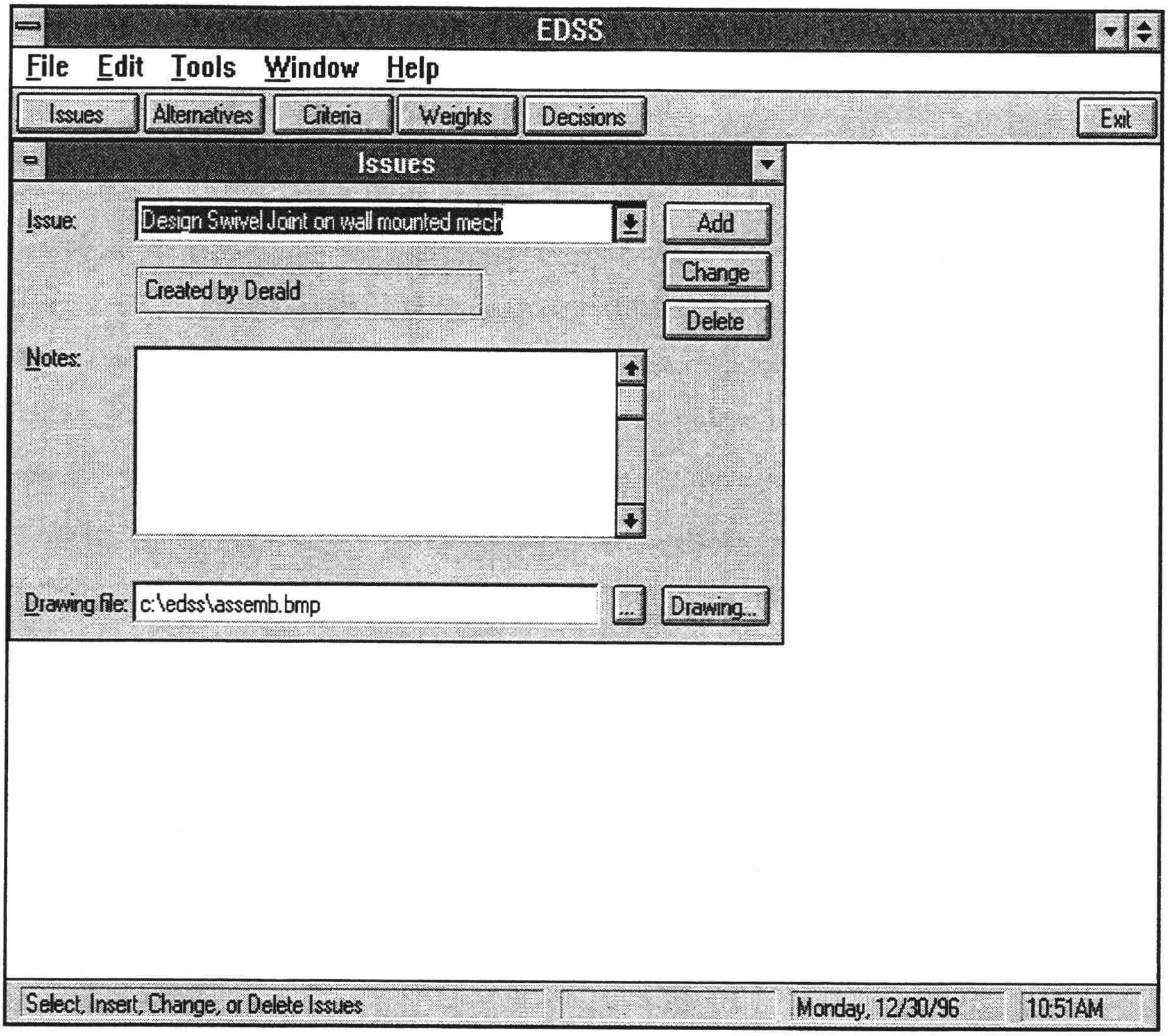

Figure 10. EDSS Issues Screen

5.1.2 Alternatives Screen

After a new issue is added either the Alternatives screen (Figure 11) or the Criteria screen (Figure 12) can be opened next for new data entry. The Alternative screen is explained first (see Section 3.2 for discussion of alternatives).

The user opens this screen in the same way as the Issues screen, by clicking on the "Alternatives" button below the menu bar. Again, depending on whether the user has opened a previously entered issue or is adding new alternatives to a new issue, two paths are possible. An explanation follows for entering information for a set of new alternatives. The same procedure would apply to viewing alternatives data for a previously entered issue. Alternatives are added to the present issue data base by using the Add button. As new alternatives are added, the participant who added the alternative can be selected from an active list for the present issue or by using the global list button. The space labeled "Notes:" is similar on all screens. Buttons OK, Cancel, and Close are consistent with other Windows® programs. Figure 11 displays six alternatives, beginning with "Alternative1-dwg4 and 5" and ending with "ROD and Plate."

Figure 11 shows "Derald" as having entered the first three alternatives because the author preprogramed a preliminary 'starter set' of alternatives and criteria as a time saving measure. The 'starter set' is explained in Chapter 7. There is no further use of this participant in the experiment.

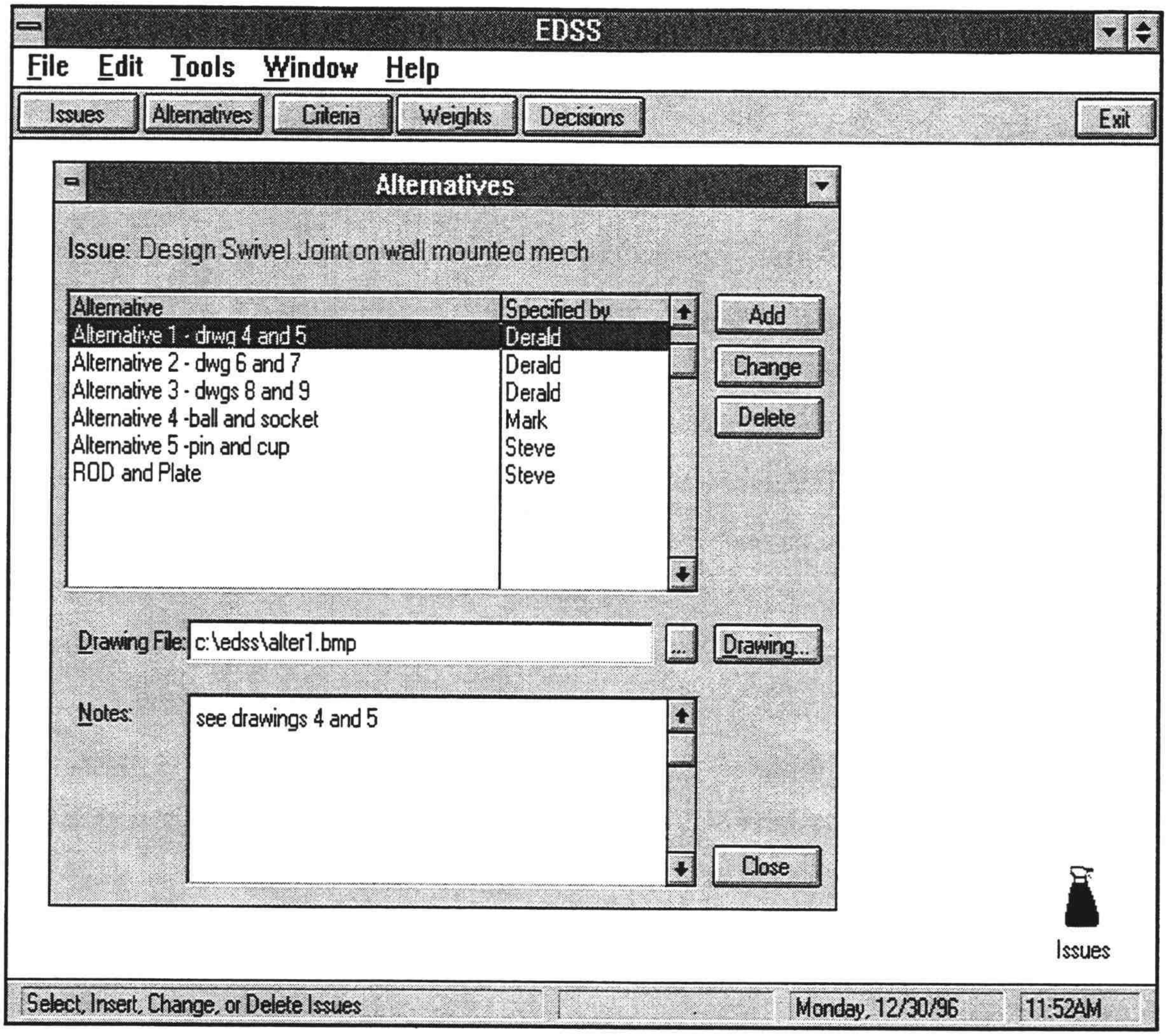

Figure 11. EDSS Alternatives Screen

One benefit of a structured decision method such as EDSS is that it overcomes one of the most common problems found in unstructured decision activities: it decouples the generation of alternatives from its immediate evaluation or generate-and-evaluate process (Dwarakanath, 1994). Formal brainstorming methods also stress this decoupling.

5.1.3 Criteria Screen

The Criteria screen (Figure12) has all the same features as the Alternatives screen described above. The criteria statements entered here are written using a Boolean syntax which requires a yes-no answer (for a discussion on criteria statements see Section 3.3).

Activation of this screen occurs through the Criteria button below the menu bar. Just as with the Alternatives screen, criteria may be viewed, added, changed and deleted. New criterion statements must be written using Boolean syntax, that is, there must be a yes or no answer to the question of whether the alternative X satisfies the criterion Y. Figure 12 lists five criteria starting with "carry the weight of optical device" and ending with "Long Life." For example, combining the "ROD and Plate" alternative with "carry the weight of optical device" produces a statement in Boolean syntax which reads, "Does alternative: ROD and Plate satisfy the criterion: carry the weight of optical device?"

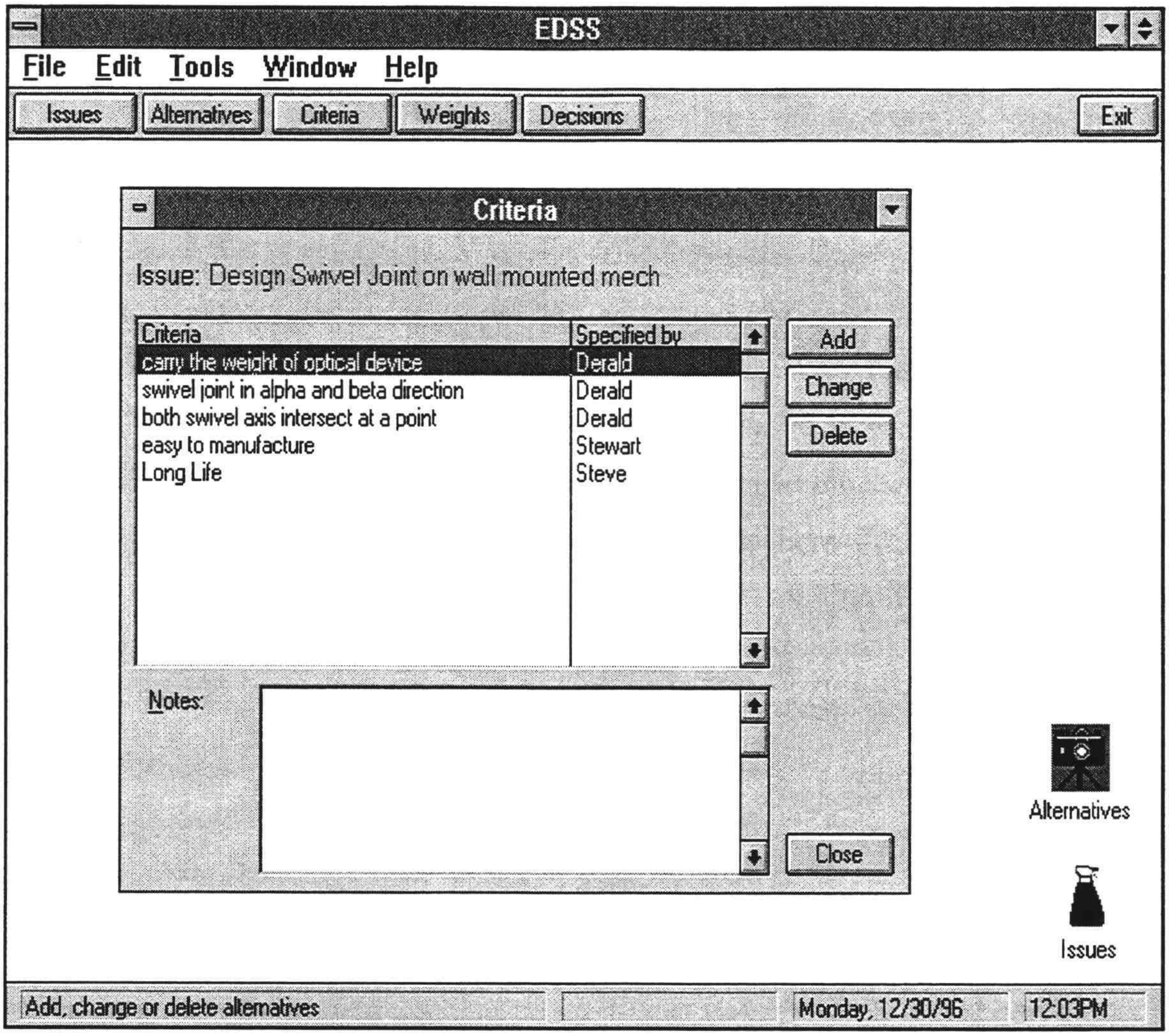

Figure 12. EDSS Criteria Screen

5.1.4 The Criteria Weights Screen

The user opens this screen by using the Weights button under the menu bar (Figure 13). Section 3.4 discusses criteria weights. A participant must be selected before values may be entered. The Weight box at the right side of the screen with the up and down arrows may be used to increase the value from 0.0 up to 1.0. Highlighting the value, by mouse clicking, then highlighting a criterion statement, enters the value. This allows the participant to show preferences for criteria. Not all criteria must have values above 0.00. If a participant places no value on a certain criterion, its value can be left at 0.00. The calculated normalized value is listed under the Normalized column heading.

Figure 13 shows that team member Stewart considered the criterion "carry the weight of optical device" as the most important, with a normalized value of .24, and the criterion "Long Life" the least important with a normalized value of .17.

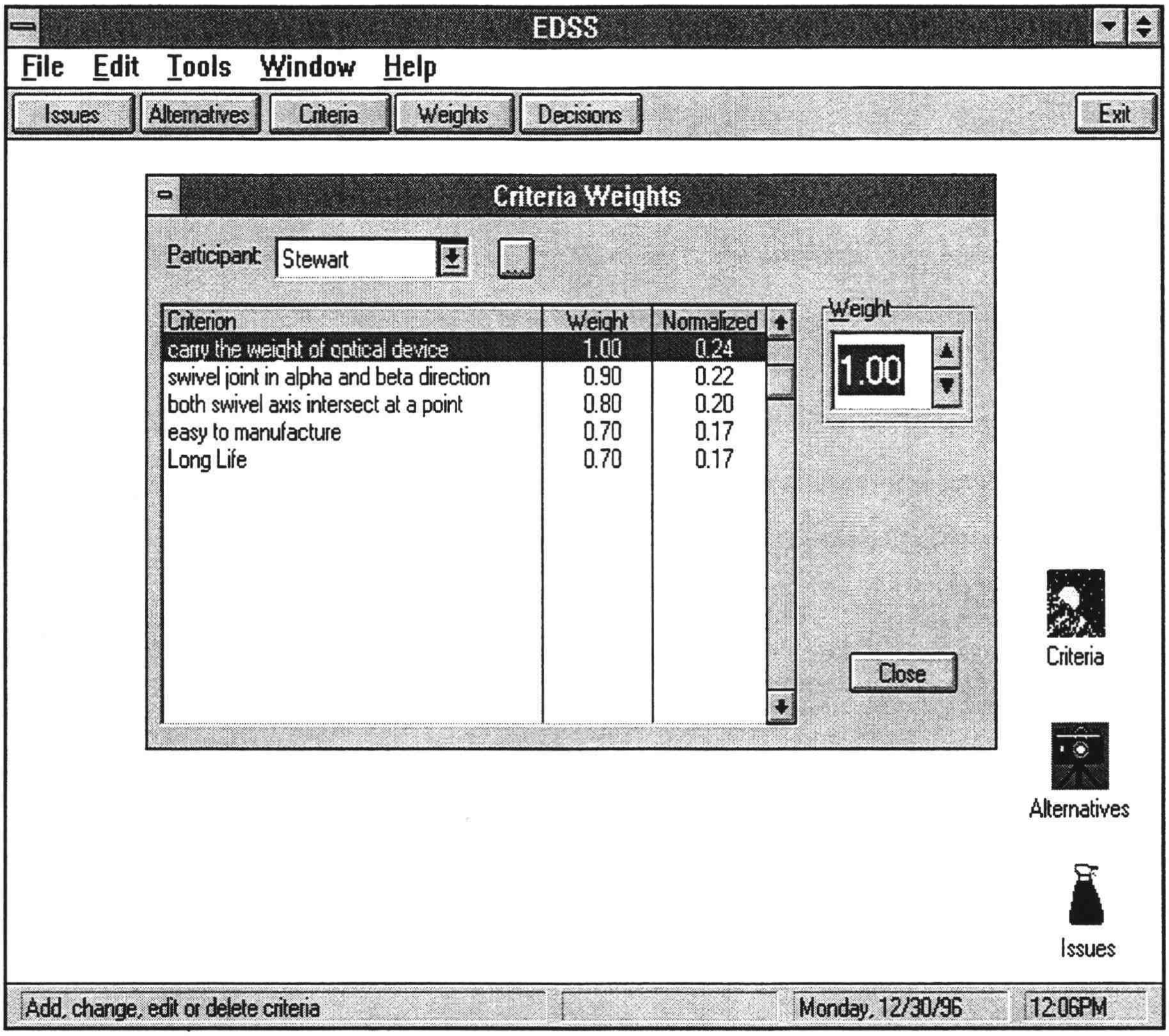

Figure 13. EDSS Criteria Weights Screen

5.2 Decisions Screen

Evaluation of alternative-criterion pairs (described in section 4.2.1) is done through the Decisions screen (Figure 14). This screen records data used for the Satisfaction Value calculation. The user follows these steps: highlighting an Alternative using the mouse; highlighting a Criterion; selecting a Knowledge radio button; selecting a Confidence radio button; and clicking on the Save button to enter data into the data base. It is possible to record comments on design rationale for individual alternative-criterion pairs, although none are shown by Stewart. Figure 14 show that Stewart has selected the alternative-criterion pair "Alternative1 - dwg4 and 5 - carry the weight of optical device." His knowledge level is "Experienced" and this confidence that this alternative satisfies the criterion is "Potential." The Delete button allows a highlighted participant to remove knowledge and confidence values for an alternative-criterion pair from the data base. The Summary and Results buttons take the user to other screens. The Add or Change buttons between the alternatives and criteria screen area allow a participant to highlight either of these two. The user can then add or change an alternative or criterion.

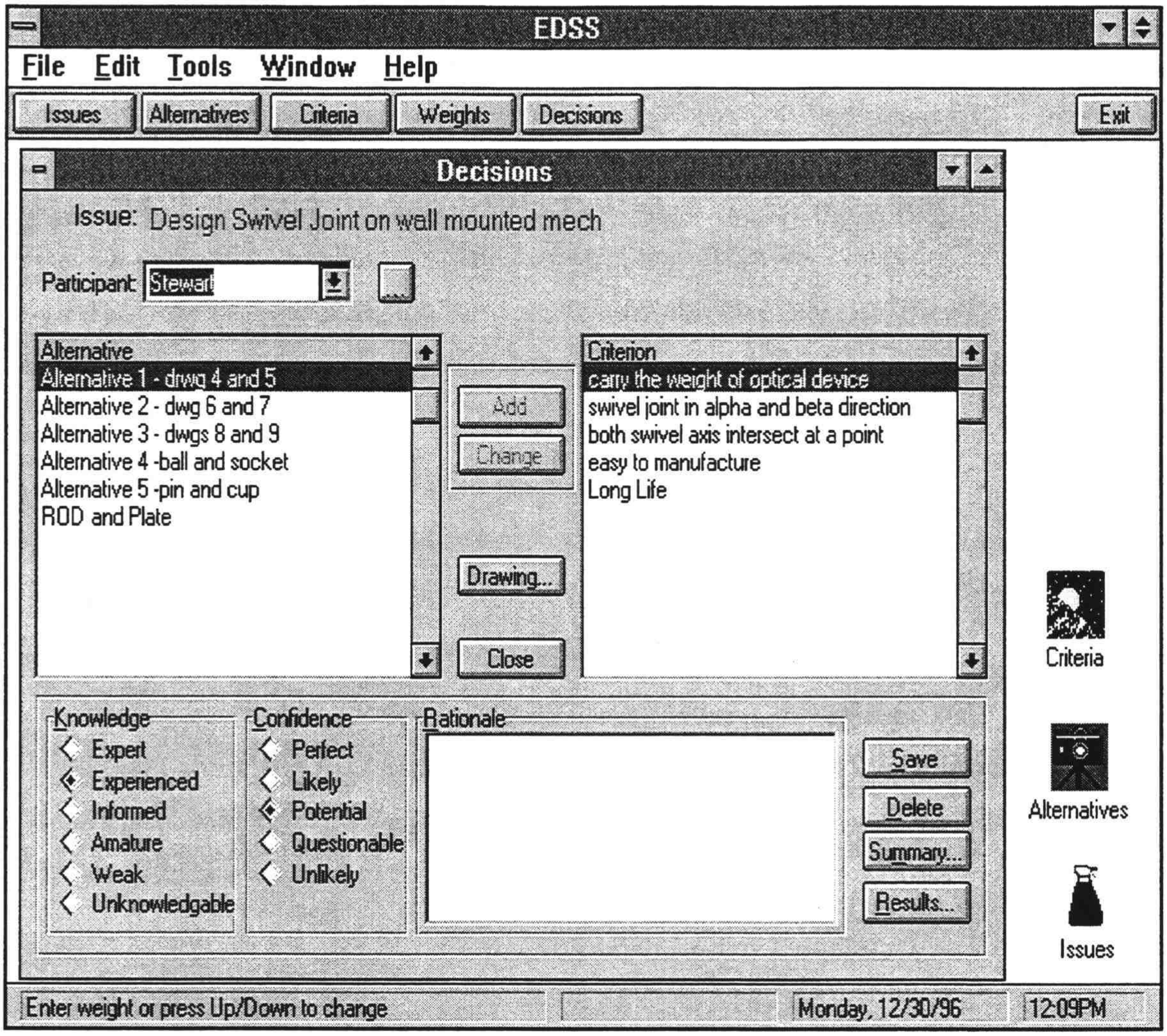

Figure 14. EDSS Decisions Screen

5.2.1 Summary Screen

The Summary screen (Figure 15) provides a matrix which indicates which alternative-criterion pair a participant has evaluated and what knowledge and confidence data values he or she entered. This version of EDSS shows the numerical values for the Knowledge (K) and Confidence (C) under each alternative column. In this screen we see that Stewart selected Knowledge level of "Experience" which shows as K=.91 and Confidence of "Potential" which shows as C=.62. This screen is reached by clicking on the Summary button shown on the Evaluation screen (Figure 15). Additionally, a printout is possible using the Print button. Consistent with the discussion of Problem Completeness - Incomplete (section 2.1.1), it is not necessary that all alternative-criterion pairs be evaluated in order for the EDSS method to provide valid decision results.

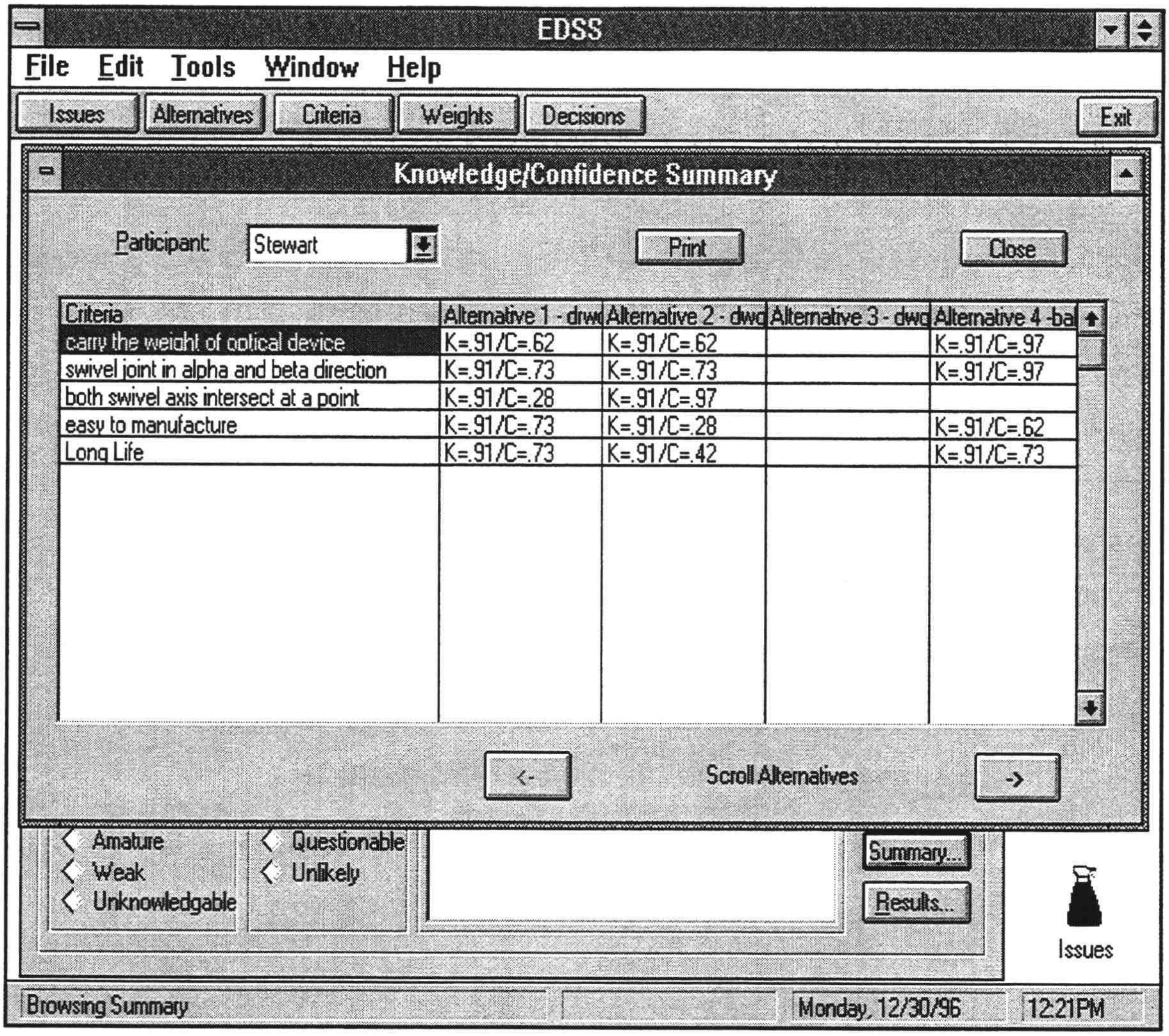

Figure 15. EDSS Summary Screen

5.2.2 Results Screen

The Results screen (Figure 16) is activated by clicking on the Results button shown on the Evaluation screen (Figure 14). Here numerical data is displayed for all the alternatives for Stewart. Each participant can be highlighted with data for the individual (based upon their Knowledge and Confidence values and Criteria Weights) displayed in the column labeled Individual. Higher values are better than lower values. Relative numerical values between different alternatives indicate relative strength as with any other relative comparison method. For additional help in understanding these values, see Program Strategy and Notes. Data results for Stewart show that he considers Alternative 5 - "pin and cup" - the best with a Satisfaction Value of .80. Two of the alternatives have no value to Stewart, were not evaluated and show a Satisfaction Value of 0.0. The Overall column is inactive in this version. The Team column shows the data based upon aggregation of all participants with their criteria weights.

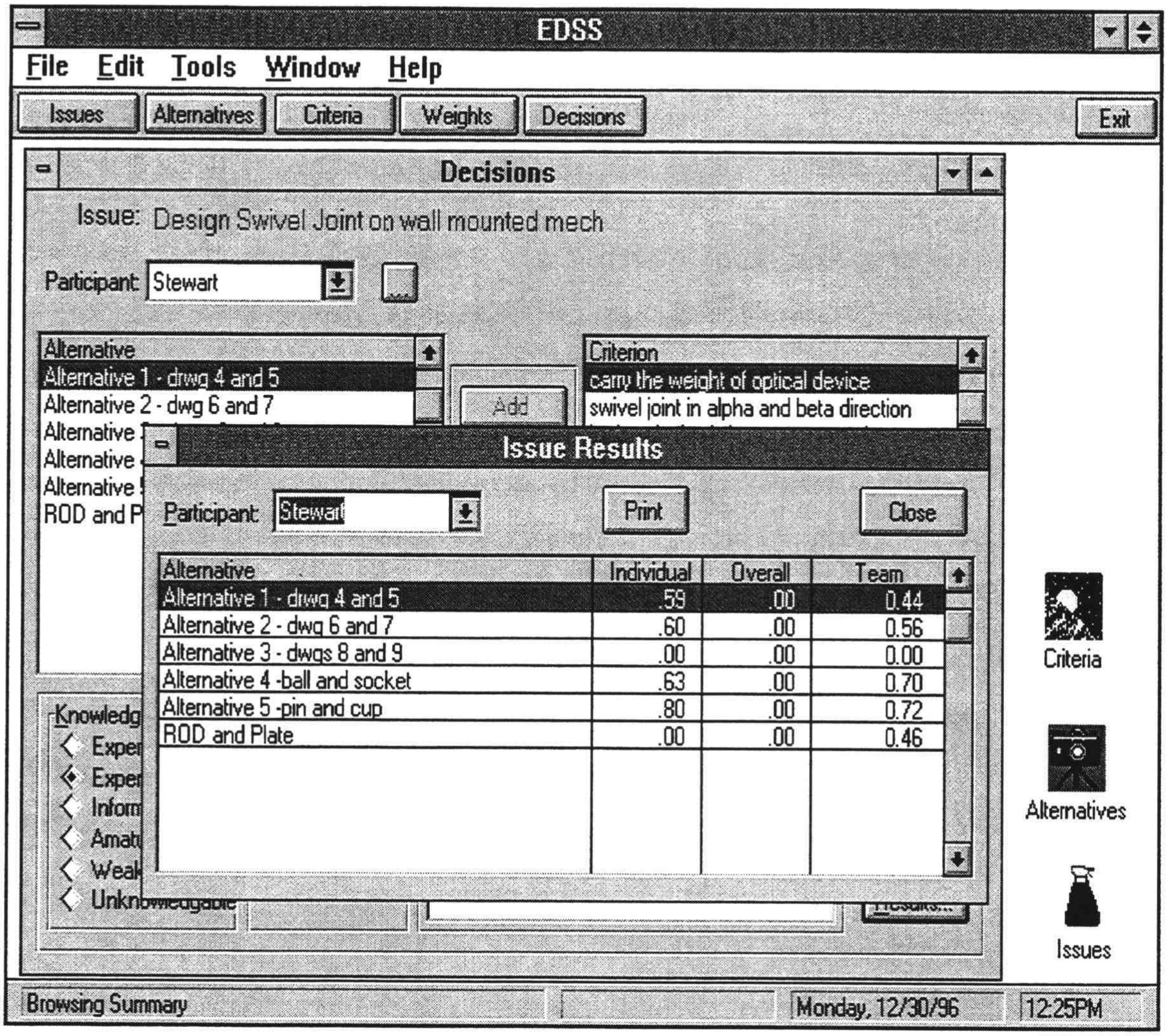

Figure 16. EDSS Results Screen

5.3 Interpreting the Output

Two columns of numbers are available for extracting an interpretation from the decision-making evaluations. They are the Individual and Team columns in the Issue Results window (Figure 16). These numbers are the Satisfaction Values (Equation 6 and 7 Section 4.3).

Satisfaction Values for each alternative are the results produced from the software calculations. Within the decision making process used in EDSS, the Satisfaction Value shows the value, in a standard utility value framework, of all alternatives evaluated based upon Knowledge, Confidence, and Criteria Weights. Within the Satisfaction Value range of 0.0 to 1.0, the user should disregard alternatives that have a value near 0.0 as they are valueless in solving the problem, while values close to 1.0 are strong candidates for being the *best* alternative. Both the absolute and the relative magnitude of the value for each alternative should be considered in selecting a final *best* alternative. For example, three alternatives with values of .80, .76, .78 would suggest that all three alternatives are strong candidates and are nearly equal in their ability to be the *best* alternative. Values of .80, .55, .35 suggest that the alternative with .80 is the *best* choice while the other two alternatives are weaker candidates.

For an individual, differences between Satisfaction Values in the two columns for the same alternative indicate that there is a difference in either or both preference and belief models (see Section 2.1). It is possible to investigate these differences by comparing data entered by others in the team. Investigating these differences can lead to greater problem understanding, and holds the potential for superior decision-making outcomes.

5.4 Conducting Sensitivity Analysis

Manual sensitivity analysis is possible with the version of EDSS that was used in the research experiments. To conduct this sensitivity analysis requires selectively modifying knowledge and confidence values for alternative-criterion pairs. Two methods are possible. The first method requires creating a Mr. Expert participant and the second uses an existing participant. The modification required is the entry of 'expert' knowledge and 'perfect' confidence evaluations for alternative-criterion pairs. The first method simulates an 'expert' participant. The changes in the Satisfaction Value for Mr. Expert or the participant are then reviewed and interpreted.

6. EXPERIMENT METRICS

This chapter presents the various metrics established for the factorial experiment, explained in Chapter 7, used in this research. The metrics are used to report on the hypothesis - that the use of EDSS shows improvements in or positive impact on the decision making activity. The chapter also presents the design or construction of the factorial experiment and how to interpret the analysis of variance, ANOVA, results from the experiment. This research uses a scientific method in conducting the decision support experiments and reporting the results. A hypothesis was formulated, and there was an objective collection of data which was measured empirically against the hypothesis. The metrics established, example used for the experiment, and procedures for data interpretation are proposed for future evaluation of decision support systems.

A review of articles on decision analysis reveals a lack of scientific testing of the methods and procedures proposed in these articles. Generally these papers show a few examples which are intended to demonstrate the efficacy of the method. The use of the metrics described below allows establishment of a clear picture of the strengths and weaknesses of the decision-support system being promoted. Reproducible and quantified evidence from scientific experiments is needed to validate the effectiveness of decision methods. The metrics below provide that evidence.

6.1 Design of Metrics

There are four primary metric categories: productivity, process, perception, and product (Sprauge, 1982). Within each category are the detailed metrics yielding a total of eighteen distinct metrics. Productivity is used to evaluate the impact of the decision support system on the decisions. Process is used to evaluate the impact of the decision support system on the process of decision making. Perception is used to evaluate the impact on the decision makers. Product evaluates the technical merits of the decision support system. The metrics in these categories, combined with statistical methods were used in testing the hypothesis of this research.

6.1.1 The Productivity Metrics

Determination of the influence from the variables on the productivity of decision making was measured with two metrics. The first metric was "total amount of time used to reach a final decision" and the second metric was "quality of the solution resulting from the final decision." Both of these are explained below.

Productivity metric #1: This metric documents the amount of time used for the complete decision activity. It allows identification of the variables that impact this time measurement. The units of this metric is time.

Productivity metric #2: This metric measures the quality of the final alternative selected by the team as being the best. It allows identification of the variable influences on this quality measurement. The units for this metric are points.

6.1.2 The Process Metrics

There are five process metrics. These metrics evaluated the influence of the variables on the decision-making process. The metrics are: number of alternatives created, number of criteria created, number of analyses stored on any medium, amount of data used during the decision making activity, and time spent on the evaluation phase.

Process metric #1: The metric counts the number of alternatives evaluated in the *Decision Space*. It allows identification of what variables influenced the number of alternatives added to the *Decision Space*. The units of this metric are the number of alternatives.

Process metric #2: The metric counts the number of criteria added to the *Decision Space* during the decision-making activity. Data from this metric indicates what variables produced the greatest number of added criteria. The units of this metric are the number of criteria statements.

Process metric #3: This metric counts the total number of documented evaluations, i.e. alternative-criterion pairs evaluated, within the *Decision Space*. Data from this metric indicates what variables produced the greatest or fewest number of evaluations. The units for this metric are number of analyses.

Process metric #4: The metric indicates the amount of data brought into the *Decision Space* from outside. It provides information about what variable effects the amount of additional data that comes into the *Decision Space*. The units of this metric, as with the ones above, are a count of the number of times a person accessed outside information or data such as catalogs or books. This activity was considered to be part of the decision making process.

Process metric #5: This metric measures the amount of time spent on the evaluation phase, using knowledge and confidence information for alternative-criteria pairs that is inside the *Decision Space* when using a decision method. The units for this metric is time. It indicates what variable gave the least or greatest time required to evaluate alternative-criterion pairs.

6.1.3 The Perception Metrics

Seven perception metrics were used to measure various perception levels that the decision makers had during the decision-making activity. These metrics required that decision makers complete a questionnaire (Appendices 5 and 6). Each question had five possible responses that followed accepted design methods for surveys (Hayes, 1992; Spector, 1992; Dillman, 1978). The seven metrics which participants responded to were: control of the decision-making process, usefulness of their decision-making method, ease of use of their decision-making method, problem understanding produced from using their decision-making method, confidence and conviction that his or her decision was right after using their decision-making method, level of satisfaction with the solution after having used their decision-making method, and perception of his or her ability to work as a team using their decision-making method.

Perception metric #1: This metric measures the level of perception that the decision makers have about his or her control of decision making. Control means that a team member's input concerning the direction of the design process was equally considered with that of other team members and there were no forms of inequality in the decision-making process. Data from this metric allows investigation into the impact of the different variable levels on the perception about his or her control of decision making.

Perception metric #2: This metric measures the level of perception that a decision maker has about the usefulness of their decision-making method. Data from this metric allows investigation into the impact of the different variable levels on the perception about the usefulness of their decision-making method.

Perception metric #3: This metric measures the level of perception that the decision makers have about the ease of use of their decision-making method. Data from this metric allows investigation into the impact of the different variable levels on the perception about the ease of use of the decision method.

Perception metric #4: This metric measures the level of problem understanding or insight held by the decision maker. Data from this metric allows investigation into the impact of the different variable levels on the perception about his or her understanding of the problem. This metric required the individual to contrast the level of problem understanding while using his or her decision-making method with the level of problem understanding during similar design activities in the past.

Perception metric #5: This metric measures the level of conviction that the final decision is right. Data from this metric allows investigation into the impact of the different variable levels on the perception about his or her conviction or confidence that their team's top three decisions (those decisions that had significant impact on the design activity outcome) were right.

Perception metric #6: This metric measures the level of satisfaction with the final solution. Data from this metric allows investigation into the impact of the different variable levels on the perception of satisfaction with the top three design decisions, regardless of how right or wrong these decisions were.

Perception metric #7: This metric measures the capacity of team members to work together in reaching decisions. Data from this metric allows investigation into the impact of the different variable levels on the perception about how the decision making method impacted their ability to act as a team.

6.1.4 The Product Metrics

These metrics are restricted to evaluation of the technical merits of EDSS only by those teams that used it as their decision method. These teams completed an additional questionnaire with four questions. These metrics measured the impact of the experience level variable on the perception about how the EDSS product responded. These metrics are: response time, comparing EDSS to manual decision-making methods, ease of use of the EDSS program, and attitude change towards the use of computer products for decision support.

Product metric #1: This metric measures the level of response time of EDSS. This metric compares expectations to experiences when using EDSS, and the programs speed in returning responses to the screen.

Product metric #2: This metric measures the perception that the computer decision method was better than a manual decision method. This metric compares EDSS to manual methods.

Product metric #3: This metric measures the ease of use perception level. This metric measures the perception that "using EDSS was the easiest decision support method I have ever used."

Product metric #4: This metric measures the attitude change towards the task (use of a computer decision support tool) and towards computers as decision methods. This metric measures the perception that using EDSS "changed my attitude to one of always wanting to use a computer decision support system tool for future decisions."

6. 2 Design of Experiment

A balanced or factorial experiment was constructed to validate the hypothesis in the four metric categories discussed above. The experiment uses two variables and within each variable there are two levels. Additionally the experiment is replicated once. The two variables for the experiment are the use of a decision support method, and team members' experience level with mechanical problems similar to the one used in the experiment. With the first variable, which is the decision support method, there are two levels. They are teams that used EDSS for their decision support method, and teams did not use EDSS. The team that did not use EDSS was free to use any decision method, or none at all. The second variable, which is experience level with mechanical problems similar to the one used in the experiment, also has two levels. The two levels are groups that had high levels of previous experience solving similar problems to the one given, and groups that were unexperienced solving similar problems to the one given. This corresponds to variables that are typically found in this kind of factorial experiment (Box, 1978).

Two variables were identified from the Background Review material of Chapter 2 as factors that would influence the results of the research experiment. The variable of the decision support method, those that used EDSS and those that did not, as a variable is self evident. The other variable, mechanical design experience related to the experiment's problem, was shown in previous research to impact decision results (Fricke, 1993). This observation formed the basis for establishing experience level as the second experiment variable. The participants were questioned to determine their experience level (Appendix 1). Two separate groups were created for those with relatively high or low experience levels, with a sizeable experience gap between them. At the first end of the experience spectrum are those who had nearly no experience with mechanical devices similar to the design problem, and at the other extreme were those that had a great deal of experience with mechanical devices similar to the design problem. Those who might be considered as in between these two extremes were excluded from the replicated experiment. This middle group was tested and used to check metric values between the two extremes. The matrix in Table 7 shows the four primary groups, shaded, used for this experiment. These four groups were replicated for a total of eight teams. Replication allows statistical error analysis. Additionally, two teams that both had experience levels between the two extremes, labeled as medium experienced, were tested. One of the medium experienced teams used EDSS, and the other did not. These two additional teams provide additional comparative data that was used in data analysis (Chapter 8).

	Experience level - high	Experience level - medium	Experience level - nearly none
Used EDSS decision method	Two teams	One team	Two teams
Did not use EDSS decision method	Two teams	One team	Two teams

Table 7. Design of Experiment Variables

The participants were mostly university mechanical engineering students, with some students from other technical subject areas. Assignment into the teams was done using a random selection. From the Background Review material of Chapter 2, it was concluded that factors such as individual creativity, grade point average, and gender were not expected to influence the metric values and the research outcome.

Replication of the experiment was included to quantify the amount of random experiment error. High levels of random experimental error or levels that are above main and interaction effects would preclude any statistically supportable conclusions being drawn from the experiment.

The experimental environment was an engineering laboratory at the university. The effect of the environment was expected to be insignificant. No other influences except the two variables and their levels were expected to influence the outcome of this experiment.

6. 3 Interpretation of ANOVA Results

Three numerical values were used for interpretation of ANOVA results and were used as the basis for making conclusive statements that are statistically significant. The first value was the main effect. This number is the average of the difference in the responses measured when only this effect is varied. For example, for the main effect of EDSS, all the responses that used EDSS as their decision method (+ EDSS) and those that did not use EDSS (- EDSS) were averaged, then the difference between these two averages was reported as the main effect for EDSS. The research experiment conducted here is a factorial experiment represented by a square with the four corners holding response values. Main effects measure opposing edges. The second numerical value was the interaction effect. This calculation measured the average values of opposing corners of the square. It checked for the effects of combining opposite main effects. The final value was the standard error which can only be calculated when an experiment is replicated. This indicated the degree of random experimental error present in the data. Additionally, a measurement of conclusiveness was used and calculated at an 80% confidence factor. This measurement statistic indicates the threshold that must be exceeded if any of the effects that are to be reported will be considered as statistically significant. Any effects below this value indicate that there was no significant effect occurring as a result of changes in the variables.

The next chapter explains the research experiment that uses the above metrics for reporting results.

7. THE EXPERIMENT

To accomplish the objective of Chapter 1, this research used an experiment, combined with the metrics of Chapter 6, for reporting on the research hypothesis. This chapter explains the experiment and its testing of the hypothesis. The experiment involved a mechanical device and required evaluation of alternative-criterion pairs for decision-making activities and completion of the problem presented. The mechanical device used in this experiment was part of a larger mechanical design problem most recently used by Blessing (1994). The complete problem used by Blessing required the subjects to design an optical device, similar to a photo enlarger used in a dark room, that was attached to a wall. The problem had an extensive list of requirements, or constraints, and required extensive mechanical creativity. This research did not investigate areas such as creative alternative generation or descriptive aspects of the mechanical design process. It focused instead on decision making, so use of a portion of the complete problem that focuses on decision making was appropriate. The following sections explain the problem, data collection from the experiment, and some post-problem reflections.

7.1 Decision Making Problem Selection

The primary characteristic necessary for the problem used in this experiment was that it required the teams to use some method of decision making. This included evaluating alternatives within the problem *Decision Space* and using the problem criteria to select one of those alternatives as the best. Since the decision making that motivated this research is selection of a single alternative from among numerous candidates, the problem needed to allow for many alternatives, or possible solutions, to the problem. Criteria, the other part of the alternative-criterion pair, was also a key component in the problem selected.

The problem selected was mechanical because the subjects were expected to be selected primarily from students in the mechanical engineering program. This subject pool provided the variation in mechanical experience levels needed for the second experiment variable, experience level. The technical aspects of the problem were also minimized so that subjects could use information-processing techniques to locate alternatives for inclusion in the *Decision Space* based on prior knowledge and experiences. The swivel joint is a very common device found on many products such as photo tripods, human hip joints, and children's toys. Proposing solutions to the problem required no new technology, processes, or products beyond what is routinely encountered by technically trained people.

One additional problem selection criterion was the desire to add to the already existing knowledge level of an established experiment. It was expected that the research outcome could be compared to previous work and act as a data base for other studies, using the same problem most recently used by Blessing.

The classroom that served as the video laboratory contained an extensive library of catalogs and reference aids. This environment was expected to provide creative stimulation for generation of additional alternatives. Even if the subjects were unable to generate additional alternatives or criteria while in this environment, they could use the starter set, explained below, and use their decision method for evaluating the alternative-criterion pairs.

The starter sets of alternatives and criteria which were provided to each team would generate a minimum of nine alternative-criterion pairs that they could use with their decision methods. If the team so chose, no creative thinking or generation of new alternatives would be required. This condition provided that any team, no matter how lacking in innovative or creative ideas, could still engage in decision making and select an alternative as a solution to the problem. The research found, however, that all teams created at least one additional alternative.

All subjects were provided with a design packet (see Appendix 2). This packet contained twelve pages. The first page was the problem statement for "Design of the Swivel Joint of a Wall Mounted Mechanism," and the second page was the "Initial Starter Set" of criteria and statements about the alternatives. Figure 17 shows the assembly drawing. The remaining pages were drawings, with various views, of the three starter set of alternatives. The subjects were told that they could use or not use any of the starter set as they chose. Use of this starter set of alternatives and criteria gave all groups the ability to use decision-making methods without having to generate any new innovative ideas or extract other criteria.

The swivel joint problem statement gave seven criteria, which are listed below.

1. The swivel joint must be able to carry the weight of the optical device.
2. The swivel joint must be able to swivel from -15 to +15 degrees in the α direction.
3. The swivel joint must be able to swivel from 0 to +15 degrees in the β direction.
4. The swivel joint axis and the column axis must intersect at one point close to the lower base of the column.
5. The swivel joint should avoid any movement except the α and β directions.
6. The swivel joint should be manufactured as economically as possible.
7. Any manufacturing must use the equipment located in the Rogers Hall machine shop.

In accordance with the use of the syntax of Equation 1, six of the seven criteria stated above are in Boolean syntax. There was a possible eighth criterion that could be considered, "the point should be at a distance of 150mm from the wall," but this never became a design constraint and was never used as a criterion. The only criteria statement that is not Boolean is number six.

All teams were given the information packet and allowed sufficient time to understand the problem. They were then allowed to ask any questions of the research aides who were videotaping the activity. At no time were the teams deprived of information from the researchers. All efforts were made to provide the teams with information that allowed them to conduct their decision-making activities expediently.

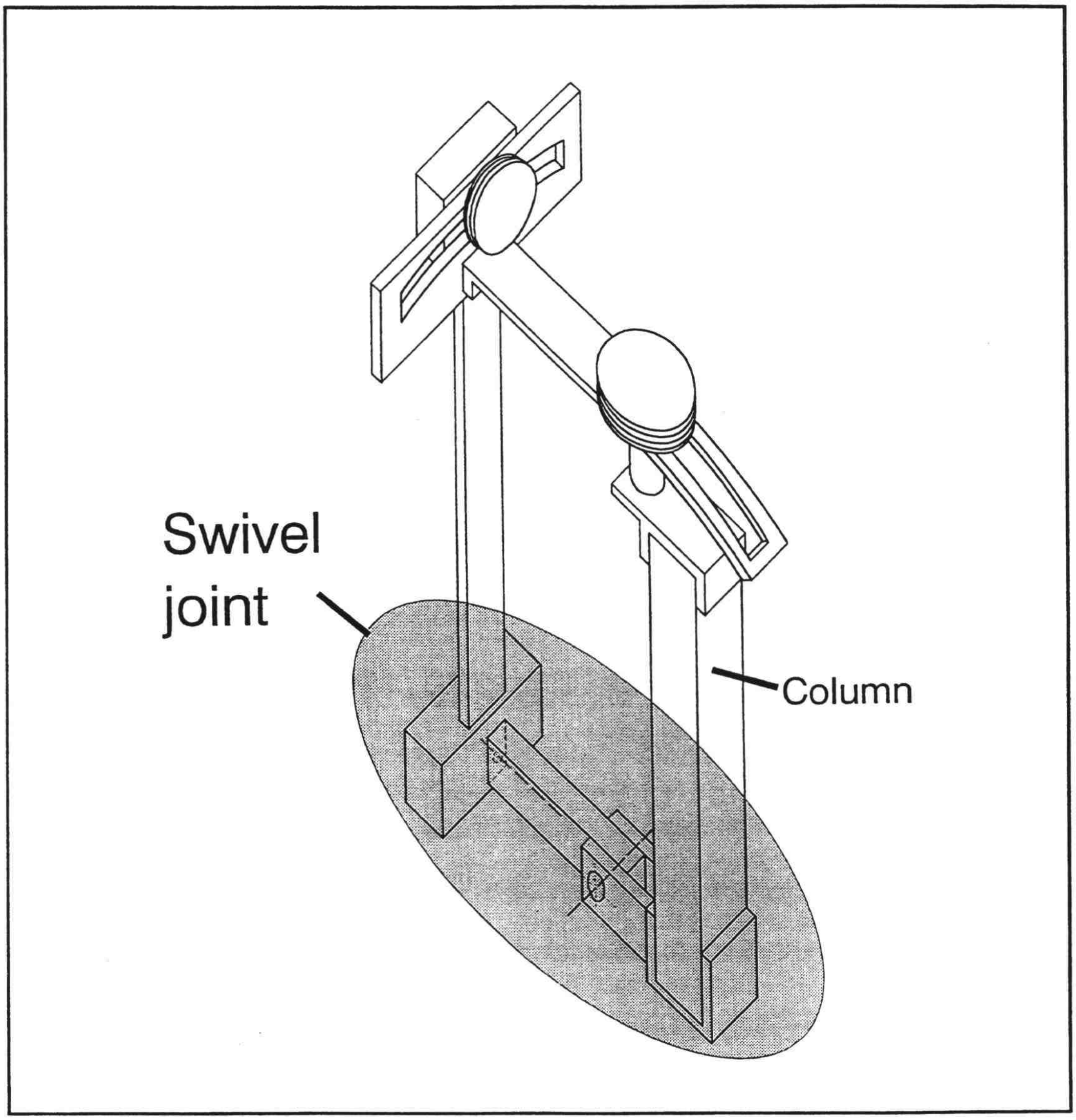

Figure 17. Experiment Swivel Joint Problem Assembly Drawing

7.2 Data Collection and Reduction

Collection of data came from four different sources. The data was collected from watching the video, from a questionnaire, from the paper tablet used by the groups for recording graphical information such as sketches of ideas and their final drawings, and for the teams using EDSS, from the EDSS data files.

Using the metrics of Chapter 6, details of data collection of each metric is explained below.

Productivity metric #1: The start time was marked when the first recognized alternative-criterion pair was discussed, indicating that an individual was using their knowledge level and confidence beliefs. The end time was recorded when the team concluded that they had selected the alternative that they believed to be the best possible.

Productivity metric #2: For this metric, each team's final alternative was judged and graded by various technically trained individuals. The judging consisted of assessing how well the final alternative met each of the seven customer requirements listed in the original problem statement, and assigning a score. Each customer requirement score ranged from five, for designs that fully met the customer requirements, to a score of one, for designs that did not meet the customer requirements at all. A minimum score of seven was possible, with a maximum of thirty-five.

Process metric #1: Each team was given a starter set of three alternatives. These were supplied to the teams so that the decision making activity could be studied even if the team did not create any new alternatives. For teams using EDSS as their decision method, the value for this metric was taken directly from the program. For teams using other decision methods, the value for this metric was taken from paper used to record their alternative ideas. In order to produce a valid entry for teams that did not use EDSS, team members were required to represent all alternatives so that other team members could deliberate over them.

Process metric #2: Each team was given a starter set of three criteria from the problem statements. These were supplied to the teams so that the decision-making activity could be studied even if the team did not recognize that there were more criteria listed in the problem statement. For teams using EDSS as their decision method, the value for this metric was taken directly from the program. For teams using other decision methods, the value for this metric was taken from paper used to record their list of criteria. For a valid entry for teams that did not use EDSS, it was required that the criteria be written out so that other team members could agree to its validity.

Process metric #3: For teams using EDSS as their decision method, the value for this metric was taken directly from the program. For teams using other decision methods, the value for this metric was taken from paper used to record evaluations or verbal discussions in which one person was speaking and the others recognized their list of criteria. For a valid entry for teams that did not use EDSS, it was required that the evaluation be written so that other team members could agree to its validity.

Process metric #4: The measurement of this metric was made by counting the number of additional pieces of information or data that were referenced. The video was reviewed and a tally of events was made for each team.

Process metric #5: A stop watch was used to time these activities from the video. For teams using EDSS, this timing activity was relatively easy since computer access could be readily seen on the video. For teams that did not use EDSS, determination of starting and stopping of an evaluation using an alternative-criterion pair was more demanding, but reasonable results were obtained. Teams that used a Pugh's decision matrix were easier to time than those that used an ad hoc decision method.

Perception metric #1: Questionnaire responses ranged from "unable to exercise control" to "able to exercise unlimited control."

Perception metric #2: Questionnaire responses ranged from "completely useless" to "completely useful."

Perception metric #3: Questionnaire responses ranged from "extremely difficult to use" to "extremely easy to use."

Perception metric #4: Questionnaire responses ranged from "having much less overall understanding of the problem" to "having much more overall understanding of the problem."

Perception metric #5: The questionnaire responses evaluated these decisions with responses ranging from "completely wrong" to "completely right."

Perception metric #6: The questionnaire responses ranged from "extremely dissatisfied" to "extremely satisfied" with the top three decisions.

Perception metric #7: The questionnaire responses ranged from "observed an extreme lack of team work" to "observed an extreme amount of team work."

Product metric #1: The questionnaire responses ranged from "extremely slow" to "extremely fast."

Product metric #2: The questionnaire responses ranged from "definitely worse than manual methods" to "definitely better than manual methods."

Product metric #3: The questionnaire responses ranged from "strongly disagree" to "strongly agreeing."

Product metric #4: The questionnaire responses ranged from "strongly disagree" to "strongly agreeing."

For data reduction, all sources of data were reviewed by no fewer than two people with engineering training. Any results with variations exceeding plus or minus 10%, or 10% of the least significant figure for the questionnaire metrics, were reviewed and reconciled.

7.3 Post Session Reflection

It appeared that the subjects were not bothered by the fact that this was an experiment and that they were being recorded with a video camera. They appeared to conduct their discussions and evaluations as if nothing was unusual. As described above, all teams added to the starter set of alternatives and criteria.

8. RESULTS OF THE EXPERIMENT

The results of the research experiment, using two variables at two levels in a replicated factorial experiment, are reported in this chapter. Data from the experiment was collected for the eighteen specific metrics introduced in Chapter 6. This chapter reports on each metric, examining the hypothesis that the use of EDSS shows improvements in, or positive impact on, the four metric categories: the decision-making productivity, the decision-making process, the decision-making perception, and the EDSS decision-making product. From the experiment, both main and interaction effects using statistical calculations are reported. For each metric there are two tables, one showing the data collected from the sources as explained in Chapter 7, and one showing the statistical results from the first table's data. Additionally, a graph shows the information from the second table.

For the experiment there were ten teams. For the first factorial experiment variable, these teams were divided into two divisions, those that used EDSS for their decision method, and those that did not. This variable is the first letter of a coding system. The teams that used EDSS have the code letter 'E' and the other teams have the letter 'O.' The next division is the second factorial experiment variable of experience. Those teams that had high levels of experience where given the letter 'H,' those with medium levels of experience the letter 'M,' and those with low levels the letter 'L.' A final number suffix was used that indicates the replication of the experiment. Those teams with the same group of letters were assigned numbers '1' and '2' to distinguish them. Table 8 below lists the ten teams in column one and the two experimental variables with their level in columns two and three.

Team	EDSS variable	Experience variable
EH1	used EDSS software	highly Experienced
EL1	used EDSS software	lacking Experience
EH2	used EDSS software	highly Experienced
EM	used EDSS software	medium Experience
EL2	used EDSS software	lacking Experience
OH1	did not used software	highly Experienced
OL1	did not used software	lacking Experience
OL2	did not used software	lacking Experience
OM	did not used software	medium Experience
OH2	did not used software	highly Experienced

Table 8. Experiment Team Groupings

Sample data for a metric is shown in Table 9, it has columns for: Team (specifies the team name), EDSS (specifies "Yes" for teams that used EDSS and "No" for teams that used any other decision making method), Experience level (high for highly experienced teams, medium, and low), Metric Value (this sample metric data is seconds), and Row average (average of the row team data values). The plus and minus in parentheses are standard factorial experimental notation and are included as Design of Experiment notation (Box, 1978). Teams are replicated; for example, EH1 and EH2 both used EDSS and were teams with high experience levels.

Team	EDSS used	Experience level	Metric Value	Row avg.
EH1 EH2	Yes (+)	High (+)	xxx xxx	xxx
....	....	....	....	....
OL1 OL2	No (-)	Low (-)	xxx xxx	xxx

Table 9. Sample Metric Raw Data Table

Figure 18 gives a graphical representation of how the data from a two variable and two level factorial experiment is numerically compared. In the figure the four circles contain values for the metric. The two axes are the two experiment variables and along each axis are the two levels that each variable can represent in the experiment. These levels are shown as plus and minus figures, which is the classical method of representing these conditions (Box, 1978). Data from Table 11 for the EH1 team, which used EDSS software and was a highly experienced team, would have metric data value inside the circle in the upper right hand corner of Figure 18. This circle is classically defined as a plus-plus (++) or high-high condition. These plus and minus terms are used in the formulas that follow.

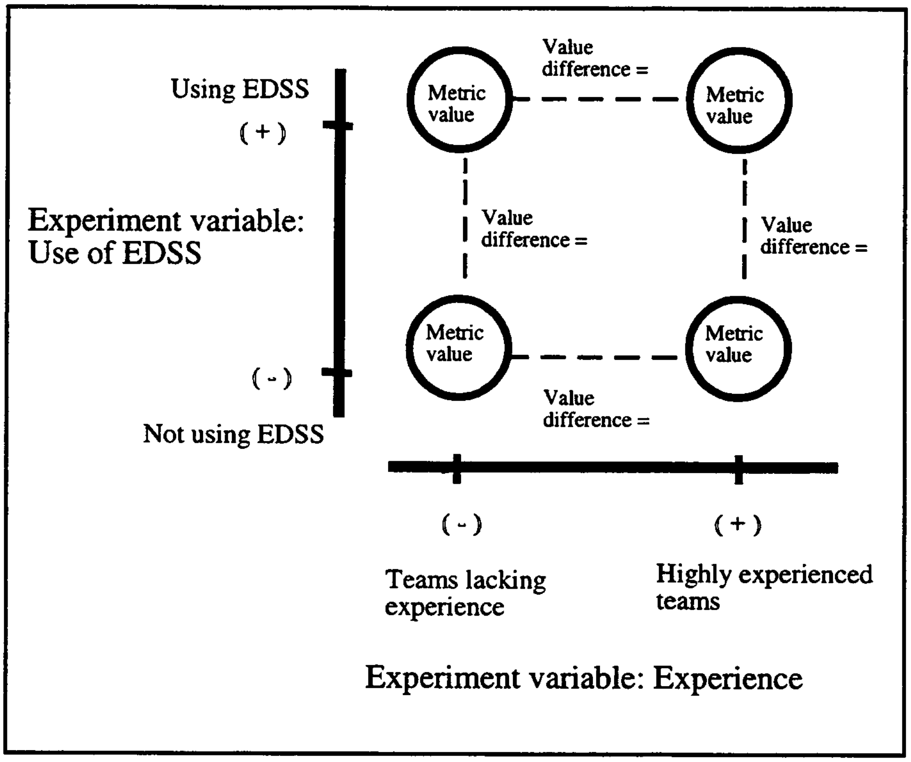

Figure 18. Factorial Experiment Metric Plot

The analysis of variance or statistical results reports a variable main effects of a factor. A variable main effect refers to the change in a yield or output value when the variable changes from a plus condition to a minus condition. For example, using Figure 18, the variable main effect is the change for a metric going from a team that used EDSS (the plus condition) to a team that did not use EDSS (minus condition). The other statistical result reported, the interaction effect, indicate if there is any interaction between the two variable main effect variables on either the yield or output value. The specific formulas are given below.

The main effect (Equation 9) is the difference between two averages. The averages for the variable at the plus or high condition and the average for the variable at the minus or low condition (Box, 1978). Using the variable of decision method, the plus or high condition corresponds to teams using EDSS, and the minus or low condition corresponds to teams not using EDSS.

$$\text{Main effect} = \overline{y_+} - \overline{y_-}$$

Equation 9. Main Effect

The interaction effect, calculated according to Equation 10, is the difference between two averages, the average for the variables that all have the same sign and the average for the variables that have different signs (Box , 1978). Those variables that have the same sign are teams that used EDSS and had high levels of experience and teams without EDSS and low levels of experience. Those variables that have opposing signs are teams that used EDSS and had low levels of experience, and those that did not use EDSS and had high levels of experience. In Figure 18 the interaction effect is the calculation of the corner averages.

$$\text{Interaction effect} = \overline{y_{\text{variable with same sign}}} - \overline{y_{\text{variable with different sign}}}$$

Equation 10. Interaction Effect

These results maybe interpreted to mean that if there is a large variable main effect and a very small interaction effect, the variable main effect acts independently of any other contributing effects, while if there is a large interaction effect then no conclusive statements about the independence of variable main effect can be made.

The standard error for an effect for this problem and replications is calculated according to Equation 11. This calculation provides an error check for the effect between replicated tests with N the population of data. The difference of duplicates is the difference in values between replications for the same set of variable conditions. A low standard error indicates that the values for each replication have been consistently reproduced, while a large standard error indicates that variations in the results are attributable to factors other than the variables.

$$Standard_{e} = \frac{(\sum(difference\ of\ duplicate)^2)^{1/2}}{N}$$

Equation 11. Standard Error for Effect with Replicated Data for this Problem

The standard error for variance about the mean for this problem and replications is given in Equation 12. This calculation provides an error check for the average values.

$$Standard_{e} = \frac{(\sum(difference\ of\ duplicate)^2)^{1/2}}{2N}$$

Equation 12. Standard Error for Variance About the Mean for this Problem

A minimum significant factor calculation using an 80% confidence factor is shown as Equation 13. This calculation gives a value used for comparison with the variable main effects values. If the variable main effects value is larger than the value from Equation 13, then it can be statistically stated, with an 80% confidence level, that the effect is significant. An 80% confidence factor was chosen as reasonable based on the accuracy of the data and the level of confidence which would be accepted by other researchers. There are no known guidelines for selection of a confidence factor for these statistical calculations. The value rho, ρ, for the four degree of freedom experiment, d.f., at 80% confidence, is 1.53. By contrast rho for 90% and 70 % respectively is 2.13 and 1.19 (Wolf, 1994). For this specific problem, the value .707 accounts for the replicated runs and the number of positive signs in the data column. The standard pooled variance is found in any standard statistics text (Box, 1978).

$$MSF_{80\%} = \rho_{4\ d.f.} * (standard\ pooled\ variance)^{.5} * .707$$

Equation 13. Minimum Significant Factor at 80% Confidence Level

Table 10 shows a sample of how the statistical data for the metric is listed. The first column gives the source of the raw data appearing in the second or Value column, and the third column gives the statistical error for the data in the Value column.

Data groupings (excluding EM&OM)	Value	Error
EH1,2,3,5 average	xxxx	+/- xxx
....	....	....
OH1,2,3,5 average	xxxx	+/- xxx

Table 10. Sample Statistical Data Results Table

Another method of displaying the data given in the sample Table 9 is a graph as shown in Figure 19, which represents data from Table 10. The experiment decision method variable is shown on the abscissa, "Variable Without EDSS/With EDSS." The metric data units, seconds in this example, are the ordinate axis. The other experiment variable, experience level, is shown in the legend on the far right side of the figure, "Experience levels from high to low." Figure 19 indicates, for example, that the teams that were highly experienced and used EDSS required more time to reach a decision than the other highly experienced teams that did not have the use of EDSS for their decision support method. Section 8.1.1 discuss the results in detail.

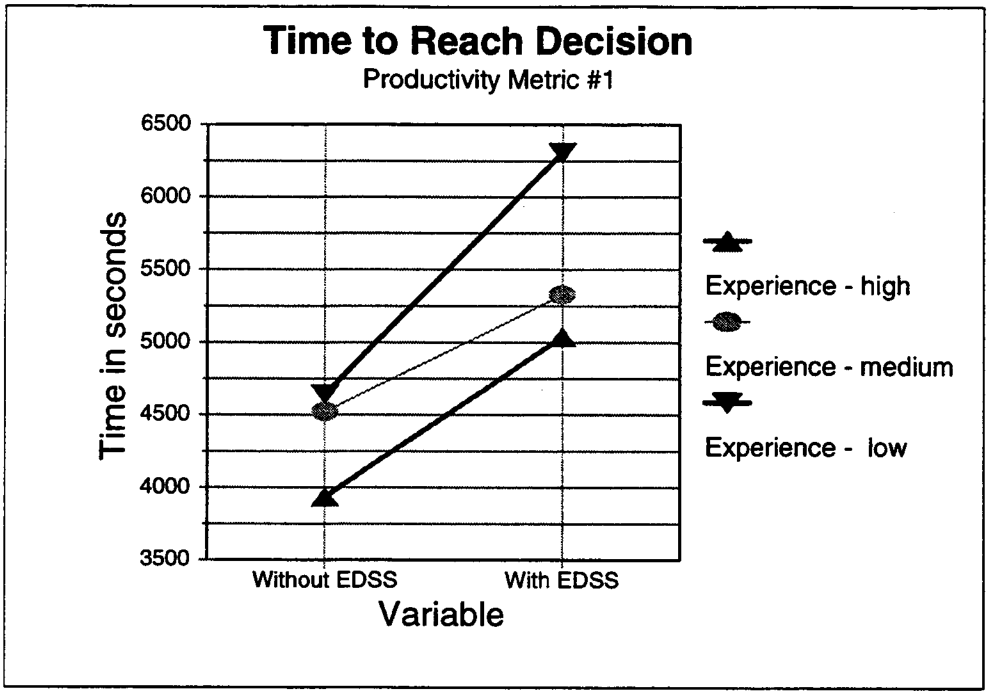

Figure 19. Graphical Display of Metric Data Example (see Table 10 of Data)

The remainder of this chapter reports on the experiment results for the four metrics, productivity, process, perception, and product. Within each section is an introduction, two tables which contain the data and the statistical results, a graphical figure displaying the data from the first table, several paragraphs giving an overview on; EDSS variable main effects, Experience variable main effects, interaction effects, and concluding comments.

8.1 Productivity Metric Results

Two metrics evaluate the productivity of decision making during design activities. The two productivity metrics are the time required to reach a final decision (measured in units of time), and quality (as measured by points) of the final alternative selected by the team at the conclusion of their decision making activity. Results from the experiment for each of these metrics are explained in detail below, beginning with the first productivity metric.

8.1.1 Productivity Metric #1

Data from the experiment is shown in Table 11. These values specify the total time used by the teams to reach their final decision, or final selection of the alternative that was their solution to the problem. Statistical results are shown in Table 12 and Figure 20.

Team	used EDSS	Experience level	Metric Value	Row avg.
EH1 EH2	Yes (+)	High (+)	3410 6660	5040
EL1 EL2	Yes (+)	Low (-)	3640 8970	6310
EM	Yes (+)	Medium	5330	
OH1 OH2	No (-)	High (+)	2770 5100	3940
OL1 OL2	No (-)	Low (-)	5210 4070	4640
OM	No (-)	Medium	4520	

Table 11. Metric: Time to Reach Decision - Raw Data (units are seconds)

Data groupings (excluding EM&OM)	Value	Error
EH1,2,3,5 average	5670	+/- 423
OH1,2,3,5 average	4290	+/- 423
EH1,2,3,5 & OH1,2,3,5 average	4980	+/- 423
Variable main effect for + EDSS	1390	+/- 846
Variable main effect for + Experience	-986	+/- 846
Interaction EDSS/Experience effect	283	+/- 846
Minimum Significant Factor at 80% confidence	2590	N/A

Table 12. Statistical Results for Metric of Time to Reach Decision (units are seconds)

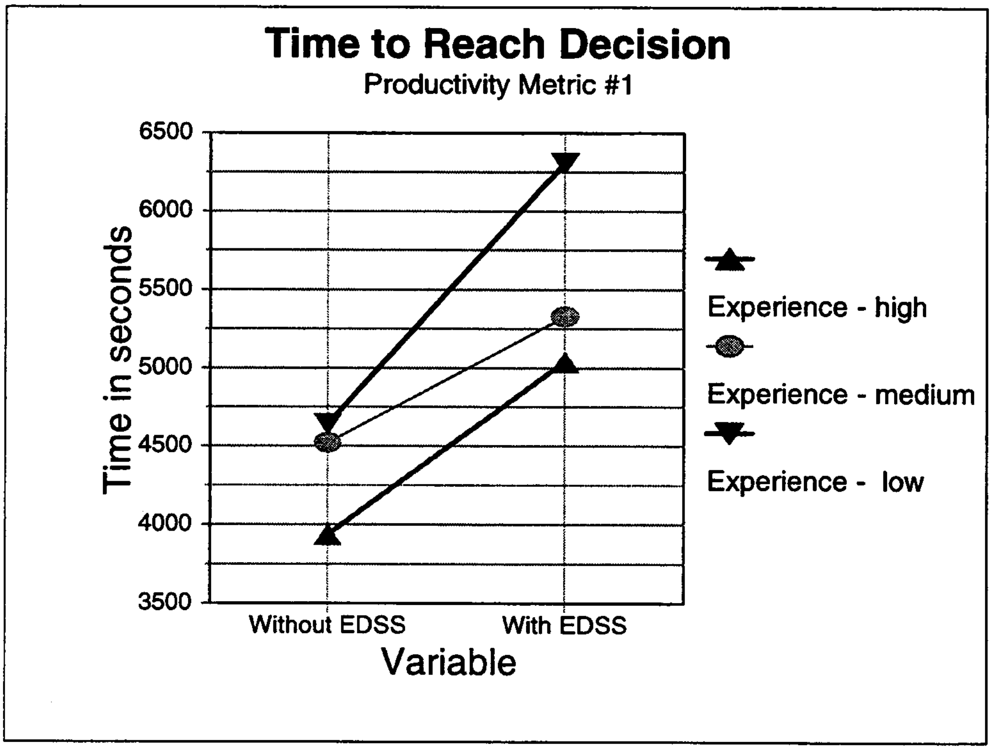

Figure 20. Graphical Display of Productivity Metric - Time to Reach Decision

Overview: The data for this metric does not support any statistically significant conclusions for either of the two variable main effects, using EDSS or having high levels of experience. For this metric the hypothesis is not supported. It can also be stated, based on statistical results, that there are no combined interaction effects between these variables.

EDSS variable main effect: Those teams that used EDSS took an average of 1390 seconds more time to select a final alternative than teams without EDSS. No statistically significant conclusions can be stated about this fact because the 80% confidence level Minimum Significant Factor of 2590 seconds (last row of Table 12) is larger that the variable main effect value of 1390 seconds. It can be stated that the variable main effect is larger than the standard error of 846 seconds (rows 5/6/7 of Table 12).

Experience variable main effect: Those teams that had higher experience levels took, on the average, 986 seconds less time than teams with lower experience. No statistically significant conclusions can be stated about this fact because the 80% confidence level Minimum Significant Factor of 2590 seconds is larger that this variable main effect value of 986 seconds. It can be stated that the variable main effect is larger than the standard error of 845 seconds.

Interaction effect: With an interaction effect of 283 seconds (row 7 of Table 12) it can be stated that there are no statistically important interaction effects between EDSS and experience levels. This fact can be seen in Figure 20 as the high and low experience lines are approximately parallel indicating nearly no interaction between variables.

Concluding statements: From an average of the replicated data, the least time taken to select a final alternative for this problem was from teams OH1/2 which both averaged 3940 seconds (row 5 of Table 11). Interestingly, these two teams could be described as nearly opposites in their application of design methodology. Team OH1 used very ad-hoc decision making methods and OH2 used a very structured method.

Without regard to statistics, two immediate conclusions can be drawn from these results. First, as expected, those with more experience took less time to solve the problem as exhibited by the "Experience - high" line being below the "Experience - low." As would be conjectured, a set of teams with a medium level of experience, EM and OM, produced metric data between the teams representing high and low experience levels. Secondly, the data shows that with the same experience level, those who used EDSS took more time. Disappointingly Figure 20 has a positive slope. This is contrary to what would have been desired, i.e. that the use of EDSS would have reduced the time required to perform the task.

A possible explanation for these results is that the computer tool caused additional cognitive effort and thus increased the time required. Whether or not the additional time produced better results and whether or not the time would be reduced after more extensive use of EDSS needs to be tested. Since using a computer decision support tool such as EDSS evidently requires more time to reach a final decision, the burden of justifying the extra expenditure of time falls on other metrics. For example, another metric that could possibly justify this additional time is total project time, if a project required use of previous data that would be available from EDSS, but not available from ad hoc decision sessions.

The only conclusive statement that can be made about the statistical results for this metric is that there is no interaction between the two variables of EDSS and experience. Each of these variables acts independently of the other in influencing the time it takes to reach a decision.

8.1.2 Productivity Metric #2:

Data from the experiment is shown in Table 13. These values specify the quality rating of final alternative selected. Statistical results are shown in Table 14 and Figure 21.

Team	used EDSS	Experience level	Metric Value	Row avg.
EH1 EH2	Yes (+)	High (+)	29.7 34.0	31.8
EL1 EL2	Yes (+)	Low (-)	27.3 25.3	26.3
EM	Yes (+)	Medium	24.3	
OH1 OH2	No (-)	High (+)	32.0 32.3	32.2
OL1 OL2	No (-)	Low (-)	18.7 33.0	25.8
OM	No (-)	Medium	30.0	

Table 13. Metric: Quality of Decision - Raw Data (units are points)

Data groupings (excluding EM&OM)	Value	Error
EH1,2,3,5 average	29.1	+/- .9
OH1,2,3,5 average	29.0	+/- .9
EH1,2,3,5 & OH1,2,3,5 average	29.0	+/- .9
Variable main effect for + EDSS	.1	+/- 1.9
Variable main effect for + Experience	5.9	+/- 1.9
Interaction EDSS/Experience effect	.4	+/- 1.9
Minimum Significant Factor at 80% confidence	5.8	N/A

Table 14. Statistical Results for Metric of Quality of Decision (units are points)

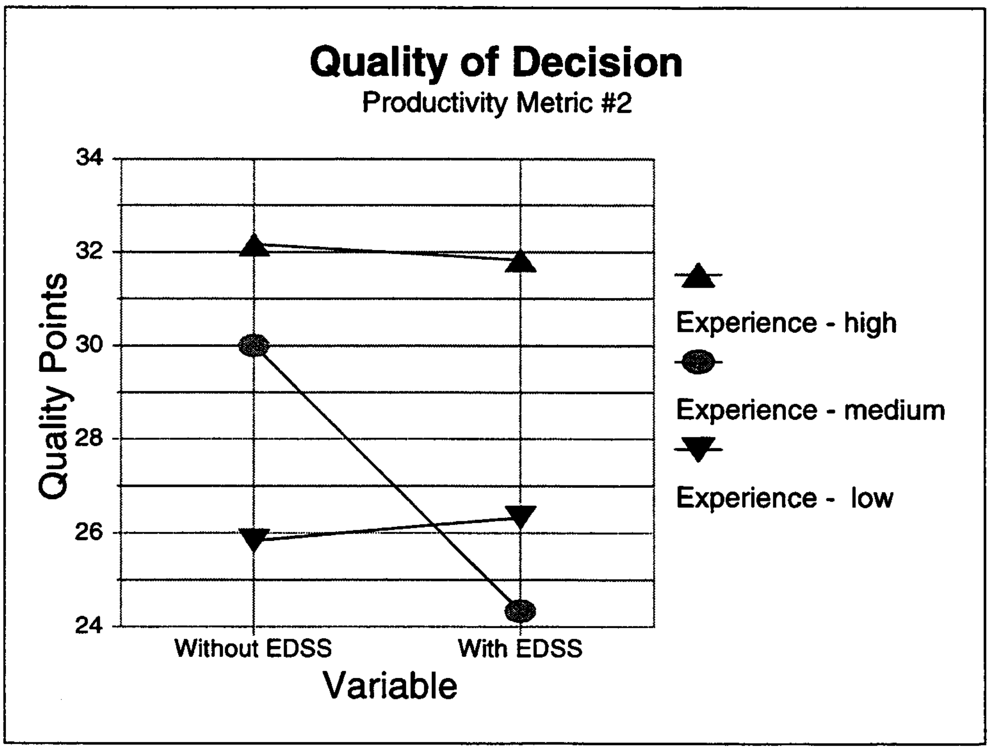

Figure 21. Graphical Display of Productivity Metric - Quality of Decision

Overview: The data supports three statistically significant conclusions. First, high levels of experience have a positive impact on the quality of the alternative selected. Secondly, there is no interaction effect between the two variables on the quality of the alternative selected. Without regard to statistics, there is no difference, for the same experience level, in the quality level of the final alternative selected for teams that did not use EDSS and those teams that did use EDSS. Lastly, the decision method used had no affect on the quality of the alternative selected.

EDSS variable main effect: Those teams that used EDSS had a higher quality design by an average of 0.1 points. No statistically significant conclusion can be stated about this fact because both the standard error, 1.9, and the Minimum Significant Factor at 80% confidence level, 5.8, are larger than the effect value of 0.1 points. It can be statistically concluded, stated in the negative, that any decision method produces the same quality of final alternative selected. This is shown by the difference in the teams that used EDSS and those that did not use EDSS average values and the horizontal slopes of each of the two experience level lines going from a condition of without EDSS to with EDSS.

Experience variable main effect: Those teams that had a higher experience level had a higher quality design by an average of 5.9 points. This is statistically significant because it exceeds both the standard error for effects, 1.9, and the Minimum Significant Factor at 80% confidence level, 5.8.

Interaction effect: There is no interaction effect, as can be seen by Figure 21, because the two experience lines are nearly parallel. The interaction effect is 0.4 points. This is statistically insignificant because it is far less than the standard error.

Concluding statements: It is disappointing that the variable main effect of using EDSS did not produce a higher quality final design artifact. It can be concluded based on this data that having a computer decision support tool with the capabilities of EDSS produces no improvement and no positive impact on the quality of the final decision.

Without regard to statistics it is to be expected that an experienced team would produce a higher quality design than an inexperienced team and this proved to be true both for teams using EDSS and for those using another decision method.

It is noteworthy that the OM team, experience level medium, produced a design with a quality between that of teams with high and low experience levels. Unfortunately the equivalent EM produced a far lower quality design than the low experienced teams using EDSS, EL1/5, as seen in Figure 21.

Table 15 shows a listing of the four teams that used EDSS and their top three designs listed as 1st/2nd/3rd. The EDSS output result of Satisfaction Value, SatVal, is listed as well as the experience level of the team. This table shows that the Satisfaction Values of the three best alternatives are really close to each other in numerical value. This indicates either that the alternatives are truly nearly equal or that these teams did not search for strong aspects of each alternative that would differentiate it from the other choices.

	EL1 (low Experience level)	Satis-faction Value	EL2 (low Experience level)	Satis-faction Value	EH1 (high Experience level)	Satis-faction Value	EH2 (high Experience level)	Satis-faction Value
1st	Ball & socket	.56	Beam - design #3-2	.78	Pin and cup	.72	Dwg 8&9	.70
2nd	Dwg 8&9	.50	Modificat-ion of design #3-2	.78	Ball & socket	.70	Modificat-ion of Dwg 8&9	.69
3rd	Dwg 6&7	.43	Modificat-ion of design #3-2	.77	Dwg 6&7	.56	Eye bolt and rubber insert	.68

Table 15. Top Three Designs for the Four Teams that used EDSS

Defining this problem as a simple problem where nearly any solution works, leads to a conclusion that the use of a structured decision process or method like EDSS does not yield an increased quality of results. The difference in the quality of results between a simple problem and a complex problem should be tested.

8.2 Process Metric Results

Five metrics measure the decision-making process during the design activities. The metrics are: number of alternatives created, number of criteria created, number of analyses stored on any medium, amount of data used during the decision making activity, and time spent on the evaluation phase. Results from the experiment for each of these metrics is explained in detail below, beginning with the first process metric.

8.2.1 Process Metric #1:

This first process metric records the number of alternatives created. Data from the experiment is shown in Table 16. Statistical results are shown in Table 17 and Figure 22. This metric only records the number of alternatives that the team created in excess of the three provided in the starter set of alternatives given in the problem

Team	EDSS used	Experience level	Metric Value	Row avg.
EH1 EH2	Yes (+)	High (+)	3 3	3
EL1 EL2	Yes (+)	Low (-)	1 4	2.5
EM	Yes (+)	Medium	5	
OH1 OH2	No (-)	High (+)	3 9	6
OL1 OL2	No (-)	Low (-)	4 5	4.5
OM	No (-)	Medium	4	

Table 16. Metric: Number of Alternatives Created - Raw Data (units are count)

Data groupings (excluding EM&OM)	Value	Error
EH1,2,3,5 average	2.8	+/- 0.4
OH1,2,3,5 average	5.3	+/- 0.4
EH1,2,3,5 & OH1,2,3,5 average	4.0	+/- 0.4
Variable main effect for + EDSS	-2.5	+/- 0.9
Variable main effect for + Experience	1.0	+/- 0.9
Interaction EDSS/Experience effect	0.5	+/- 0.9
Minimum Significant Factor at 80% confidence	2.6	N/A

Table 17. Statistical Results for Metric of Number of Alternatives Created (units are count)

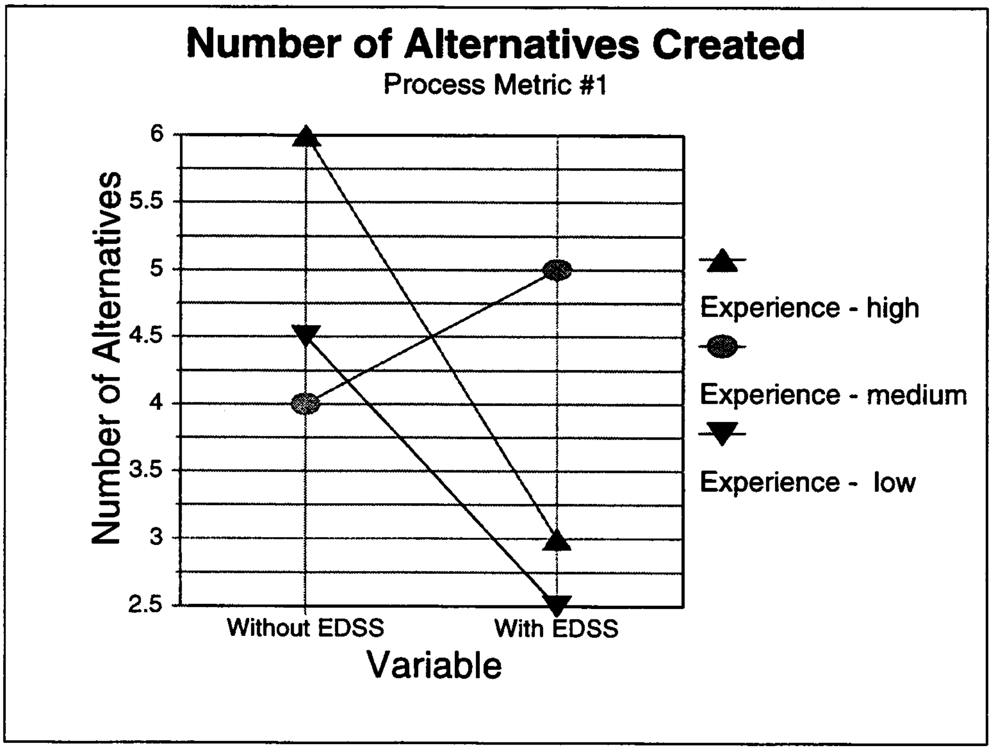

Figure 22. Graphical Display of Process Metric - Number of Alternatives Created

Overview: The data do not support any statistically significant conclusions that can be stated for either of the two variable main effects, using EDSS or having high levels of experience. It can be stated based on statistical results that there are no combined interaction effects between these variables.

EDSS variable main effect: Those teams that used EDSS produced an average of 2.5 fewer alternatives than teams that did not use EDSS. This value is above the standard error, 0.9, but is just below the Minimum Significant Factor (MSF) at 80% confidence level, at a value of 2.6.

Experience variable main effect: Those teams with high levels of experience created on the average 1.0 more alternatives than those with low levels of experience. No statistically significant conclusion can be stated about this fact because this value is below the MSF.

Interaction effect: With an interaction effect of 0.5 it can be stated that there are no statistically important interaction effects between EDSS and experience levels. This can be seen in Figure 22, in which the high and low experience lines are approximately parallel.

Conclusions: The desired graphical representation of this data would have been a positive slope indicating that more alternatives would have been generated when teams used EDSS as their decision method. Interestingly, the two data points for the medium experienced teams do have a positive slope. In the replicated experiment, fewer alternatives (2.5) were created by teams that used EDSS. The reason for this performance can only be speculated. One speculation is that teams using EDSS were lulled into a less aggressive search for alternatives because of the computer support provided by EDSS. A review of other metrics such as conviction of decision, satisfaction of decision, understanding of problem, quality of decision, and raw Satisfaction Value for final alternative selection reveals nothing which appears to offer an explanation for this interaction effect. The correlations are mixed, as seen on Figure 22. The extreme performance of team OH2, which had more than double the number of alternatives of any other team, may be explained by the fact that each member was a highly experienced engineer who had designed many products that were similar to that in the given problem. This position is supported by statistical data from the set of teams, EM...OH2, for the number of alternatives created by teams with high experience. This was five times more than the EH1...OL1 teams for the same variable. The results for all teams with high experience levels showed that they created an average of 1.0 more alternatives than the teams with low experience levels, and this was consistent with the common sense expectation that a more experienced team would generate more alternatives. If one excludes the single team of OH2, which has the extreme value for this metric compared with all other teams, one can conclude with statistical significance from this experiment only that neither variable level of a computer decision support system nor high or low levels of experience, contributes to creating more alternatives for a problem solution. An additional conclusion that can be drawn from this experimental data is that the number of alternatives created for a design problem is a function of some other variable, rather than of decision methodology or experience levels. These results lend support to the commonly held belief that generation of solutions to a problem is related to concepts of general creativity.

Disappointingly, Figure 22 shows a complete reversal of what this researcher would have expected for those teams with high levels of experience using EDSS. The expectation would be that these teams would have generated more alternatives, which would have demonstrated improvements in and positive impact on the process .

8.2.2 Process Metric #2:

This second process metric records the number of criteria created. Data from the experiment is shown in Table 18. Statistical results are shown in Table 19 and Figure 23. This metric only records the number of criteria that the team created in addition to the three provided in the starter set given in the experiment problem statement.

Team	EDSS used	Experience level	Metric Value	Row avg.
EH1 EH2	Yes (+)	High (+)	2 4	3
EL1 EL2	Yes (+)	Low (-)	2 7	4.5
EM	Yes (+)	Medium	4	
OH1 OH2	No (-)	High (+)	0 8	4
OL1 OL2	No (-)	Low (-)	5 4	4.5
OM	No (-)	Medium	2	

Table 18. Metric: Number of Criteria Generated - Raw Data (units are count)

Data groupings (excluding EM&OM)	Value	Error
EH1,2,3,5 average	3.8	+/- .6
OH1,2,3,5 average	4.3	+/- .6
EH1,2,3,5 & OH1,2,3,5 average	4.	+/- .6
Variable main effect for + EDSS	-.5	+/- 1.2
Variable main effect for + Experience	-1.	+/- 1.2
Interaction EDSS/Experience effect	.5	+/- 1.2
Minimum Significant Factor at 80% confidence	3.7	N/A

Table 19. Statistical Results for Metric of Number of Criteria Listed (units are count)

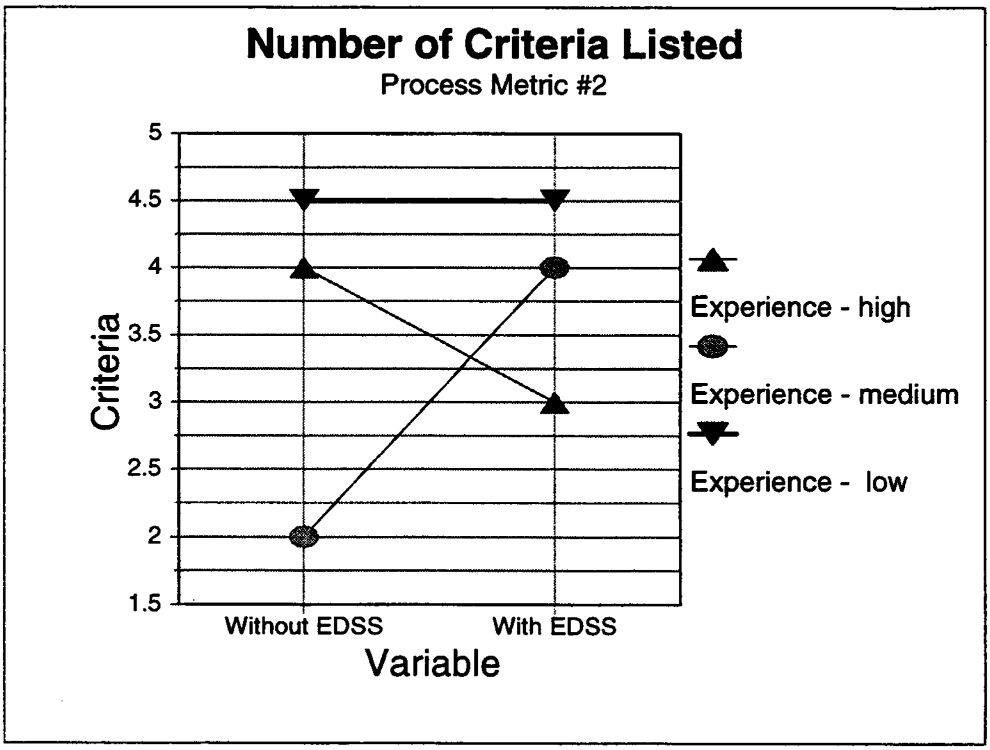

Figure 23. Graphical Display of Process Metric - Number of Criteria Listed

Overview: The data does not support any statistically significant conclusion about the variable main effect of EDSS or levels of experience. It can be stated with statistical significance that there is no interaction effect between the use of EDSS and experience levels. Without regard to statistics it is noteworthy that the less experienced teams produced more criteria than the experienced teams.

EDSS variable main effect: Those teams using EDSS listed an average of .5 fewer criteria than those teams not using EDSS. The variable main effect value for + EDSS was -.5. No statistically significant conclusions can be stated about this fact because the variable main effect value is less than both the standard error (1.2) and the MSF (3.7).

Experience variable main effect: Those teams that had a high level of experience produced on the average 1.0 fewer criteria than those with low levels of experience. No statistically significant conclusions can be stated about this fact because the variable main effect value is less than both the standard error (1.2) and the MSF (3.7).

Interaction effect: With an interaction effect value at .5 it can be stated that there is no statistically important interaction between EDSS and experience levels. This fact can be seen in Figure 23 as the two experience lines do not cross.

Concluding statements: From this experiment and its data it can be concluded that the number of additional criteria specified in addition to the three provided in the starter set is not a function of the decision analysis method or tool, or of the experience level. It was disappointing to see both the fact that those teams with less experience actually specified more criteria than those with high levels of experience, and that EDSS did not stimulate teams to search for and record more criteria. It can be seen that two teams, EL2 and OH2, specified a larger than average number of criteria. Had both of these teams recorded values closer to the mean all of the threshold statistics would have been drastically reduced. Cross referencing this metric with the problem understanding metric produced no further understanding into the performance of these teams in regards to this metric.

8.2.3 Process Metric #3:

Data from the experiment for the metric of number of alternative-criterion pair evaluations specified is shown in Table 20. Statistical results are shown in Table 21 and Figure 24.

Team	EDSS used	Experience level	Metric Value	Row avg.
EH1 EH2	Yes (+)	High (+)	47 72	60
EL1 EL2	Yes (+)	Low (-)	41 80	60
EM	Yes (+)	Medium	50	
OH1 OH2	No (-)	High (+)	0 59	30
OL1 OL2	No (-)	Low (-)	39 0	19
OM	No (-)	Medium	0	

Table 20. Metric: Number of Alternative-Criterion pairs Evaluated - Raw Data (units counts)

Data groupings (excluding EM&OM)	Value	Error
EH1,2,3,5 average	60	+/- 5.4
OH1,2,3,5 average	24	+/- 5.4
EH1,2,3,5 & OH1,2,3,5 average	42	+/- 5.4
Variable main effect for + EDSS	35	+/- 11
Variable main effect for + Experience	4.7	+/- 11
Interaction EDSS/Experience effect	5.5	+/- 11
Minimum Significant Factor at 80% confidence	32	N/A

Table 21. Statistical Results for Metric of Number of Alternative-Criterion pairs Evaluated (units are counts)

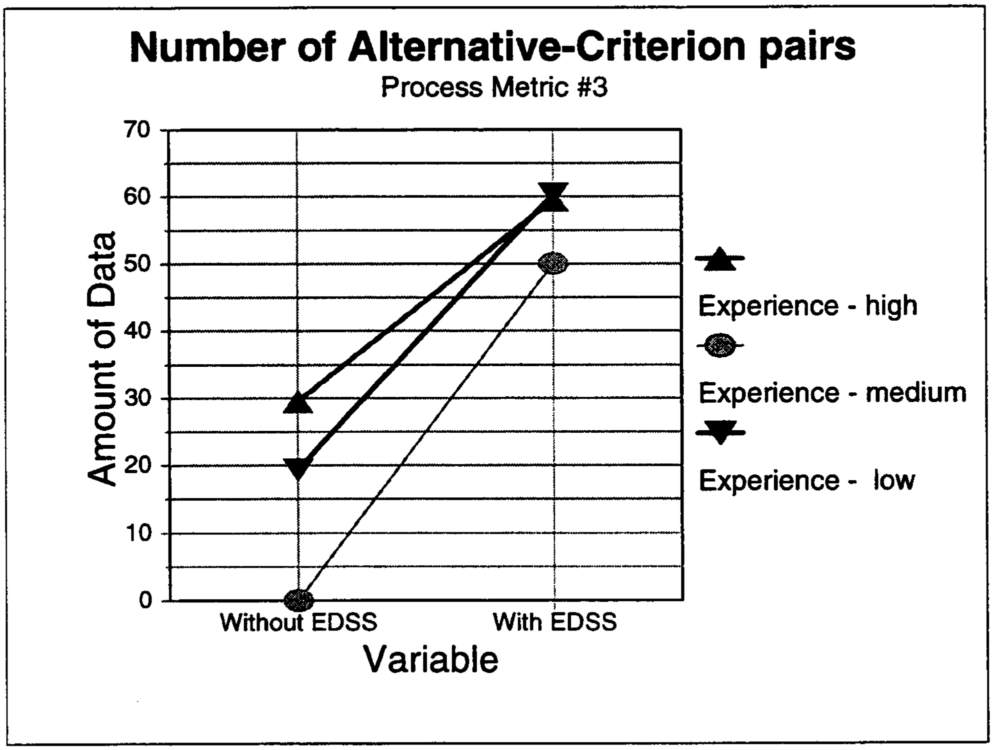

Figure 24. Graphical Display of Process Metric - Number of Alternative-Criterion pairs Evaluated

Overview: The data supports a statistically significant variable main effect with the use of EDSS. The data also supports that there is essentially no effect for an increased level of experience and no interaction between these variables.

EDSS variable main effect: Those teams that used EDSS conducted 36 more alternative-criterion pair evaluations compared with those teams that did not use EDSS. This is statistically significant because it is greatly in excess of both the standard error (11) and the MSF (32).

Experience variable main effect: It can be conclusively stated that there is no variable main effect for teams that had higher experience levels compared with those teams that had low levels of experience. The variable main effect value for experience was only 4.7.

Interaction effect: With an interaction effect of 5.5 and both the standard error and MSF stated above it can be stated with statistical significance that there is no interaction effect. This effect can be seen in Figure 24.

Concluding statements: Figure 24 of this metrics data produced results consistent with the researcher's expectations. Teams with high levels of experience produced more alternative-criterion pair evaluations. The data indicate that EDSS produced statistically significant results, supporting the hypothesis by demonstrating improvement in, and positive impact on, the area of this process metric. Use of EDSS did produce statistically significant results.

Comparison of this metric with data from productivity Metric #2, Quality of the final solution, did not yield any correlation. In other words, those teams that are recorded as having used a larger amount of data, as evidenced by evaluation of more alternative-criterion pairs, did not produce a better quality design.

8.2.4 Process Metric #4

Data from the experiment for - the amount of data used metric, is shown in Table 22. Statistical results are shown in Table 23 and Figure 25.

Team	EDSS used	Experience level	Metric Value	Row avg.
EH1 EH2	Yes (+)	High (+)	4 8	6
EL1 EL2	Yes (+)	Low (-)	0 59	30
EM	Yes (+)	Medium	4	
OH1 OH2	No (-)	High (+)	0 14	7
OL1 OL2	No (-)	Low (-)	6 51	29
OM	No (-)	Medium	23	

Table 22. Metric: Amount of Data Used - Raw Data (units are count)

Data groupings (excluding EM&OM)	Value	Error
EH1,2,3,5 average	18	+/- 5
OH1,2,3,5 average	18	+/- 5
EH1,2,3,5 & OH1,2,3,5 average	18	+/- 5
Variable main effect for + EDSS	0	+/- 10
Variable main effect for + Experience	-23	+/- 10
Interaction EDSS/Experience effect	1	+/- 10
Minimum Significant Factor at 80% confidence	29	N/A

Table 23. Statistical Results for Metric of Amount of Data Used (units are counts)

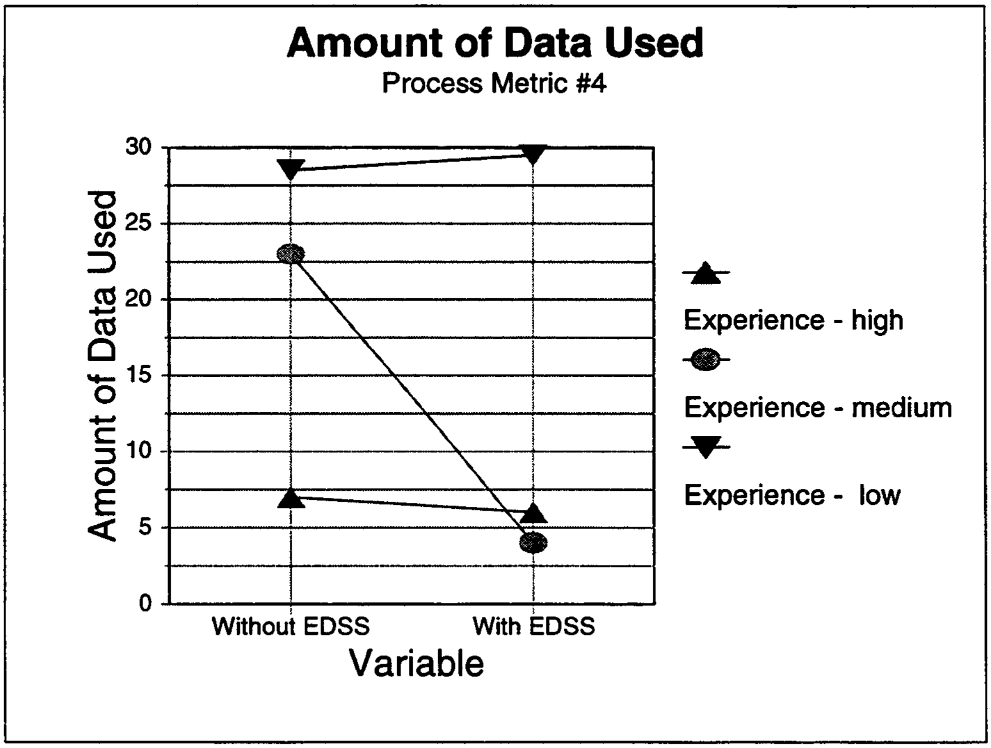

Figure 25. Graphical Display of Process Metric - Amount of Data Used

Overview: Statistical results indicate that there is no variable main effect for teams using EDSS, nor is there any interaction between the two variables. It can be statistically concluded that there is no variable main effect for experience level as it is below the MSF. The data also indicates that there is nearly no difference between teams that used EDSS and those that did not for the same experience level.

EDSS variable main effect: There is not a statistically significant effect for using EDSS contrasted with not using EDSS. The variable main effect for those using EDSS was on the average 0.0 pieces of additional data.

Experience variable main effect: Those teams that had lower levels of experience accessed an average of 23 more sources of data than those with high levels of experience. No statistically significant conclusions can be stated about this fact because this effect value is below the MSF value at 80% confidence factor at 29.

Interaction effect: It can be statistically stated that there is no interaction effect between these variables. The effect is 1 which is far below both the standard error and the MSF value.

Concluding statements: Teams with low levels of experience would be expected to consult more outside data sources, and the data confirms this. It could be argued that this metric might be considered an indicator of creative or brainstorming activity but on the other hand, it could also be considered as a tool to verify the decision reached or a means of equalizing experience levels. Unfortunately, it is not certain which of these this metric may address, nor is it clear how a researcher could quantify the difference. This has to remain an unanswered question. It can be stated that teams do not rely significantly less on outside information when using a computer decision support tool such as EDSS. Since the quality of decision metric data does not support any statistically supportable conclusions these two metrics cannot be combined to yield any support for the hypothesis.

Two teams, OL2 and EL2, had large numbers for this metric. Cross referencing the quality of the decision, productivity metric #2, with data for these two teams related to this metric gave no correlation between having a high quality of design and referencing large amounts of outside data.

8.2.5 Process Metric #5

Data from the experiment for the time spent on evaluation of alternative-criterion pairs is shown in Table 24. Statistical results are shown in Table 25 and Figure 26.

Team	EDSS used	Experience level	Metric Value	Row avg.
EH1 EH2	Yes (+)	High (+)	1450 1500	1470
EL1 EL2	Yes (+)	Low (-)	1760 1760	1760
EM	Yes (+)	Medium	1420	
OH1 OH2	No (-)	High (+)	1020 1320	1170
OL1 OL2	No (-)	Low (-)	2500 160	1330
OM	No (-)	Medium	1670	

Table 24. Metric: Time Spent on Evaluation Phase - Raw Data (units seconds)

Data groupings (excluding EM&OM)	Value	Error
EH1,2,3,5 average	1620	+/- 148
OH1,2,3,5 average	1250	+/- 148
EH1,2,3,5 & OH1,2,3,5 average	1430	+/- 148
Variable main effect for + EDSS	364	+/- 295
Variable main effect for + Experience	-221	+/- 295
Interaction EDSS/Experience effect	64	+/- 295
Minimum Significant Factor at 80% confidence	904	N/A

Table 25. Statistical Results for Metric of Time Spent on Evaluation Phase (units are seconds)

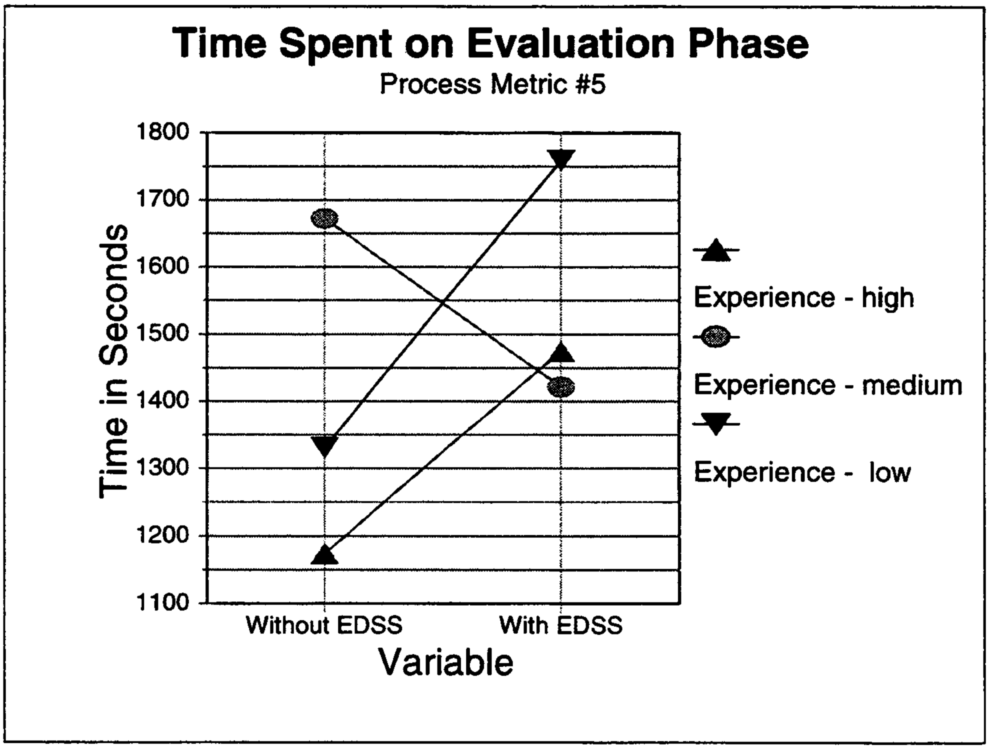

Figure 26. Graphical Display of Process Metric - Time Spent on Evaluation Phase

Overview: The data does not support any statistically significant conclusions that can be stated for either variable main effects or for their interaction.

EDSS variable main effect: The teams that used EDSS took 364 seconds more time evaluating alternative-criterion pairs of information. This is statistically insignificant as it is less than the MSF value of 904, but greater than the standard error of 295 seconds.

Experience variable main effect: Those teams with more experience used 221 fewer seconds in evaluating the alternative-criterion pairs of information than teams with low levels of experience. With the 80% confidence MSF value of 904 seconds and a standard error of 295, this effect is not statistically significant.

Interaction effect: It can be stated with statistical significance that there is no interaction effect between these two variables for this metric. The interaction effect is 64 seconds.

Concluding statements: This data and its conclusions for this metric are very disappointing. The highly experienced teams would have been expected to have shorter evaluation times than the less experienced teams, which they did, but evaluation times increased when teams used EDSS, rather than decreasing.

Calculating the percentage of time spent on evaluation across all teams, as a part of the total time (process metric #1), yields a value of 29%. This agrees reasonably well with a value of 40% that Olson (1992) found in his study. The difference can be explained by understanding that his value was for time spent in "design discussion" and not the more restrictive evaluation activity this metric records.

8.3 Perception Metric Results

This section explains the statistical results from questionnaire data on seven perception metrics. The questions that were asked regarded: control of the decision making process, usefulness of their decision-making method, ease of use of their decision-making method, problem understanding produced from using their decision-making method, confidence and conviction that his or her decision was right after using their decision-making method, level of satisfaction with the solution after having used their decision-making method, and perception of their ability to work as a team using their decision-making method.

8.3.1 Perception Metric #1

Data from the experiment is shown in Table 26. Statistical results are shown in Table 27 and Figure 27. This metric question, the control of decision making, asked: "Control means that your input concerning the direction of the design process as a team member was equally considered with other team members and there was no forms of inequality in the decision making process. Which one of the following best represents your control of the decision making process? (Circle one number)."

The questionnaire responses were:

1 I was unable to exercise any control.

2 I was able to exercise a little control.

3 I was able to exercise a moderate amount of control.

4 I was able to exercise a large amount of control.

5 I was able to exercise nearly unlimited amount of control.

Team	EDSS used	Experience level	Metric Value	Row avg.
EH1 EH2	Yes (+)	High (+)	3.7 2.0	2.8
EL1 EL2	Yes (+)	Low (-)	3.0 4.0	3.5
EM	Yes (+)	Medium	3.0	
OH1 OH2	No (-)	High (+)	3.0 3.7	3.3
OL1 OL2	No (-)	Low (-)	4.3 3.0	3.7
OM	No (-)	Medium	3.0	

Table 26. Metric: Control of Decision Making - Raw Data (units 1/5 w/5= unlimited control)

Data groupings (excluding EM&OM)	Value	Error
EH1,2,3,5 average	3.2	+/- 0.2
OH1,2,3,5 average	3.5	+/- 0.2
EH1,2,3,5 & OH1,2,3,5 average	3.3	+/- 0.2
Variable main effect for + EDSS	-0.3	+/- 0.3
Variable main effect for + Experience	-0.5	+/- 0.3
Interaction EDSS/Experience effect	0.2	+/- 0.3
Minimum Significant Factor at 80% confidence	0.9	N/A

Table 27. Statistical Results for Metric of Control of Decision Making (units are 1/5 w/5= unlimited control)

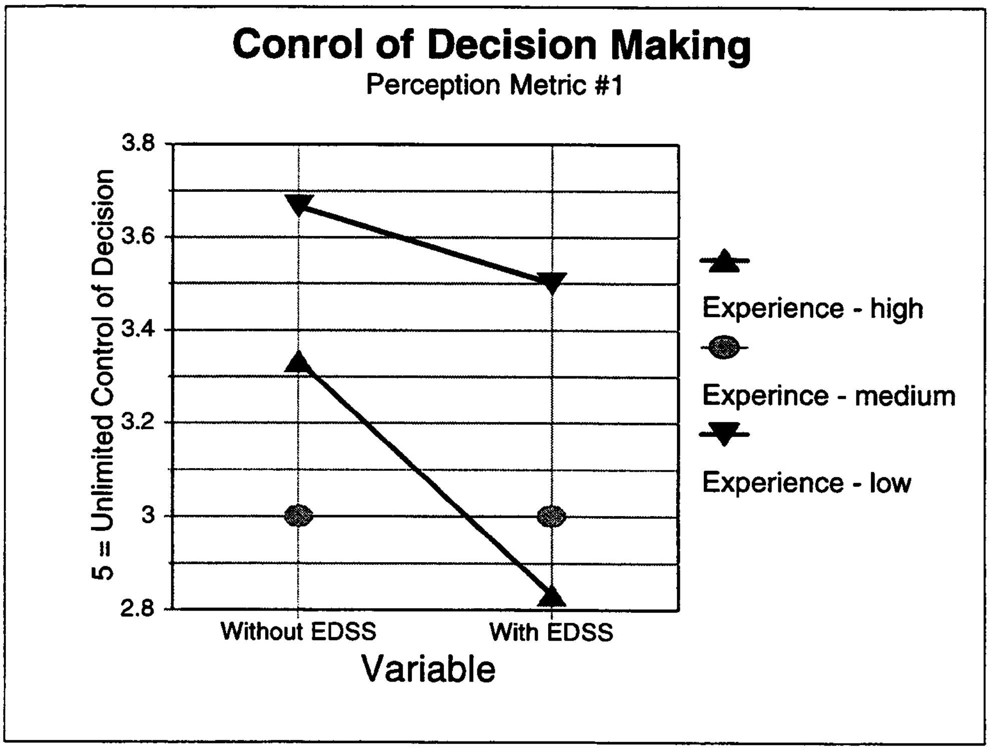

Figure 27. Graphical Display of Perception Metric - Control of Decision Making

Overview: The data does not support any statistically significant conclusions for either of the two variable main effects, using EDSS or having a high levels of experience. It can be stated based on statistical results that there is no interaction effect between these two variables.

EDSS variable main effect: With the variable main effect of EDSS at -0.3 and the standard error of .3 nothing of statistical significance can be stated. The MSF value is 0.9.

Experience variable main effect: The variable main effect of teams having higher experience is a reduction in the amount of control of the decision making process by 0.5. Nothing of statistical significance can be stated with the MSF at 0.9. Without regard to statistics it is not clear why more experienced teams reported a lower sense of control over the decision-making process than less experienced teams.

Interaction effect: With the interaction effect of 0.2 it can be stated that there is no statistically significant interaction between these two variable as it influences control of the decision making process.

Concluding statements: This metric did not indicate that members of the more experienced teams perceived that they had more control of the decision making process than members of the less experienced teams. No other metric cross referencing offers any aid in understanding this fact. Also it is disappointing that teams that used EDSS did not have a positive variable main effect, i.e. that using EDSS was not reported as giving the teams a perception of greater control of the decision making process. The reason for this is also unknown. The two teams that had low levels of experience and did not use EDSS, OL1 and OL2, recorded the highest level of control of the decision making process. A partial explanation could be that all teams that used EDSS felt, due to their limited previous familiarity with the program, that they were not in control due to lack of EDSS familiarity. But unfortunately when one reviews the "ease of use of decision method" metric data it appears that those that used EDSS rated it more easy. The exact reason is still elusive.

8.3.2 Perception Metric #2

Data from the experiment is shown in Table 28. Statistical results are shown in Table 29 and Figure 28. This metric question, usefulness of the teams decision support method or tool, asked: "Rate the usefulness of your decision support method. (Circle one number)."

The questionnaire responses were:

1A Our decision support method was completely useless (question for team without EDSS).

1B EDSS was completely useless (question for team with EDSS).

2 Our decision support method was somewhat useless.

3 Our decision support method was neither useful nor useless.

4 Our decision support method was somewhat useful.

5 Our decision support method was completely useful.

Team	EDSS used	Experience level	Metric Value	Row avg.
EH1 EH2	Yes (+)	High (+)	4.0 2.7	3.3
EL1 EL2	Yes (+)	Low (-)	4.7 4.0	4.3
EM	Yes (+)	Medium	4.0	
OH1 OH2	No (-)	High (+)	4.3 4.3	4.3
OL1 OL2	No (-)	Low (-)	4.3 4.0	4.2
OM	No (-)	Medium	3.3	

Table 28. Metric: Usefulness of Your Decision Making Method - Raw Data (5=completely useful)

Data groupings (excluding EM&OM)	Value	Error
EH1,2,3,5 average	3.8	+/- 0.1
OH1,2,3,5 average	4.3	+/- 0.1
EH1,2,3,5 & OH1,2,3,5 average	4.0	+/- 0.1
Variable main effect for + EDSS	-0.4	+/- 0.2
Variable main effect for + Experience	-0.4	+/- 0.2
Interaction EDSS/Experience effect	0.6	+/- 0.2
Minimum Significant Factor at 80% confidence	0.6	N/A

Table 29. Statistical Results for Metric of Usefulness of Your Decision Making Method (5=completely useful)

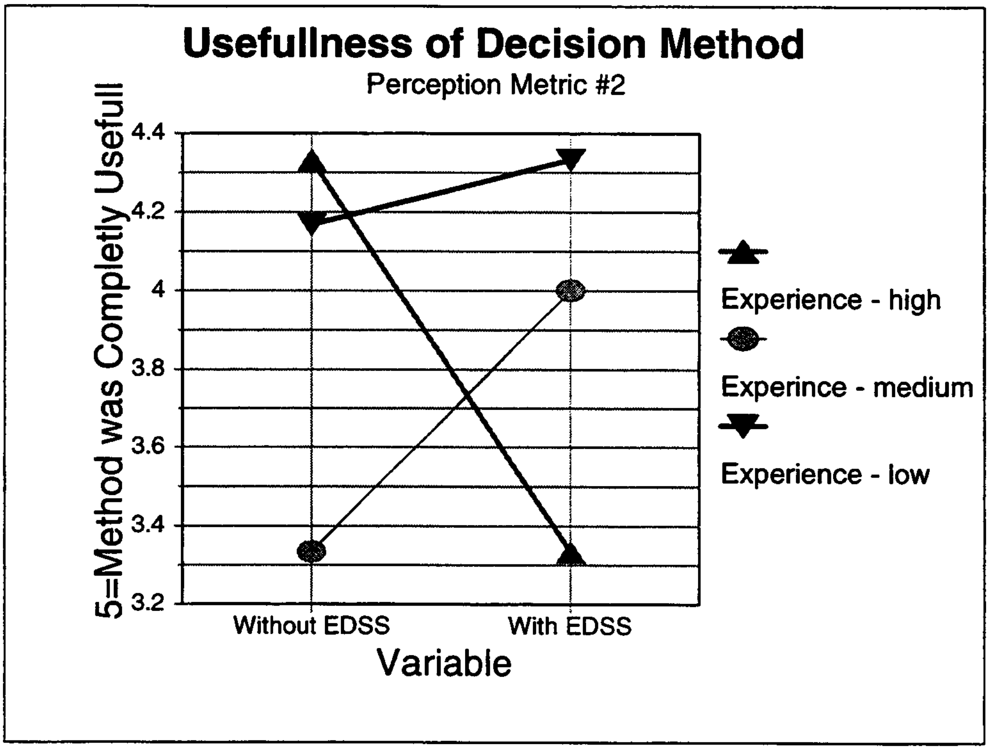

Figure 28. Graphical Display of Perception Metric - Usefulness of Decision Method

Overview: It is statistically significant that there is an interaction between the two variables. Nothing of statistical significance can be stated for the variable main effects because of this strong interaction.

EDSS variable main effect: Teams that used EDSS recorded a 0.4 lower rating of the usefulness of EDSS as a decision method compared with teams that used other methods. The standard error is 0.2 and the MSF is 0.6.

Experience variable main effect: Teams that had high levels of experience recorded lower usefulness of decision method ratings of 0.4.

Interaction effect: There is a strong interaction between these variable as demonstrated by the interaction effect value of 0.6. There is no indication as to the basis of the interaction. The teams with high experience levels and without the use of EDSS recorded the same level of usefulness as did teams that were inexperienced and used EDSS for their decision method.

Concluding statements: It appears that on the average all teams rated their decision support method as "somewhat useful." But no statistically significant changes in the usefulness of the decision method based on use of EDSS or difference experience level were statistically evident. The responses from the team members for this metric are completely frustrating. This researcher would have predicted that the graph of the data would have positive slopes for both levels of experience when the variable of EDSS changed from without EDSS to with EDSS. The only teams that conformed to the desired direction and had statistically significant data, were the two teams with medium experience, EM and OM.

8.3.3 Perception Metric #3

Data from the experiment is shown in Table 30. Statistical results are shown in Table 31 and Figure 29. This metric question, rate the ease of use of your decision support method or tool, asked: "Rate the difficulty or ease of using your decision support method during the problem activity (Circle one number)."

The questionnaire responses were:

1 Our decision support method was extremely difficult to use.

2 Our decision support method was difficult to use.

3 Our decision support method was neither difficult nor easy to use.

4 Our decision support method was easy to use.

5 Our decision support method was extremely ease to use.

Team	EDSS used	Experience level	Metric Value	Row avg.
EH1 EH2	Yes (+)	High (+)	3.3 3.3	3.3
EL1 EL2	Yes (+)	Low (-)	4.0 4.0	4.0
EM	Yes (+)	Medium	4.0	
OH1 OH2	No (-)	High (+)	3.0 4.0	3.5
OL1 OL2	No (-)	Low (-)	3.3 3.7	3.5
OM	No (-)	Medium	3.0	

Table 30. Metric: Rate the Ease of Using Your Decision Support Method - Raw Data (5=extremely easy to use)

Data groupings (excluding EM&OM)	Value	Error
EH1,2,3,5 average	3.7	+/- 0.1
OH1,2,3,5 average	3.5	+/- 0.1
EH1,2,3,5 & OH1,2,3,5 average	3.6	+/- 0.1
Variable main effect for + EDSS	0.2	+/- 0.1
Variable main effect for + Experience	-0.3	+/- 0.1
Interaction EDSS/Experience effect	0.3	+/- 0.1
Minimum Significant Factor at 80% confidence	0.4	N/A

Table 31. Statistical Results for Metric of Rate the Ease of Use of Your Decision Method (5=extremely useful)

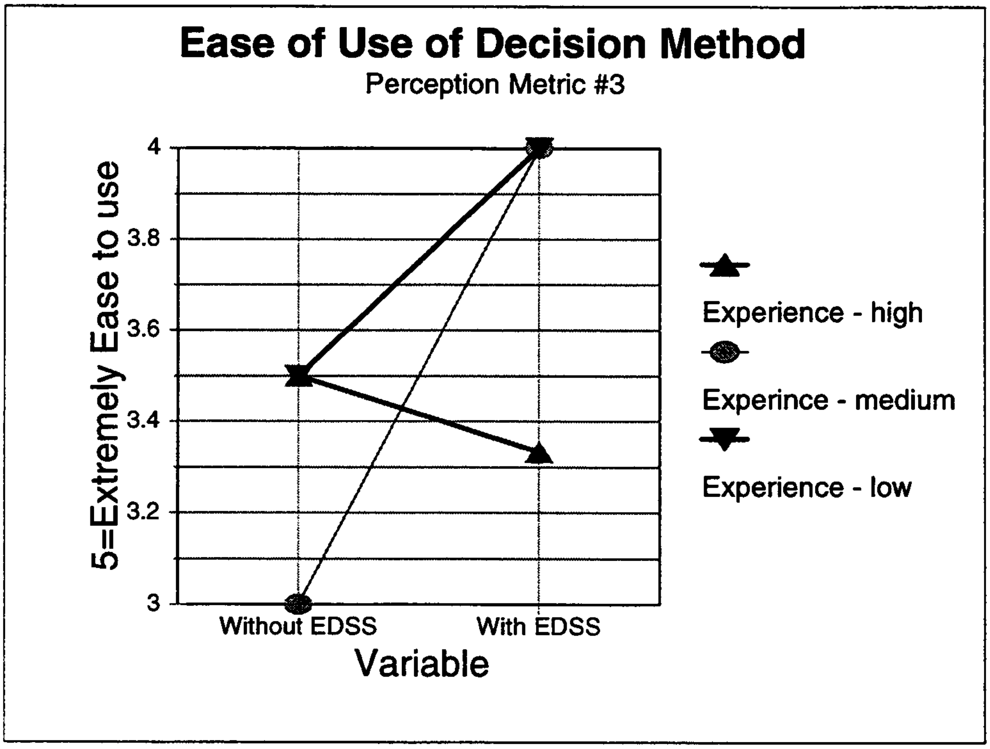

Figure 29. Graphical Display of Perception Metric - Ease of Use of Decision Method

Overview: Even a strong interaction between variables is not strong enough to qualify as statistically significant. The standard error for this data set is extremely low.

EDSS variable main effect: Teams that used EDSS recorded a slight increase in their perception (0.2) that "The EDSS support system was easier to use than other methods," but this increase is less than the MSF, 0.4, so no statistically significant statements can be made about this fact.

Experience variable main effect: Teams with high levels of experience recorded a reduction in perception of 0.3 but like the EDSS variable main effect this is less than the MSF of 0.4.

Interaction effect: The interaction effect (0.3) is equal to the experience variable main effect (0.3) and larger than the EDSS variable main effect (0.2). Therefore nothing can be stated with statistical significance about the variable main effects.

Concluding statements: Unfortunately nothing conclusive can be said about this metric except that the standard error is very low.

8.3.4 Perception Metric #4

Data from the experiment is shown in Table 32. Statistical results are shown in Table 33 and Figure 30.This metric question, understanding of the problem (insight), asked: "Which one of the following best describes your experience while working on this decision activity as compared to work with other similar design activities (Circle one number)."

The questionnaire responses were:

1 I had much less overall understanding of the problem.

2 I had less overall understanding of the problem.

3 I had about the same overall understanding of the problem.

4 I had more overall understanding of the problem.

5 I had a much more overall understanding of the problem.

Team	EDSS used	Experience level	Metric Value	Row avg.
EH1 EH2	Yes (+)	High (+)	3.3 2.3	2.8
EL1 EL2	Yes (+)	Low (-)	4.7 3.5	4.1
EM	Yes (+)	Medium	3.5	
OH1 OH2	No (-)	High (+)	3.0 2.3	2.7
OL1 OL2	No (-)	Low (-)	2.3 3.0	2.7
OM	No (-)	Medium	3.3	

Table 32. Metric: Problem Understanding - Raw Data (5=had more understanding)

Data groupings (excluding EM&OM)	Value	Error
EH1,2,3,5 average	3.5	+/- 0.1
OH1,2,3,5 average	2.7	+/- 0.1
EH1,2,3,5 & OH1,2,3,5 average	3.1	+/- 0.1
Variable main effect for + EDSS	0.8	+/- 0.2
Variable main effect for + Experience	-0.6	+/- 0.2
Interaction EDSS/Experience effect	0.6	+/- 0.2
Minimum Significant Factor at 80% confidence	0.7	N/A

Table 33. Statistical Results for Metric of Problem Understanding (5=had more understanding)

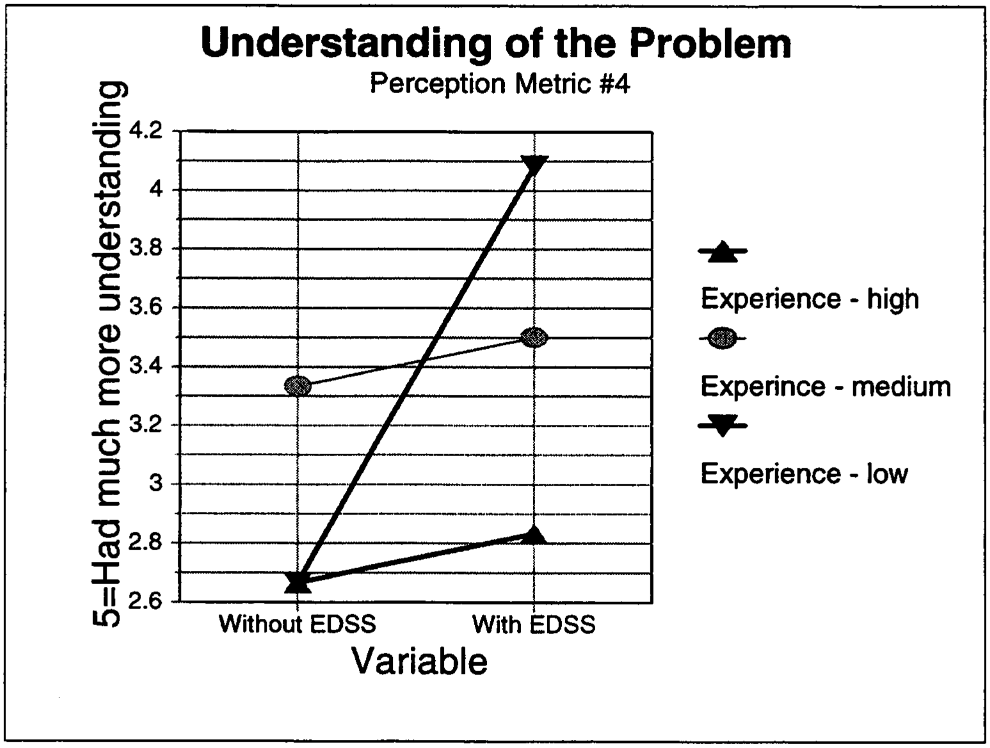

Figure 30. Graphical Display of Metric - Understanding of the Problem

Overview: In spite of the strong interaction, the data support a statistically significant conclusion that EDSS exhibited a variable main effect that showed an increased understanding of the problem recorded by those teams that used EDSS for their decision support.

EDSS variable main effect: The variable main effect of using EDSS was an increase of understanding of 0.8. This is greater than the standard error of 0.2 and the MSF of 0.7.

Experience variable main effect: There was no variable main effect of experience level. The effect value is a reduction of 0.6 points.

Interaction effect: There is an interaction effect. The effect is 0.6, which is 0.1 below the MSF value (0.7). This influences making strong statements about variable main effects without interactions. This interaction is somewhat less than the EDSS variable main effect but the data shows that there is a strong increase in understanding for low experienced teams using EDSS as compared with those not using EDSS.

Concluding statements: Additionally, there was a short question portion where participants could explain, "Why you feel you had (less/more) overall understanding of the problem." There were no comments from the teams that used EDSS that would elaborate on the variable main effect of EDSS.

8.3.5 Perception Metric #5

Data from the experiment is shown in Table 34. Statistical results are shown in Table 35 and Figure 31. This metric question, conviction that the decision is right, or confidence, asked: "Which one of the following best describes your conviction that the top three decisions (the decision that had significant impact on the design activity outcome) were not right/correct/best? (Circle one number)."

The questionnaire responses were:

1 The decisions were completely wrong/incorrect/worst possible.

2 The decisions were unacceptable.

3 The decisions were neutral, neither unacceptable nor acceptable.

4 The decisions were acceptable.

5 The decisions were completely right/correct/best possible.

Team	EDSS used	Experience level	Metric Value	Row avg.
EH1 EH2	Yes (+)	High (+)	4.0 4.0	4.0
EL1 EL2	Yes (+)	Low (-)	4.3 4.5	4.4
EM	Yes (+)	Medium	4.0	
OH1 OH2	No (-)	High (+)	4.0 4.3	4.2
OL1 OL2	No (-)	Low (-)	4.3 4.0	4.2
OM	No (-)	Medium	4.0	

Table 34. Metric: Conviction About Top Decisions - Raw Data (5=completely right/../best)

Data groupings (excluding EM & OM)	Value	Error
EH1,2,3,5 average	4.2	+/- 0.0
OH1,2,3,5 average	4.2	+/- 0.0
EH1,2,3,5 & OH1,2,3,5 average	4.2	+/- 0.0
Variable main effect for + EDSS	0.0	+/- 0.1
Variable main effect for + Experience	-0.2	+/- 0.1
Interaction EDSS/Experience effect	0.2	+/- 0.1
Minimum Significant Factor at 80% confidence	0.2	N/A

Table 35. Statistical Results for Metric of Conviction About Top Decisions (5=completely right/.../best)

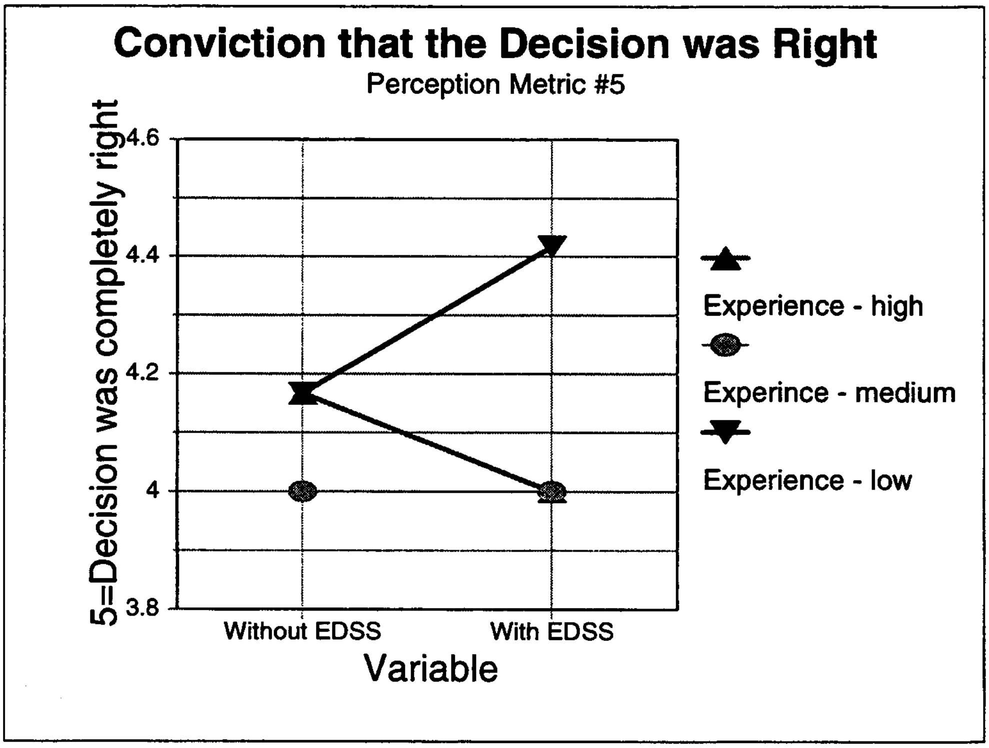

Figure 31. Graphical Display of Perception Metric - Conviction that the Decision was Right

Overview: Strong interaction effects precludes stating anything statistically significant about these variables with this metric.

EDSS variable main effect: Disregarding the strong interaction effect, there is no EDSS variable main effect. The EDSS variable main effect value is 0.0 with a standard error of 0.1.

Experience variable main effect: Nothing can be stated about the impact of individual experience levels for this metric with a value of -0.2. This is the same value as both the interaction effect and MSF.

Interaction effect: A strong interaction effect precludes any statements about either of the variables acting individually.

Concluding statements: These data have a very small value for the standard error (0.1). It was hoped that the data would conform to a positive slope and that the more experienced teams would have a higher level of conviction about the decisions made. The reason for the unpredicted pattern is unknown.

8.3.6 Perception Metric #6

Data from the experiment is shown in Table 36. Statistical results are shown in Table 37 and Figure 32. This metric question, what factors contributed to the sense of satisfaction with the solution, asked: "Even though the top three (3) decisions (the decisions that had the most significant impact on the design activity outcome) may have been right, you may still not be satisfied with the decisions. Please indicate your level of satisfaction or dissatisfaction with the decisions (Circle one number)."

The questionnaire responses were:

1 I am extremely dissatisfied with these decisions.

2 I am dissatisfied with these decisions.

3 I am neutral about these decisions.

4 I am satisfied with these decisions.

5 I am extremely satisfied with these decisions.

Team	EDSS used	Experience level	Metric Value	Row avg.
EH1 EH2	Yes (+)	High (+)	4.3 3.7	4.0
EL1 EL2	Yes (+)	Low (-)	4.7 3.0	3.8
EM	Yes (+)	Medium	4.0	
OH1 OH2	No (-)	High (+)	4.3 4.0	4.2
OL1 OL2	No (-)	Low (-)	4.0 4.3	4.2
OM	No (-)	Medium	3.7	

Table 36. Metric: Level of Satisfaction with Decision - Raw Data (5= extremely satisfied with decisions)

Data groupings (excluding EM&OM)	Value	Error
EH1,2,3,5 average	3.9	+/- 0.1
OH1,2,3,5 average	4.2	+/- 0.1
EH1,2,3,5 & OH1,2,3,5 average	4.0	+/- 0.1
Variable main effect for + EDSS	-0.3	+/- 0.2
Variable main effect for + Experience	0.1	+/- 0.2
Interaction EDSS/Experience effect	0.1	+/- 0.2
Minimum Significant Factor at 80% confidence	0.7	N/A

Table 37. Statistical Results for Metric of Level of Satisfaction with Decision

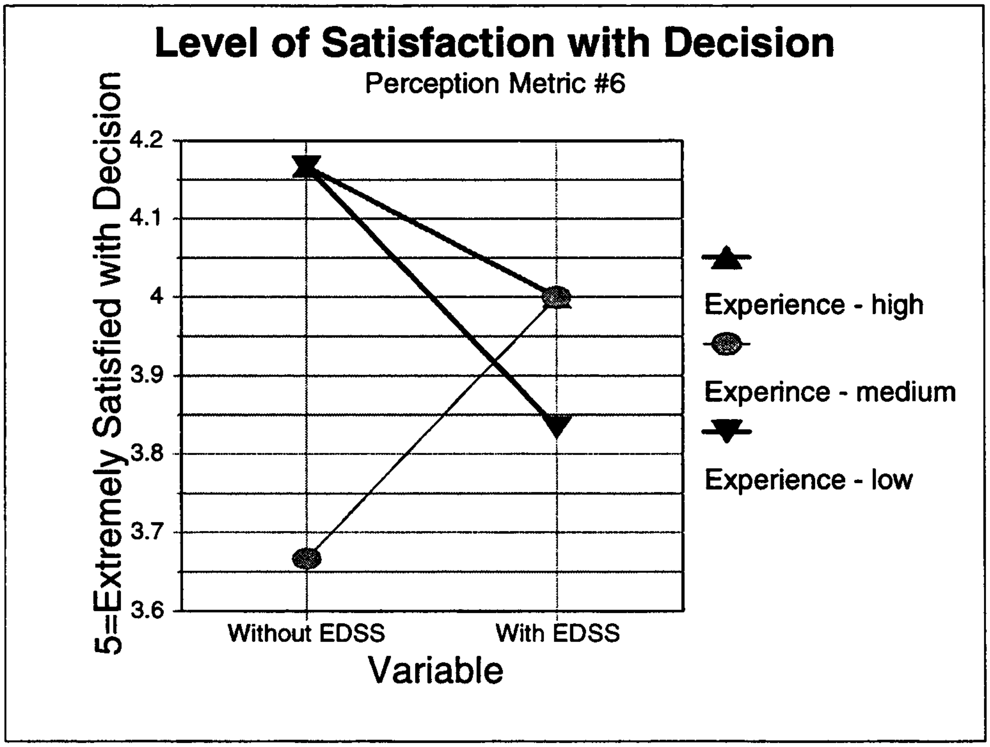

Figure 32. Graphical Display of Perception Metric - Level of Satisfaction with Decision

Overview: No evidence is available from this metric to support the hypothesis of an improvement in, or positive impact on, decision-making perception. None of the metric values exceed the MSF.

EDSS variable main effect: With the value from the variable main effect of EDSS at 0.3, being nearly equal to the standard error of 0.2, and far below the MSF at 0.7, it is clear that this metric does not support the hypothesis.

Experience variable main effect: It can be stated, with a value of 0.1, that there is no statistically significant variable main effect for experience levels.

Interaction effect: It can be stated that there is no statistically significant interaction effect for this metric with the value of 0.1.

Concluding statements: For support of the hypothesis, that there be an improvement in, or positive impact on, the decision-making perception, the variable main effect values must exceed the MSF value. This did not occur for either of the variable main effects investigated. Two metric values, the variable main effect for experience and the interaction effect, were below the standard error for an effect. It can then be stated with statistical confidence that neither of these impacted this perception metric level of satisfaction/dissatisfaction with the final decision reached.

8.3.7 Perception Metric #7

Data from the experiment is shown in Table 38. Statistical results are shown in Table 39 and Figure 33. This metric question, capacity of team members to work together in reaching the decision, asked: "Which one of the following best describes your observations about the ability of the team members to work together in reaching the decision? (Circle one number)."

The questionnaire responses were:

1 I observed an extreme lack of team work.

2 I observed a moderate lack of team work.

3 I am neutral about the level of team work.

4 I observed a moderated amount of team work.

5 I observed an extreme amount of team work.

Team	EDSS used	Experience level	Metric Value	Row avg.
EH1 EH2	Yes (+)	High (+)	4.0 3.0	3.5
EL1 EL2	Yes (+)	Low (-)	4.3 4.8	4.5
EM	Yes (+)	Medium	3.5	
OH1 OH2	No (-)	High (+)	4.0 4.7	4.3
OL1 OL2	No (-)	Low (-)	4.3 4.7	4.5
OM	No (-)	Medium	3.3	

Table 38. Metric: Capacity of Team Members to Work Together - Raw Data (5=extreme amount of team work)

Data groupings (excluding EM&OM)	Value	Error
EH1,2,3,5 average	4.0	+/- 0.1
OH1,2,3,5 average	4.4	+/- 0.1
EH1,2,3,5 & OH1,2,3,5 average	4.2	+/- 0.1
Variable main effect for + EDSS	-0.4	+/- 0.2
Variable main effect for + Experience	-0.6	+/- 0.2
Interaction EDSS/Experience effect	0.4	+/- 0.2
Minimum Significant Factor at 80% confidence	0.5	N/A

Table 39. Statistical Results for Metric of Capacity of Team Members to Work Together

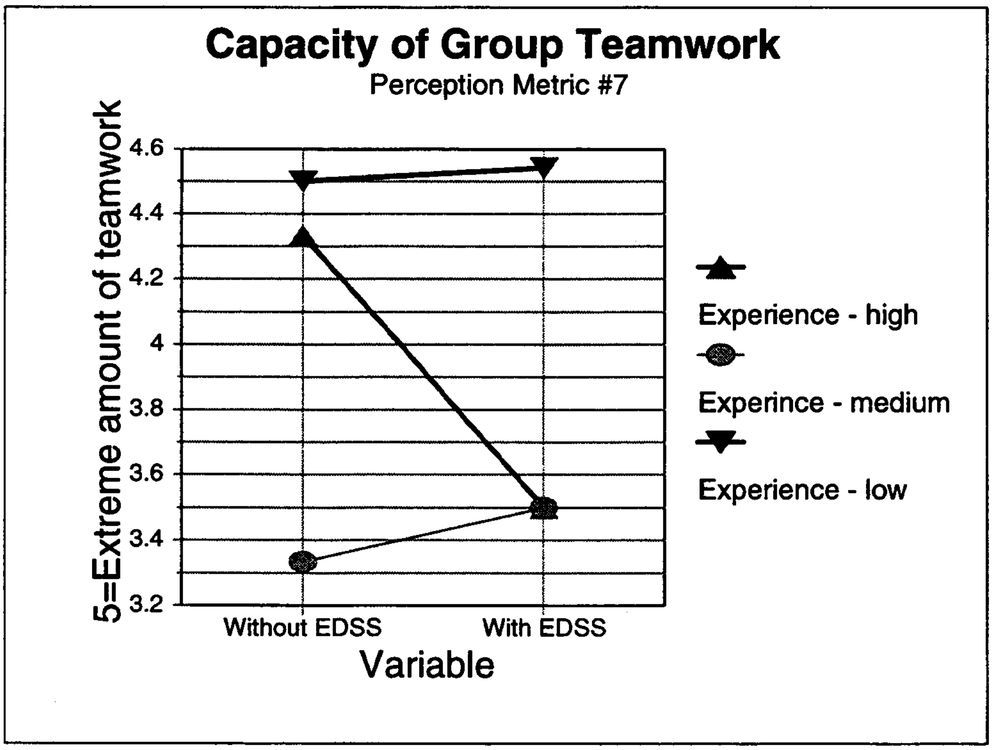

Figure 33. Graphical Display of Perception Metric - Capacity of Team Members to Work Together

Overview: Even with a strong interaction between the two variables there was a statistically significant main effect from those with high levels of experience. Unfortunately, this main effect was in the direction that runs counter to the hypothesis. With the interaction effect, it supports the conclusion that using EDSS for decision support does not encourage greater capacity for teamwork, especially for highly experienced teams.

EDSS variable main effect: The variable main effect for this metric for EDSS is -0.4. This value is below the MSF value of 0.5 but larger than the standard error of 0.2.

Experience variable main effect: The experience variable main effect is 0.6. This value is above the MSF and standard error but because there is a large interaction effect (0.4), nothing can be stated about the experience variable main effect acting independently of other variables. With this data it is observed that those highly experienced teams show a sharp decrease in their response when going from a condition of not using EDSS to using EDSS for their decision method.

Interaction effect: The interaction effect value is 0.4. A value this large compared with the variable main effects, MSF, and standard error precludes any statements about variable main effects acting independently.

Concluding statements: Disappointingly there is no indication from the data that would yield an understanding as to why the metric did not produce increased capacity of groups to work as teams when using EDSS. The use of EDSS did not support an increased sense of team work in arriving at a final solution. Teams that had high experience levels did show a decreased sense of teamwork over teams that were less experienced. The fact that there is a strong interaction effect with these two variables is also significant. It can be concluded based on this research that part of the sense of teamwork comes from not only the members' experience level but also the kind of decision support system or method used. This researcher had hoped that use of EDSS would promote a greater sense of teamwork independent of the experience level. This did not prove to be true. Additionally, from the comments recorded for this perception question, it is strikingly clear that constructive communication and the ability to work toward a common goal was a key factor in participants' sense of teamwork. From this metric one would infer that decision analysis over a network without open discussion would produce less than satisfactory results. A similar conclusion was reached by Stetter (1995) after his review of the work of others on teamwork in design studies.

8.4 Product Metric Results

This set of metrics evaluates the technical merits of EDSS contrasted with other conditions. These other conditions, such as "what you would expect" or "better than manual methods," act as the contrasting or control team for the metric statistics. These conditions are far less definitive than the above three metric. Results can only be reported for the teams that used EDSS. The only variable with high and low conditions for these metrics are experience levels.

8.4.1 Product Metric #1

Data from the experiment is shown in Table 40. Statistical results are shown in Table 41. This metric question, response time of the EDSS program, asked : "Compared to what you had expected, please rate the speed of EDSS in returning responses to the screen (Circle one number)."

The questionnaire responses were:

1 EDSS was extremely slow.

2 EDSS was slower than I expected.

3 EDSS was as about what I expected.

4 EDSS was faster than I expected.

5 EDSS was extremely fast.

Team	Experience	Value
EH1	High (+)	3.3
EL1	Low (-)	3.3
EH2	High (+)	3.7
EM	Medium	3.0
EL2	Low (-)	3.0

Table 40. Metric: Screen Response Time of EDSS - Raw Data (units are 5 = response time extremely fast)

Data groupings (excluding EM)	Value	Error
EH1...5 average	3.3	+/- 0.1
Variable main effect for + Experience	0.2	+/- 0.1
Minimum Significant Factor at 80% confidence	0.5	N/A

Table 41. Statistical Results for Metric of Screen Response Time of EDSS (units are 5 = response time extremely fast)

All teams rated EDSS a little above "about what I expected." With the MSF value of 0.5 and the variable main effect for highly experienced teams at 0.2, no statistically significant results are shown for high experience level users and the impact of this variable on the response times of EDSS. This indicates that the level of expected response is independent of experience levels. This metric does not support the hypothesis with an average value of 3.3 for all teams. This researcher would expect an average in excess of 4.0 in order to support the hypothesis of improvement in or positive impact on the response time. For the problem size of this experiment, the computer and software returned calculation results to the screen in less than two seconds for most of the data used. The conclusion is that if a computer and software returns results that do not require the user to wait past some reasonable time threshold the use of a computer decision support should be rated as satisfactory by a person of any experience level. By inference, response time of EDSS is independent of the user's experience level and dependent on the computer and the software it is written with. Since response time was at or above some reasonable perception it can be questioned if this metric can show valid results for the hypothesis of improvement or impact from the use of EDSS independent of the computer.

8.4.2 Product Metric #2

Data from the experiment is shown in Table 42. Statistical results are shown in Table 43. This metric question, is the computer better than manual, asked: "Compared to manual methods, which one of the following best describes your opinion of EDSS (Circle one number)."

The questionnaire responses were:

1 EDSS was definitely worse than manual methods.

2 EDSS was somewhat worse than manual methods.

3 EDSS was about equal with manual methods.

4 EDSS was somewhat better than manual methods.

5 EDSS was definitely better than manual methods.

Team	Experience	Value
EH1	High (+)	4.7
EL1	Low (-)	4.3
EH2	High (+)	4.0
EM	Medium	4.0
EL2	Low (-)	4.0

Table 42. Metric: Computer was Better than Manual - Raw Data (units are 5 = definitely better than manual methods)

Data groupings (excluding EM)	Value	Error
EH1...5 average	4.2	+/- 0.1
Variable main effect for + Experience	0.1	+/- 0.2
Minimum Significant Factor at 80% confidence	0.7	N/A

Table 43. Statistical Results for Metric of Computer was Better than Manual Methods (units are 5 = definitely better than manual methods)

All teams rated EDSS "somewhat better than manual methods" of decision making. With the MSF value of 0.7 and the variable main effect for highly Experienced teams at 0.1, no statistically significant result is shown for high experience level users and the impact of this variable on the opinion that the computer is better than manual methods. This result indicates that this metric is not affected by the experience level of the participant. The word "better" was not defined in the question. This leaves this result open to criticism unless it is assumed to refer to a total integration of decision method attributes.

8.4.3 Product Metric #3

Data from the experiment is shown in Table 44. Statistical results are shown in Table 45. This metric question, EDSS was the easiest decision support method used, asked: "Using EDSS was the easiest decision support method I have ever used (Circle one number)."

The questionnaire responses were:

1 Strongly disagree.

2 Disagree.

3 Neither agree nor disagree.

4 Agree.

5 Strongly agree.

Team	Experience	Value
EH1	High (+)	3.7
EL1	Low (-)	3.7
EH2	High (+)	3.0
EM	Medium	4.5
EL2	Low (-)	3.5

Table 44. Metric: EDSS was the Easiest Decision Support Method Used - Raw Data (units are 5 = strongly agree)

Data groupings (excluding EM)	Value	Error
EH1...5 average	3.7	+/- 0.1
Variable main effect for + Experience	-0.1	+/- 0.2
Minimum Significant Factor at 80% confidence	0.7	N/A

Table 45. Statistical Result for Metric of EDSS Was the Easiest Decision Support Method Used - (units are 5 = definitely better than manual methods)

Results indicate that all teams on the average agree that EDSS is the easiest decision support method that they have used. Again the word "easiest" is not specifically defined. With the MSF value of 0.7 and the variable main effect for highly experienced teams at -0.1, no statistically significant result is shown for high experience level users and the impact of this variable on the opinion that this computer software is the easiest decision support method ever used. This result indicates that this metric is not affected by the experience level of the participant.

8.4.4 Product Metric #4

Data from the experiment is shown in Table 46. Statistical results are shown in Table 47. This metric questions, the attitude change towards the task (use of a computer decision support tool) and towards computers, asked: "Using EDSS changed my attitude to one of always wanting to use a computer decision support system tool for future decisions (Circle one number)."

The questionnaire responses were:

1 Strongly disagree.

2 Disagree.

3 Neither agree nor disagree.

4 Agree.

5 Strongly agree.

Team	Experience	Value
EH1	High (+)	3.7
EL1	Low (-)	3.7
EH2	High (+)	3.3
EM	Medium	4.0
EL2	Low (-)	3.0

Table 46. Metric: Attitude Change Towards the Use of Computer - Raw Data (units are 5 = strongly agree)

Data groupings (excluding EM)	Value	Error
EH1..5 average	3.5	+/- 0.1
Variable main effect for + Experience	0.1	+/- 0.2
Minimum Significant Factor at 80% confidence	0.7	N/A

Table 47. Statistical Results for Metric of Attitude Change Towards the use of Computers (units are 5 = Strongly agree)

All teams rated EDSS somewhat above "neither agree nor disagree.." With the MSF value of 0.7 and the variable main effect for highly experienced teams at 0.1, no statistically significant result is shown for high experience level users and the impact of this variable on the opinion that the computer software is better than manual methods. This result indicates that this metric is not affected by the experience level of the participant.

This result, showing that the teams were between a neutral position and agreement position on the question of an attitude change as a result of using EDSS, was rather disappointing. Those teams with higher experience levels did not alter this outcome. A conclusion that can be drawn from this metric is that the level of decision support provided by the experimental version of EDSS did not provide enough features to distinguish it above the decision methods that the users had previously used.

8.5 Qualitative Results Across all Metrics

Three additional tables were constructed to show qualitative comparisons of the metric data.

Table 48 indicates any metric change, no matter how small, that supports the research hypothesis for the three experience levels. If EDSS, version 0.21, shows an improvement, the response is shown as "Yes," if no improvement or positive impact exists, the response is shown as "No." Each metric category also has a subtotal shown. This table shows that EDSS was unsuccessful in demonstrating improvements for the productivity metrics with only one yes response out of six possible (row 5). This table shows that EDSS had mixed results in demonstrating improvements for the process metrics with only six yes response out of a twelve possible (row 11). Process metric #4 - "amount of external data sources brought into the design space" improvement expectations are filled with question marks because it is uncertain if this metric increase or decrease with the use of EDSS contrasted with a condition of not having EDSS. This table shows that EDSS also had mixed results in demonstrating improvements for the perception metric with eleven yes responses out of a twenty-one possible (row 19, 3 columns times 7=21). Based on data from this table is can be concluded that EDSS demonstrates a very weak improvement in or positive impact on the alternative-criterion pair decision making process. The reason for this result is still postulated as a lack of problem complexity and the resulting decision making requirements as stated previously.

Results in Table 49 indicates if the medium experience level team metric data value was between the high and low experience levels for both conditions of not using and using EDSS for the decision method. The reason for creating this table was to gain further understanding into the team experience levels effect on metric values. It was expected for nearly all of the metrics, excluding the ones with questions marks in the rows (row 13 & 14), that the medium experienced team would have metric values between the two other experience levels. The results were disappointing as only three out of a possible twenty-eight produced the expected results. Since only one data point existed for each of the two medium experienced teams, no conclusive results can be drawn from this data in this table.

Information in Table 50 shows if the three experience levels were ordinally ranked as would be expected for the metric at the two variable conditions of EDSS. Again the results are disappointing and no further understanding into the decision making process is apparent beyond that which has been stated previously.

Metric		Experience level			Total
		Low	Medium	High	
Productivity	1.1 Total time to reach final alternative selection decision	No	No	No	
	1.2 Quality rating of final alternative selected	Yes	No	No	
	Total of Yes for this metric	1/2	0/2	0/2	1/6
Process	2.1 Number of additional alternatives created	No	Yes	No	
	2.2 Number of additional criteria specified	No	Yes	No	
	2.3 Number of alternative-criterion pair evaluations specified (quantified)	Yes	Yes	Yes	
	2.4 Amount of external data sources brought into the design space	?	?	?	
	2.5 Total time used for evaluation of alternative-criterion pairs	No	Yes	No	
	Total of Yes for this metric	1/4	4/4	1/4	6/12
Perception	3.1 Control of the decision making process	No	No	No	
	3.2 Usefulness of the decision support method or tool	Yes	Yes	No	
	3.3 Ease of use of the decision support method or tool	Yes	Yes	No	
	3.4 Understanding of the problem	Yes	Yes	Yes	
	3.5 Conviction that the decision was right	Yes	No	No	
	3.6 Satisfaction with the final alternative selection	No	Yes	No	
	3.7 Capacity of team members to work together in reaching the final decision	Yes	Yes	No	
	Total of Yes for this metric	5/7	5/7	1/7	11/21
	Total of all Yes for these metrics	**7/13**	**9/13**	**2/13**	**18/39**

Table 48. Qualitative Results for EDSS Showing an Improvement in or Positive Impact for All Metrics for each Experience Level

Metric		EDSS level		Total
		'-'	'+'	
Productivity	1.1 Total time to reach final alternative selection decision	Yes	Yes	
	1.2 Quality rating of final alternative selected	Yes	No	
	Total of Yes for this metric	2/2	1/2	3/4
Process	2.1 Number of additional alternatives created	No	No	
	2.2 Number of additional criteria specified	No	No	
	2.3 Number of alternative-criterion pair evaluations specified (quantified)	No	No	
	2.4 Amount of external data sources brought into the design space	No	No	
	2.5 Total time used for evaluation of alternative-criterion pairs	No	No	
	Total of Yes for this metric	0/4	0/4	0/8
Perception	3.1 Control of the decision making process	No	No	
	3.2 Usefulness of the decision support method or tool	?	?	
	3.3 Ease of use of the decision support method or tool	?	?	
	3.4 Understanding of the problem	No	No	
	3.5 Conviction that the decision was right	No	No	
	3.6 Satisfaction with the final alternative selection	No	No	
	3.7 Capacity of team members to work together in reaching the final decision	No	No	
	Total of Yes for this metric	0/7	0/7	0/14
	Total of all Yes for these metrics	**2/14**	**1/14**	**3/28**

Table 49. Qualitative Results for Medium Experience Levels Being Between High and Low Experience Levels

Metric		EDSS level		Total
		'-'	'+'	
Productivity	1.1 Total time to reach final alternative selection decision	Yes	Yes	
	1.2 Quality rating of final alternative selected	Yes	Yes	
	Total of Yes for this metric	2/2	2/2	4/4
Process	2.1 Number of additional alternatives created	Yes	Yes	
	2.2 Number of additional criteria specified	No	No	
	2.3 Number of alternative-criterion pair evaluations specified (quantified)	Yes	Yes	
	2.4 Amount of external data sources brought into the design space	No	No	
	2.5 Total time used for evaluation of alternative-criterion pairs	No	No	
	Total of Yes for this metric	2/5	2/5	4/10
Perception	3.1 Control of the decision making process	No	No	
	3.2 Usefulness of the decision support method or tool	?	?	
	3.3 Ease of use of the decision support method or tool	?	?	
	3.4 Understanding of the problem	No	No	
	3.5 Conviction that the decision was right	No	No	
	3.6 Satisfaction with the final alternative selection	No	Yes	
	3.7 Capacity of team members to work together in reaching the final decision	No	No	
	Total of Yes for this metric	0/7	1/7	1/14
	Total of all Yes for these metrics	**4/14**	**5/14**	**9/28**

Table 50. Ordinal Ranking of Experience Levels for the two EDSS Variable Levels

8.6 Summary

Performance of EDSS matched but did not statistically exceed the ad-hoc and Pugh's decision matrix performance for the two productivity metrics. Of the five process metrics, only one metric supported the hypothesis by statistically exceeding the non-EDSS methods which was that more alternative-criterion pairs were evaluated with EDSS than with other decision methods. The other four process metrics matched the performance of the other two decision methods observed. Of the seven perception metrics, only one, increased problem understanding supported the hypothesis. Here too, the remaining perception metrics matched the performance of the other decision methods. The four product metrics matched but did not statistically exceed the non-EDSS decision methods and therefore did not supported the hypothesis. Apparently the simplicity of the experimental problem did not force the teams to challenge their assumptions and positions, exhaustively search for the best solution, and use extensive negotiations.

9. COMMENTS ON THE DECISION MAKING PERFORMANCE OF THE DIFFERENT GROUPS

This chapter includes quotes and observational comments on the decision-making performance of the teams. It provides additional information about the teams and their decision making activities that cannot be directly quantified or related to metrics. No attempt is made to compare this research with other research which focuses on the mechanical design process (Hales, 1986; Stauffer, 1987; Tang, 1989; Dylla, 1991; Minneman, 1991; Fricke, 1993; Blessing, 1994). This research focuses instead on decision making which is part of the overall mechanical design process. Also, no comments contrasting group decision making and individual decision-making activities is made. The observational comments below are based on reviewing material from two sources: observations of the decision making activities from the videos and review of the questionnaire comments (see Appendix 4). The questionnaire comments come from the perception portion of the questionnaire that begins with the metric "understanding of the problem" and concludes with the last product metrics.

9.1 Productivity

Based on observations of the teams, the single most noticeable factor enhancing group productivity during the decision making process was the aggressiveness of single members. On one notable team there was an individual who took active leadership in moving the decision making process towards a successful conclusion, apparently demonstrating natural team dynamics. This person did not exercise inappropriate influence, but his coaching was clearly evident in the group's productivity as demonstrated by the metric data recorded for this team.

9.2 Process

No comments seem to be significant beyond those which have already been mentioned above and in the discussions of process metrics.

9.3 Perception

For the metric category of perception, participants wrote comments on four metrics. For the metric of "understanding of the problem," no team made any direct reference to their respective decision support method as giving them less or more problem understanding. For the metric "conviction that the decision was right," participants recorded statements of satisfaction that were not strongly stated in an affirmative manner. All teams were satisfied with the decision methods they used. For the metric "satisfaction with the final alternative selection," participants who used EDSS expressed positive statements about the use of EDSS and its ability to aid the user in decision making. Once again, participants did not explore the decision space in support of their position statements about satisfaction with the final alternative selection. Responses to the metric "capacity of team members to work together in reaching the final decision," indicated the level of teamwork was high, and no comment seemed to indicate that their decision support method enhanced this condition. In other words, it appeared that the members worked together as a team and the use of a decision support method neither aided nor detracted from this sense of teamwork. Any indication of arguments between team members and resulting increased time for the team to reach a final decision would have been appropriate signs of a decrease in productivity.

9.4 Product

Although comments from the teams that used EDSS indicated that EDSS confirmed what the user expected, these comments did not indicate that use of EDSS had any definable benefits contrasted with manual decision analysis methods or simple group discussions. Responses from the team members that used EDSS, about their overall experience with using EDSS for their decision support, included the comments: "I liked the program," "It was very handy," and, "[it] sped up the process of evaluating." Comments from members of the teams that did not use EDSS did not include reference to their experience with their decision support method(s).

9.5 Other

The participants wrote many comments that are typical examples of the conventional group decision making processes (Fisher, 1990). An example from the questionnaire such as, “we discussed different ideas and asked questions of each other,” shows that conventional aspect. Unfortunately, no team attempted to explore the solution space by investigating refinements of their alternatives that would indicate superior levels of decision-making processes. This observation supports the findings of Stauffer (1987), who reported that "designers find satisfactory rather than optimal solutions to design problems.” All teams worked together harmoniously and professionally. There were no comments made by team members or observations made from watching the videos that would indicate that any group displayed qualities of a truly effective group (Fisher, 1990). The group interaction was adequate. No group exhibited robust or optimizing decision making. Robust decision making or making a robust decision is defined as selecting the best alternative after rigorously exploring the impact of all known and unknown factors that might render the alternative choice less than optimum. Comments on the level of team work while reaching a decision were directed towards expressing how discussion and "no friction" greatly contributed to numerous statements such as "this was a good team." Once again, this kind of condition cannot be directly associated with inferior or superior decision-making performance.

Teams which used EDSS and teams that did not made comments in response to the metric dealing with "understanding of the problem" which were similar to those discussed in the mechanical design studies above. Members said, for example, "hard to understand at first," "[I] was able to visualize the problem," "[that the] criteria were easily defined," and "once I was able to picture the problem I understood it and immediately got ideas." A qualitative conclusion based on these statements is that the subjects used for this experiment appear to resemble others used in similar design studies. When participants were asked to comment on their "feeling that the top three decisions were wrong/unacceptable or right/acceptable" these responses showed similarly expected statements. Statements that their solution was best because it "met the requirements" were recorded by both groups of teams. The teams that used EDSS had numerous comments that indicated EDSS was used to confirm "my gut feel about what would work." No comments from any teams indicated a polarization of positions, or "my solution is best." In other words, the problem was conventional and therefore did not motivate team members to campaign vigorously for acceptance of their solution as the final choice. It should be noted that no group conducted or commented on solution optimization or robustness.

The problem solved in this research appeared to be very simple and uncontroversial. Negotiations are an essential part in collaborative design (Stetter, 1995), and had the problem in this research been complex and controversial the expected result would have been to see examples of intense negotiations taking place. No intense negotiation were observed. Comparison of metrics for teams that used EDSS and those that did not across all four metric categories leads to the conclusion that for simple and conventional problems nearly any decision analysis method produces acceptable decision results. It appears that only when a problem becomes complex and controversial does one need a rigorous decision support method or tool. EDSS has the components that support complex and controversial problems that require the qualities of effective group functioning (Fisher, 1990). It is this researcher's opinion that had the participants been asked if this problem were complex and demanded intense negotiations, they would have answered unanimously in the negative. It is postulated that this single fact is why the hypothesis was not supported. Based on this conclusion, and with a complex problem, a new metric should be included, "did your decision support method support the team's need for negotiations?"

10. COMPARISON OF EDSS RESULTS WITH OTHER STUDIES AND ALTERNATIVE SELECTION METHODS

This chapter compares and contrasts engineering design studies and alternative-criterion pair selection methods with the results of this work. The studies and methods chosen correspond to the motivations and objectives of this research. Additionally, comments on the results of using EDSS to solve other decision method example problems are given.

A sampling of decision methods that addresses similar problem domains as the EDSS experiments are listed below with their results. Comparison of results between other decision methods and the EDSS decision method means selection of one alternative from a group of alternatives using criteria as an evaluation measurement. In the comparisons of the problem solutions of other decision methods, the EDSS knowledge level used for program data input was always the expert level. The rationale for using the expert level is based on what this research believes the user would have used as a definition of his or her own knowledge level category.

Decision analyses and their results do not lend themselves to traditional validation using mathematical or statistical methods. Traditional validation is comparing experimental results with a known equation or model where parametric results are possible. EDSS does not yield a predictive model which can be used to validate statistical repeatable experimental results, as in traditional validation. To duplicate a decision analysis experiment with statistical accuracy would require a group of subjects with exactly the same set of criteria preferences, the same levels of experience, knowledge levels, and a duplicated ability to quantify risks or confidence levels in a completely deterministic manner. This is functionally impossible.

Accurate validation of results also demands that each new experiment tested use the same set of metrics that was used with previous work. No quantitative set of metrics is known to exist that allows valid comparison and contrasts of different decision analysis methods in a specific problem domain of any description. The best effort presently available is to compare in a qualitative manner the results of this research and what EDSS yields using example problems with that of work of others. One comparison between other design study research and this research is to look at the groups in this experiment that did not use EDSS and the results of other design studies. Comparisons using groups that used EDSS in this research with that of other design studies who use a different problem type requires a number of subjective transformations of information. These transformations are open to criticism, so the reader is advised to not draw more than directional conclusions from the results below.

The first sections discuss engineering decision making and design studies. The second grouping of sections beginning with section 10.4, discusses decision methods that provide alternative selection.

10.1 Comparison with Ad Hoc Decision Making Methods

The ad hoc decision methods used by teams that did not use EDSS for their decision method can be compared with a recent ad hoc mechanical design study. The design study and its video, The Delft Protocol Workshop problem (Cross, 1996), was analyzed by Ullman (1996). The mechanical problem presented to a team of three professional designers/engineers for solving was the design of a commercial product that would allow a conventional backpack to be mounted on a standard mountain bike. The decision-analysis method used by the team of three experienced people was exclusively ad hoc. Alternatives and criteria were listed and preferences were expressed during the design activity.

Two comparisons were made. The first comparison was between the ad hoc methods used by the Delft team and the teams that did not use EDSS. Both groups exhibited classical ad hoc characteristics which included an inconsistent preference model, single-belief model dimension, and an incomplete belief model. The second comparison that was made involved duplicating the decision-making activity of the Delft study using EDSS as the decision-making method. One of the important decisions, where to mount the pack, was duplicated in EDSS. Translation of the details of the decision activity was done as accurately as possible by the author. EDSS indicated that the best location was the same location determined by the team. No other results or metric comparisons are possible from this example. Arguably the comparison of these two groups is completely subjective and qualitative, but it provides a degree of validity to the ad hoc teams in this study - that they were performing within the envelope of expected responses for ad hoc decision making. Therefore there are no grounds for excluding experimental data gathered from the teams in this research. It should also be noted that the decision activity of the Delft team was observably conforming to the motivations of this research. Additionally, this comparison supports the objectives of this research in EDSS's ability to faithfully reproduce the same decision-making results as those achieved from an ad hoc team of this example.

10.2 Comparison with Observations from Design Experiments

Comparison of the findings from decision making in design experiments that used the same design problem, with the findings from this research, is possible. Dwarakanath (1994) shows that 50% of design process time was spent on arguments. Averaging all the teams in the EDSS research for the two metrics of total time, productivity metric #1, and time spent on evaluation, process metric #6, yields a value of 30%. It is suspected that the value from this research's experiment most certainly is on the conservative side or less time than what is reported in Dwarakanath, and what is include as arguments in his study is on the liberal end of the definition. As such it appears that the experiments conducted in this research yielded similar results. It should be noted that the problem used in this research is the same optical device described in Dwarakanath's work. No other comparison can be made between this work and Dwarakanath. From this comparison a conclusion can be reached that this research produced specific category times that are in reasonable agreement with other researchers.

10.3 Comparing with PROSUS

This section compares and contrasts results from the EDSS experiments and appropriate hypotheses from work conducted by Blessing (1994). The central purpose of PROSUS is to improve the mechanical design activity through computer support. The primary method or tool around which PROSUS is built is a design matrix (Blessing, 1994). A design problem and an experiment with two groups, one with PROSUS and one without, were conducted. A portion of this design problem used by Blessing was used in this research. Although specific decision-support aspects of PROSUS are not tested, where appropriate, comparisons between PROSUS and this work is made.

For comparison of the work of Blessing (1994) with this research, only those teams that had high levels of experience (which match Blessing's work) can be used. Those teams are EH1, EH2, OH1, and OH2. Only hypotheses that can be appropriately compared with metrics in this research are compared, explaining the gaps in the hypothesis numbering system listed, which is that used by Blessing.

Blessing's (1994) hypothesis hII.1 is, "Compared to designers working without design matrices (PROSUS), designers using design matrices (PROSUS) generate more concepts." Blessing found, "Compared to designers working without design matrices, designers using design matrices generated significantly more concepts. The designers using design matrices also spend significantly more time on documenting the concepts. The time spent on generating concepts was found to have a negative correlation with the familiarity of designers with design methods." This can be compared with process metric #1 - number of alternatives generated. From replicated data the results of this research are in oppositions to the findings of Blessing. This research records fewer alternatives generated for highly experienced teams using EDSS, compared with teams who were highly experienced and did not use EDSS.

Hypothesis hII.2 is, "Compared to designers without design matrices, designers using design matrices document more arguments and decisions related to the evaluations and selection of their design." The finding of Blessing was, "Compared to designers working without design matrices, designer using design matrices documented significantly more arguments and decisions related to the evaluation and selection of their design." This research had the same findings as Blessing's. From replicated data, those using EDSS documented significantly more arguments (evaluations of alternative-criterion pairs - process metric #3) than those that did not have EDSS.

Hypothesis hA.1 is, "Compared to designers working without design matrices, designers using design matrices have more confidence in their solutions, i.e. are less convinced that there are other concepts or alternatives they would have liked to consider if there had been more time." The finding of Blessing was, "Compared to designers working without design matrices, designers using design matrices have slightly (but not significantly) more confidence in their solution. Designers in both groups, however, would have liked to consider other concepts or alternatives." From replicated data the results of this research were opposite to those found by Blessing. This research found that teams that used EDSS were slightly (but not significantly) *less* confident in their solution, as measured by conviction that their solution was right, perception metric #5, and satisfaction with their solution, perception metric #6.

Hypothesis hA.2 was, "Compared to designers working without design matrices, designers using design matrices have a higher confidence backed up by a good solution, i.e. have a genuine as opposed to a false confidence." The finding by Blessing was, "Compared to designers working without design matrices who had a highly ranked solution, designers using design matrices and having a highly ranked solution had a higher confidence in their solution." The results of this research are in opposition to that found by Blessing. From a single datum, the EH2 team, who used EDSS and had high solution scores, had a lower level of confidence with their solution as measured by conviction that their solution was right, perception metric #5, and satisfaction with their solution, perception metric #6.

Hypothesis hA.3 was, "Compared to designers working without design matrices, designers using design matrices have a higher confidence backed up by a larger number of assessments (evaluation of alternative-criterion pairs: process metric #3)." The finding of Blessing was, "A significant correlation between the level of confidence of (re)designers and the number of documented assessments was found." The results of this research are in opposition to those found by Blessing. From a single datum, the EH2 team, who used EDSS and had high assessments, had lower confidence levels as measured by their conviction that the decision was right, perception metric #5, and their level of satisfaction with the solution, perception metric #6.

Hypothesis hB.1 was, "Compared to the solutions of designers working without design matrices, the solutions of designers using design matrices fulfill more demands." The finding of Blessing was, "No difference has been measured between designers working without design matrices and designers using design matrices in the degree to which their design solutions fulfill more wishes." The results of this research support the findings of Blessing. From replicated data, the quality of the solutions, productivity metric #2, for those teams using EDSS, was equal to those who did not use EDSS.

Hypothesis hB.3 was, "Compared to designers working without design matrices, designers using design matrices address more criteria in the assessment of their concepts." The finding of Blessing was, "Compared to designers working without design matrices, designers using design matrices address more criteria in the evaluation of the concepts. This does not relate to a higher quality product." Using the metric of additional criteria generated, process metric #2, as meaning the same as "address more criteria in the evaluation of their concepts", the results of this research are in opposition to the findings of Blessing. From replicated data, the number of additional criteria generated for teams that used EDSS were less than those which did not use EDSS.

Hypothesis hC.1 was, "Compared to designers working without design matrices, designers using design matrices spend less time on the design process." The finding of Blessing was, " Compared to designers working without design matrices, designers using design matrices spent likely significant more time on their design process, but addressed more issues related to the later phase in the product life cycle. More experienced designers need less time." Using the metric - total time to reach a final decision, productivity metric #1, the results of replicated data from this research support the findings of Blessing. Those teams that used EDSS spent more time reaching a final decision. Using the metric of time spent on evaluation of alternative-criterion pairs, process metric #6, yields the same results, that those that used EDSS took more time evaluating alternative-criterion pairs.

Hypothesis hC.3 was, "Compared to designers working without design matrices, designers using design matrices have a higher quality/design time ratio, i.e. are more efficient." The finding of Blessing was, " Compared to designers working without design matrices, designers using design matrices had a slightly lower ratio quality/design time which was mainly due to higher design time, rather than to a lower quality of the solution. The difference was not significant." Using the metric - quality of solution, productivity metric #2, divided by - total time to reach a final decision, productivity metric #1, and quality of solution, productivity metric #2, divided by - time used for evaluation of alternative-criterion pairs, process metric #6, the results of replicated data from this research support the findings of Blessing.

10.4 Comparison with Pugh's Decision Matrix

Pugh's decision matrix results can be directly compared with the results obtained using the EDSS decision method. The design of an accelerometer switch problem (Otto, 1995) with four alternatives and five criteria was duplicated in EDSS. The same alternative indicated by the use of Pugh's decision matrix with this problem was also indicated by EDSS. No other results or metric comparisons are possible from this example.

10.5 Comparison with Multiattribute Values

The results obtained from a problem using multiattribute analysis and the results using EDSS are directly comparable. This problem is not strictly engineering like the accelerometer problem above, but it is technically oriented and is an alternative-criterion pair evaluation decision problem. Using even criteria weigths, an implicit condition of the problem, for a car purchase problem (Edwards, 1994), EDSS duplicated the author's results to within two percent. This problem had four alternatives and four criteria with all criteria considered as measured. A later version of EDSS, v0.39, than the version used in the experiment was used, and each alternative-criterion evaluation used an optimistic satisfaction value equal to that of the author's attribute value and a pessimistic value one percent lower. This later version of EDSS allows for data input that models value functions. An example of value functions for the Edwards problem is the miles per gallon alternative attribute. If alternative one gets twice as much gas mileage as alternative two, then alternative one must have a higher value function assigned to the attribute of gas mileage. No other results or metric comparisons are possible from this example. The results of this comparison were encouraging because EDSS was able to duplicate the same results as the multiattribute values given in the Edwards problem.

10.6 Comparison with the Analytic Hierarchy Process

The results obtained from a problem using Analytic Hierarchy Process and the results using EDSS are directly comparable. Using the problem of which house to buy (Saaty, 1990), EDSS, version 0.39, duplicated the author's results within seven percent. Again, even though this is not an engineering problem, it has alternative-criterion pair evaluations. All the criteria were considered as Boolean, testing both the accuracy of EDSS to duplicate the problem and matching the problem statement construction. As a comparison of interest, two different cases using EDSS were conducted, one with a complete matrix of alternative-criterion pairs of evaluations (*Decision Space - Problem Completeness*) and one with a sparse matrix (*Decision Space - Problem Incompleteness*). In both cases, EDSS criteria weights were set to those of Saaty, the knowledge level was specified as expert for all evaluations as mentioned previously, and the confidence levels duplicated the values for the author's priority vector as closely as possible using the set of confidence values in EDSS. The complete matrix results from EDSS were within seven percent of those values listed by the author. The sparse matrix comparison produced results within two percent of that shown in the article. As an additional note, EDSS duplicated within two percent the author's results using a sparse matrix. It should be pointed out that in criterion of size of house, with priority vector values of (.754, .181, .065), it should be obvious that house A is the only house that has any value in satisfying the criterion. The other two alternatives provide nearly no contribution towards knowing which alternative is the best. In accordance with this rationale, the sparse matrix case or *Decision Space - Problem Incompleteness,* had only house A information recorded for this criterion. Additionally, it can be seen that the criterion - age of house, with a vector of (.333,.333,.333), contributes no ability to differentiate alternatives. Based on this same rationale, all three of these alternatives were not evaluated for this criterion in the sparse matrix EDSS case. Examples such as these and the accurate results that EDSS produced provide firm validation that a *Decision Space - Problem Incompleteness* evaluation of alternative-criterion pairs of information does not yield inferior results. Both of these EDSS cases were reproduced in less than ten minutes of total time. This small amount of time required for providing decision results from EDSS should be noteworthy. No other results or metric comparisons are possible from this example. This favorable comparison adds support to the motivation and objectives of this research.

10.7 Comparison with Method of Imprecision (MoI)

The decision making method MoI (Scott, 1995) is based on fuzzy sets theory. It purports to allow manipulation of preliminary design information of alternatives and provides for choosing the best overall design from the alternatives. The example given has two alternatives and seven criteria. The MoI method produced alternative preferences for the two alternatives of 0.70 and 0.64 based on a scale of 0.0 to 1.0. EDSS produced the exact same results. This final direct numerical comparison bodes favorably for the ability of EDSS to provide decision results that are consistent with other methods.

10.8 Conclusions

It is concluded that the motivations and objectives of this research were validated. The decision activities observed in this research are in agreement with observations of others. EDSS compares favorably with other alternative-criterion pair decision methods that provide numerical results. One important distinction with these methods and their numerical results is that they assume that the user possesses expert knowledge in evaluations of alternative-criterion pairs. This does not agree with the observed facts. Distinctively, EDSS accounts for differences in knowledge level and provides results based on those differences.

11. CONCLUSIONS AND DISCUSSIONS

11.1 Conclusions

This research has successfully created a decision support method that provides for:

- A separation of knowledge and confidence in the Belief Model of decision making.
- Decision results without complete evaluation of all alternative-criterion pairs.
- Aggregation of preferences from team members.
- A convenient means for investigating decision improvements.

The decision support method successfully created in this research matches ad-hoc and Pugh's decision matrix in sixteen out of 18 metric measurements and also statistically exceeded these methods in two important areas.

- More evaluations of alternative-criterion pairs occurred with teams that used EDSS.
- These same teams showed an increased problem understanding in contrast with teams that did not use EDSS.

11.2 Discussion - Support of Hypothesis

Experiment results that statistically exceeded the performance of ad-hoc and Pugh's decision matrix, the non-EDSS decision methods, are that more evaluations of alternative-criterion pairs occurred with teams that used EDSS, and that these same teams showed an increased problem understanding in contrast with teams that did not use EDSS. Support of the hypothesis is defined as EDSS producing statistically significant improvements in or positive impact on, the decision-making activity. Experiment results which matched but did not statistically exceed the other metrics for the non-EDSS decision methods are apparently a consequence of the simplicity of the experimental problem which precluded the need for extensive solution evaluations or for a rigorous decision method such as EDSS. The four hypothesis areas of productivity, process, perception, and product are discussed below.

11.2.1 Productivity

EDSS statistically matched but did not exceed the non-EDSS decision methods in the two productivity metrics, "total time to reach a final decision" and "quality of the final decision". The greater amount of total time used by teams that used EDSS in this experiment was consistent with the findings of Blessing (1994), that using a computer tool as part of the design process increased the amount of time spent on the activity. Matching the performance of the non-EDSS methods does not lead to the conclusion that the use of EDSS failed to meet the research objectives, and thus invalidate the research motivations.

Even though more time to reach a final decision was required by teams that used EDSS this yielded a better understanding of the problem as seen in Figure 30 (Perception Metric #4 - Understanding of the Problem). This result is wholly consistent with the research motivation of providing an improvement in the decision making activity. For the "quality of final solution" metric there was no statistically significant difference between teams that used EDSS and teams that did not, suggesting that the problem was not demanding enough to require a decision method such as EDSS.

Still unanswered is the question that has emerged from analysis of this research which is whether a more complex problem would produce extensive negotiations among team members and require an optimized or robust decision that would justify the added time required to use a computer decision support tool such as EDSS?

11.2.2 Process

Data for the first two of five process metrics, "the number of additional alternatives created" and "number of additional criteria listed," demonstrated that EDSS matched but did not have any statistically significant improvement or impact that was observable from the experiment with regard to teams that used EDSS. These facts can be understood based upon the observations mentioned above that the problem was not complex and that decision makers settled for a solution that was adequate rather than rigorously exploring the decision space and alternatives.

For the metric "number of evaluation of alternative-criterion pairs," use of EDSS statistically supported the hypothesis and exceeded the use of non-EDSS decision methods. It appears that using EDSS for evaluation of alternative-criterion pairs significantly increases this process value for teams at both experience levels. The conclusion is that teams using EDSS conducted increased evaluations which led to increased problem understanding. This result conclusively meets the research motivation and objective.

For the metric "amount of data used during the design activity," use of EDSS matched the performance of the non-EDSS methods. This result can also be explained by the problem's lack of complexity

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For the fifth process metric, "amount of time spent on evaluation of alternative-criterion pairs," use of EDSS also matched the performance observed in the teams that did not use EDSS. Effectiveness in this context is unquantifiable but it can be conjectured that evaluation time was more effectively used as teams gained greater problem understanding, as is reported in the perception metric #4 below.

11.2.3 Perception

For the first three of seven perception metrics, "control of the decision making process," "usefulness of the groups decision making method or tool," and "ease of use of your decision support method," EDSS did match the perceptions recorded for the non-EDSS methods. It can only be concluded that the lack of problem complexity precluded the need for a decision support system such as EDSS to provide more decision making control, usefulness, or ease of use beyond that provided by an ad hoc process or Pugh's decision matrix.

For the perception metric of problem understanding, perception metric #4, EDSS did support the hypothesis of showing improvement and impact on the decision-making process compared to the non-EDSS methods. This result can be demonstrated to come from the fact that those who used EDSS conducted statistically significantly more evaluations of alternative-criterion pairs of information than those who did not use EDSS. This metric gives strong statistical support for the common notion that if decision makers conduct more evaluations of alternative-criterion pairs they should also have more problem understanding. The support provided from this metric for the experiment hypothesis appears to be independent of problem complexity.

For the perception metrics "conviction about the top decision" and "level of satisfaction with the solution," EDSS matched the performance of the other decision methods used in this research. It appears that the limited negotiations to solve a relatively simple problem did not provide an environment in which EDSS could statistically exceed the other decision methods.

For the final perception metric of "capacity of team members to work together in reaching a decision," EDSS was not identified as supporting the hypothesis but only as matching the performance of other methods. Statistically, the use of EDSS did not support an increased or decreased a sense of teamwork in arriving at a final solution. It can be seen in Figure 33 that teams that had high experience levels reported much less sense of team work compared with less experienced teams. It can be conjectured that the experienced teams using EDSS reported a decreased sense of teamwork due to previous team experiences. They may have expected a certain level of teamwork interaction which using EDSS did not provide.

11.2.4 Product

It appears that in general the users of EDSS expressed satisfaction with the program but did not perceive any single attribute as particularly outstanding. The four product metrics, "EDSS response time," "EDSS better than manual methods," "EDSS ease of use," and "Attitude change after using EDSS," statistically matched but did not exceed expectations. From the data it can be stated that these responses are independent of experience level. The performance of EDSS as a decision product successfully matched expected product levels.

11.3 Discussion - Impact of Criteria Statement Wording on Decision Analysis

No investigation was conducted during this research to indicate any impact on alternative-criterion pair decision making contributed to criteria statement syntax. The importance of criteria syntax for this research comes from two sources. The first source is the mathematics used to develop the Satisfaction Value for EDSS, and the other is the lack of coherent treatment of this subject in alternative-criterion pair decision analysis literature. Criteria statements, constructed with wording that is either Boolean or measured, produce different mathematical formulas. There must be a rigorous treatment of criteria statements if consistent and reliable results are to be obtained when alternative-criterion decision-making methods are used.

11.4 Discussion - EDSS Appropriate Problems and Conditions

Even without statistically confirmed support for the hypothesis for all metrics, EDSS was demonstrated, with one possible qualification, as appropriate for any decision making when evaluation of alternative-criterion pairs is conducted. That qualification is that simple and routine problems must have other requirements, beyond selecting an adequate alternative, to justify the use of EDSS. It is expected that research involving more complex problems, where extreme viewpoints exist and rigorous negotiations are conducted, would indicate that EDSS allows for more optimal alternative selection.

11.5 Additional Discussions

Five variables were not originally identified in the experiment. These may have influenced the reported research outcome. These variables are the version or capabilities of EDSS that were used for the experiment, the complexity level of the problem used in the experiment, the homogeneousness of the team members, the level of EDSS user training, and EDSS implementation.

The version of EDSS program that was used for the experiment allowed only absolute Boolean criteria statements and had no expert calculation methods available. EDSS versions 0.39 and later have both absolute and relative Boolean and measured criteria statements and allow for expert calculation. The early version of EDSS used in the experiment only allowed users to input their evaluations and view the results, and allowed only rudimentary methods, such as what-if investigations. It should be noted that no group with or without EDSS conducted any kind of what-if or sensitivity analysis on their results.

Originally it was thought that a design problem of moderate mechanical complexity would provide research results that would be independent of the problem. This has not been demonstrated. Problem complexity appears to have influenced the experimental results. The effect of the problem complexity on results must be tested and confirmed.

The idea that personality profiles of the team members may influence decision making activities comes from two sources. First, research is presently underway into how personalities impact creativity (Wilde, 1995). Results from this research may have an important influence on decision- making methods for various environments. Secondly, in one of the team sessions a dynamic and aggressive individual appeared to be very influential in that team's activities. Personality factors might be difficult to translate into an experiment variable, but investigation into this subject is warranted.

The level of experience with the EDSS software and the way it was implemented may have influenced the metric results and the outcome of the experiment. These specifics were not separately tested, but based on results of the perception metrics it can be concluded that neither of these adversely impacted the metric results and that they definitely do not negate the research motivation or objective.

Implementation of EDSS as a computer tool, especially in the area of data input and results display, did not affect the results of this research in either a positive or negative manner. This result justifies more investigation into other implementation schemes.

12. RECOMMENDATIONS FOR FUTURE RESEARCH

There are four areas where recommendations are made. These are the areas of: improving the metrics used for measuring decision making improvements, problem complexity, EDSS program changes, and team composition changes. All of these recommendations are targeted towards documenting improvements or positive impacts on decision making with alternative-criterion pair evaluation.

12. 1 Metrics for Measuring Decision Making Improvements

Questions should be added to the existing questionnaire that quantify the effectiveness perceptions of the teams as specified by Fisher (1990).

Possible questions such as:

1. Did your decision method allow for an effective team?
2. Did your decision method empower your team to be effective?
3. Did your decision method prohibit empowerment of your team to be effective?
4. Did you know what qualities made an effective team?

Two variables could be created with these metrics. Those teams that were trained in effective team qualities and those that were not trained.

Another question that is expected to provide more decision-making performance understanding is a problem satisfaction threshold question. A set of questions addressing the possibility that the team may have had an unspecified threshold for a satisfactory problem solution. This threshold may have been a determining factor in the final decision-making solution or activities. It may have been an implicit criteria. Discovering implicit criteria should provide more performance understanding.

12.2 Problem Complexity

A more complex problem should be tested against a simple problem that is similar to the one in this research. In a two level factorial experiment the high value would be the complex problem and the low value the simple problem. It is expected that a more complex problem would provide stronger justification for use of a decision support method or tool such as EDSS. It is also expected that the present set of metrics would be sufficient for this factorial experiment.

12.3 EDSS Program Areas

There is a tremendous amount of research into possible graphical decision display performance improvements. Determining what decision making performance changes occur with various graphical information displays. The whole field of Human Factors Engineering of software and information display awaits research for discipline of technical decision making.

EDSS as a decision tool and the data base that is created by its use have tremendous potential for giving understanding into the process of decision analysis. As an example: application of statistical tools to the data set can reveal if one person is dominating the decision because of the sheer number of alternative-criterion pairs that have been evaluated by the dominating person. Data analysis can reveal if there is a subset of criteria that is influencing the decision results. Data analysis can reveal if there is only a subset of alternatives that also received the majority of the evaluations.

The version of EDSS that was used in the experiments had only a Boolean absolute alternative-criterion comparison method. The latest version has added, Boolean relative and measured comparison methods, and an expert calculation. As explained previously, this expert calculation greatly increases the usefulness of EDSS as a decision support method. Testing of this latest version of EDSS, including the expert capabilities, is needed in a two level factorial experiment with the high value being the latest version of EDSS and the low value the version used in this research. It is expected that more capabilities would provide stronger justification for use of more rigorous decision-support methods than available in the present version of EDSS. Additionally, support for the implication that more robust decisions are more desirable than ones where no sensitivity verification was conducted, would be possible with this experiment. It is also expected that the present set of metrics would be sufficient for this factorial experiment.

The EDSS algorithm investigation areas include, criteria modeling and capture, criteria weighting capture, Satisfaction Value algorithm, Knowledge and Confidence capture, and sensitivity analysis.

12.4 Team Member Composition Areas

Recent research (Wilde, 1995) into assembling teams with a Myer-Briggs Type Indicator has implications for assembling teams for effective decision making. Teams composed of different indicator combinations should be tested. Presently the appropriate factorial level of this kind of experiment is unclear. It is conjectured that certain team mixes would provide improved decision performance.

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APPENDICES

Appendix 1

Experience Level Questionnaire

EXPERIENCE LEVEL QUESTIONNAIRE

______________________________ ____________________ ______________

Name (print) I.D. number Date

General Design experience

1. From your past **employment** (from high school years to present), count the number of times that your job required you to design/create/build any type of mechanical devices/products that did not previously exist or significantly redesigned/modify any type of mechanical devices/products. (The assumption is that the need for you to engage in this activity was prompted by a 'design problem' that had to be solved and a readily available solution did not exist)

Circle the number of times that you engaged in this 'design problem' solving activity.

---0---1---2---3---4---5---6---7---8---9---10---11---12---13---14+

2. From your past at **home/school/community/other places** where you were not an employee, count the number of times that you designed/created/built any type of mechanical devices/products that did not previously exist or significantly redesigned/modified a mechanical devices/products. Examples are: model airplanes, modifying a bicycle, or student design projects.

Circle the number of times that you engaged in this 'design problem' solving activity.

---0---1---2---3---4---5---6---7---8---9---10---11---12---13---14+

Group Collaboration experience

Circle the number of times that you have worked on a design `team' project from either of the two areas above and where a collaborative design decision was required. A collaborative design decision means that the group had to reach a united decision.

---0---1---2---3---4---5---6+

Definitions: The word "device/product" used above can range from very simple to complex but must be 'predominately' mechanical in nature. The word "mechanical" is meant to be very broad in meaning.

Appendix 2

Experiment Problem Package

Design of the Swivel Joint of a Wall Mounted Mechanism

Design the swivel joint of a mechanism that is at the bottom of a optical device guiding column mounted to a wall (see drawings 1, 2, and 3).

The height of the optical device can be adjusted on the guiding column by means of a slider. The column is a square tube (AlMgSi0.5, 25 mm square, thickness 2 mm). The device should be able to slide at least 175 mm along the column. A mechanism to lock the slider exists (this mechanism is not shown in the drawings, in drawing 3 also the optical device is not shown).

The swivel joint should be able to carry the weight of the optical device (the mass is about 2 kg, the distance between the column's axis and the center of gravity of the optical device is about 100 mm). The swivel joint should enable the column to swivel (-15° to $+15^{\circ}$ in α-direction and 0° to $+15^{\circ}$ in β-direction). A combination of movements in α and β direction should be possible. The swivel axes and column axis should intersect in one point close to the lower end of the column. This point should be at a distance of 150 mm from the wall. Any movements of the column, other than those specified above should be avoided if possible.

The mechanism is a one-off product to be manufactured as economically as possible with the shop equipment located in the basement of Rogers Hall. The production technologies available in this shop are described "Description of the shop equipment located in the basement of Rogers Hall".

It is required to produce a paper layout drawing of the swivel joint and adjacent parts including major dimensions (similar to drawings 5, 7, 9). These drawings should adequately define the geometry of the swivel joint.

Initial 'Starter set'

Three intial 'starter set' alternatives for the swivel joint have already been generated. These alternatives are shown on drawings 4 - 9 (the optical device is not shown in these drawings). You may use these alternatives, change them or generate new alternatives.

Furthermore three initial 'starter set' criteria have already been created. These criteria are:

1. **The swivel joint can carry the weight of the optical device.**
2. **The swivel joint enables the column to swivel in α- and β-direction.**
3. **Both swivel axes and the column axis intersect in point close to the lower end of the column.**

You may use these criteria for your decision analysis, change them, or generate new criteria.

The 'status quo' is alternative 1, this alternative is not satisfactory, because the swivel axes and the column axis do not intersect in one point. The optical device undergoes therefore an unwanted altitude change during swiveling in β-direction.

If you have any questions, please ask the experiment leader at any time.

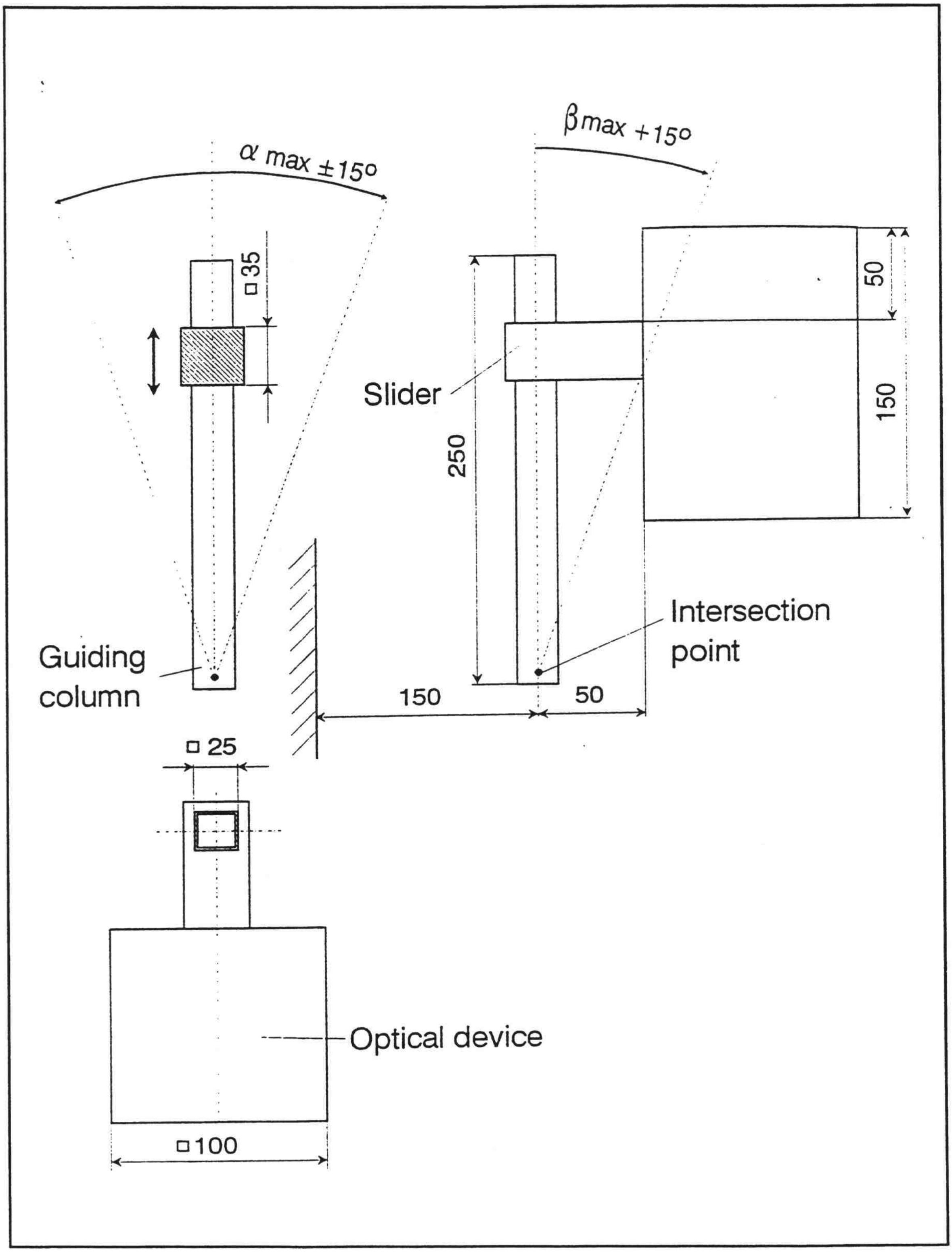

Figure A1. Drawing 1: Optical Device on Column

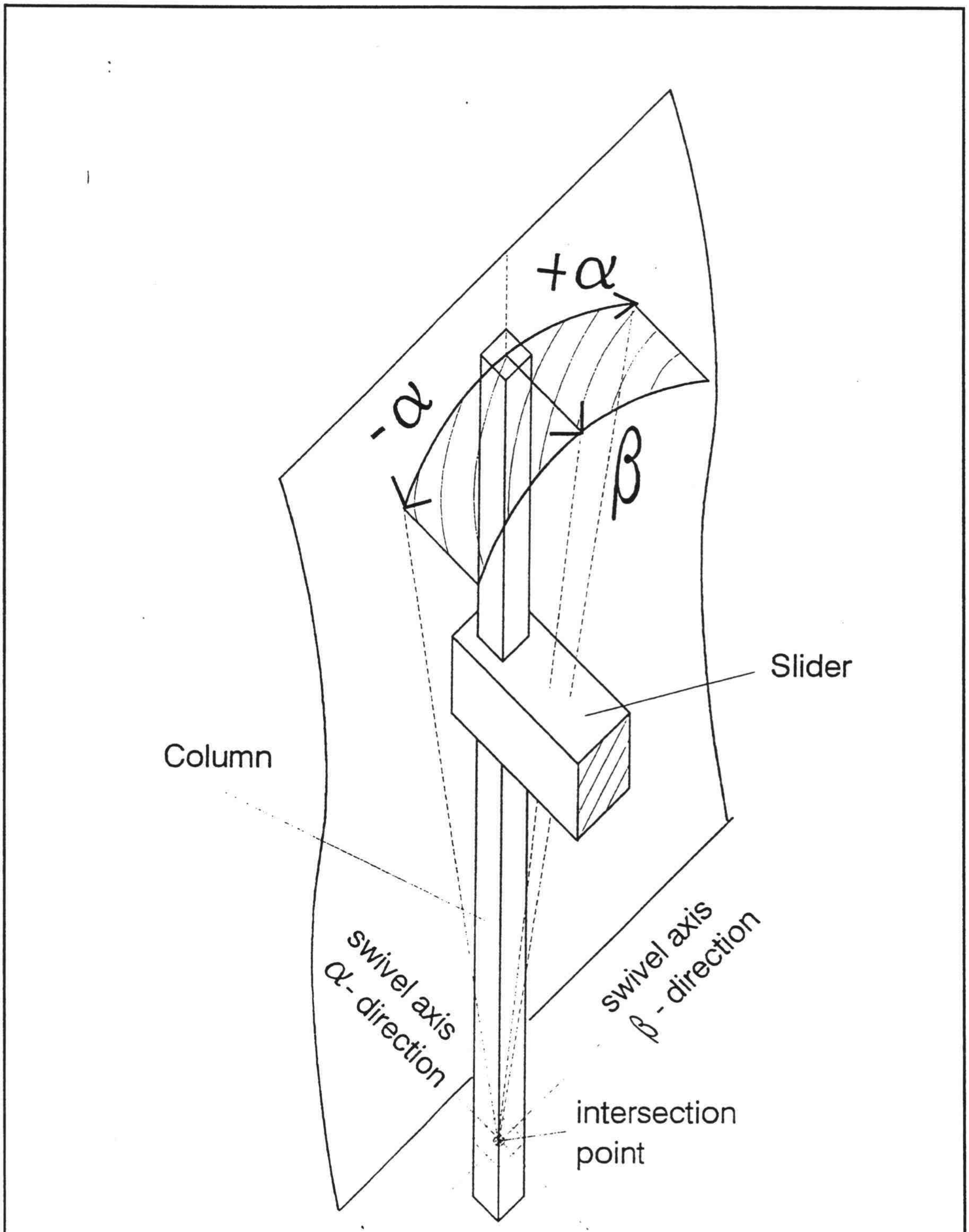

Figure A2. Drawing 2: Angle alpha and beta

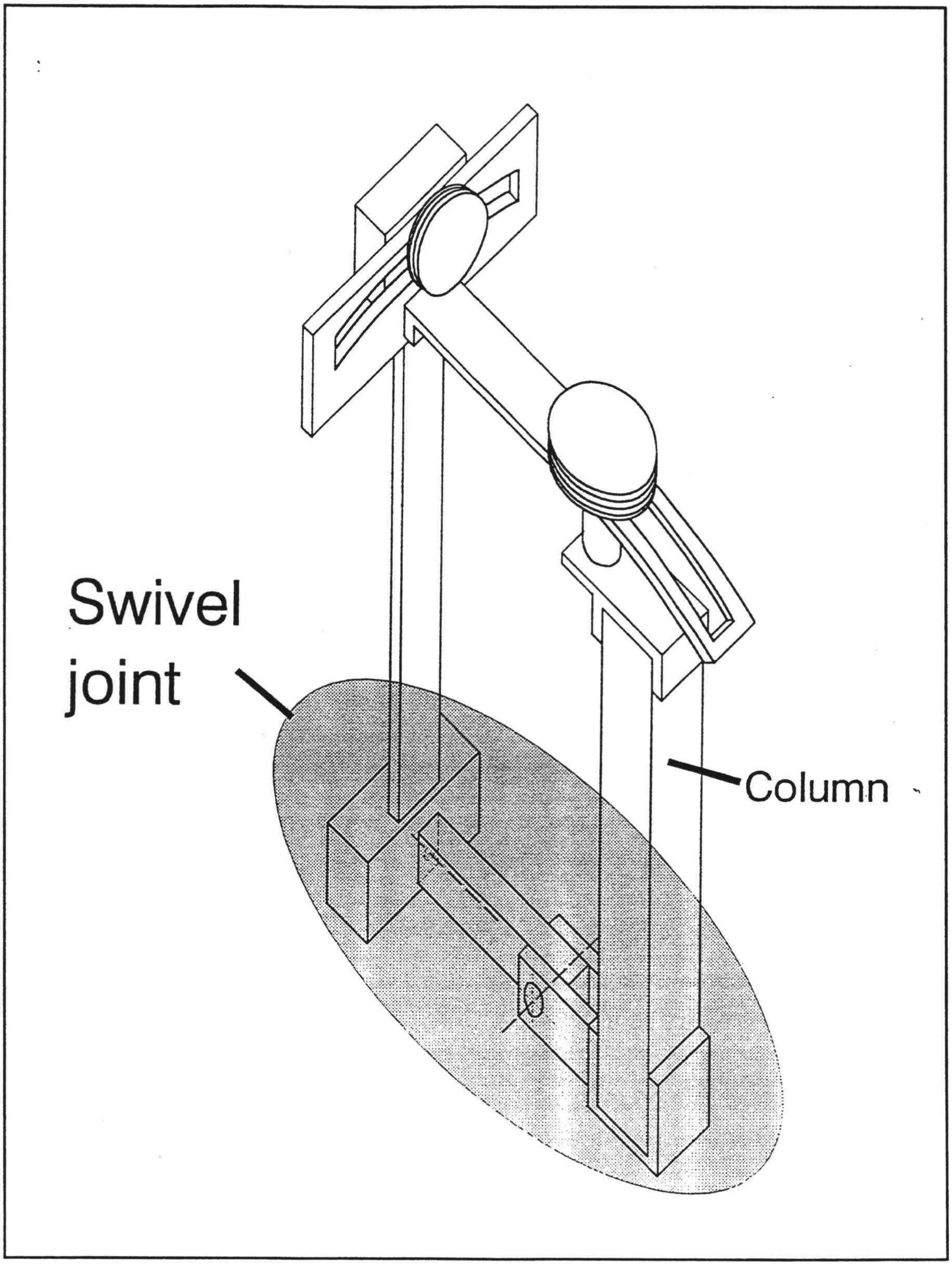

Figure A3. Drawing 3: Swivel Joint

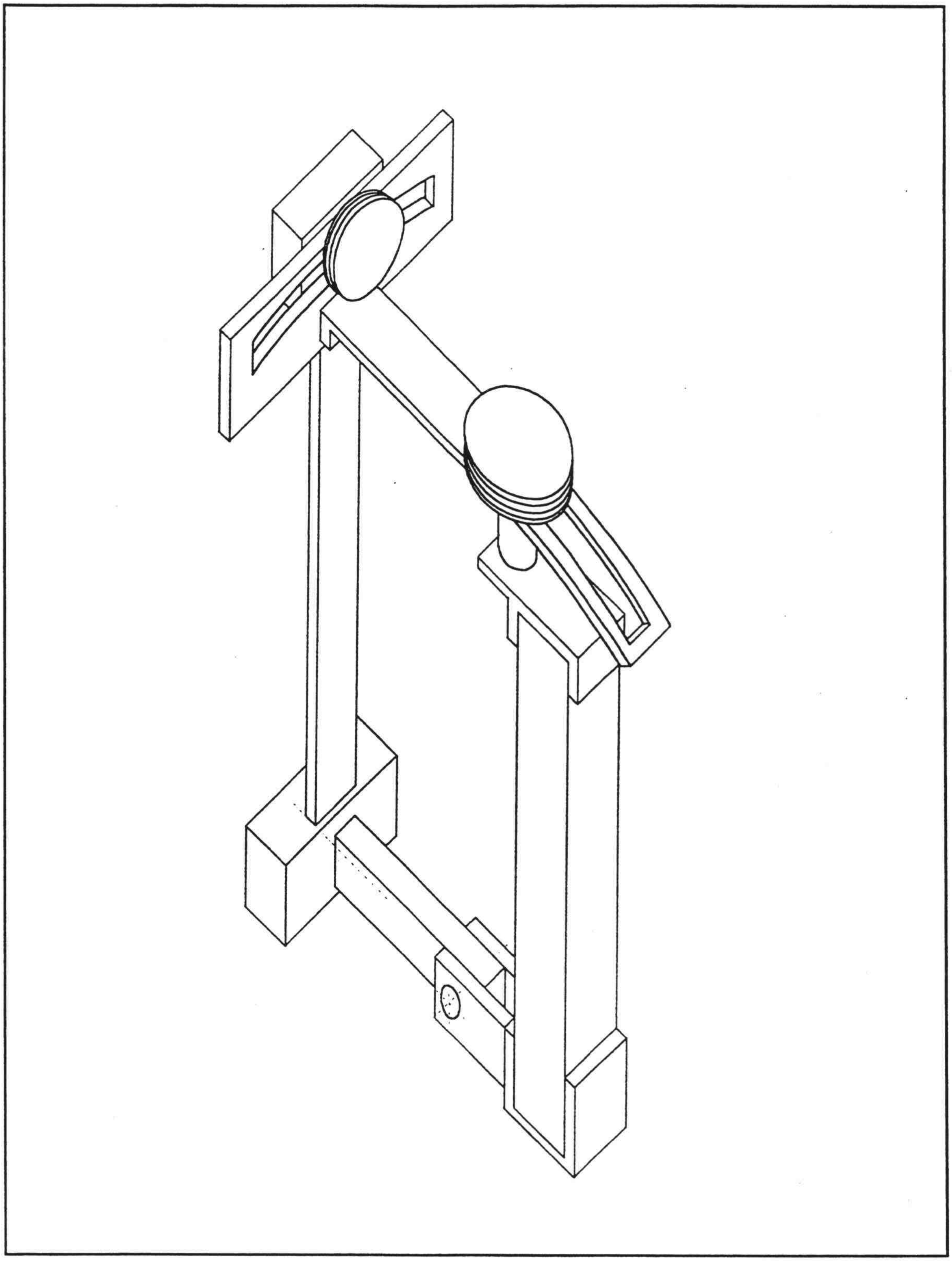

Figure A4. Drawing 4: Alternative 1

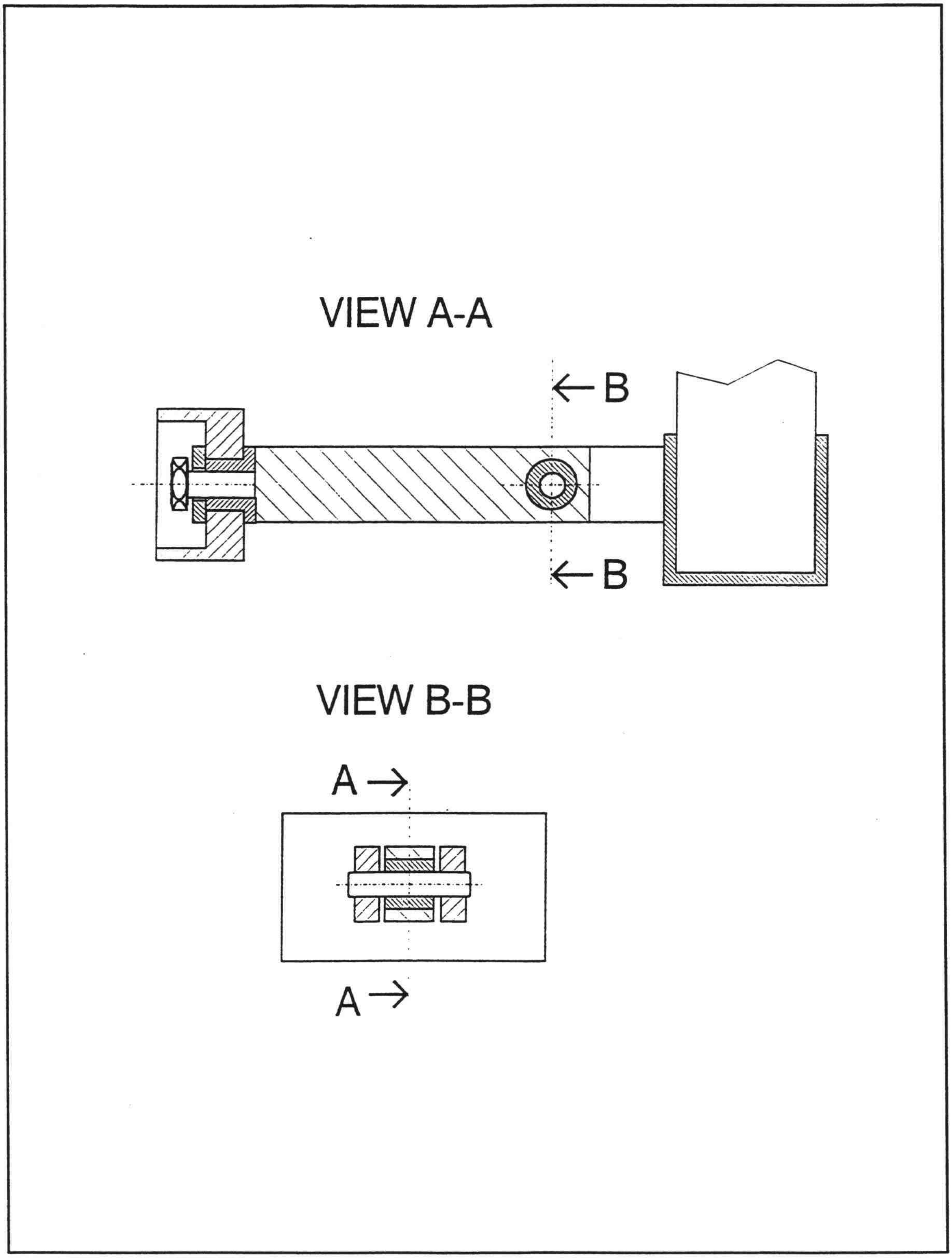

Figure A5. Drawing 5: Alternative 1 View A-A and B-B

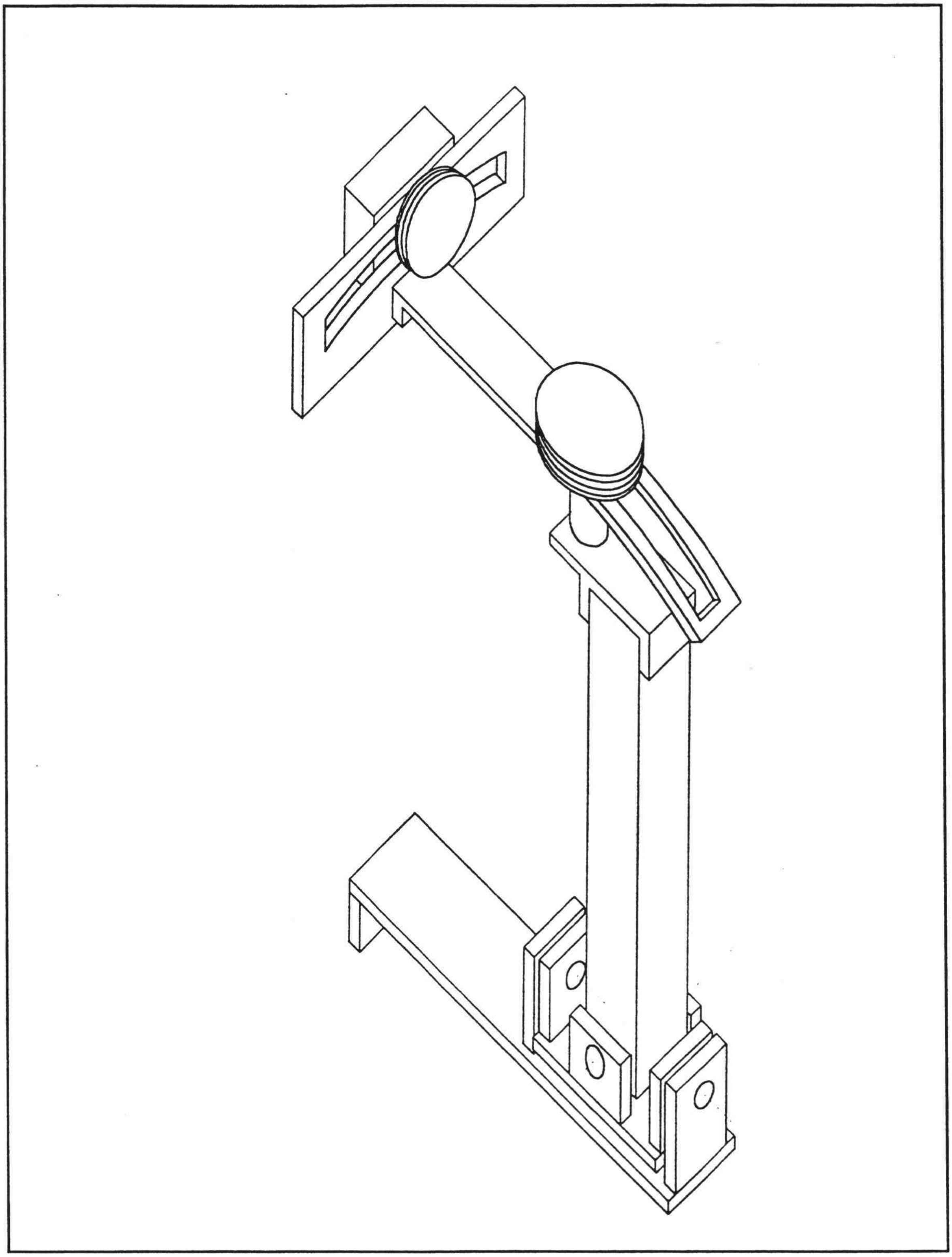

Figure A6. Drawing 6: Alternative 2

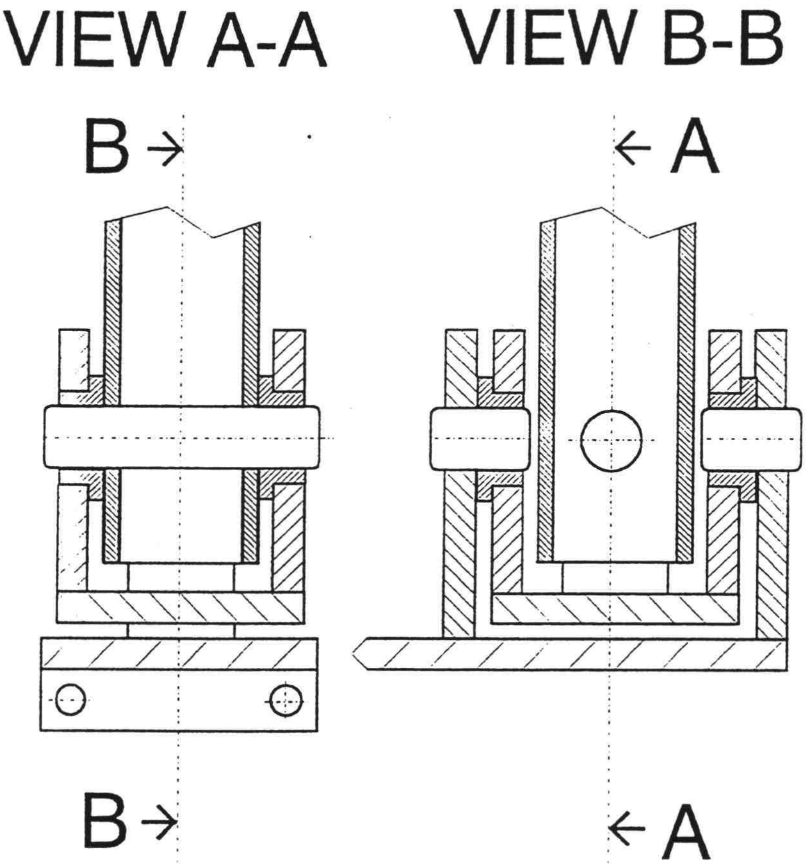

Figure A7. Drawing 7: Alternative 2 View A-A and B-B

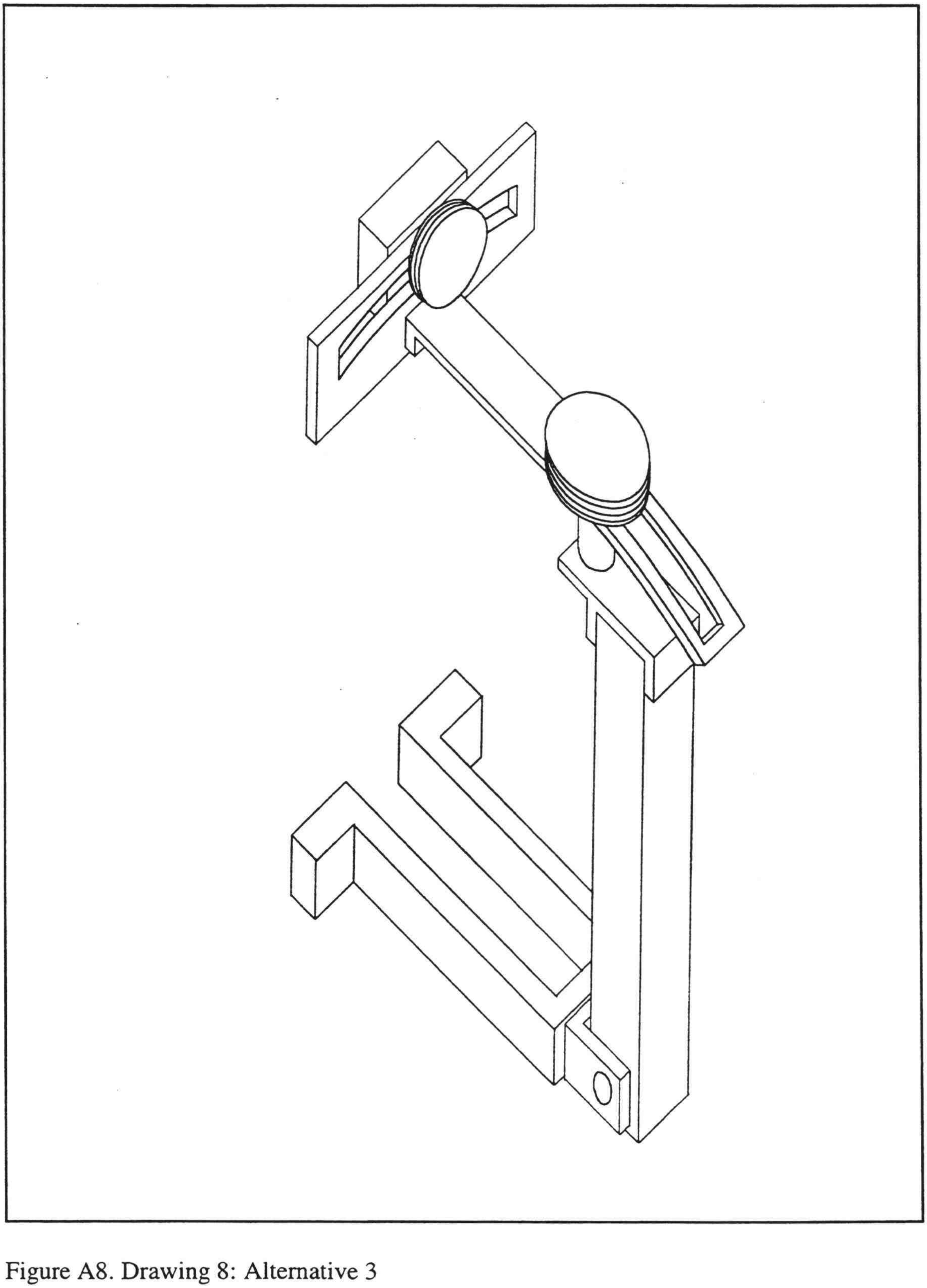

Figure A8. Drawing 8: Alternative 3

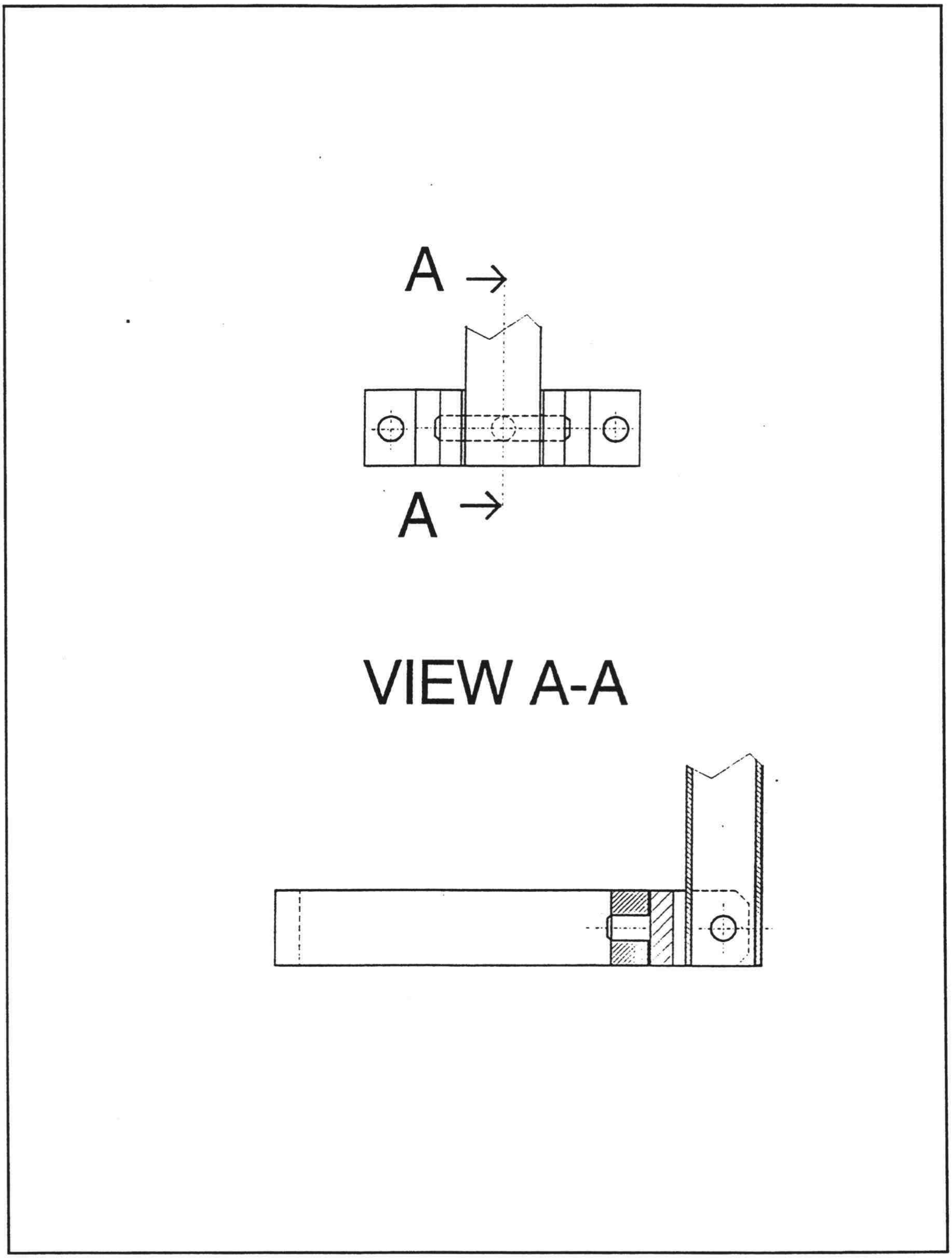

Figure A9. Drawing 9: Alternative 3 View A-A and B-B

Appendix 3

Data Recording Sheet for Metrics

METRICS used in the ANOVA data analyiss

The following four areas will be measured
Productivity: evaluate the productivity (design results) of idea processing during design decision analysis activities
Process: evaluate the impact of factors on the decision making process
Perception: evaluate the impact on the decision makers
Product: evaluate the technical merits of EDSS

Team___________, file:________, evaluator:____________________, date:___________

1. **Productivity:** evaluate the productivity (design results) of idea processing during design decision analysis activities

1.1Time to reach decision.
Metrics = time

1.2 Quality of decision (output is acceptable to customer).
Product of decisions (output) will have to be judged by a panel, with points given. What factors give better decision results.
Metrics = points

2. **Process:** evaluate the impact of factors on the decision making process

2.1 Number of alternatives created.
What factors gave a greater number of alternatives created?
Metrics = count of alternatives.

2.2 Number of criteria generated.
What factors gave a greater number of criteria or objectives generated?
Metrics = count of criteria generated.

2.3 Total number of analyses done for the complete problem, i.e. number of alternative-criteria pairs evaluated over the complete design problem.
What factors gave a greater number of alternative-criteria paris that were evaluated.

Metrics = count.

2.4 Number of analysis stored on any means
Metrics=count

2.5 Amount of data used.
Concept is what additional data comes into the design space that aids in decision analysis. We'll have to determine some way of counting data, right now we are still thinking about this.
Metric = count.

2.6 Time spent on evaluation phase, dealing with Knowledge and Confidence values for Alternative-Criteria pairs using EDSS or the equivalent, for decision making.
Metric = time.

Perception: evaluate the impact on the decision makers

3.1 Control of decision making.
Did you have control of the decision making process? Control means that your input concerning the direction of the design process as a team member was equally considered with other team members and there were no forms of inequality in the decision making process.

3.2 Usefulness of EDSS.
Usefulness of EDSS during the problem activity

3.3 Ease of use of EDSS.
Ease of use of EDSS during the problem activity

3.4 Understanding of the problem (insight).
While working on this design activity and contrasting it with other similar past design activities

3.5 Conviction that the decision is right, confidence.
Conviction that the top three (3) decisions (the decisions that had significant impact on the design activity outcome) were right/correct/best possible/etc.

3.6 What factors contributed to the sense of satisfaction with the solution?
Even though the top three (3) decisions (the decisions that had the most significant impact on the design activity outcome) may have been right, you may still not be satisfied with the decisions

3.7 Capacity of team members to work together in reaching the decision.
For the top three (3) decisions (the decisions that had the most significant impact on the design activity outcome)

Product: evaluate the technical merits of EDSS

4.1 Response time.
Compared to what I expected, was the use of EDSS fast enough in returning responses to the screen?

4.2 Computer better than manual.
Compared to manual methods, was the use of EDSS a better method?

4.3 Ease of use.
Using EDSS was the easiest decision support method I have ever used.

4.4 Attitude change towards the (use of a computer decision support tool) task and towards computers.
Using EDSS changed my attitude to one of always wanting to use a computer Decision Support System tool for future decisions.

Appendix 4

Questionnaire Responses from Teams

QUESTIONNAIRE RESPONSES

TEAMS THAT USED EDSS

4a. Briefly explain why you feel you had (less/more) overall understanding of the problem.

1. It is hard to consider a problem in such a short amount of time for this project.
2. Problem required implementing a device that I was familiar with.
3. Given fixed problem with clear dimensions and criteria. Not a lot of room for questions to arise.
4. Easy to visualize and easy to find out what we want to accomplish.
5. I submitted the idea we followed, so I saw it in my head.
6. Was able to visualize the problem.
7. Maybe because I have not much time to do some research on this project. I do need more time.
8. You had the opportunity to check each alternative to criteria.
9. Less because of no preconceived ideas.
10. The drawing handout was difficult to decipher.
11. Maybe need actual first design and have operator explain problems.
12. The criteria were easily defined. (i.e. many "musts and few "wants") The more criteria, the easier to design.

5a. Briefly explain why you feel the top three decisions were (wrong/unacceptable) or (right/ acceptable).

1. They seemed to fit in with the generally accepted way that we considered the problem.
2. My "gut feel" about what would work was supported by the subsequent decisions.
3. The top 3 decisions were acceptable because they met the criteria best.
4. Acceptable in the sense it gave a good criteria for comparison.
5. I liked my own idea, and the computer verified this.
6. Could tell they solved the problem.
7. Gut feeling, they fit the requirements best.
8. Because we only considered four alternatives.
9. Right/Acceptable: They filled all requirements and were cheap and easy to manufacture
10. People weight ideas differently.
11. Many alternatives are right/acceptable, we just had to pick the best one out of them.
12. The top three decisions were made with little or informed knowledge and likely confidence. Even though my knowledge was low, my confidence reflected my sureness.

6a. Briefly explain why you were (dissatisfied) (satisfied) with these decisions.

1. The outcome seemed to be based on the ease of assembly. I was satisfied because of the limited opportunities.
2. Felt the product had it's weaknesses, but it's overall strengths made it the best decision.
3. I believe the final choice was the correct one since it met all the criteria and had the edge since it was easier to manufacture than its closest rival.

4. Because our solution came out from alternative #3 which made much more sense then the other two alternatives.
5. I (again) liked my own idea, so EDSS agreeing was good.
6. Solved the problem.
7. I think it met team decisions.
8. My personal choice was the team choice.
9. Because I feel EDSS went my way.
10. The design chosen wasn't the one I preferred, thanks to EDSS, but would still work.
11. We couldn't come to an agreement. Let the computer decide.
12. My individual decisions were consistent with the groups.
13. Not a lot of indepthness in the criteria. They all came out so close.

7a. Briefly describe your observations about the level of teamwork you observed while reaching decisions.

1. We all seemed to work well together. I felt everyone had a say in the final product.
2. Team worked well together, but all were a little (I believe, at least for me) bit inhibited by the "stage".
3. I would consider extreme to harsh a word so I picked moderate. The team worked well together in my view. Each of us came up with ideas and contributed and got on with the job well.
4. They both discussed in much more detail. I had not much to input.
5. We all put our thoughts into the computer, and were able to agree on points. The other members gave ideas I hadn't thought of.
6. Team asked questions of each other, explained answers and included everyone.
7. Knowledge of individual.
8. With two people it was easy teamwork.
9. Diverging team opinions.
10. We each came up with designs, and had the computer pick the best one.
11. Good ideas. Just couldn't come to complete agreement on result.
11. We both discussed pros and cons. There was no "my design is better" or "my alternatives best" feeling. We reasoned decisions out in a logical way.
12. No friction, good input of ideas, not afraid to disagree or question each other.

14. Is there anything else you would like to say about your experience using EDSS in the decision making process.

1. It seems it would have been better used one at a time instead of with a group. I liked the program though.
2. It was really helpful in clarifying the importance of the criteria and finding the best alternative.
3. It is very handy.
4. I've never used anything before. This was good.
5. Sped up the process of evaluating each team members opinion of alternatives and deciding on the best one.
6. I do like it. It make decision a lot more easier then I think.
7. Allows for everyone input into design process. Lets no one take control.
8. No.

9. The ideas of the program were good. The user interface was not very good.
10. It was hard to decide a confidence level. And the design problem had narrow alternative options so all designs ended up neck and neck. It came down to little things and a gut feeling to decide between the top two!
11. In a group setting, completely understanding the problem as well as being consistent was very important. Other decision matrix types have similar problems so this doesn't increase my understanding of the problem or help me be consistent. It does help me evaluate or have a support my gut feeling or the decision. Also it would help if you had some way of showing the knowledge and confidence points of all the alternatives rather then checking them individually. Also, for this design, I thought we were focusing more on the differences rather then how well it met our criteria. The alternatives were very close.

QUESTIONNAIRE RESPONSES

TEAMS THAT DID NOT USE EDSS

4a. Briefly explain why you feel you had (less/more) overall understanding of the problem.

1. The problem was hard to understand at first, but once it was understood it was about the same.
2. I understood in general what needed to be made, but was not sure about how good the product had to be, accuracy,strengtht....
3. I think the problem is presented in a very clear way.
4. The problem was conceptual on paper, not hands on with an actual device.
5. It took some time to understand the problem statement, and in the past the problem was not just on paper, but hands-on.
6. I had about the same overall understanding of the problem. I generally got more comfortable with the problem through further information and exploration of the problem.
7. Less in the understanding that I never actual got to see the problem, more that there was someone to answer questions.
8. Once I was able to picture the problem I understood it and immediately got ideas.
9. I haven't done many design problems, so I don't have much to compare it with.
10. The brief was laid down specifically and there were only certain limitations to work within.
11. Less: No samples of column optical device, no samples of materials from which to make products.

5a. Briefly explain why you feel the top three decisions were (wrong/unacceptable) or (right/ acceptable).

1. We met the outlines of the customer requirements with or final idea.
2. We decided to make it sturdy. Maybe more than necessary, but we are only making one and want it to last.
3. There are somehow and somewhat ????? in another new idea. It seems the decisions are fit the requires.
4. Decision used the knowledge at hand, along with our intuition and experience.
5. I thought the top three ideas were feasible and good solutions. I would not say that they were the only three good ideas, but I think they would have worked.
6. Our three decisions met our customer requirements and also our engineering requirements. These decisions were the best concepts out of our spectrum that fit the problem.
7. They were acceptable because we tried to exhaust solutions and took the best that seemed to work.
8. We looked at our criteria and the top two met every criteria.
9. They fit all the requirements of the problem.
10. The decisions of being able to make the parts here, the cost and the limitations being met acceptable because we agreed that these were important for the customer from the criteria stated.
11. We eliminated ideas on the basis that they would be difficult to manufacture or to

costly. One idea although conceivable involved buying 24 extra items that would not be needed.

12. It satisfied the requirements, we all agreed and had no arguments over the decision, and no other ideas looked better.
13. We chose the best possible solution given the details of our analysis.
14. Right/Acceptable: Used decision matrix, had three people with different strengths.
15. The criteria became clearer as we progressed.

6a. Briefly explain why you were (dissatisfied) (satisfied) with these decisions.

1. We came up with a group consensus and we seem to have come up with a workable solution.
2. I think we improved upon the design ideas we were given.
3. Overall, all the requirements at customer are met and it seems easy to manufacture.
4. In the time allowed we examined the problem as in depth as possible.
5. I would like to know more about machining parts so I felt better about some of the decisions we made.
6. I felt our decision was the best possible solution to the problem at hand that incorporated both the customer requirements and engineering requirements.
7. There must be a better way.
8. I fell that the decision we choose was the best at meeting the criteria all around.
9. I'm satisfied, yet I felt like I needed to design something new.
10. They seemed to fit what we think and what was stated by the criteria.
11. I was satisfied with the design as I feel it could be built by the machinery down stairs. Also, no extra parts (specialized) will have to be ordered.
12. Felt we needed more ideas and a wider variety of products to be used. Thought there would be a better idea that could have been used.
13. There were some deeper, "number crunching" things that could have been done.
14. Satisfied: Decision matrix, expertise of members.
15. It was the best alternative. I believe we worked through the alternatives very well.

7a. Briefly describe your observations about the level of teamwork you observed while reaching decisions.

1. The teamwork level was high. We all were in a no-pressure situation and we all realized this.
2. We discussed options and made decisions together.
3. It will has some disagreements. However, after modify ????? idea and reach our decision.
4. Teamwork was hampered by lack of communication due to the unfamiliarity with the team members.
5. I thought we all gave each other time to contribute, and I think that we worked off of each others ideas.
6. The team worked together not only on making the decision but also informing other teammates on the aspects of a concept.
7. We worked together well but had separated or slow decisions we all had to do it before deciding.
8. We all built off ideas from each other.

9. We all put in our own words and ideas to evaluate the alternatives and criteria to solve the design problem.
10. The level of teamwork was very good. We discussed different ideas and asked questions of each other.
11. The level of enthusiasm was lacking when tackling the problem. However we did work well together with no major conflicting ideas.
12. We were not focused. We had minimal ideas and were stuck on one idea.
13. There was equal understanding, respect, and communication for each others ideas.
14. Had recorder, idea generator, draftsperson, and consensus decision making.
15. This was a good team. Somehow we knew that each had expertise to contribute. No one dominated.

10. Is there anything else you would like to say about your experience using your decision support method in the decision making process.

1. I didn't think much about our method until doing this form.
2. It is good because it forces us to ??????? or do something in a short period of time. Over time, our decision making efficient will get better and better.
3. I enjoyed it.
4. I want to use the EDSS system, just for the experience and to see how it works.
5. I felt that I could have been more enthusiastic about the problem. It's late on Friday.
6. Decision matrices are usually a more formal approach then I prefer. I usually perform a similar dynamic method in my head.

Appendix 5

Questionnaire for Teams That Have EDSS as the Decision Method

ENGINEERING DECISION SUPPORT SYSTEM EVALUATION

1. Control means that your input concerning the direction of the design process as a team member was equally considered with other teams members and there were no forms of inequality in the decision making process. Which one of the following best represents your control of the decision making process? *(Circle one number)*

    1 I was unable to exercise any control
    2 I was able to exercise a little control
    3 I was able to exercise a moderate amount of control
    4 I was able to exercise a large amount of control
    5 I was able to exercise a nearly unlimited amount of control

2. Rate the usefulness of EDSS. *(Circle one number)*

    1 EDSS was completely useless
    2 EDSS was somewhat useless
    3 EDSS was neither useful nor useless
    4 EDSS was somewhat useful
    5 EDSS was completely useful

3. Rate the difficulty or ease of using EDSS during the problem activity. *(Circle one number)*

    1 EDSS was extremely difficult to use
    2 EDSS was difficult to use
    3 EDSS was neither difficult nor easy to use
    4 EDSS was easy to use
    5 EDSS was extremely easy to use

4. Which one of the following best describes your experience while working on this design activity as compared to work with other similar design activities. *(Circle one number)*

    1 I had much less overall understanding of the problem
    2 I had less overall understanding of the problem
    3 I had about the same overall understanding of the problem
    4 I had more overall understanding of the problem
    5 I had a much more overall understanding of the problem

    4a. Briefly explain why you feel you had (less)(more) overall understanding of the problem.

(PLEASE TURN THE PAGE)

5. Which one of the following best describes your conviction that the top three decisions (the decisions that had significant impact on the design activity outcome) were or were not right/correct/best? *(Circle one number)*

   1 The decisions were completely wrong/incorrect/worst possible
   2 The decisions were unacceptable
   3 The decision were neutral, neither unacceptable nor acceptable
   4 The decisions were acceptable
   5 The decisions were completely right/correct/best possible

   5a. Briefly explain why you feel the top three decisions were (wrong/unacceptable) or (right/acceptable).

6. Please indicate your level of satisfaction or dissatisfaction with the decisions. *(Circle one number)*

   1 I am extremely dissatisfied with these decisions
   2 I am dissatisfied with these decisions
   3 I am neutral about these decisions
   4 I am satisfied with these decisions
   5 I am extremely satisfied with these decisions

   6a. Briefly explain why you were (dissatisfied) (satisfied) these decisions.

7. Which one of the following best describes your observations about the ability of the team members to work together in reaching the decision. *(Circle one number)*

    1 I observed an extreme lack of team work
    2 I observed a moderate lack of team work
    3 I am neutral about the level of team work
    4 I observed a moderated amount of team work
    5 I observed an extreme amount of team work

7a. Briefly describe your observations about the level of teamwork you observed while reaching decisions.

8. Compared to what you had expected, please rate the speed of EDSS in returning responses to the screen. *(Circle one number)*

    1 EDSS was extremely slow
    2 EDSS was slower than I expected
    3 EdSS was about what I expected
    4 EDSS was faster than I expected
    5 EDSS was extremely fast

9. Compared to manual methods, which one of the following best describes your opinion of EDSS. *(Circle one number)*

    1 EDSS was definitely worse than manual methods
    2 EDSS was somewhat worse than manual methods
    3 EDSS was about equal with manual methods
    4 EDSS was somewhat better than manual methods
    5 EDSS was definitely better than manual methods

(PLEASE TURN THE PAGE)

10. Please indicate if you strongly agree **(SA)**, agree **(A)**, neither agree nor disagree **(N)**, disagree **(D)**, or strongly disagree **(SD)** with each of the following statements. *(Circle one number for each)*

	(SA)	(A)	(N)	(D)	(SD)
a. Using EDSS was the easiest decision support method I have ever used	1	2	3	4	5
b. Using EDSS changed my attitude to one of always wanting to use a computer Decision Support System tool for future decisions.	1	2	3	4	5

12. In which group were you?

_________________________GROUP

13. Where you person number: *(Circle one)*

1 ONE
2 TWO
3 THREE

14. Is there anything else you would like to say about your experience using EDSS in the decision making process?

(THANK YOU FOR YOUR COOPERATION)

Appendix 6

Questionnair for Teams That Did Not Have EDSS as the Decision Method

DECISION SUPPORT EVALUATION

1. Control means that your input concerning the direction of the design process as a team member was equally considered with other teams members and there were no forms of inequality in the decision making process. Which one of the following best represents your control of the decision making process? (Circle one number)

    1 I was unable to exercise any control
    2 I was able to exercise a little control
    3 I was able to exercise a moderate amount of control
    4 I was able to exercise a large amount of control
    5 I was able to exercise a nearly unlimited amount of control

2. Rate the usefulness of your decision support method. (Circle one number)

    1 Our decision support method was completely useless
    2 Our decision support method was somewhat useless
    3 Our decision support method was neither useful nor useless
    4 Our decision support method was somewhat useful
    5 Our decision support method was completely useful

3. Rate the difficulty or ease of using your decision support method during the problem activity. (Circle one number)

    1 Our decision support method was extremely difficult to use
    2 Our decision support method was difficult to use
    3 Our decision support method was neither difficult nor easy to use
    4 Our decision support method was easy to use
    5 Our decision support method was extremely easy to use

4. Which one of the following best describes your experience while working on this design activity as compared to work with other similar design activities. (Circle one number)

    1 I had much less overall understanding of the problem
    2 I had less overall understanding of the problem
    3 I had about the same overall understanding of the problem
    4 I had more overall understanding of the problem
    5 I had a much more overall understanding of the problem

    4a. Briefly explain why you feel you had (less)(more) overall understanding of the problem.

(PLEASE TURN THE PAGE)

5. Which one of the following best describes your conviction that the top three decisions (the decisions that had significant impact on the design activity outcome) were or were not right/correct/best? (Circle one number)

1 The decisions were completely wrong/incorrect/worst possible
2 The decisions were unacceptable
3 The decision were neutral, neither unacceptable nor acceptable
4 The decisions were acceptable
5 The decisions were completely right/correct/best possible

5a. Briefly explain why you feel the top three decisions were (wrong/unacceptable) or (right/acceptable).

6. Please indicate your level of satisfaction or dissatisfaction with the decisions. (Circle one number)

1 I am extremely dissatisfied with these decisions
2 I am dissatisfied with these decisions
3 I am neutral about these decisions
4 I am satisfied with these decisions
5 I am extremely satisfied with these decisions

6a. Briefly explain why you were (dissatisfied) (satisfied) these decisions.

(PLEASE GO ON TO THE NEXT PAGE)

7. Which one of the following best describes your observations about the ability of the team members to work together in reaching the decision. (Circle one number)

1 I observed an extreme lack of team work
2 I observed a moderate lack of team work
3 I am neutral about the level of team work
4 I observed a moderated amount of team work
5 I observed an extreme amount of team work

7a. Briefly describe your observations about the level of teamwork you observed while reaching decisions.

8. In which group were you?

________________________GROUP

9. Where you person number: (Circle one)

1 ONE
2 TWO
3 THREE

10. Is there anything else you would like to say about your experience using your decision support method in the decision making process?

(THANK YOU FOR YOUR COOPERATION)

Appendix 7

Drawings of Team's Final Alternatives

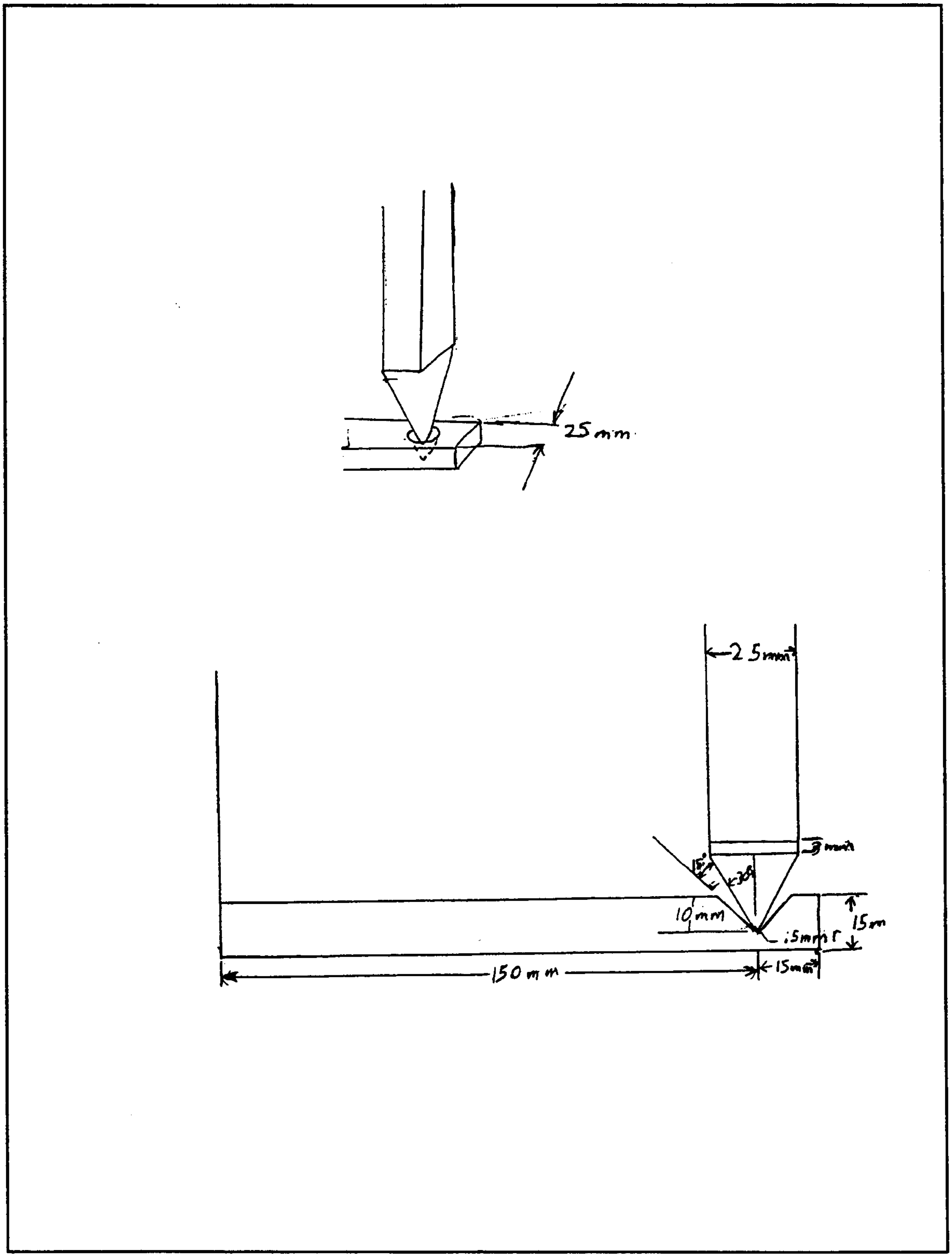

Figure A10. Team: EH1 Final Alternative Drawing

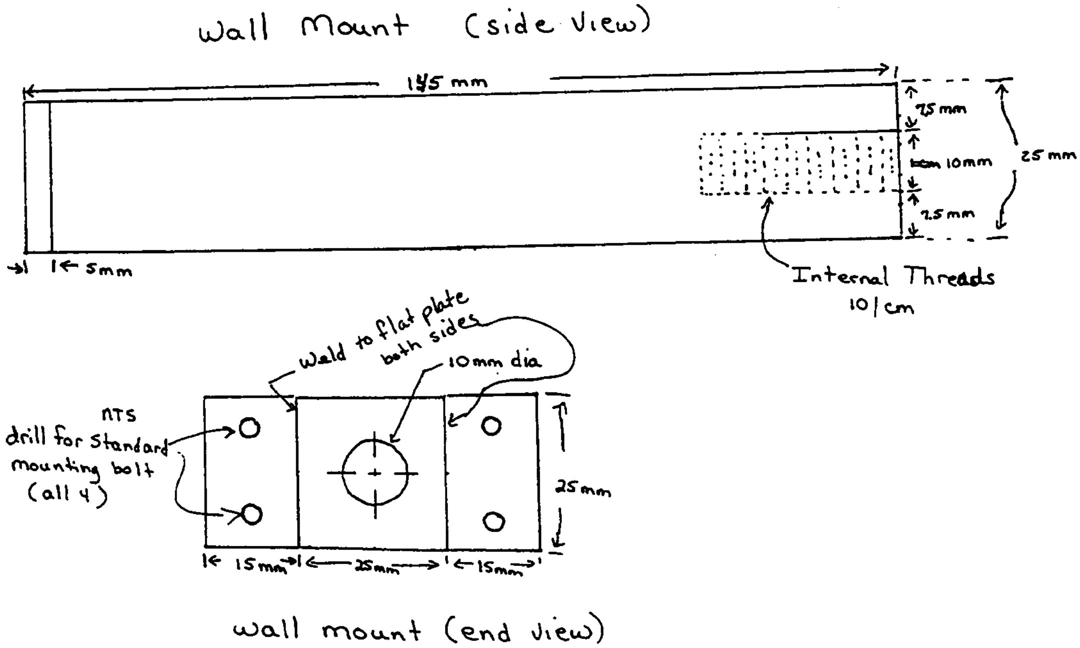

Figure A11. Team: EL1 Final Alternative Drawing 1/2

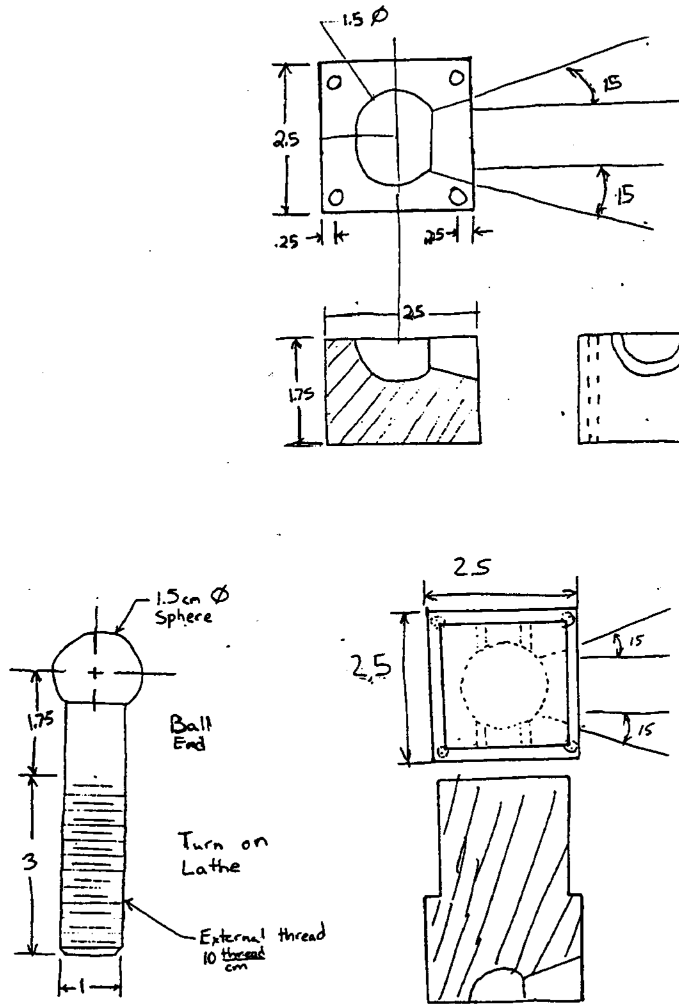

Figure A12. Team: EL1 Final Alternative Drawing 2/2

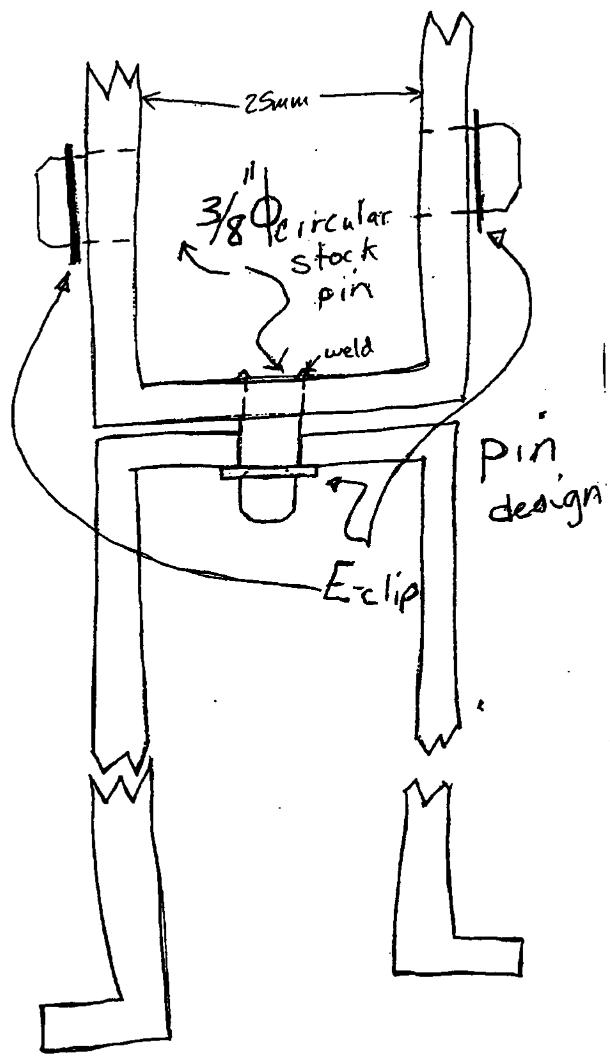

Figure A13. Team: EH2 Final Alternative Drawing

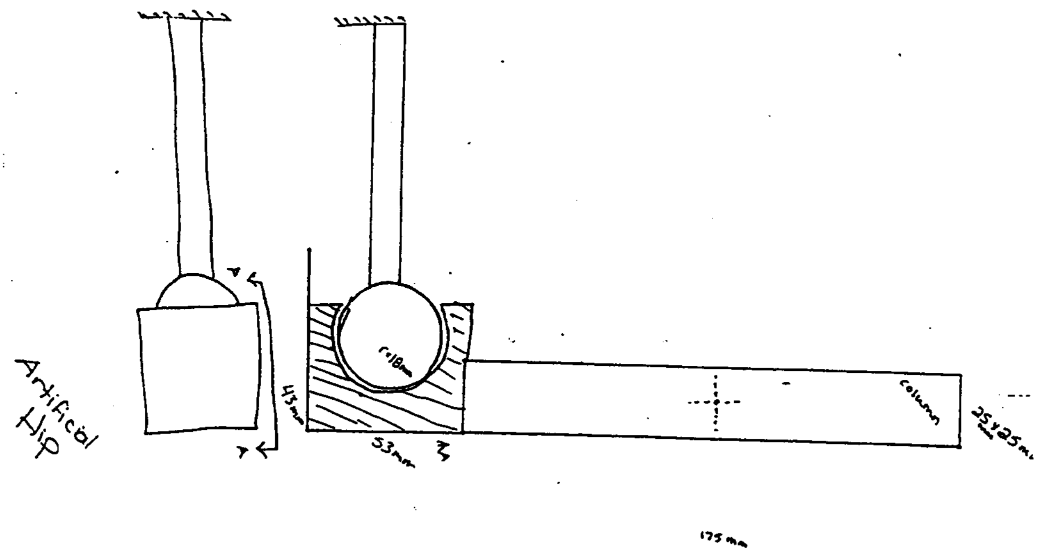

Figure A14. Team: EM Final Alternative Drawing

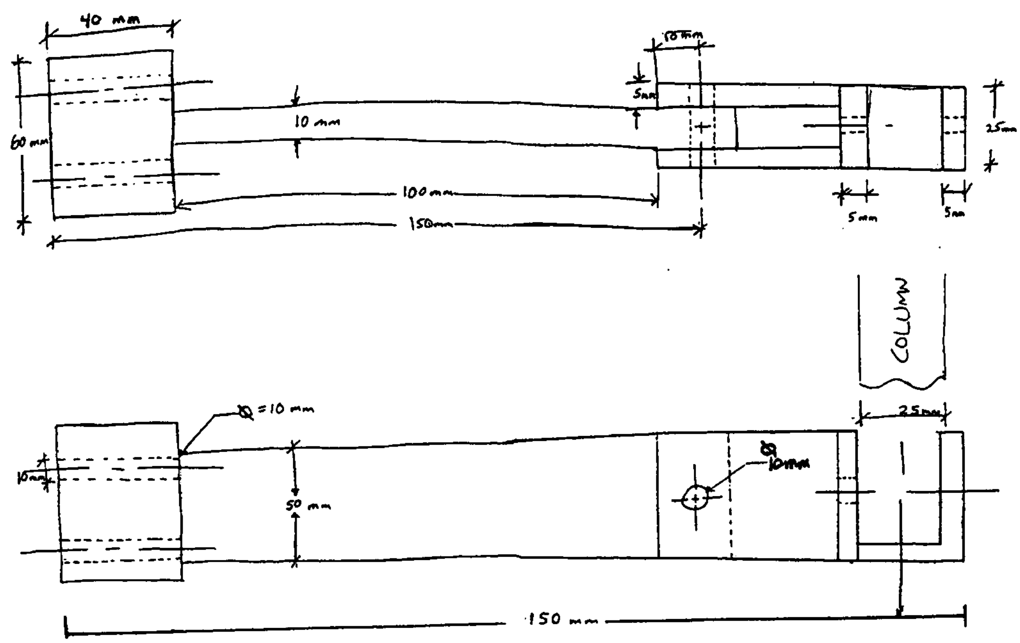

Figure A15. Team: EL2 Final Alternative Drawing

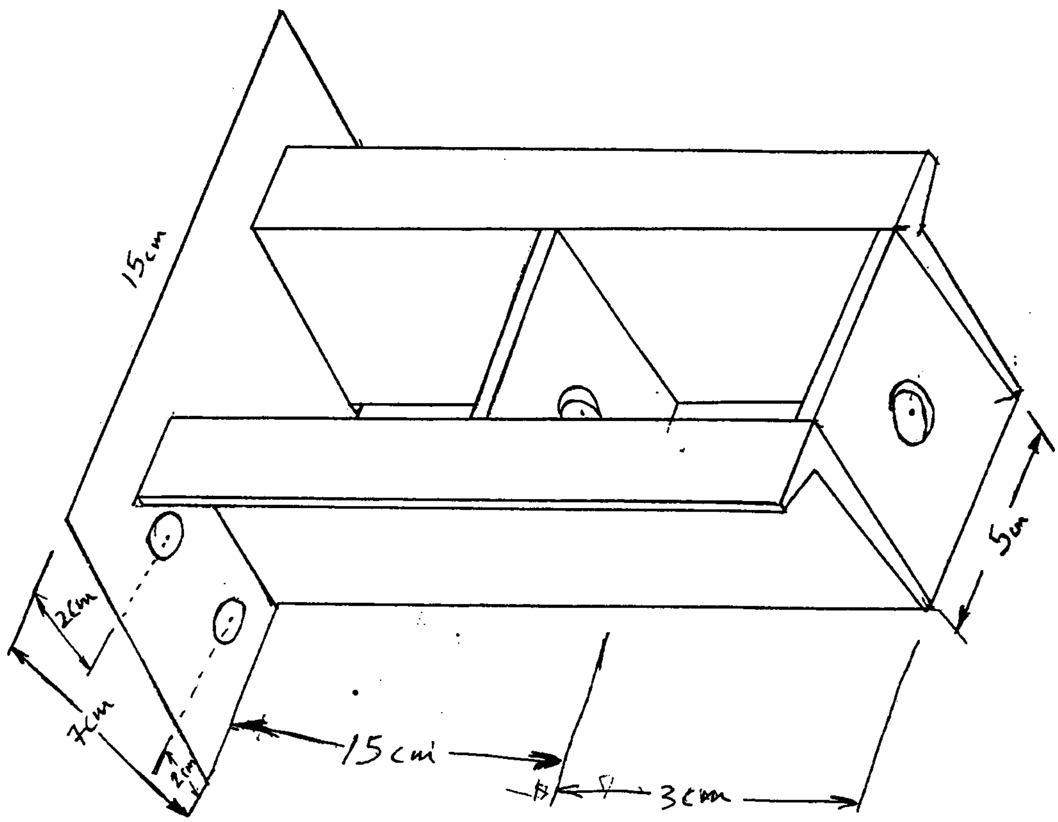

Figure A16. Team:OH1 Final Alternative Drawing

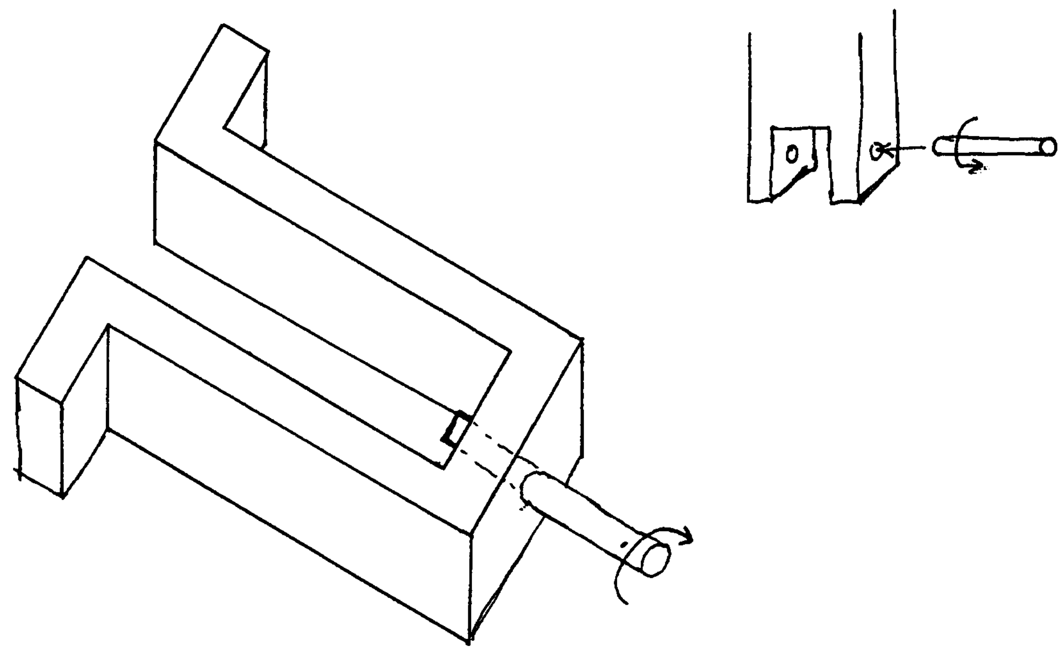

Figure A17. Team:OL1 Final Alternative Drawing

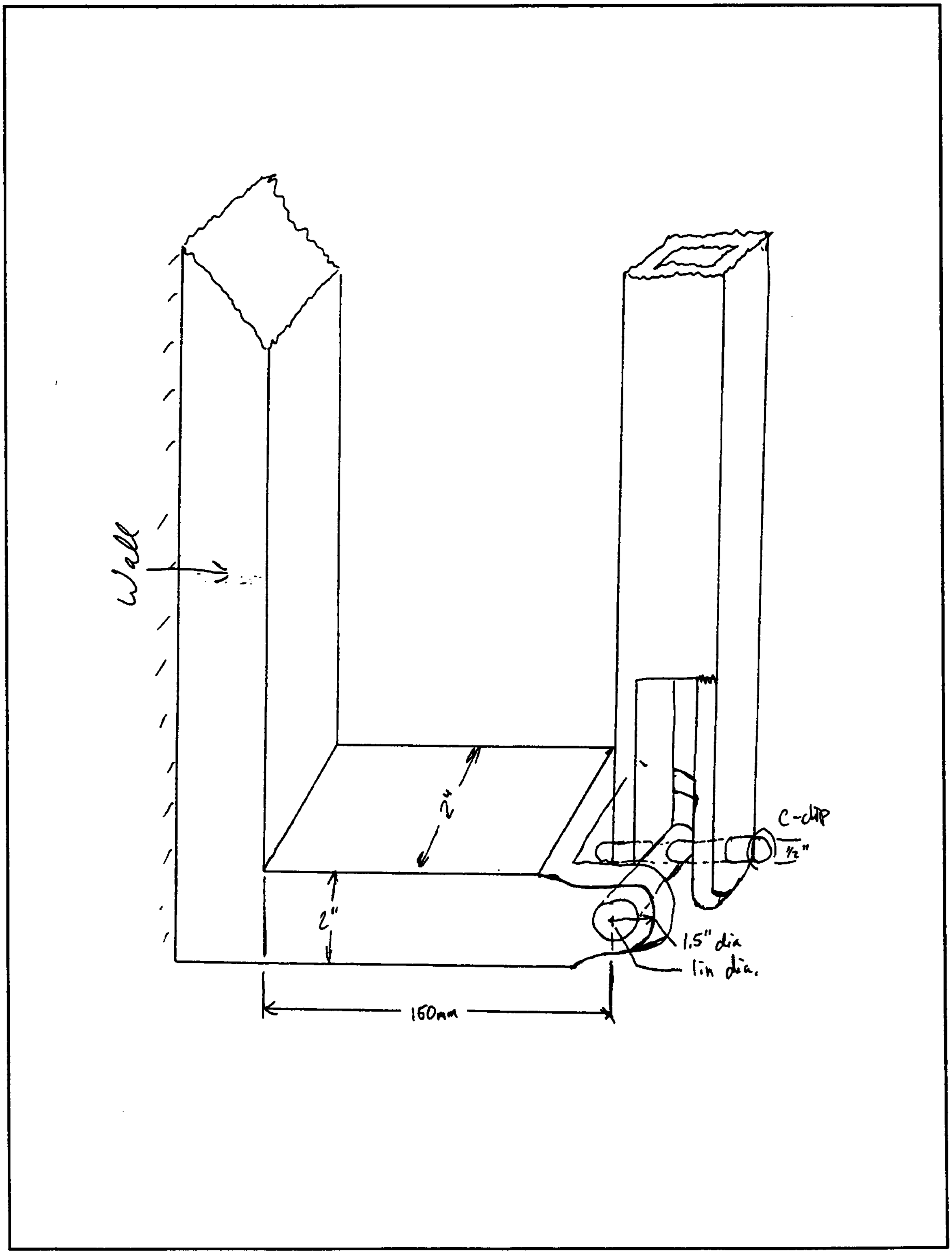

Figure A18. Team: OL2 Final Alternative Drawing

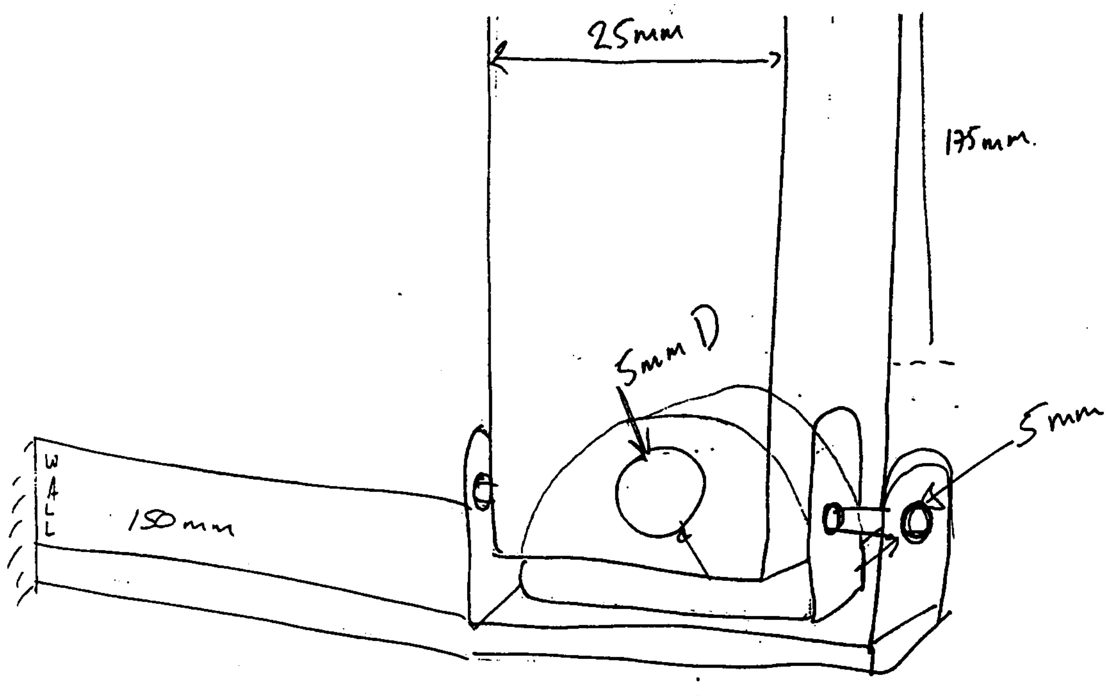

Figure A19. Team:OM Final Alternative Drawing

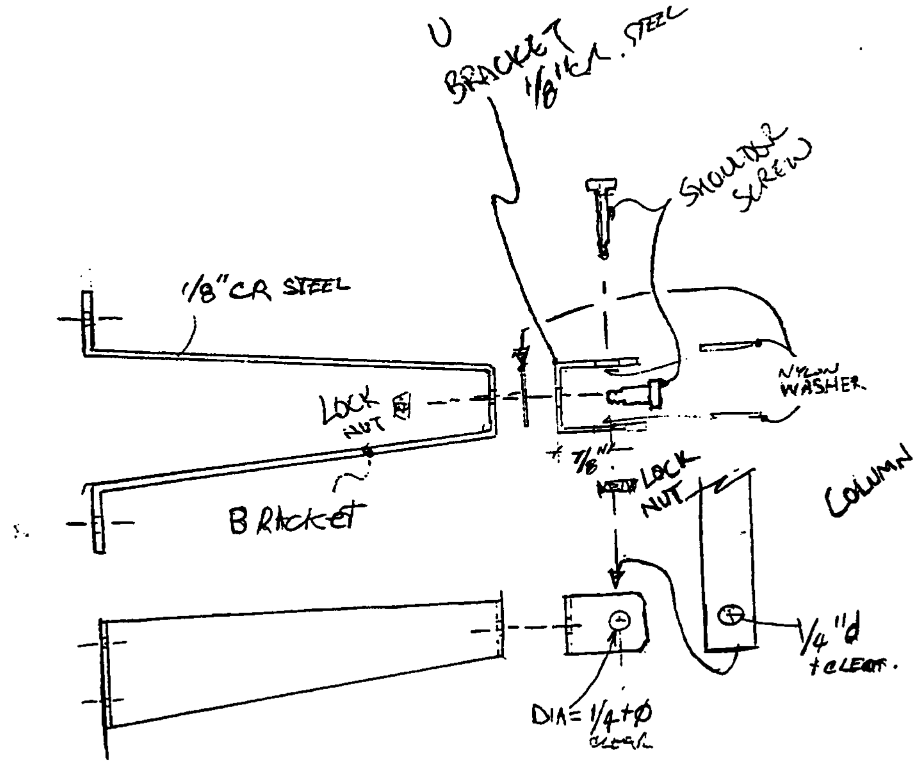

Figure A20. Team: OH2 Final Alternative Drawing