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COMPUTER SUPPORT FOR DESIGN TEAM DECISIONS

D G Ullman & D Herling

1. INTRODUCTION

Design of even simple devices requires decision making based on incomplete and conflicting information. Decisions made early in the design process, when the information is the least refined, can have far reaching consequences as the device matures. To date, there have been few methods to help engineers make these critical decisions. In this paper, a new method, called the Engineering Decision Support System, EDSS, will be described[1]. The method has been programmed on a PC Windows system that is still in development.

This presentation begins with an example, typical of problems encountered in design. In this problem, a team of engineers is developing a concept for a mechanical device. Characteristics of the problem that make decision support difficult are identified in Section 3. In Section 4, a system which can support the characteristics, the Engineering Decision Support System, EDSS, is demonstrated through an example. The underlying mathematics, a probabilistic method for supporting decision making, are introduced in Section 5. Finally, in Section 6, the plans for testing the system in practice and extensions to more difficult problems are discussed.

2. A TYPICAL DESIGN PROBLEM

To demonstrate the complexity of design problems encountered in early product development, a simple and rather typical problem is used as an example. This problem is taken from one used extensively in European research on design, [1], [3] and [4]. It has been solved by many individual designers and some of their solutions are used as a basis for this fictitious team example.

The problem, in abbreviated form, is:

> *Design a mechanism to mount an optical device to a wall. The mechanism should be able to carry the weight of the device (2kg with center of gravity 100mm from mounting base) and allow the device to be adjusted ±15° parallel to the plane of the wall and 0-15° out of the plane of the wall. Any angle in the range should be possible with an accuracy of ±0.5°. The movements should be smooth and continuous, and the position set must be held. Only one such mechanism will be manufactured.*

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The sub-problem used as an example here concerns only the side-to-side adjustment and locking mechanism. In this example, the problem is being solved by a team composed of: Johan, a mechanical engineer specializing in small mechanisms; Hans, a manufacturing engineer; and Iris, an industrial engineer specializing in human factors.

During a 2 hour meeting to develop ideas for the positioning and locking mechanism the three alternatives shown in Figures 1-3, were developed.

The first alternative (taken from Kurt's design in [3]) utilizes a slot and a thumbscrew. This idea was proposed by Johan who liked its simplicity. However, he was concerned that it would be hard to position accurately and might not hold its setting. Hans, from manufacturing, liked its simplicity, thought that the screw wouldn't be too difficult to position and would easily hold the position, and thought it would be easy to manufacture. Iris agreed with Johan that it would be hard to position accurately.

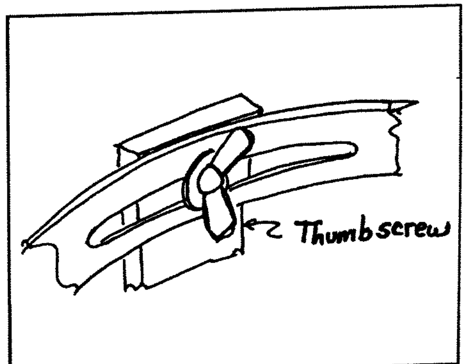

Figure 1 The Thumbscrew Alternative

The second alternative (Taken from Hans' design in [3]) utilizes cranks and locks. This alternative was proposed by Hans who likened the device to a milling machine. He argued that even though it would not be easy to make, it would be easy to adjust and to lock in position. Iris also liked it for its strong human factors. Johan was concerned with its lack of simplicity.

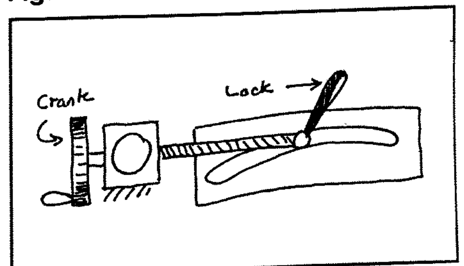

Figure 2 The Cranks & Locks Alternative

The third alternative (Taken from Ingo's design in [3]) utilizes a threaded rod, a sliding block and two lock nuts. This idea generated heated discussion concerning

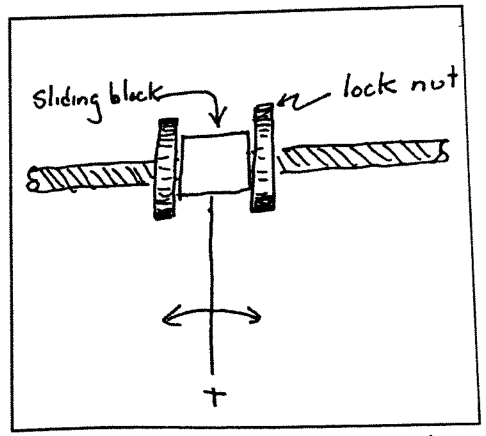

Figure 3 The Threaded Rod Alternative

whether or not it could meet the design requirements. When originally proposed by Iris, Hans raised the issue that, as the block slider was moved off center the device would jam. Iris added the pivot to offset this problem and there was still disagreement. Johan liked the simplicity.

At the end of the meeting the team now had to decide where to put their time and effort. They need to determine which of the alternatives they should spend time refining. Before showing how the Engineering Decision Support System could assist them, characteristics of the problem that make a decision difficult are identified.

3. CHARACTERISTICS OF THE DECISION PROBLEM

This simple example shows a number of characteristics typical of design problems, especially those requiring concept development.

1. The problem is incomplete, there are more criteria and alternatives than the team discussed. Most decision support techniques require complete problem information. It would be useful if a technique could support incomplete problems.
2. The alternatives are qualitative, simple sketches. Thus, there is no numerical analysis possible to support the decision making process.
3. There is no optimum solution. The decision must be made based on the judgement of the engineers.
4. The judgement of the engineers is inconsistent. Sometimes, what one team member favors, another will have low confidence in its potential to work at all.
5. The judgement of the designers is based on differences in knowledge and confidence in the proposed solutions.
6. The evaluation is not complete by any of the team members, meaning that each engineer evaluates each alternative relative to each criteria. This is the case in the example as shown in Table 1, where the alternative-criteria combinations discussed by the team are listed.
7. The issue addressed, the side-to-side adjustment and locking function of the device, is not independent of other issues or sub-problems in the design effort. The results of the work on this issue may affect other aspects of the device.

8. A decision made at the end of the design session may be changed later. The team may reconvene on this issue after refining one or more of the alternatives or the results of another issue may force reconsidering this issue.

ALTERNATIVES / CRITERIA	Thumbscrew	Cranks and Locks	Threaded Rod
Position Accuracy	Johan, Hans and Iris	Hans and Iris	
Locking Sureness	Johan and Hans	Hans and Iris	
Simplicity	Johan and Hans	Johan	Johan
Manufacturing Ease	Hans	Hans	Johan
Functionality			Hans, Iris and Johan

Table 1: Summary of the Evaluations made by the Design Team

Ideally, a decision support system should be able to address all eight of the characteristics. In the next section the EDSS is used to demonstrate the potential of such a system and how it can help the team decide which alternative to refine.

4. A TOOL TO SUPPORT TEAM DECISION MAKING

The Engineering Design Support System is still in the development stage. The windows shown in the figures are from an operational prototype system. The underlying mathematics for this system are briefly discussed in the next section of the paper. Plans for its testing and extension are discussed in the final section of the paper.

EDSS is written in Paradox, a Windows database system. This program allows for easy development of a user's interface, for manipulating data and interfacing with other Window's applications. A data base was chosen for this system as there are 19 records needed to record the information in Table 1 (the number of alternative, criteria, evaluator triads). If any of the engineers adds more alternative or criteria, or revises their evaluation of any of the nineteen existing evaluations, new records will be generated. Thus, for a large problem, the amount of information to be stored and queried warrants the use of a database.

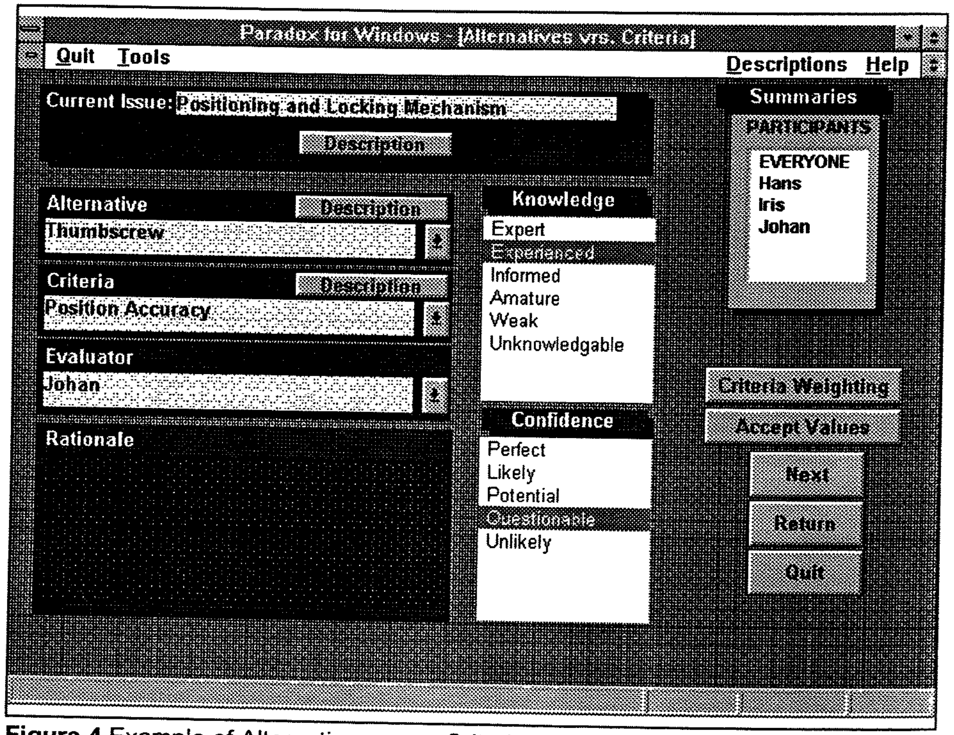

Figure 4 Example of Alternative versus Criteria Window

EDSS allows the users to input the alternatives. Currently, alternatives are represented as word strings, and sketches, as shown in Figures 1-3, will be supported as the program is refined. The alternatives can be input anytime during the use of the tool. Each entry is time stamped for later historical use in a design history or design intent system [9]. The same holds true for the input of criteria information. Either type of information may be entered on the "Alternatives vrs. Criteria" screen shown in Figure 4 or on screens available for adding details about input information (not shown). Figure 4 is the Alternative vrs. Criteria window for Johan's input of his evaluation of the "Thumbscrew" alternative versus the criteria for "Position Accuracy."

In the upper left of the window in Figure 4, the name of the current issue is listed, "Positioning and Locking Mechanism." A detailed description is available (if input by the user)

by selecting the description button just below the name of the current issue. Beneath the current issue box is the area for identifying the alternative, the criteria used to evaluate the alternative and the team member performing the evaluation. Evaluation data is input for each alternative/criteria/evaluator combination listed in Table 1. For each of the three pieces of information there is a pull down menu of previously input options and a button for detailed description. New alternatives, criteria or evaluators can be added here also. In the example shown, the evaluation of the "Thumbscrew" alternative is being evaluated against the "Position Accuracy" criteria by "Johan."

In the middle of the window, there are two areas labeled "Knowledge" and "Confidence." Evaluation of the alternative relative to the criteria is expressed to the EDSS in terms of these two measures. Where most decision support tools have a single measure of utility [10], the EDSS uses two: knowledge and confidence. For each alternative/criteria combination, each evaluator can input his/her knowledge about the combination and their confidence in the ability of the alternative to meet the criteria. Confidence is a measure of the chance the alternative has in actually meeting the intent of the criteria. In the example shown, Johan is "Experienced" in the use of thumbscrews for accurately positioning mechanisms and his confidence for the use of thumbscrews in this application is "Questionable."

The Summaries section on the top right of the window of Figure 4 gives data similar to that shown in Table 1. This table is available for all evaluators, "EVERYONE", or for each individual listed. Thus the completeness of the evaluation for the team or any individual can be readily reviewed. Note that there is no need in EDSS for complete evaluation by any or all of the team members.

Another piece of information needed by EDSS as a basis for decision support is the relative importance of the criteria. This information is entered in the Criteria Weighting Window, Figure 5. Here the relative importance of the criteria can easily be input for each team member doing the evaluation. On the left side of the screen, the evaluators who have input alternatives, criteria or alternative versus criteria information are listed. Any one of them can be selected, then the weights are set by using the arrows in the center of the screen. The values are relative and can be changed at any time, facilitating sensitivity analysis. In the example, Johan's name is

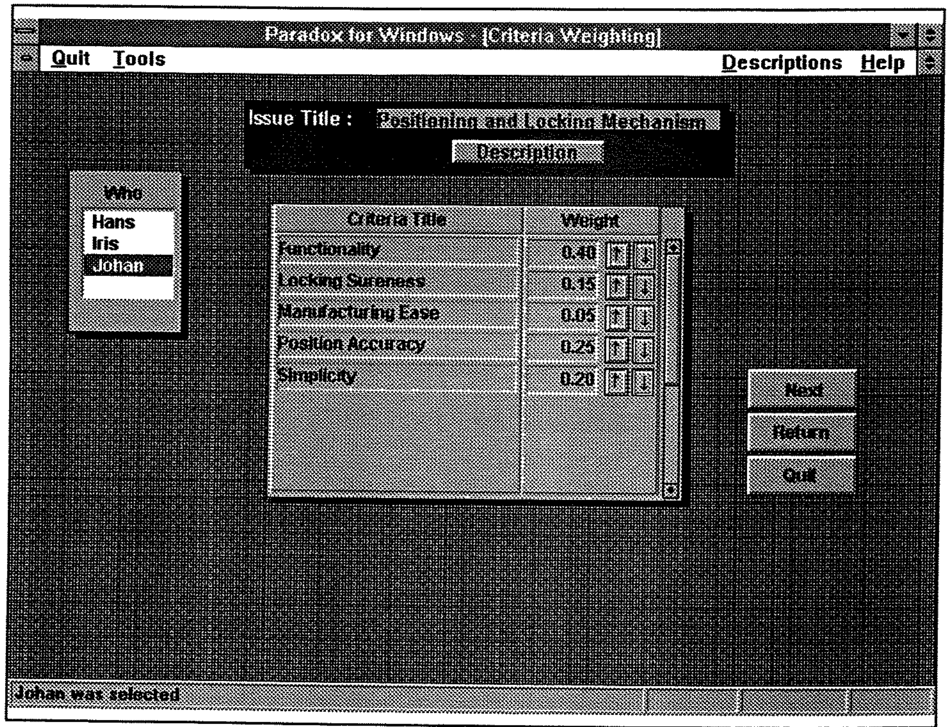

Figure 5 Criteria Weighting Window

highlighted so the values shown are for him only. Here, he considers "Functionality" most important and "Manufacturing Ease" least important.

The evaluation results for this example are shown in Figure 6. These results may be different depending on which evaluator's criteria weightings are used. Thus, in the upper left hand corner, the evaluator can be selected and easily changed. The output is in terms of relative satisfaction. As can be seen in the Figure, with Johan's weightings, the Crank and Locks alternative ranks highest, .45, with the thumbscrew second and the threaded rod last. This result does not tell the team what decision to make. It only gives them a single number based on the sum of all the information input about the problem. These satisfaction scores are based on all the available alternative versus criteria evaluations and Johan's weighting of importance of the criteria. It is easy to change the weightings, update evaluations as new information is learned and add alternatives and criteria to the model of the problem. As each change is made, new records are

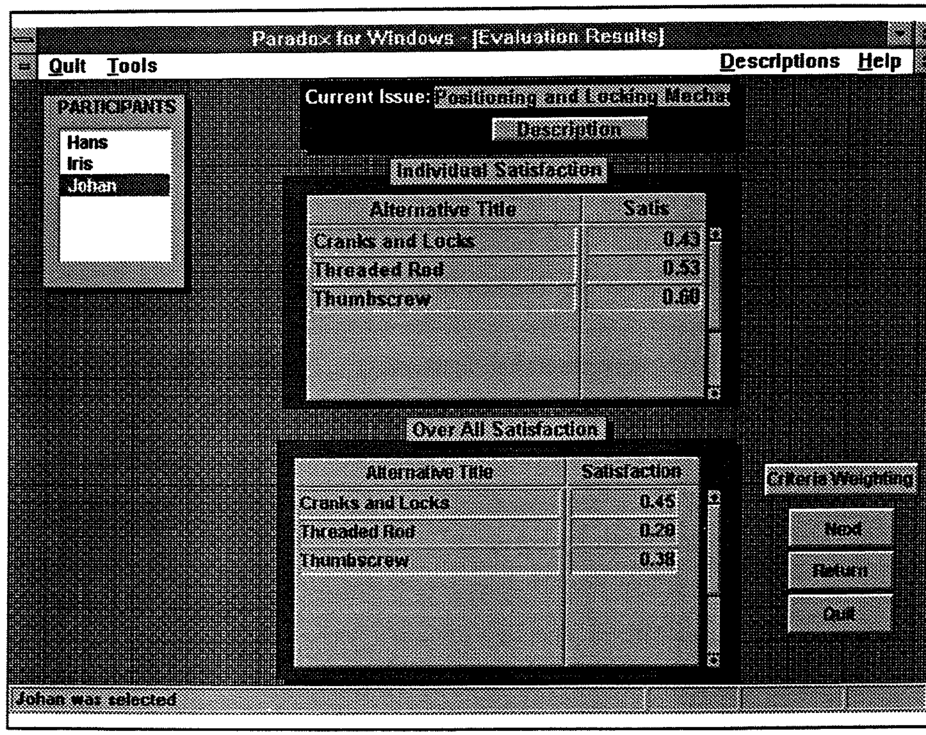

Figure 6 The Satisfaction Window

developed in the database resulting in a complete record of the evolution of the device. Thus, the system supports exploration of what might happen if more is learned about an alternative or criteria, if one evaluator changes his/her evaluation, or if another team member is added.

The use of EDSS supports the eight design problem characteristics listed in the previous section. Since EDSS uses whatever information is available it can support incomplete problem formulations (item 1) and incomplete evaluations (item 6). The alternatives considered can be qualitative (item 2). The judgement of these alternatives (item 3) is based on the evaluator's knowledge and confidence (item 5) which may be inconsistent (item 4). Finally, changes are easily supported (item 8). Currently, the system only addresses a single, independent issue and thus does not support interdependent problems (item 7). However, issue interdependence is a planned extension of the system.

5. MATHEMATICAL BASIS

The decision analysis in EDSS is based on the use of Bayes equation of conditional probability to develop a utility for each alternative/criteria pair. The method uses probability to quantify each evaluator's knowledge of the alternatives and criteria, and his/her confidence in an alternative's ability to meet the criteria. Knowledge is a measure of how much the evaluator knows about the alternative/criteria space. During design activities, knowledge is generally increased by building prototypes, doing simulations (analytical and physical) and finding additional sources of information (e.g. books, experts, consultants). Confidence is a measure of how well the evaluator believes the alternative actually meets the criteria. In the example, Johan is experienced in the use of thumbscrews for position accuracy (his knowledge); he thinks it is questionable that a thumbscrew is good for position accuracy (his confidence).

The explanation of how EDSS mathematically uses this information to develop the satisfaction scores (Figure 6) is detailed elsewhere [5]. The following is only a brief overview.

In EDSS, the words describing knowledge and confidence are converted into numerical probabilities. "Experienced" is equivalent to a numerical value of a probability of 91%. This is based on a scale in which 100% is perfect knowledge and 50% is total ignorance. In the following, the probability of perfect knowledge is noted by, p(k). Thus, p("experienced")=.91 implies that an experienced evaluator would give the correct answer 91 times out of 100 questions asked about the alternative evaluated relative to the criteria. The relationship of the term "experienced" to a value of .91 was determined through surveys of subjects [5].

To measure confidence, p(c) is the probability that the alternative fully meets the criteria. The scale ranges from 100% for an alternative that perfectly meets the criteria, to 0% for one that does not meet it at all. In the example, Johan thinks the alternative is questionable. EDSS translates this into p("questionable")= .42 implying that there is only a 42% odds that the alternative meets the criteria.

These values for knowledge and confidence along with similar values for the other 18 evaluations listed in Table 1, form the base data for the analysis. For each evaluation (i.e. each alternative-criteria pair evaluated by a single individual), the satisfaction of the criteria by the alternative is calculated by:

$$p(\text{criteria}|\text{alternative}) = p(k) \times p(c) + (1 - p(k)) \times (1 - p(c)).$$

This calculation gives the likelihood of the confidence given the knowledge and is based on Bayes rule. The combined satisfaction for each alternative-criteria pair is found by taking the product of all the p(criteria|alternative) values. If there was no evaluation for a pair, then a value of .5 is assumed as the probability of the alternative meeting the criteria is 50/50. For example, in Table 1, the thumbscrew concept was evaluated by all three team members and so its overall utility is the product of the satisfaction for each. The threaded rod, on the other hand was never evaluated for position accuracy and thus the utility is set at .5 representing a 50/50 chance that the alternative meets the criteria.

The overall satisfaction of the alternative is found by summing the utility for each criteria, weighted by the values input by the evaluators. Thus, the satisfaction values shown in Figure 6 are based on Johan's weightings as input in Figure 5.

EDSS is programmed so that changes in any of the input values can rapidly be reflected in the satisfaction values. Thus, it is easy to update the system as new information is learned, arguments are made to change other's confidence in alternatives or new evaluators are added to the team.

6. CONCLUSIONS AND PLANNED FUTURE WORK

The Engineering Decision Support System described in this paper is work in progress. The windows shown in Figures 4-6 are from an operational prototype which is currently being tested. Early testing consists of using the system on a laptop computer in actual industrial design situations. As the system is refined, balanced laboratory based tests are planned. It is hypothesized that, beyond giving support for decision making, use of the system will also encourage the development of more alternatives and criteria and a more thorough evaluation of the information available. These hypothesis need to be scientifically tested.

The use of Paradox as a platform for this prototype has proved both helpful and frustrating. There are three components to the system: the user interface, the analytical code and the database. Paradox is a strong database with good user interface development capability. However, the ability to program the analysis within Paradox has proved difficult and limiting.

Thus, before extending the system, the analysis will be moved to C++ which can easily be extended and can, within the windows environment, be linked to Paradox.

Planned extensions to EDSS fall into four main areas. First, the current capture of information is exclusively textual. Since designers often work graphically, sketches and drawings, need to be supported. Sketch capture has been studied, [6] and [8], and is being integrated into the system. This will enable information like that shown in Figures 1-3 to be part of the database record of the product evolution. Second, as noted earlier, the database is a history of the information considered in the development of the product. The concept of a design history is well studied, [2], [7] and [9], although the use of the data in EDSS to give a history is not refined. Third, EDSS currently only supports a single design issue. Most design problems have multiple, interdependent issues. The mathematical theory and the computer program must both be extended to support multiple issues. Finally, even if the satisfaction values generated by EDSS are ignored by the design team, it has been demonstrated that the information organization and display helps support team decision making [11]. Thus, refinement of the user's interface to further enhance the capture and organization of the design information is expected to add value and this too will be tested.

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