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A MODEL FOR THE DESCRIPTION AND EVALUATION OF TECHNICAL PROBLEM SOLVING

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ABSTRACT

Tape-recorded weekly protocols were gathered from three different engineers engaged on the same problem in a three-way parallel R&D project. Based on these protocols and a post-project interview with each engineer, a model of the individual technical problem solving process is developed. The model is in the form of a process flow chart and details the engineer's interaction with sources of technical information.

The results of the study indicate that the problem solver need not view the process as one in which the best solution is to be found for a fixed problem. Often the best approach lies in the direction of adapting to existing solutions the criteria which must be met.

Several methods for testing the model are suggested. As an illustration, one of the methods is implemented using additional data from the three engineers.

With the important role research and development have assumed in today's technically oriented society the need has arisen to understand, and possibly predict, the decision behavior of an individual engaged in the process of technical problem solving. An increased understanding of problem solving will enable management to improve the organizational support of the process and, in so doing, increase the effectiveness of the total R&D effort.

For a technical problem there is no correct, or even best, solution in the long run. In fact there is frequently no terminal state; the solutions themselves are often dynamic. The interaction of the researchers with their environment is also continual and changing. The goals for the problem's solution may be established when the process is initiated, but they are subject to change as the process proceeds.[1] They do not explicitly contain the criteria by which the solution is to be evaluated, since the criteria are a matter of judgment and differ among individual evaluators.

The present report is a model based on empirical study of the problem solving procedures of research engineers, modified from one presented by Allen (1966a).

The approach to construction of the model is provided in part by the work of Clarkson and Pounds (1964) who stress the importance of isolating and identifying the decision process in order to explain technical decision behavior. Before the model is discussed, however, the reader must understand what is meant by "explaining" behavior. Clarkson and Pounds present the following definition of a "scientific explanation":

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[1]See for example National Academy of Sciences (1967) Report of the Materials Advisory Board.

> In providing a scientific explanation for the occurrence of an event, three conditions must be met. The first is that the occurrence of the event must be deducible as a direct consequence from the conjunction of the theory and the appropriate initial conditions. For this condition to be satisfied, the theoretical system must conform to the general rules of logic that govern the formation and manipulation of deductive systems. Theories which are stated in verbal or mathematical form are able to meet these conditions as well as theories stated in terms of a computer program. In all cases the theory can be constructed so that the process of deducing the occurrence of an event will conform to the general rules governing deductive systems.
>
> The second condition is that the theory itself must contain at least one general hypothesis or law that has been subjected to and survived a process of refutation by empirical test. Accordingly, at least one of the major hypotheses of a theory must be stated in such a manner that it can be corroborated or refuted by empirical test.
>
> The third condition requires that the statements describing the initial conditions be empirically true (1963, p. 21).

One qualification concerns the "appropriate initial conditions." In engineering, one speaks of the transient response of a system to a given input as determined by the initial conditions specified. The initial conditions are essentially "stored" in the memory of the system. If one thinks in terms of computers, the model or "explanation" is the physical circuitry of a simple computer, and the initial conditions are the information stored in the memory of the computer. The transient response concept of problem solving is effective in describing the process, except that it does not take into account the dynamic aspects of the solution. If, however, the process is thought of as a series of inputs, where the initial conditions change with each input, the dynamic aspects of decision making can be taken into account. The program is initiated and the computer allowed to run until the introduction of additional information. Based on the nature of the input, either or both of two things may happen: the new input may change the original data in storage and/or the computer may re-initiate the program.

Since the dynamic aspects of the problem solving process are of major importance, a time study rather than a cross-section study was conducted. Data were collected in the form of protocols; following is a description of such protocols by Clarkson and Pounds (1964):

> A more reliable guide to decision processes is a protocol of an individual's decision behavior. A protocol is a tape recorded transcript of the verbalized thoughts and actions of a subject who has been instructed to think or problem-solve out loud. Since a protocol is a description of what a person does, it avoids some of the problems inherent in the interview and questionnaire techniques.

The researcher obtained the cooperation of engineers working on a parallel research and development project of about six months' duration. Parallel contracts are frequently awarded by government agencies in order to obtain more than one approach to a problem. "Protocols" were obtained from one lead engineer in each of three competing organizations working on the same problem.

The system to be developed in the course of the contracted project under investigation was one to be used in lunar scientific exploration. The overall system is divided into several subsystems: for processing data, for supplying power, for providing thermal control, and for providing ground support.

The data subsystem or data processor is the heart of the system, and was selected for study. It must monitor the experiments, sample the information from each experiment, process the information for transmission to earth, and finally transmit the information to receivers on earth. In other words, it is a special purpose analog to digital converter. The input to this subsystem is in the form of analog signals from the scientific instruments. The problem was to design a subsystem which was capable of accepting such input signals and converting them to a form which was suitable for transmission back to earth, and finally accomplish that transmission reliably. The problem thus involves not only designing the general conceptual form for

accomplishing such a task, but a great amount of detailed design right down to the selection of special electronic components. Although the other subsystems interact with the data subsystem, there is no need to describe them in detail.

RESEARCH METHODS

The goal of the study was to collect very detailed descriptions of the engineers' decision making processes. The ideal situation would be to have the decision makers carry portable tape recorders with them and describe their mental processes each time a decision is made. The closest feasible method was to gather information through weekly reports which were recorded on tape and returned by mail about once a month.

A framework for the engineers to describe their decision making process was provided by a questionnaire. The engineers were told that they need not restrict their discussion to the questions, but that the questions were to give them an idea of the information desired.

During the first month of data collection, it became obvious that the questionnaire was not providing the desired information. The respondents were giving straight answers to the questions but were not really discussing the actual decision process. Consequently it was decided to ask the participants to forget the questions and simply describe, in as much detail as possible, the most significant decision made in the course of the week's work. In response to the change in instructions, two of the engineers' reports improved, bringing more of the decision process into focus.

The third engineer's reporting declined, and upon investigation the reason became clear. The contractor involved had performed a previous study in which a

data subsystem had been developed which was quite similar to that required for the present project. As a result, the engineer's approach to the present problem was to modify the results of the previous study to meet the new requirements. A good part of the modification was accomplished early in the study, so many of the major design decisions had already been made by the time the change in reporting procedure was initiated. This case provides another example of the impact of a solution set upon the problem solving process in research and development (Allen and Marquis, 1964).

Tape-recorded reports were collected from the other two engineers for about three months after the change in reporting procedure was initiated. At the end of this period, the technical problem solving aspects of the study had terminated, and the participants were interviewed to complete the information.

RESULTS

A Model of the Technical Problem Solving Process

The first goal in formulating the model is the reduction of conflict between the original model (Allen, 1966a) and observed behavior, by clarifying and expanding the description and thus reducing the ambiguity. The introduction of processes which are not contained in the preliminary model is the second goal for the model's development.

Initial Conditions

The model, in order to explain the technical problem solving process, must act on initial conditions. An important part of the description of the process is the definition of the initial conditions (information available to the problem solver when the process was initiated) and their interface with the model.

The three major sources of information are the customer, environment, and experience. Customer sources are the representatives of, or documentation generated by, the government agency for which the project is performed. Because of the relationship between the problem solver and the customer, information received through this channel may have greater impact than identical information received from another source. The problem solver's environment contains nine sources of information cited in Table 1.

The model (Figure 1) is divided into two processes which are initiated simultaneously. The first set of processes (10-50) describes the generation of critical dimensions, the criteria against which a solution is to be evaluated. A primary source of information (initial condition) on which the process depends is the customer's generation or definition of the first-level problem. Since technical personnel representing the customer are the final judges of all solutions, they naturally play a dominant role in the generation of critical dimensions. It is possible that the technical personnel may not have the criteria fixed in their minds or that the researcher may not be able to obtain the information. In this case, experience usually makes the major contribution. Critical dimensions may be dictated explicitly by management or implicitly through management policy.

The distinction between fixed requirements and the remaining dimensions is similar to that made by Soelberg (1966), and is highly important to a description of the problem solving process. The distinction can best be described when the technical quality of a solution is considered as the composite score of its evaluation on each dimension. For a fixed requirement, the score of a solution is measured on a discontinuous scale. An example for a maximum allowable weight is shown in Figure 2. On the remaining critical dimensions, a solution is scored

Table 1

Nine Sources of Information in the Problem Solver's Environment

Management:	the management of the contractor's firm.
Project group:	engineers and scientists assigned directly to the project.
Technical staff:	engineers and scientists in the laboratory who are not assigned to the project.
Company research:	any other project performed previously or simultaneously in the laboratory regardless of its source of funding.
Experimentation:	results of tests or experiments with no immediate input of information from any other source.
Analysis:	results of analysis conducted in the course of the study with no immediate input of information from any other source.
Literature:	books, professional, technical and trade journals and other publicly accessible written material.
Vendors:	representatives of, or documentation generated by, suppliers or potential suppliers of design components.
External sources:	sources outside the laboratory which do not fall into the two categories above. These include paid and unpaid consultants and representatives of government agencies other than the customer agency.
Personal experience:	ideas which were used previously by the engineer for similar problems and are recalled directly from memory.
Common knowledge:	standard practices of the industry with which the engineer is familiar.

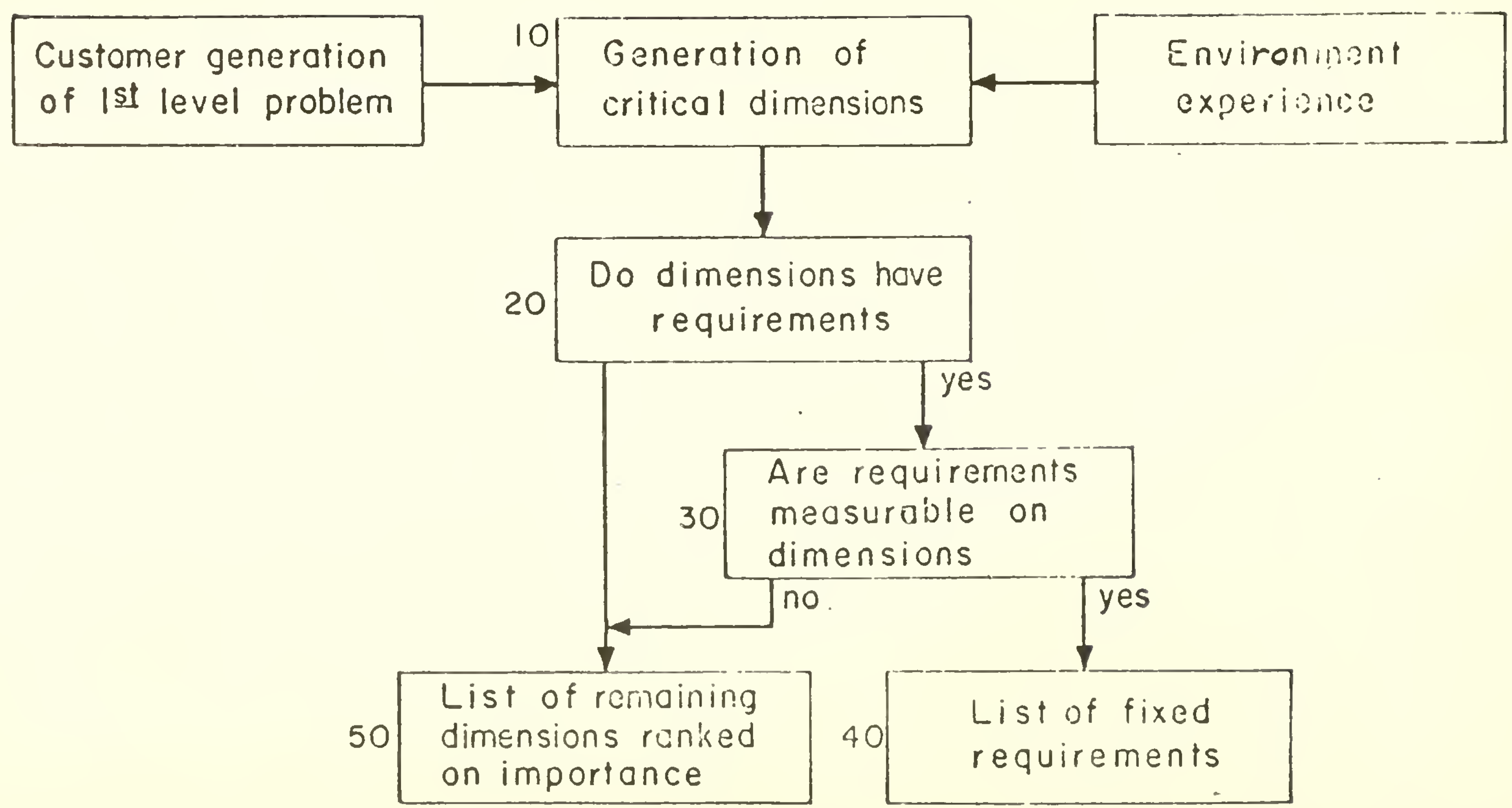

Figure 1. Model: Processes (10-50)

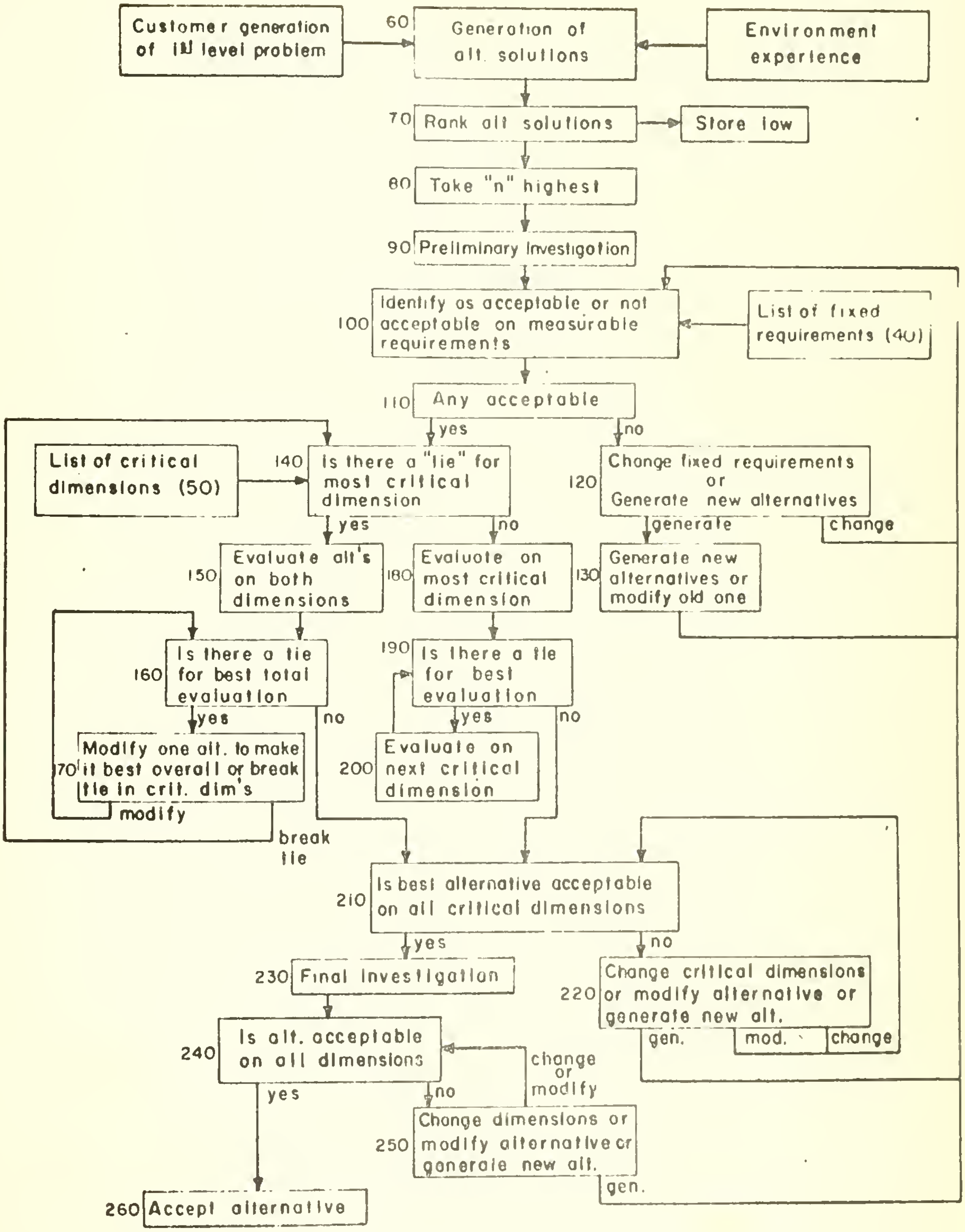

Figure 1. Model: Processes (60-260)

on a linear scale over an acceptable range of the dimension. Cost is given as an example in Figure 3. Because solutions are not always measurable on all dimensions in the early phases of the process, the fixed requirements are screened for measurability before they are stored (30 and 40). Measurable fixed requirements and the remaining critical dimensions are then ranked in order of importance and listed (50). Lists of fixed requirements and critical dimensions are used as information inputs in the second process.

The generation of alternate solutions (60) is similar to the generation of critical dimensions, although the use of information sources is more evenly distributed. When a large number of alternatives is generated, the following two processes are necessary. Based on the information used to generate the approaches, they are ranked on the probability that they will be acceptable on all critical dimensions (70), and further consideration is limited to the "n" top ranking alternatives (80). The problem solver now subjects the remaining approaches to a preliminary investigation (90) in which he normally consults the literature and vendors, and performs simple analysis. On the basis of the preliminary investigation and the measurable, fixed requirements (40), the approaches are identified as acceptable or not acceptable (100). The purpose early in the study is to eliminate alternatives which have no promise. If no approaches meet the requirements (110, no), the main process flow must be interrupted. The problem solver must now utilize the information sources in one of two ways: either the fixed requirements are changed or new alternatives are generated. The engineer may decide that the requirements are not realistic or are unattainable and will negotiate with the customer for their modification (120). He will then return to the main process (100). Frequently, an attempt will be made to modify an alternative or to generate new ones (130). In some cases, it has been observed that vendors and external sources

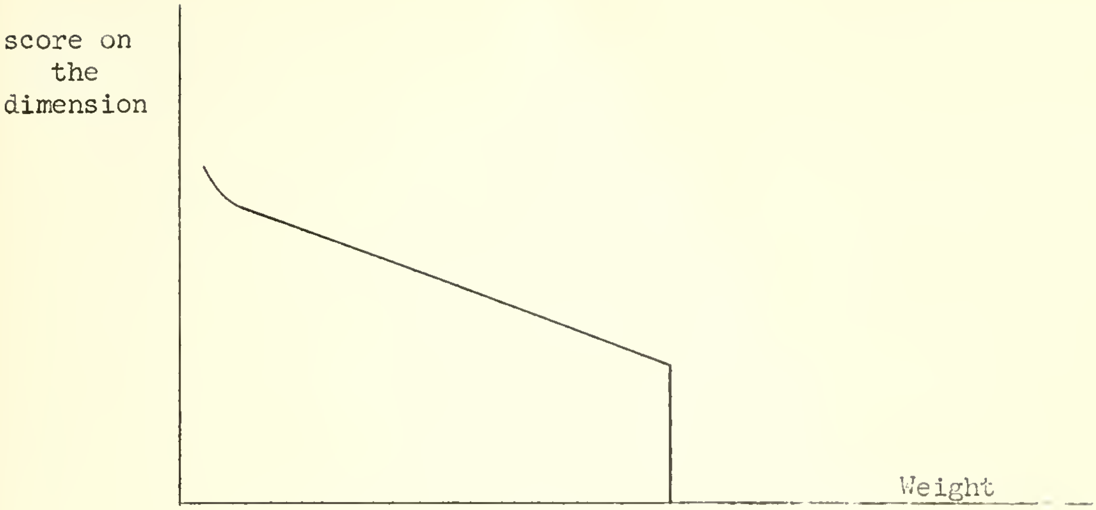

Figure 2. Example of a Critical Dimension With a Fixed Requirement

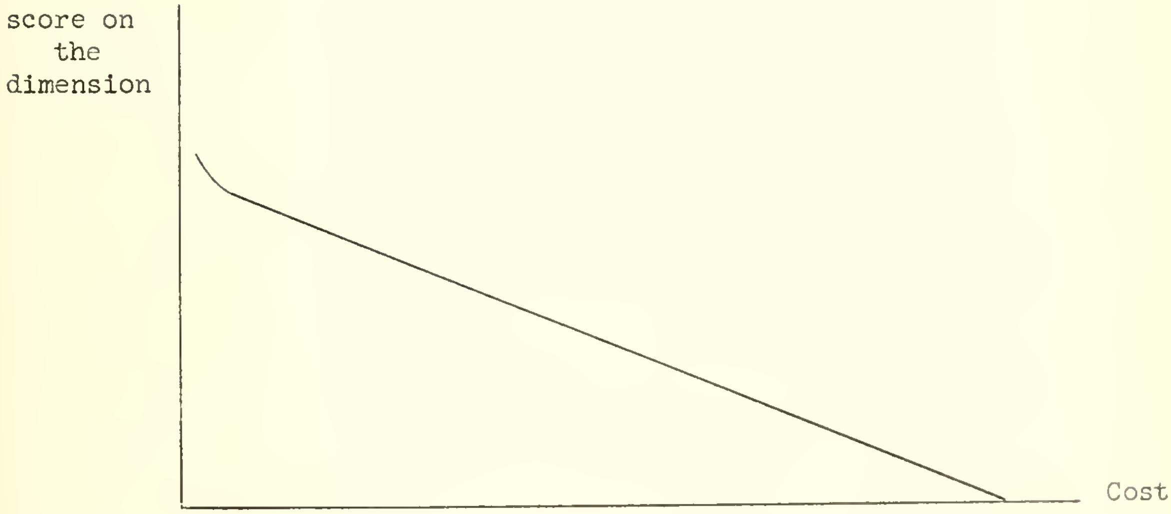

Figure 3. Example of a Critical Dimension With No Fixed Requirement

are relied upon more heavily at this stage than in the original process of generating alternatives (160).

Those alternatives which are judged acceptable (110, yes) now pass through an evaluation process (140). If, on the list of critical dimensions, there are two dimensions which are equally important, the alternatives are evaluated on both (150). In some cases, two approaches may be tied in the overall evaluation (160, yes). If the two alternatives are also tied on each of the two equally most important dimensions, they are evaluated on the third most critical dimension in (200). It is also possible for each approach to score better on only one of the dimensions. This situation is described by one of the engineers in the following way:

> Two types under consideration ... NRZ mark increases the error rate ..., but is very easy to operate (complexity). NRZ change does not change the error rate, but requires an increase in complexity ... Trade off between the increased complexity and an increase in error rate.

The two alternatives, NRZ mark and NRZ change, were tied in overall evaluation on the dimensions, error rate and complexity. To break the tie in total evaluation, the problem solver may modify one alternative such that its overall evaluation is higher (i.e., it scores higher than the other alternative on one dimension and is at least equal to it on the other). In this case, the process proceeds through (160) to (210). The engineer may also break the tie between the critical dimensions:

> ... reversal of our original philosophy ... we approached this with the viewpoint of keeping the spacecraft simple ... and increasing complexity on ground.

Here the importance of complexity is increased to break its tie with error rate. In this case, the process proceeds through (140) and (180) to (190) where the alternatives are evaluated on the most critical dimension. If two approaches tie for best evaluation (190, yes), they are evaluated on the next most critical

dimension and the total evaluations are compared. The loop is negotiated until the tie is broken (190, no) and the process continues to (210).

The remaining alternative is evaluated on all critical dimensions (210) and judged as acceptable or not acceptable. If the approach is not acceptable, the problem solver repeats processes (120 and 130), except that he changes critical dimensions rather than fixed requirements in (220), and returns to (210). When the alternative is acceptable on all dimensions, it is subjected to the final investigation (230). Based on the results of final investigation, the alternative is evaluated on all dimensions. If it is not acceptable, the engineer repeats the combination of processes (120, 130, and 220) in (250). When the alternative solution is acceptable on all dimensions, the process moves on to the next problem level.

Exogenous information

It is possible for exogenous information to enter and affect the problem solver's decision process. The effect which this information produces is largely determined by its nature and the time at which it is received. Exogenous information will either tend to confirm or disconfirm the acceptability of the dominant alternative. Confirming information is naturally accepted, but in many cases, disconfirming information will be rejected as Allen (1965) has stated:

> As engineers invest time and effort in the formulation and development of a technical approach, they become more and more committed to that approach, and hence more resistant to disconfirming information ... What is being suggested here is that an engineer tends to develop a similar threshold as he becomes committed to a technical approach, and that this threshold severely inhibits the effect of information which should tell him that the approach is defective in some way. In addition, it appears to gate our information related to new alternative approaches.

If the information concerns fixed requirements or the importance of critical dimensions, it is more likely to be accepted by the problem solver. When

disconfirming, exogenous information is accepted by the engineer, he will either make some change in the dimensions, modify the alternative, or generate new alternatives and return to the main process.

Testing the Decision Model

The model was tested by means of a Turing Test (Turing, 1956) which is an attempt to answer the question: Can machines think? The "game" is played with an interrogator and one human and a machine. The object for the interrogator is to correctly identify the two players. The machine's goal is to fool the interrogator into thinking that it is the human, while the human is doing his best to reveal his true identity. The game is played a number of times, and if the interrogator is unable to correctly identify the players on a greater than chance basis, the machine is declared able to think.

Miller, Galanter and Pribram (1960) describe the relevance of this test to psychology:

> The import of Turing's work for psychologists was that if they could describe exactly and unambiguously anything that a living organism did, then a computing machine could be built that would exhibit the same behavior with sufficient exactitude to confuse the observer. The existence of the machine would be the test of the accuracy of the description.

To perform a test on the model, the game was modified in the following manner: The record of a human problem solver's decision behavior and the information available to him are collected. The model is allowed to operate on the information, and its output is compared with the record of decision behavior. The degree to which the output and record are similar determines the ability of the model to explain behavior. This comparison can be carried out at several levels. The only restriction is the level of detail of the data that can be gathered on the human's decision processes and relevant information inputs. A simulation of

part of the model was conducted with the assistance of a doctoral candidate in the Sloan School of Management.[2]

Simulation

The simulation of processes (140-200) was run for each of the two engineers. The following additional information for the simulation was gathered from them.

-- Critical dimensions, ranking or weightings of critical dimensions, and changes in the dimensions over time.

-- Initial alternative approaches, changes in any alternative, and entry of new alternatives.

-- A ranking of the alternatives considered by the engineer at four intermediate points in time as well as his final choice.

The two engineers each independently developed identical sets of critical dimensions to evaluate the alternative approaches. These dimensions included: flexibility (ability to handle a variety of experimental complements), reliability, cost, schedule, and complexity. The two rankings of importance given by the engineers to each dimension over time were similar, and changes in the ranking occurred at about the same points in time. The engineers also considered sets of alternatives which were quite similar.

An important problem encountered in the simulation was the definition of technical alternatives. A distinction must be made between different level problems For example, first-level problems are those whose solution affects the system concept while second-level problems (subproblems of the higher-level problems) are the problems associated with implementing the first-level decisions.

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[2] The authors are deeply indebted to Jim Utterback who actually performed the simulation as part of a graduate term project.

The alternatives originally considered by the engineers were ranked according to processes (140-200), based on the initial ranking of the critical dimensions. Each time that a dimension changed in importance, an alternative was modified, or a new alternative was introduced, the approaches were re-ranked. In this manner, a number of outputs, representing the state of the problem solver's process, were obtained at several points in time. To test the model, the records of the engineer's decision behavior are compared with the output. The model is considered successful if:

1. Its final choice is correct;
2. its ranking of alternatives at any point in time corresponds to that given by the design engineer.

Table 2 shows the importance rankings of critical dimensions at given points in time. Flexibility is initially ranked as most important by both engineers.

Table 2

Ranking of the Importance of Critical Dimensions for the Evaluation of Technical Alternatives at Given Points in Time

	Company A				Company B		
	1	4	17	Week	1	6	12
Primary Dimensions							
Flexibility	1	1	-		1	1	2
Reliability	3	1	2		2	1	1
Cost	-	-	1		3	2	2
Schedule	2	3	3		-	-	-
Complexity	-	2	2		-	-	-

Its importance later decreases as the importance of reliability and cost rise. This change is due in part to the reduction in flexibility of the experiments

during the course of the project. The rise in reliability and cost resulted primarily from customer information inputs.

The rankings of the alternatives considered by one engineer (Contractor A) are presented for several points in time in Table 3. Each point in time represents a change in the importance of a dimension or a change in the nature of

Table 3

Test of the Model Using Data from Contractor A

Actual Ranking of the Alternatives by the Engineer in Terms of Probability of that Alternative Being His Final Selection

Rank \ Week	1	2	4	6	17
1	A	A	A	D*	E
2	C	C	E		
3	B				

Ranking Obtained Using the Model

Rank \ Week	1	2	4	6	17
1	A	A	A	D	E
2	C	C	E	E	D
3	B	B	C	B	
4			B		

*D is a new alternative which is the combination of A and C.

one or more alternatives. For example, in the fourth week the engineer reported that the dimensions of flexibility and reliability had been tied in importance. The tie between dimensions was broken in favor of flexibility because in that particular laboratory management had a strong bias toward flexibility. Alternative A continued to be ranked first on the basis of its flexibility, but alternative E was now ranked second because of its high

reliability. The second table presents the ranking produced by the model. Alternatives below the solid line were assigned a zero probability of success by the engineer, but were processed by the model. The second engineer's record (Contractor B) is presented in Table 4 above the output of the model. There is

Table 4

Test of the Model Using Data from Contractor B

Actual Ranking of the Alternatives by the Engineer in Terms of Probability of that Alternative Being His Final Selection

Week	1	4	6	12	17
Rank					
1	a	a	a	b	b
2	c	b	b	a	
3		c			

Ranking Obtained Using the Model

Week	1	4	6	12	17
Rank					
1	a	a	a	b	b
2	c	b	b	a	a
3		c			

perfect agreement between the actual rankings and the predictions by the model for both engineers.

The procedure described above could be modified to provide a method for testing more completely a particular section of the model. For a fixed input of time, the engineer, by limiting the subject of his report to a particular decision procedure, can report in greater detail than would be possible if he were discussing the entire problem solving process. If the researcher is interested in the trade-off process, for example, he would ask the engineers to

report their behavior only when they are engaged in making trade-off decisions. Protocols which are "in-process" reports of actual decision behavior rather than weekly summaries can be obtained in this manner.

The protocols may then be used to test the trade-off section of the model in two ways. First, the output of the section is compared with the actual decision reported in the protocol. Second, because of the greater detail, the individual processes that make up the trade-off section of the model can be compared with the engineer's reported procedure. By subjecting each section of the model to this dual testing method, it can be determined whether or not the model provides a scientific explanation.

CONCLUSIONS

While the major purpose of the model developed in this study is to provide an explanation of the decision process, it has a normative impact as well. When a study is initiated, an engineer is normally provided with a set of dimensions on which to evaluate any solution he may propose. In the course of the project, the engineer often discovers that none of his proposed solution alternatives is acceptable according to the given set of dimensions. The normal reaction in such a case is to modify the solution or to generate a new one. The results of this study, however, suggest that these two alternatives are not the engineer's only course of action. It is also possible to modify the set of dimensions, thus changing the problem. The concept of a variable problem is of great importance to problem solvers, yet many of them do not recognize it.

The technical problem solving process is normally thought of as a process which generates the best or correct solution to a given problem. This is due largely to the engineer's educational training. Students are expected to find the one correct solution to a given problem, not to question the problem itself.

Engineers tend to view their professional environment in a dichotomous fashion -- problems are either given, and therefore fixed, or they are to be generated. The results of this study demonstrate that the technical problem solving process is a blend of two extremes. At one extreme there is the process of finding the best solution to a fixed problem and at the other, the process of fitting a problem to an existing solution. The combination of these two processes is important in light of its impact upon the problem solving process.

The development of the model in this study is only a small contribution to the understanding of human decision behavior. Future research should involve more detailed investigations of various sections of the model. The lack of detail in the data on which the model is based resulted in a large variance in the level of process descriptions. For example, trade-off decisions are represented by four processes while the generation of alternative solutions is presented as a single process. Research effort should be directed toward individual sections of the model. When all the sections of the model have been expanded and subjected to empirical test, the interaction of the model with information sources may be investigated. In this manner, the scope of the model can include the problem solver's interaction with his environment.

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