

# Penguin modern management Readings



## Management decision making

edited by Lawrence A. Welsch  
and Richard M. Cyert

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# Management Decision Making

Edited by Richard M. Cyert  
and Lawrence A. Welsch

Penguin Modern Management Readings

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# **Management Decision Making**

**Selected Readings**

Edited by Richard M. Cyert and Lawrence A. Welsch

Penguin Books



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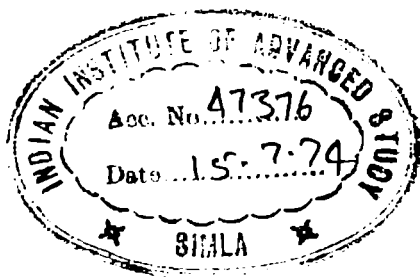
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# Introduction

The editors of *Management Decision Making* have two objectives. The first is to illustrate how actual decision-making processes that have occurred in the firm have been described; the second is to present some of the optimum decision rules that have been prescribed for managers. The frame of reference within which we shall fulfil these objectives stems from the work done at the Graduate School of Industrial Administration of Carnegie-Mellon University. We view decision making as synonymous with managing. The manager's behaviour in finding opportunities for decision making is part of this process. His identification of and analyses of alternative solutions for his problem are additional parts of the decision-making activity. His comparison of the alternatives and his choice among them, which becomes his decision, are also included in decision making. Carrying out decisions is again decision-making activity.

In Part One (Reading 1) Simon describes the traditional or classical techniques which have been used by managers to aid their decision making since earliest recorded times. He also discusses some of the modern techniques available to managers for decision making, most of which have been introduced since the Second World War. Taylor (Reading 2) gives an overview of the scholarly development of the 'Carnegie' approach. Together, the articles reveal some of the history and the character of our theoretical framework.

Parts Two and Three of this book aim at accomplishing our first objective. They consist of six essays containing seven descriptive field studies of actual managerial decision making as it occurs in the firm. To make them researchers went into the firms and observed all the decision-making activity pertaining to a selected decision. They recorded all the events that they perceived as influencing the decision under observation. Their data included all the rules followed in arriving at those sub-decisions pertinent to the decision. They interviewed all the participants involved in the decision and inspected all the records of the firm which related to the decision.

The seven studies resolve themselves into two categories. The first group of four is designated as 'non-programmed decisions'. In the words of Simon's essay (Reading 1), that means that they are one-shot, ill-structured, novel, policy decisions which must be handled by general problem-solving processes. The second group of three falls under the heading 'programmed decisions'. Such decisions are repetitive and well-structured, and specific problem-solving processes exist for them.

Although the two categories imply a sharp, polar distinction between the two types of decisions, a particular decision may lie at any point in the continuum between the non-programmed and the programmed classifications. The manager who makes a decision over and over again gains experience. His decision rules become more structured and fixed and the decision moves away from the non-programmed classification towards the programmed end of the continuum.

Parts Four and Five are intended to meet our second objective. They contain studies which prescribe how decisions should be made to achieve particular goals. The studies illustrate some of the techniques that have been developed by management scientists over the last twenty years. Part Four includes examples of heuristic models and Part Five of algorithmic models applied to marketing, production and planning decisions. A heuristic approach does not, of course, give an optimum solution. The virtue of the approach is that it leads to better solutions than currently exist for problems that cannot be solved analytically.

Having indicated the area of decision making that is encompassed in our book, we now wish to denote and comment on those dimensions of our subject outside the range of this volume. We have not, for example, described the history of decision making which has its beginnings in the works of many earlier scholars – Aristotle, Max Weber, Barnard, Taylor, Fayol, to mention a few.

Nor have we included developments of game theory as applied to management decision making. This is not because we regard this area as unimportant. There is no question that such developments have had impact – at least on the students of the area. It is only that something must give when choices must be made.

Literature which describes what the values or objectives of a certain decision ought to be is not included. The work of

determining ultimate values is outside empirical science and such wisdom can neither be proved nor disproved. Those normative models illustrated in Parts Four and Five exemplify how the manager should make decisions to accomplish specified or given objectives or values.

The behavioural sciences have contributed much work of relevance to managerial decision making which could not be incorporated. The elements of decision making may be studied in the laboratory as aspects of the psychology of cognition – perception, learning, problem-solving, creativity and so forth. Psychiatrists, psychologists and social psychologists have explained the limitations on man's reasoning. Some of these researchers have studied the constraints of group processes upon decision making. Sociologists are interested in determining the relations between organizational structure and managerial decision behaviour, and anthropologists in studying the values of the decision maker and the effect of the culture upon his decisions.

We do not wish to deny the importance or the usefulness of any of the above approaches to managerial decision making. However, we have restricted ourselves to that research which we believe is of most interest and importance to the manager. The concept of bounded rationality and the related theories described in Part One provide a cohesive framework for our view of managerial decision making. The field studies in Parts Two and Three illustrate the method by which the manager may study decisions made or being made by his subordinates, his superiors and himself. By charting the decision processes and analysing them, the manager can decide whether or not they are the procedures which should be followed and redesign them into a better system. The normative studies presented in Parts Four and Five can provide the manager with an appreciation of the heuristic and algorithmic models that have been developed to solve problems. What more vital information can the manager have than the knowledge of how decisions are actually being made in his organization, together with an understanding of how these decisions might be made in an improved fashion by the use of new tools?

## Part One Theory

Theories of managerial decision making might be ordered along a spectrum of assumptions concerning the rationality of man. At one end of this spectrum is the man of complete rationality described by traditional economists. At the other would be found the fellow analysed by some psychiatrists, psychologists and sociologists, the man whose decisions are largely determined by forces other than reason. Between these two extremes falls the managerial decision maker of bounded rationality. Herbert A. Simon is the originator of this concept.

Simon's essay (Reading 1) classifies decision making into four categories. Those divisions he calls 'traditional programmed decision making' and 'traditional non-programmed decision making' are illustrated in the field studies presented in Parts Two and Three, respectively. His 'modern non-programmed decision making' classification is represented in the articles presented in Part Four, and his 'modern programmed decision making' is illustrated by the Readings in Part Five.

The Taylor essay (Reading 2) gives some of the background of the theory of decision making developed by scholars of the Simon School, who embrace the idea of bounded rationality and look at problem solving in terms of information processing systems.

# 1 H. A. Simon

## The New Science of Management Decision

Excerpts from H. A. Simon, 'The new science of management decision', in *The Shape of Automation for Men and Management*, Harper & Row, 1965, pp. 57-79.

The executive's job involves not only making decisions himself, but also seeing that the organization, or part of an organization, that he directs makes decisions effectively. The vast bulk of the decision-making activity for which he is responsible is not his personal activity, but the activity of his subordinates.

Nowadays, with the advent of computers, we can think of information as something almost tangible; strings of symbols which, like strips of steel or plastic ribbons, can be processed – changed from one form to another. We can think of white-collar organizations as factories for processing information. The executive is the factory manager, with all the usual responsibilities for maintaining the factory operation, getting it back into operation when it breaks down, and proposing and carrying through improvements in its design.

There is no reason to expect that a man who has acquired a fairly high level of personal skill in decision-making activity will have a correspondingly high skill in designing efficient decision-making systems. To imagine that there is such a connexion is like supposing that a man who is a good weight lifter can therefore design cranes. The skills of designing and maintaining the modern decision-making systems we call organizations are less intuitive skills. Hence, they are even more susceptible to training than the skills of personal decision making.

### *Programmed and non-programmed decisions*

In discussing how executives now make decisions, and how they will make them in the future, let us distinguish two polar types of decisions. I shall call them *programmed decisions* and *non-programmed decisions*, respectively. Having christened them, I hasten



to add that they are not really distinct types, but a whole continuum, with highly programmed decisions at one end of that continuum and highly unprogrammed decisions at the other end. We can find decisions of all shades of gray along the continuum, and I use the terms programmed and non-programmed simply as labels for the black and the white of the range.<sup>1</sup>

Decisions are programmed to the extent that they are repetitive and routine, to the extent that a definite procedure has been worked out for handling them so that they don't have to be treated *de novo* each time they occur. The obvious reason why programmed decisions tend to be repetitive, and vice versa, is that if a particular problem recurs often enough, a routine procedure will usually be worked out for solving it. Numerous examples of programmed decisions in organizations will occur to you: pricing ordinary customers' orders; determining salary payments to employees who have been ill; reordering office supplies.

Decisions are non-programmed to the extent that they are novel, unstructured and consequential. There is no cut-and-dried method for handling the problem because it hasn't arisen before, or because its precise nature and structure are elusive or complex, or because it is so important that it deserves a custom-tailored treatment. General Eisenhower's D-Day decision is a good example of a non-programmed decision. Remember, we are considering not merely the final act of ordering the attack, but the whole complex of intelligence and design activities that preceded it. Many of the components of the decisions were programmed – by standard techniques for military planning – but before these components could be designed they had to be provided with a broader framework of military and political policy.

I have borrowed the term program from the computer trade, and intend it in the sense in which it is used there. A *program* is a detailed prescription or strategy that governs the sequence of responses of a system to a complex task environment. Most of the programs that govern organizational response are not as detailed or as precise as computer programs. However, they all have the same intent: to permit an adaptive response of the system to the situation.

1. See March and Simon (1958, pp. 139–42 and 177–80) for further discussion of these types of decisions. The labels used there are slightly different.

In what sense, then, can we say that the response of a system to a situation is non-programmed? Surely something determines the response. That something, that collection of rules of procedure, is by definition a program. By non-programmed I mean a response where the system has no specific procedures to deal with situations like the one at hand, but must fall back on whatever *general* capacity it has for intelligent, adaptive, problem-oriented action. In addition to his specific skills and specific knowledge, man has some general problem-solving capacities. Given almost any kind of situation, no matter how novel or perplexing, he can begin to reason about it in terms of ends and means.

This general problem-solving equipment is not always effective. Men often fail to solve problems, or they reach unsatisfactory solutions. But man is seldom completely helpless in a new situation. He possesses general problem-solving equipment which, however inefficient, fills some of the gaps in his special problem-solving skills. And organizations, as collections of men, have some of this same general adaptive capacity.

The cost of using general-purpose programs to solve problems is usually high. It is advantageous to reserve these programs for situations that are truly novel, where no alternative programs are available. If any particular class of situations recurs often enough, a special-purpose program can be developed which gives better solutions and gives them more cheaply than the general problem-solving apparatus.

My reason for distinguishing between programmed and non-programmed decisions is that different techniques are used for handling the programmed and the non-programmed aspects of our decision making. The distinction, then, will be a convenient one for classifying these techniques. I shall use it for that purpose, hoping that the reader will remind himself from time to time that the world is mostly gray with only a few spots of pure black or white.

The fourfold table below will provide a map of the territory I propose to cover. In the northern half of the map are some techniques related to programmed decision making, in the southern half, some techniques related to non-programmed decision making. In the western half of the map I placed the classical techniques used in decision making – the kit of tools that has been used by executives and organizations from the time of the earliest

recorded history up to the present generation. In the eastern half of the map I placed the new techniques of decision making – tools that have been forged largely since the Second World War, and that are only now coming into extensive use in management in this country. I shall proceed across the map from west to east, and from north to south, taking up, in order, the north-west and the south-west quadrants (section B), the north-east quadrant (section C), and the south-east quadrant (section D). [ . . . ]

Let us examine the western half of our map of decision-making techniques (Table 1). This half represents methods that have been widely understood and applied in human organizations at least from the time of the building of the pyramids. In painting with a broad brush, I may convey the impression that there was no progress in organizational matters during the course of three millennia. I do not believe this to be true, and I do not intend to imply it. But the progress that was made did not enlarge the repertoire of basic mechanisms to which I shall refer.

We shall consider, in turn, techniques for making programmed decisions and techniques for making non-programmed decisions.

### **A. Traditional Techniques for Programmed Decisions**

Man [says William James] is born with a tendency to do more things than he has ready-made arrangements for in his nerve centres. Most of the performances of other animals are automatic. But in him the number of them is so enormous, that most of them must be the fruit of painful study. If practice did not make perfect, nor habit economize the expense of nervous and muscular energy, he would therefore be in a sorry plight (James, 1890, p. 113).

Habit is the most general, the most pervasive, of all techniques for making programmed decisions. The collective memories of organization members are vast encyclopedias of factual knowledge, habitual skills and operating procedures. The large costs associated with bringing new members into organizations are principally costs of providing the new members, through formal training and experience, with the repertoire of skills and other habits they need in their jobs. Partly, the organization provides these habits; partly, it acquires them by selecting new employees who have already learned them in the educational and training institutions that society maintains.

*Table 1* Traditional and Modern Techniques of Decision Making

| <i>Types of decisions</i>                                                                                                  | <i>Decision-making techniques</i>                                                                                                                                                     |                                                                                                                                       |
|----------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                                            | <i>Traditional</i>                                                                                                                                                                    | <i>Modern</i>                                                                                                                         |
| <b>Programmed:</b><br>Routine, repetitive decisions<br>Organization develops specific processes for handling them          | 1. Habit<br>2. Clerical routine:<br>Standard operating procedures<br>3. Organization structure:<br>Common expectations<br>A system of subgoals<br>Well-defined informational channels | 1. Operations Research:<br>Mathematical analysis<br>Models<br>Computer simulation<br>2. Electronic data processing                    |
| <b>Non-programmed:</b><br>One-shot, ill-structured novel, policy decisions<br>Handled by general problem-solving processes | 1. Judgement, intuition and creativity<br>2. Rules of thumb<br>3. Selection and training of executives                                                                                | Heuristic problem-solving technique applied to:<br>(a) training human decision makers<br>(b) constructing heuristic computer programs |

Closely related to habits are standard operating procedures. The only difference between habits and standard operating procedures is that the former have become internalized – recorded in the central nervous system – while the latter begin as formal, written, recorded programs. Standard operating procedures provide a means for indoctrinating new members into the habitual patterns of organizational behavior, a means for reminding old members of patterns that any one member uses so infrequently that they never become completely habitual, and a means for bringing habitual patterns out into the open where they can be examined, modified and improved.

Organization structure, over and above standard operating procedures, is itself a partial specification of decision-making programs. The organization structure establishes a common set of presuppositions and expectations as to which members of the organization are responsible for which classes of decisions; it establishes a structure of subgoals to serve as criteria of choice in various parts of the organization; and it establishes intelligence responsibilities in particular organization units for scrutinizing specific parts of the organization's environment and for communicating events requiring attention to appropriate decision points.

In the past, the improvement of programmed decision making in organizations has focused largely upon these techniques: upon improving the knowledge, skills and habits of individual employees by means of training programs and planned tours of duty; upon developing better standard operating procedures and securing adherence to them; and upon modifying the structure of the organization itself, the division of labor, the subgoal structure, the allocation of responsibilities.

Mankind has possessed for many centuries an impressive collection of techniques for developing and maintaining predictable programmed responses in an organization to those problems posed by its environment that are relatively repetitive and well-structured. The history of the development of these techniques has never been written – much of it is undoubtedly buried in pre-history – but one can point to particular periods of innovation. The scientific management movement, and particularly the development of standard methods for performing repetitive work, is one of the most recent of these.

## B. Traditional Techniques for Non-Programmed Decisions

When we turn to the area of non-programmed decisions, we have much less to point to in the way of specific, describable techniques. When we ask how executives in organizations make non-programmed decisions, we are generally told that they 'exercise judgement', and that this judgement depends, in some undefined way, upon experience, insight and intuition. If the decision we are inquiring about was a particularly difficult one, or one that yielded especially impressive results, we may be told that creativity was required.

There is a scene in *Le Malade Imaginaire* in which the physician is asked why opium puts people to sleep. 'Because it possesses a dormitive faculty,' he replies triumphantly. To name a phenomenon is not to explain it. Saying that non-programmed decisions are made by exercising judgement *names* that phenomenon but does not explain it. It doesn't help the man who lacks judgement (i.e. who doesn't make decisions well) to acquire it.

Making programmed decisions depends on relatively simple psychological processes that are somewhat understood, at least at the practical level. These include habit, memory, simple manipulations of things and symbols. Making non-programmed decisions depends on psychological processes that, until recently, have not been understood at all. Because we have not understood them, our theories about non-programmed decision making have been rather empty and our practical advice only moderately helpful.

One thing we have known about non-programmed decision making is that it can be improved somewhat by training in orderly thinking. In addition to the very specific habits one can acquire for doing very specific things, one can acquire the habit – when confronted with a vague and difficult situation – of asking, 'What is the problem?' We can even construct rather generalized operating procedures for decision making. The military 'estimate of the situation' – a checklist of things to consider in analysing a military decision problem – is an example of such an operating procedure.

There is nothing wrong with such aids to decision making except that they don't go nearly far enough. They graduate the

decision maker from nursery school to kindergarten, perhaps, but they don't carry his education much further.

How then do executives discharge their responsibilities for seeing that decision making in their organizations, non-programmed as well as programmed, is of high quality? Let me propose an analogy. If you have a job to do, and you don't have the time or the skill to design and produce just the right tool to do it, you look around among the tools you have or can get at the hardware store and select the best one you can find. We haven't known very much about how to improve human decision-making skills, but we observe that some people have these skills much better developed than others. Hence, we rely on selection as our principal technique for improving complex decision-making skills in organizations.

Even our selection techniques are not nearly as adequate as we should like. To some limited extent we have found out how to assess human qualities by formal testing. In the main, however, we select a good decision maker for an organizational position by looking for a man who has done a pretty good job of decision making in some other organizational position that is almost equally taxing. This is a simple-minded approach to the problem, but it is the only moderately successful one that we know.

We supplement our selection techniques with two kinds of training: the professional training in basic principles that generally precedes entrance into organizational life, and the training through experience and planned job rotation that the organization itself can provide. Man is a learning animal. If he is subjected to a sequence of problem situations of progressively greater difficulty and of difficulty appropriate to the level of skill he has attained, he will usually show an increasing capacity to handle the problems well. For problems of a non-programmed sort neither he nor we know from whence the improvement comes. The processes of learning have been as mysterious as the processes of problem solving. But improvement there is. We are thus able, in a crude way, to use training and planned experience as a means for improving non-programmed decision making in organizations.

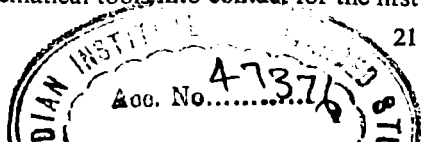
Appropriate design of the organization structure is important for non-programmed, as it is for programmed, decision making.

An important principle of organization design that has emerged over the years has been called facetiously 'Gresham's Law of Planning'. It states that programmed activity tends to drive out non-programmed activity. If an executive has a job that involves a mixture of programmed and non-programmed decision-making responsibilities, the former will come to be emphasized at the expense of the latter. The organizational implication of Gresham's Law is that special provision must be made for non-programmed decision making by creating specific organizational responsibilities and organizational units to take care of it. The various kinds of staff units that are so characteristic of large-scale modern organizations are mostly units specialized in particular aspects of the more complex non-programmed decision-making tasks. Market research units and research departments, to cite some examples, specialize in the intelligence phase of decision making; planning departments and product development departments specialize in the design phase. The creation of organizational units to carry on these activities allocates brain power to non-programmed thought, and provides some minimal assurance that such thought will occur in the organization.

In summary, we have not had, in the past, adequate knowledge of the processes that are involved in decision making in complex situations. Human thinking, problem solving and learning have been mysterious processes which we have labeled but not explained. Lacking an understanding of these processes, we have had to resort to gross techniques for improving non-programmed decision making: selection of men who have demonstrated their capacity for it; further development of their powers through professional training and planned experience; protection of non-programmed activity from the pressure of repetitive activity by establishing specialized organizational units to carry it on. We cannot say that these traditional techniques have failed - decisions do get made daily in organizations. Neither can we say that we might not do very much better in the future as our knowledge of the decision-making process grows.

### C. New Techniques for Programmed Decision Making

The Second World War brought large numbers of scientists trained in the use of mathematical tools into contact for the first





time with operational and managerial problems. Designers of military aircraft could not plan aircraft armament without making assumptions about the formations in which the planes would be flown and the strategy of their commitment to action. Mathematical economists responsible for material allocation had to come to grips with complex logistics systems. The need for solving these problems, coupled with the tools of quantitative analysis that the scientists and econometricians brought with them, have produced some new approaches to management decision making that are of fundamental importance. (See Table 1, 'eastern' half.)

### *Operations research*

Many people – notably some of the pioneer operations researchers themselves – have tried to define operations research. The net result is usually to identify it with scientific method or straight thinking applied to management problems, and to imply that it is something that can be done only by natural scientists. Definitions of this kind, unintentionally imperialistic, raise the hackles of those identified with the earlier phrase 'scientific management', who had thought that clear, scientific thinking is what they had always been doing. Except in matter of degree (e.g. the operations researchers tend to use rather high-powered mathematics), it is not clear that operations research embodies any philosophy different from that of scientific management. Charles Babbage and Frederick Taylor will have to be made, retroactively, charter members of the operations research societies.

A more understandable and defensible definition of operations research is a sociological one. Operations research is a movement that, emerging out of the military needs of the Second World War, has brought the decision-making problems of management within the range of interests of large numbers of natural scientists and, particularly, of mathematicians and statisticians.<sup>2</sup> The operations researchers soon joined forces with mathematical economists who had come into the same area – to the mutual benefit of both groups. And by now there has been widespread fraternization

2. Some standard works on operations research by leading members of the group are Churchman, Ackoff and Arnoff (1957); and Morse and Kimball (1951). The Operations Research Society of America publishes the journal *Operations Research*.

between these exponents of the 'new' scientific management and men trained in the earlier traditions of scientific management and industrial engineering. No meaningful line can be drawn any more to demarcate operations research from scientific management or scientific management from management science.<sup>3</sup>

Along with some mathematical tools, which I shall discuss presently, operations research brought into management decision making a point of view called the systems approach. The systems approach is no easier to define than operations research for it is a set of attitudes and a frame of mind rather than a definite and explicit theory. At its vaguest, it means looking at the whole problem – again, hardly a novel idea, and not always a very helpful one. Somewhat more concretely, it means designing the components of a system and making individual decisions within it in the light of the implication of these decisions for the system as a whole (see Churchman, Ackoff and Arnoff, 1957, pp. 109–11). We now know a *little* about how this might be done:

1. Economic analysis has something to say about rational behavior in complex systems of interacting elements, and particularly about the conditions under which the choices that are optimal for subsystems will or will not be optimal for a system as a whole. Economic analysis also has a great deal to say about the price system as a possible mechanism for decentralizing decision making (see Koopmans, 1951).

2. Mathematical techniques have been developed and adapted by engineers and economists for analysing the dynamic behavior of complex systems. Under the labels of servo-mechanism theory and cybernetics, such techniques underwent rapid development at about the time of the Second World War. They have considerable usefulness in the design of dynamic systems.<sup>4</sup>

Systems design is such a modish, if not faddish, word at the moment that I don't want to exaggerate the amount of well-

3. The term 'management science' was the trademark invented by the quantitatively oriented social scientists, primarily econometricians, who entered this area and who initially distinguished themselves from the operations researchers. The Institute of Management Sciences was organized in 1954. Its journal is the quarterly *Management Science*.

4. The word cybernetics was first used by Wiener (1948, p. 19). A good exposition of these techniques may be found in Tustin (1953).

understood technique that stands behind it. Nevertheless, it is fair to say that we can approach the design and analysis of large dynamic systems today with a good deal more sophistication than we could ten years ago.

### *The mathematical tools*

Operations research progressed from the talking to the action stage by finding tools with which to solve concrete managerial problems. Among the tools, some of them relatively new, some of them already known to statisticians, mathematicians, or economists were linear programming, dynamic programming, game theory and probability theory. Behind each of these formidable terms lies a mathematical model for a range of management problems. Linear programming, for example, can be used to provide a mathematical model for the operations of a gasoline refinery, or a commercial cattle-feed manufacturing operation. Dynamic programming can be used as a model for many inventory and production planning situations. Game theory models have been used to represent marketing problems. Probability models have been used in a wide variety of contexts – they have been, perhaps, the most versatile of all.

Whatever the specific mathematical tool, the general recipe for using it in management decision making is something like this:<sup>5</sup>

1. Construct a *mathematical model* that satisfies the conditions of the tool to be used and which, at the same time, mirrors the important factors in the management situation to be analysed.
2. Define the *criterion function*, the measure that is to be used for comparing the relative merits of various possible courses of action.
3. Obtain *empirical estimates* of the numerical parameters in the model that specify the particular, concrete situation to which it is to be applied.
4. Carry through the mathematical process of finding the course of action which, for the specified parameter values, maximizes the criterion function.

In any decision-making situation where we apply this recipe successfully, we have, in fact, constructed a *program* for the

5. See Churchman, Ackoff and Arnoff (1957, ch. 5).

organization's decisions. We have either annexed some decisions that had been judgemental to the area of programmed decision making,<sup>6</sup> or we have replaced a rule-of-thumb program with a more sophisticated program that guarantees us optimal decisions – optimal, that is, within the frame work of the mathematical model.

But certain conditions must be satisfied in order to apply this recipe to a class of decision problems. First, it must be possible to define mathematical variables that represent the important aspects of the situation. In particular, a quantitative criterion function must be defined. If the problem area is so hopelessly qualitative that it cannot be described even approximately in terms of such variables, the approach fails. Second, the model will call for certain parameters of its structure to be estimated before it can be applied in a particular situation. Hence, it is necessary that there be ways of making actual numerical estimates of these parameters – of sufficient accuracy for the practical task at hand. Third, the specification of the model must fit the mathematical tools to be used. If certain kinds of non-linearities are absolutely crucial to an accurate description of the situation, linear programming simply won't work – it is a tool adapted to mathematical systems that are, in a certain sense, linear. Fourth, the problem must be small enough that the calculations can be carried out in reasonable time and at a reasonable cost.

Some relatively simple management problems – for example, many problems of factory scheduling – turn out to be far too large for even such a powerful tool as linear programming. It is easy for the operations research enthusiast to underestimate the stringency of these conditions. This leads to an ailment that might be called mathematician's aphasia. The victim abstracts the original problem until the mathematical intractabilities have been removed (and all semblance to reality lost), solves the new simplified problem, and then pretends that this was the problem he wanted to solve all along. He expects the manager to be so dazzled by the beauty of the mathematical results that he will not remember that his practical operating problem has not been handled.

It is just as easy for the traditionalist to overestimate the stringency of the conditions. For the operations research

6. Thus, operations research, in addition to providing techniques for programmed decisions, also expands their boundaries.

approach to work, nothing has to be exact – it just has to be close enough to give better results than could be obtained by common sense without the mathematics. Furthermore, it is dangerous to assume that something is essentially qualitative and not reducible to mathematical form until an applied mathematician has had a try at it. For example, I have often been told that ‘you can’t place a dollar value on a lost order from inventory runout’. But why, the answer goes, can’t you estimate the penalty cost of taking emergency action to *avoid* losing the order – shipping, for example, by air express? Thus, many things that seem intangible can be reduced, for management decision-making purposes, to dollars and cents.

But we need not spin out these generalities. Mathematical techniques are now being applied in a large number of situations. In many of these situations, when mathematical techniques were first proposed there was much head shaking and muttering about judgement. The area of application is large. It is growing. But there is no indication that it will cover the whole of management decision making. [. . .]

### **D. Heuristic Problem Solving<sup>7</sup>**

However significant the techniques for programmed decision making that have emerged over the last decade, and however great the progress in reducing to sophisticated programs some areas that had previously been unprogrammed, these developments still leave untouched a major part of managerial decision-making activity. Many, perhaps most, of the problems that have to be handled at middle and high levels in management have not been made amenable to mathematical treatment, and probably never will.

But that is not the whole story. There is now good reason to believe that the processes of non-programmed decision making will soon undergo as fundamental a revolution as the one which is currently transforming programmed decision making in business organizations. Basic discoveries have been made about the nature of human problem solving. While these discoveries are still at the stage of fundamental research, the first potentialities for business application are beginning to emerge (see Table 1,

7. See Newell, Shaw and Simon (1958, pp. 151–66; 1959, pp. 10–17) and Newell and Simon (1958, pp. 1–10, 449–50).

'southeast' quadrant). We may expect this second revolution to follow the first one, with a lag of ten to twenty years.

There are several conceivable ways in which the limitations of the new approaches to programmed decision making might be transcended. One of these would be to discover how to increase substantially the problem-solving capabilities of humans in non-programmed situations. Another way would be to discover how to use computers to aid humans in problem solving without first reducing the problems to mathematical or numerical form. Both of these possibilities hinge on our deepening our understanding of human problem-solving processes. If we understand how something is accomplished, and the processes that are involved, we can either try to improve those processes or find alternatives to them. Of course, we might invent synthetic processes without understanding how the natural process works. Airplanes were invented before we understood the flight of birds. And linear programming was applied to refinery scheduling before we knew how humans had scheduled refineries. Nevertheless, when we run out of ideas for handling poorly structured problem-solving tasks, it seems plausible to examine more closely the processes used by humans who have handled such tasks – not always efficiently, to be sure – for several millennia.

### *Understanding human problem-solving processes*

But how shall we gain an understanding of the processes that humans use in problem solving and non-programmed decision making? We have been trying to explain these processes for many years. If we examine the result of these efforts, as Johnson (1955) does in his survey of research on problem solving, we get the impression that they are still a far way off from explanation.

Some things have been known, however, about problem solving, both from psychological research and from commonsense observation of what goes on around us (and in our own heads, too), for a very long time. We know, for example, that problem solving involves a great deal of search activity of one sort or another, that it often uses abstraction and imagery, that small hints can have dramatic effects on the ease of solution of a problem, and so on. But all the processes observed in problem solving – particularly the search activities and the use of relatively

obvious perceptual clues – appear so simple that we do not believe they can account for the impressive outcomes. The achievements of the problem-solving process – the bridges it designs, the organizations it builds and maintains, the laws of nature it discovers, have an impressiveness all out of proportion to the groping, almost random, processes that we observe in the problem solver at work. Little wonder that we invent terms like ‘intuition’, ‘insight’ and ‘judgement’, and invest them with the mystery of the whole process.

In the psychological laboratory, we give a subject a problem – say, proving a theorem in Euclidean geometry – and ask him to think aloud while he solves it. We have no illusion that all his thought processes will rise to the level of consciousness or be verbalized, but we hope to get some clues about the course his thought takes. We tape record what he says during the ten or fifteen minutes he works on the problem (Newell and Simon, 1959).

From the tape recording, we observe that the subject compares the theorem to be proved with some theorems he knows – he looks for similarities and differences. These suggest subproblems, whose solution may contribute to the solution of the main problem: ‘I have to prove two triangles congruent. Are any pairs of sides equal? Can I prove some pairs of sides equal?’ Subproblems may, in turn, generate new subproblems, until he comes to a problem he can solve directly. Then he climbs back up to the next level of problems above. He gradually begins to assemble results that look as though they will contribute to the solution of the whole problem. He persists as he gets warmer, backs off to another direction of search when he finds a particular trail getting cooler.

At one level, nothing seems complicated here – nothing is very different from the white rat sniffing his way through a maze. But still the feeling persists that we are seeing only the superficial parts of the process – that there is a vast iceberg underneath, concealed from our view and from the consciousness of the subject.

Perhaps this feeling of mystery is an illusion. Perhaps the sub-conscious parts of the process are no different in kind from the parts we observe. Perhaps the complexity of the problem-solving process that makes its outcome so impressive is a complexity

assembled out of relatively simple interactions among a large number of extremely simple basic elements.

Even if we find such a hypothesis appealing, how would we go about testing it? If we could construct a synthetic thought process and show that, step by step, it matched every element in the verbalized part of the human thought process – noticed the same clues in the situation, generated the same subproblems, drew from memory the same theorems – we would be justified in concluding that we understood what was going on in the human process.

The actual synthesis of thinking processes that parallel closely some thinking processes of human subjects has in fact been achieved within the past five years. The range of problem-solving tasks that has been studied in this way is still extremely narrow. However, little doubt remains that, in this range at least, we know what some of the principal processes of human thinking are, and how these processes are organized in problem-solving programs.

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## 2 D. W. Taylor

### Decision Making and Problem Solving

Abridged from D. W. Taylor, 'Decision making and problem solving', in J. G. March (ed.), *Handbook of Organizations*, Rand-McNally, 1965, ch. 2, pp. 48-86.

#### Decision Making

##### *Models*

In many areas the scientist may find the construction of a model to be an important aid to the understanding of the phenomena under investigation. The key role played by models in scientific thinking has been explored by Bross, among others, in his little book, *Design for Decision* (1953). Physical models are often employed. In some cases these models may be built to resemble just as accurately as possible the full-scale physical situation being modeled. This might be true, for example, in the study of the performance of a model airplane in a wind tunnel.

The construction of even a physical model, however, often involves abstraction. The more abstract model is built to represent only certain essential properties of the phenomena under study. Thus, an example would be a representation of the solar system involving little metal spheres which revolve on wire arms around a big sphere. Such physical models may often be replaced by verbal models. These verbal models constructed in a natural language have important uses, but they also have the important limitation of imprecision or ambiguity. In many instances, therefore, verbal models have been replaced by models employing the concepts of mathematics. These abstract mathematical models have the important advantage of rigor. They may also have the advantage of better representing the properties of the phenomena to be understood; whether this is in fact the case remains an important question in many of the models employed in behavioral science. In a very real sense, science often advances by the replacement of a primitive or less adequate model by a somewhat more adequate model, and that model in turn by a still better one.

In the investigation of decision making, the construction of models has been particularly important. Two quite different objectives are involved. One is essentially 'normative', i.e. to construct models which would tell the decision maker how he *should* make that class of decisions for which the model is appropriate. The other is 'descriptive', i.e. to construct a model which simulates as accurately as possible the behavior of the decision maker.

The author has often found the following demonstration helpful in clarifying the difference between the normative and the descriptive approach to decision making. Two identical decks of bridge cards are employed. From the first deck the club suit is removed. From the second deck the diamond suit is removed and then added to the first deck to create a deck containing three red suits and one black suit. This is all done in full view of the audience. Subjects are told that they are going to be asked to make a series of decisions and that they are to attempt to make just as many correct choices as possible. The deck containing three red suits and one black suit is then shuffled thoroughly, and subjects are asked to record what they believe the color of the top card to be. The top card is exhibited to the audience and then replaced in the deck, the deck being shuffled two or three times. Again the subjects are asked to record the color of the top card, the card is exhibited, replaced in the deck, and the deck then shuffled. This procedure is repeated twenty or thirty times.

The normative approach to such decision making would involve an analysis designed to tell the decision maker what he should do if he wishes to maximize the number right. Let  $C$  be the number guessed correctly,  $N$  the total number guessed, and  $B$  the number called black. Since the probability of being correct when calling red ( $N-B$ ) is  $\frac{3}{4}$  and when calling black is  $\frac{1}{4}$ , it would be expected on the average that

$$C = \frac{3}{4}(N-B) + \frac{1}{4}B = \frac{3}{4}N - \frac{1}{4}B.$$

Hence, to maximize  $C$  one must minimize  $B$ , i.e. call all red and no black.

Most subjects do not, in fact, exhibit the behavior which the normative analysis demonstrates to be optimal. What they ordinarily do is call red and black in the proportions of about

three to one. The objective of a descriptive model would be to explain or predict as accurately as possible such behavior on the part of the subjects. This so-called binary choice behavior has been the subject of a number of experiments by psychologists, and more than one theory has been advanced to account for the 'event-matching' observed in such behavior (Bruner, Goodnow and Austin, 1956; Bush and Mosteller, 1955; Estes and Straughan, 1954; Feldman, 1962; Galanter and Gerstenhaber, 1956; Hake and Hyman, 1953; Humphreys, 1939).

Research on decision making is of interest not only to the psychologist or behavioral scientist, but also to the economist, political scientist, statistician, management scientist, or specialist in operations research, and to men in other disciplines as well. The psychologist has come relatively late to the study of decision. Most of the work has been carried out by investigators from other areas. A large part of this work, however, has been essentially normative in character. The mathematical statistician, the operations analyst, the management scientist, and frequently the economist has as his primary objective construction of models which will tell the decision maker how he should make decisions. Statistical decision theory, linear programming, game theory, and queuing theory are all examples of normative models. The primary objective of game theory, for example, is not to predict the behavior of individuals in playing games, but rather to determine the optimal choice of strategy in those decision situations for which game theory is appropriate.

The psychologist, or behavioral scientist, in contrast, has as his objective the development of models or theories which will account for actual behavior in decision. The economist has a descriptive as well as a normative interest. Indeed, much of the descriptive theoretical and experimental work completed thus far has been carried out by economists. [. . .]

### *Administrative man*

Two books are familiar to nearly all students of administration. They are *The Functions of the Executive*, by Chester I. Barnard (1938), and *Administrative Behavior*, by Herbert A. Simon (1947). Both emphasize the crucial role of a theory of decision in any

theory of administration or of organization. Thus, Barnard has written:

What is important here, however, is the superlative degree to which logical processes must and can characterize organization action as contrasted with individual action, and the degree to which decision is specialized in organization. It is the deliberate adoption of means to ends which is the essence of formal organization (1938, p. 186).

The subtitle of Simon's book is 'A Study of Decision-Making Processes in Administrative Organization'. Elsewhere he has written:

A theory of administration or of organization cannot exist without a theory of rational choice. Human behaviour in organizations is best described as 'intendedly rational'; and it merits that description more than does any other sector of human behaviour (Simon, 1957b, p. 196.)

This emphasis on 'logical processes' or upon 'rational choice' might well lead to the expectation that economic man would have a central role in the development of the theory of administration. This, however, is far from being true. Simon, in fact, has been the outstanding critic of the limitations of both classic and modern economic theories of decision as descriptive of decision making in organizations. He has said: 'Traditional economic man, however attractive he is to the economic theorist, has little or no place in the theory of organization . . .' (Simon, 1957b, p. 198). In his classic book (1947) he called for the development of a more adequate theory of human choice; he also made some start towards its construction. In subsequent papers and books (see, for example, 1955, 1956, 1957b, 1960), he has contributed more than anyone else to the development of the descriptive model of administrative man.

*Values in decision making.* One contribution of Simon's early book (1947) was to emphasize the importance of distinguishing between the role of facts and of values in decision making. Decision always involves both questions of fact and questions of value. Questions of fact are questions of what *is*. Questions of value are questions of what *ought* to be. The answer to a factual question may often not be known, but in principle at least it can be empirically determined. For example, one may lack knowledge of the consequences of the choice of a particular alternative and may be able

only to conjecture what they will be, but the question of what they will be is a factual question. The question of whether the consequences of a particular alternative will satisfy a value important to the decision maker is also a factual question. But the question of whether the decision maker should hold the value is a value question, one which has no empirical answer.

The central role of values in decision making is well recognized in the use of normative models. Bross (1953), in his book concerned with such models, devotes a chapter entitled 'Values' to emphasizing that the use of any normative model presupposes that the user knows what set of criteria or value system he wishes to employ. The normative model does not provide the value system. The statement was made above that normative models 'tell the decision maker how he *should* make that class of decisions for which the model is appropriate'. This statement requires an important addition: 'provided that he knows what values he wishes to attain'.

The question of what values should be employed in decision making is not only outside the province of the builder of normative models. It is also outside the province of psychology or the other empirical sciences, at least in so far as the choice of ultimate values is concerned. The methods of science provide no basis for determining what ultimate values should be. At least, this is the view of the majority of contemporary philosophers of science (for an exception, see Pepper, 1958).

The view just expressed has a very important implication with respect to the evaluation of any decision. The question as to whether a given decision was a 'good' or a 'correct' decision can never be completely answered on a factual or a scientific basis. It is possible to determine, at least within limits, whether the alternatives considered were those factually available, whether the consequences anticipated were those which in fact would have ensued, and whether the choice made was the one to be preferred, given the individual's value system. If all of these conditions were met, then the decision may be said to have been 'good' or 'correct'. But one cannot on a factual or scientific basis say whether the value system employed by the individual was 'good' or 'correct'.

What the ultimate values of an individual or an organization

*should be* is not a question for science. But what the values of an individual or an organization *are* is a question which is not only appropriate for the behavioral scientist, but also one which in the view of many is central to the better understanding of human behavior (Taylor, 1960).

*Bounded rationality.* There are at least two major differences between administrative man and economic man, either classical or modern. Economic man is assumed (a) to be completely informed, and (b) to maximize something. In beginning the development of his theory of human choice, Simon (1947) took the important step of rejecting the first of these two assumptions. In subsequent papers (1955, 1956), he rejected the second assumption as well, substituting the concept of 'satisficing' for that of maximizing (see the following section).

Simon (1947) proposed that the term 'objective rationality' be used to refer to the kind of rationality represented by the concept of economic man. Actual behavior falls short, he argued, in at least three ways, of objective rationality thus defined:

1. Rationality requires a complete knowledge and anticipation of the consequences that will follow on each choice. In fact, knowledge of consequences is always fragmentary.
2. Since these consequences lie in the future, imagination must supply the lack of experienced feeling in attaching value to them. But values can be only imperfectly anticipated.
3. Rationality requires a choice among all possible alternative behaviors. In actual behavior, only a very few of all these possible alternatives, ever come to mind (p. 81).

Subsequently, Simon proposed what he called the *principle of bounded rationality*:

The capacity of the human mind for formulating and solving complex problems is very small compared with the size of the problems whose solution is required for objectively rational behavior in the real world – or even for a reasonable approximation to such objective rationality (1957b, p. 198).

In his view, an adequate theory of administrative man must realistically reflect the limits imposed upon rationality in decision making in organizations.

Economic man is assumed to deal with the 'real world' in all its complexity – with full knowledge of *all* alternatives, full knowledge of the consequences of each alternative, and even of the probabilities of occurrence of each. In contrast, administrative man is assumed to construct a simplified model of the real situation in order to deal with it. He behaves rationally only with respect to this model – only in terms of his limited knowledge of alternatives and consequences. He exhibits what has been called 'subjective rationality' (Simon, 1947). To predict the behavior of the decision maker, one must understand the way in which his simplified model of the world is constructed; the construction will certainly depend upon the way in which human beings perceive, learn and think.

While impatient with the 'preposterously omniscient rationality' of economic man, Simon is equally impatient with those concerned only with the irrational aspects of human behavior:

The past generation of behavioral scientists has been busy, following Freud, showing that people aren't nearly as rational as they thought themselves to be. Perhaps the next generation is going to have to show that they are far more rational than we now describe them as being – but with a rationality less grandiose than that proclaimed by economics (1957a, p. xxiii).

*Satisficing.* Limits upon rationality in decision making are imposed by lack of knowledge. At least equally if not more important, however, are the limits imposed by the processes of which the thinker is capable.

Consider what is implied even in decision under certainty by the assumption that the thinker can weakly order his preferences with respect to utility. Upon what is an individual's utility for a given consequence dependent? Presumably it is often a function of more than one value which the individual seeks. Take as an example the task of the individual who plans to buy a new car and who is confronted by somewhat more than 300 alternative models. How does he determine his utility for a given model? What are the values that he seeks in a car? Economy? Prestige? Capacity? Leg room? Speed? Acceleration? Durability? Length? To arrive at an overall figure of merit for a given model of a given car, he must somehow determine which values are relevant, the extent to which the given alternative meets each

value, the relative weight to be given each value, and then combine the weighted values into a single index. This presupposes that the several values have somehow been measured on, or are transformed to, a common scale. How many units of acceleration, for example, are equal to how many units of leg room? How many units of prestige are equal to how many units of durability?

Consider the demands upon the thinker that are implicit in the theory of decision under risk. Suppose for the moment that in a given situation he may know all of the many alternatives available to him and all of the consequences of each alternative, together with the probabilities that each consequence will occur. He must still somehow determine his utility for each consequence, multiply it by its probability, sum across all consequences for each alternative in turn, and then choose the one which maximizes his expected utility. This is clearly an imposing computational task to be done without aid even of pencil and paper and often without awareness.

Whenever many alternatives are involved, each with consequences to which multiple values are relevant, the concept of economic man implies severe demands upon the computational capacities of the individual, even in decision under certainty. If risky decision is involved, the computational demands implicit in maximizing utility make economic man even less plausible as a model generally descriptive of decision making. Simon (1957b, p. 246) argues 'that there is a complete lack of evidence that, in actual human choice situations of any complexity, these computations can be, or are in fact, performed'. What must be done to develop a more adequate descriptive theory of human choice is to conceive processes which are within the powers of human computation under the circumstances and within the time limits in which decisions are ordinarily made. In Simon's view (1957b, p. 204), 'the key to the simplification of the choice process . . . is the replacement of the goal of *maximizing* with the goal of *satisficing*, of finding a course of action that is 'good enough'. This proposal is central to his theory of administrative man.

Administrative man, confronted with a situation in which he must make a decision, is assumed to begin by searching for possible alternative courses of action and for information concerning the consequences of each alternative. He is assumed to select the



first alternative he encounters which meets some minimum standard of satisfaction with respect to each of the values he is seeking to attain – in other words, he satisfices. The substitution of satisficing for maximizing greatly reduces the demands upon the computational capabilities of the thinker.

Return to the example of the individual involved in purchasing a new car. He sets out to find alternative possibilities. In the examination of each in turn there may be implicit or explicit the thought that he wants a car which will sell for not more than \$3000, be regarded as one appropriate to a man of his status, hold five adult men comfortably, have sufficient leg room to be occupied by men six feet tall in both front and rear, attain a top speed of at least eighty miles per hour, accelerate from a standing stop to fifty miles per hour in eleven seconds, last seven years, and have an overall length of not more than 208 inches. The concept of satisficing would predict that he would continue to search for alternatives until he found one which met all of his minimum standards. He, having found such an alternative, would not be expected to search further in some effort to maximize his choice.

The concept of satisficing should not be misinterpreted to imply that an individual confronted simultaneously with several alternatives will fail to pick the optimal one, selecting instead one less than optimal but one which met the minimum standard with which he approached the choice situation. The small boy approaching his father with the hope of obtaining a quarter, will, if simultaneously offered the choice of a nickel, a dime, a quarter, and a half-dollar, undoubtedly pick the half-dollar even though he would have been quite satisfied to receive the quarter. The concept of satisficing is closely linked to the concept of search. The essential idea is that the individual searches until he finds an alternative which is 'good enough'. The same small boy searching for coins in the chairs in which his father often relaxes might be expected to continue his search after finding a nickel or a dime, but upon finding a quarter to stop hunting.

There is another important difference between satisficing and maximizing, at least as these concepts have ordinarily been employed. Theories which assume maximization of utility also ordinarily assume that such utility is constant over time. This

assumption is essential in uses made of such theories in macro-economics.

In contrast, it is expected that satisficing administrative man will as a result of experience modify the minimum standards he seeks to attain. If search for a satisficing alternative proves unsuccessful for an extended period, then the decision maker is expected to reduce his minimum standards. If, on the other hand, a satisficing alternative is easily found on one occasion, then upon subsequent occasions of the same general character, the decision maker may well increase his expectations. Thus, a professor seeking to employ a secretary may search initially for one who can type accurately at sixty-five words per minute and take dictation at eighty words per minute, but may after three months of unsuccessful effort reduce his aspirations to a typing speed of fifty words per minute and dictation speed of sixty words per minute. On the other hand, if he is successful within three days in reaching his original expectations, he may on a subsequent occasion well begin by searching for one who can type at eighty words per minute and take dictation at one hundred words per minute.

The concept of satisficing is closely related to the concept of *level of aspiration*, a concept which has been the subject of considerable research in psychology. Lewin, Dembo, Festinger and Sears (1944) have provided a good summary of the earlier work together with a careful theoretical statement. That research, among other things, shows clearly the effect of success and failure upon changes in level of aspiration over time (Child and Whiting, 1949).

The contrast between economic man and administrative man serves to emphasize an important paradox. Rational behavior is central to administration or organization. In fact, the major normative problem of a theory of organization is to find ways for increasing the rationality of behavior within organizations. If, however, the members of an organization were individuals capable of the kind of objective rationality attributed to economic man, then the theory of an organization would be vacuous. In Simon's words:

If there were no limits to human rationality administrative theory would be barren. It would consist of the single precept: Always select that alternative, among those available, which will lead to the most complete

achievement of your goals. The need for an administrative theory resides in the fact that there *are* practical limits to human rationality, and that these limits are not static, but depend upon the organizational environment in which the individual's decision takes place (1947, pp. 240–41).

*More than one.* A serious difficulty arises for theories of utility maximization whenever a decision is to be made not by an individual, but by a group of persons. If the decision is to maximize utility not for an individual, but for the group, then the utilities of the individual members must somehow be combined to provide a group utility (or expected utility) for each alternative. If the utility functions for one member of the group were identical with those of each of the other members of the group, then, of course, this problem would be trivial. But if, as is highly probable, utility functions do vary from one member to another, then the question of how utilities are combined in arriving at a group decision is an unsolved problem (Arrow, 1951).

Since [the problem of interpersonal comparisons of utility] is not solved, one can either assume that such comparisons are possible, knowing that this creates (at least at present) an Achilles' heel in the theory, or one can attempt to devise theories in which comparisons are not made (Luce and Raiffa, 1957, p. 34).

Group decision presents much less of a problem for the concept of satisficing. It will be expected that different members of a group approaching a choice will do so with different minimum expectations with respect to a given value and may even see different values as relevant to the decision to be made. If the rule in the group is that the decision must be unanimous, then satisficing would predict that the group continue to search for alternatives until one was found which met the minimum standards of all members of the group with respect to all of the values that any member perceives as relevant. If, however, the decision is by majority vote, the concept of satisficing would predict that the group would continue to search for an alternative until one was found which met the minimum standards for all members of the majority for all values seen by some member of that majority as relevant. It should be recalled that aspirations of individual members may rise or fall as a function of experience in search.

Values regarded as relevant may also change as a function of the experience in the group.

### Problem Solving

No attempt will be made here to provide a general review of the published research on problem solving. For this reason, the reader may find a useful supplement to the present discussion in the chapters by Johnson (1950), Taylor and McNemar (1955), and Gagné (1959) which have appeared in the *Annual Review of Psychology* or in the review by Duncan (1959). Nor will any attempt be made to present a comprehensive discussion of theories of problem solving. Instead, the present discussion will be limited almost entirely to a consideration of one approach, that which regards the thinker as an information processing system. The decision to focus on this approach was made in the belief that it presently offers the most promise for the understanding of processes involved in problem solving and decision making. There have been, of course, a number of other approaches to the study of problem solving, some of which deserve serious consideration by the student of organization. Fortunately, adequate introductions to them are readily available elsewhere.

In a chapter entitled 'Problem solving and insight', Osgood (1953) has presented a very useful description and comparison of the two approaches which have received the most attention among psychologists. One is that of the behaviorist whose primary interest is in learning. Important among the concepts which the behaviorist employs in accounting for process in problem solving are those of 'goal gradient', 'habit-family hierarchy', and 'generalization' as developed by Hull (1932, 1934, 1935, 1938, 1943) and others (see, for example, Maltzman, 1955).

Osgood (1953) compares and contrasts the behavioristic interpretation of problem solving with that offered by Gestalt psychology. Humphrey (1951) also provides a very useful summary of the Gestalt approach. Among those who have been important in contributing to this work are Duncker (1945), Koffka (1935), Köhler (1929), Luchins (1942) and Maier (1930, 1931, 1945). Wertheimer was the individual who probably had the most influence upon the development of the Gestalt view of human problem solving, in spite of the fact that his own stimulating book,

*Productive Thinking*, was published posthumously (1945). This influence occurred through his teaching and early investigations.

Central to the Gestalt theory of problem solving is the hypothesis that the presentation of a problem sets up within the psychological field of the individual tension or stresses which give rise to processes that eventually lead to solution of the problem. The tension or stresses lead to restructuring or reorganization of the forces in the psychological field. Important in problem solving, such reorganization may occur suddenly and may be accompanied by the experience of insight. Gestalt psychologists emphasize that the best thinking is not reproductive but productive. It results in something which is essentially new and is not to be accounted for simply in terms of reproduction of what has been learned in the past.

### *The thinker as an information-processing system*

The newest, and also possibly the most promising, approach to problem solving thus far developed is that proposed by Newell, Shaw and Simon (1958b). In a paper entitled 'Elements of a theory of human problem solving', they suggested essentially that the individual solving problems be regarded as an information processing system. Such a system includes:

1. A control system consisting of a number of *memories*, which contain symbolized information and are interconnected by various ordering relations. . . .
2. A number of *primitive information processes*, which operate on the information in the memories. Each primitive process is a perfectly definite operation for which known physical mechanisms exist. . . .
3. A perfectly definite set of rules for combining these processes into whole *programs* of processing. From a program it is possible to deduce unequivocally what externally observable behaviors will be generated.

At this level of theorizing, *an explanation of an observed behavior of the organism is provided by a program of primitive information processes that generates this behavior* (Newell, Shaw and Simon, 1958b, p. 151).

Viewed as a theory of behavior, a program is highly specific in that it represents only the behavior of one individual in one set of situations. If either the individual or the class of situations is changed, the program must be changed. (An important resulting advantage is that precise predictions may be made concerning the

behavior of single subjects.) However, as Newell, Shaw and Simon point out, there will be important similarities among the programs which represent the behavior of the same individuals in different situations, or among those which represent the behavior of different individuals in the same situations. On the basis of these similarities it should be possible to produce a quite general program representing behavior in a wide variety of situations.

An investigator employing this approach to problem solving begins by selecting for study some particular kind of problem solving. His first task is to attempt to identify the processes involved in the kind of thinking which he has chosen for examination. In this attempt, he may examine the records of behavior of subjects solving such problems, have subjects 'think aloud' while working, examine his own experience, or use whatever source of information may aid in understanding what occurs in solution of the class of problems under investigation. When he has formulated tentative hypotheses as to the processes involved, he next attempts to write the program that employs these processes and that simulates the thinking of the human problem solver. The objective in writing the program is not only to achieve the result which the human thinker achieves, but also to employ the same processes in doing so.

*Simulation.* Such programs are written not in English or in any other natural language, for all such languages are imprecise. Instead, the program is written in an artificial language – a fully precise language especially constructed for this purpose. By using one of these fully precise languages, one may write an unambiguous program for simulating whatever behavior is under study. Moreover, because the program is written in a precise language, an important additional advantage is gained. Such a program may be run on any large high-speed electronic computer by supplying the computer with the 'interpretive deck'. The computer translates and carries out in machine language the instructions which it receives in the special information-processing language (Green, 1963). [One example of such a special language would be IPL-V (Newell, 1961).] It should be emphasized that the purpose is not to make the computer think but simply to use the computer as a tool for determining precisely the

consequences of a given program once it is constructed. In principle, the computer is irrelevant. Once a program has been written, one could determine its consequences by what is called 'hand simulation', i.e. simply sit down with paper and pencil and determine step by step what results the program would produce when carried out. While such hand simulation is possible in principle, it might in fact take months for a moderately complex program, and even then one could not be certain of the accuracy of the results. Though not required in principle, the use of the computer is essential to make this approach to the investigation of human problem solving really feasible.

The use of simulation by programming a computer is, of course, not limited to the study of problem solving. One may undertake to simulate almost any behavior of individuals or of groups. In fact, for all of the social sciences, simulation promises to be one of the most useful tools available (Taylor, 1963).

The use of such simulation has several advantages. A model or theory expressed in the form of a computer program is fully precise. By employing a computer, one may determine quickly and rigorously the consequences of models or theories of a complexity which would otherwise be unmanageable. It may often be feasible to include within theories expressed in computer programs many more variables than can be handled within theories employing the more familiar methods of mathematics. Whereas mathematical models to be manageable must often be limited to linear relations among variables, the model expressed in an information-processing language may easily include non-linear relations.

*Algorithmic versus heuristic processes.* Before discussing programs which have been written to simulate the various types of problem solving, it will be necessary to distinguish between two kinds of processes important in thinking. The distinction to be made is that between algorithmic and heuristic processes. An algorithm is a process for solving a problem which guarantees a solution to a problem in a finite number of steps if the problem has a solution. An example of a very simple algorithm would be that for obtaining temperature on the Centigrade scale when the value for a Fahrenheit scale is known: Subtract thirty-two and

multiply the result by five-ninths. Another example would be that for finding the maximum of the function for which the equation is known: Take the first derivative, set it equal to zero, solve for  $x$ , and then continue with one of three alternative procedures.

A heuristic is a process for solving a problem which may aid in solution, but offers no guarantee of doing so. In his little book *How To Solve It*, the mathematician Polya (1945) presents heuristics useful in problem solving at the level of high-school mathematics. One heuristic which he describes, for example, is that of 'working backwards': Begin with the result which you wish to obtain and work backwards step by step towards that which is given. This same heuristic was described earlier by Duncker (1945), who believed that it was generally useful in problem solving. More recent evidence, however, suggests that it will be an effective aid in the solution in certain classes of problems, but may even be detrimental if employed in attacking others (Newell, Shaw and Simon, 1962). A familiar and widely employed heuristic is the use of analogy: Look for an analogy between the situation with which you are attempting to deal and some other situation with which you have successfully dealt in the past. This may aid you in attacking the present problem. In his two-volume work, *Mathematics and Plausible Reasoning*, Polya (1954) dealt at greater length with the role of heuristic procedures in mathematical problem solving.

Some heuristics are specific to a given class of problems. Thus, for example, the following two heuristics would be appropriate for use only in the discovery of proofs in geometry (Gelernter and Rochester, 1958, pp. 340-41): 'If the diagram consists of a bare simple polygon, a construction will probably be required.' 'If two apparently parallel lines are crossed by a transversal, attempt to establish the parallelism by considering the angles.'

Other heuristics, however, may aid in solving quite varied kinds of problems. One example of a more generally useful heuristic is what is called 'means-end' analysis: Compare what you have with what you wish to obtain; identify a difference between the two; find and carry out an operation which may reduce the difference; repeat this procedure until the problem is solved. Another generally useful heuristic is the one called 'make-a-plan': Find a problem which is similar to the one which you are attempting to



solve, and which is also simpler; solve the simpler problem; use the procedures successful in solving the simpler problem as a plan for solving the more complex problem.

The importance of heuristics in problem solving has until recently not been widely recognized. For those classes of problems for which simple algorithms are known, such procedures are, of course, to be preferred. They guarantee solution if the problems have solutions. But for many important classes of problems, no algorithms are known, and for some types of problems for which algorithms are known, such procedures cannot be employed because of the enormous amount of time which would be required to carry them out. There is, for example, an algorithm for playing chess: Consider all possible continuations of the game from the existing position to termination and then select one move which will lead to checkmate of the opposing king. An estimate made by the mathematician Shannon (1950) indicates that if this procedure were employed, it is unlikely that a single game would be completed within a lifetime, even if the players worked at the speed of the fastest electronic computers. The use of the algorithm in playing chess is simply not feasible. Instead, those who play chess employ such heuristics as: 'protect your king', 'develop your pawns', 'try to control the centre of the board', etc. (Newell, Shaw and Simon, 1958a).

*Simulation of problem solving.* In the past few years, a number of programs have been written employing heuristic processes and simulating various kinds of human problem solving. One of the first was the *Logic Theorist*, by Newell, Shaw and Simon (1958b). In writing it, they began by attempting to identify the heuristics involved in discovering proofs for theorems in elementary symbolic logic. The program which they constructed produced impressive results in a number of experiments carried out by running it under various conditions upon Johnniac, a high-speed digital computer. *Principia Mathematica*, by Whitehead and Russell, is, of course, a classic of modern symbolic logic. In one experiment, the *Logic Theorist*, employing the same axioms, definitions, and rules as in *Principia*, was presented with the problem of constructing in turn a valid proof of each of the fifty-two theorems in chapter 2 of the *Principia* in the order in which they

appear there. Whenever a theorem was proved, it was stored in memory and was available, together with the original axioms, for use in proving subsequent theorems. Under this condition, the *Logic Theorist* discovered proofs for thirty-eight of the fifty-two theorems, and did so in times ranging from less than a minute to more than fifteen minutes. Why did it fail to discover proofs for the other fourteen? The answer is that no one knows. Heuristics may be helpful, but they are not guaranteed to work, they are not algorithms.

It should be noted that an algorithm has in fact been developed more recently for the discovery of proofs in symbolic logic (Wang, 1960). In appraising the significance of this algorithm, a distinction must be made between two kinds of objectives in writing computer programs to solve problems. Those whose interest is in artificial intelligence have as their primary objective the writing of programs which will best solve problems, regardless of whether the procedures employed are similar to those which human thinkers employ. For them, the development of the algorithm represents an important advance over the *Logic Theorist*. Those whose interest is in simulation, however, have as their primary objective the writing of programs which will best approximate the procedures employed by human thinkers, regardless of whether the procedures employed are optimal for problem solving. For them, the development of the algorithm in no sense reduces interest in the *Logic Theorist*, in so far as the latter may be taken to simulate human problem solving.

The *Logic Theorist* has in a sense been replaced by another heuristic program, the *General Problem Solver* (Newell, Shaw and Simon, 1959; Newell and Simon, 1961). Work on this program began with a study of 'thinking aloud' protocols produced by subjects engaged in solving problems of the type originally devised by O. K. Moore (Moore and Anderson, 1954). These problems also involve symbolic logic, but the task is different from that of discovering proofs for theorems. In spite of the fact that the original purpose was to simulate the behavior involved in solving the Moore type of problem, evidence available indicates that the program constructed can also do trigonometric identities, perform formal integration, and solve algebraic equations; moreover, there is reason to hope that it can be extended to an even

wider range of tasks (Newell and Simon, 1959). It is for this reason that the program is called 'general' and not because it can solve problems in general. Of particular interest is the fact that the *General Problem Solver* employs only two principal heuristics, the 'means-end' heuristic and the 'make-a-plan' heuristic, both of which were described above. Such procedures formerly were often considered as trivial if indeed they were considered at all. One major result thus far of the use of simulation has been the rigorous demonstration of the potential power of heuristic processes in solving problems.

At this point some may object that in view of the high speed and accuracy with which a computer works, it is hardly surprising that the *Logic Theorist* is successful in discovering proofs for a variety of theorems, or that the *General Problem Solver* can find answers for other problems in logic or mathematics. The objection may stem from the incorrect belief that such programs involve either a random search or an exhaustive search of all possible alternatives. Indeed, for simple problems such random or exhaustive search by a computer program might well be effective. But for problems of the complexity of those being solved, such random or exhaustive search is simply out of the question. A further look at the structure of such problems may help to make clear that this is the case.

### *The maze as an abstract model of problem solving*

Newell, Shaw and Simon have pointed out that:

The maze provides a suitable abstract model for most kinds of problem-solving activity. A maze is a set of paths (possibly partly overlapping), some subset of which are distinguished from the others by having rewards at their termini (see Figure 1). These latter are the 'correct' paths; to discover one of them is to solve the problem of running the maze. We can abstract one stage further, and characterize problem solving by the following rubric: Given a set,  $P$ , of elements, to find a member of a subset,  $S$ , of  $P$  having specified properties (1962, pp. 70-71).

As they illustrate, the maze serves well as a model for such varied activities as those involved in solving crossword puzzles, finding the combination of a safe, playing chess, proving a theorem in logic or geometry, programming a computer to invert a matrix, translating a German article into English, or designing a machine.

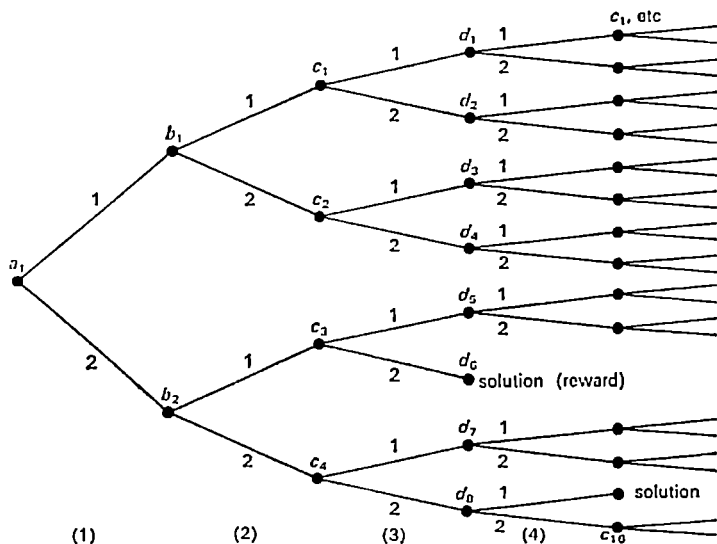


Figure 1 A problem maze. Alternatives at choice points,  $m = 2$ ; minimum length of path to solution,  $k = 3$ . The shortest path to a solution is given by the choices 2-1-2; it runs from choice point  $a_1$ , through  $b_2$  and  $c_3$  to  $d_6$ , the solution (reproduced, by permission of the authors and publisher, from Newell, Shaw and Simon, 1962, pp. 63-119)

Thus, for example, the task of the thinker in discovering the proof of a theorem in logic may be regarded as that of finding one of the paths through a very complex maze which begins with one or more of the axioms and ends in the specified theorem. The maze consists of all possible paths which might have been taken. Or, in other words (Newell, Shaw and Simon, 1962, p. 71): 'Take as  $P$  the set of all possible sequences of expressions in a formal language for logic; and as  $S$  the subset of sequences that: (a) are valid proofs, and (b) terminate in the specified theorem.' The problem is to find a member of the subset,  $S$ .

The use of a maze as a model for problem solving is closely related to the concept of a 'game tree', a mathematical abstraction important in modern game theory (Luce and Raiffa, 1957). From one node representing the first choice of the game radiate

branches representing the alternative moves available. At the end of each of these branches is another node; from this node in turn radiate branches representing the alternatives which become available if the branch leading to this node represents the first move chosen, and so on. The complete tree represents all possible moves that may be made in playing the game. The first node may represent a choice to be made by the first player, the second node a choice to be made by a second player, the third node a choice to be made by the first player (or, if it is a three-person game, by the third player) and so on. In a maze representing the solving of a problem, all of the choices are usually conceived as being made by the same individual. In this respect, the maze and the game tree differ. In sequential decision making by a single individual, however, one may speak with equal appropriateness of a decision tree or of a maze. [For still another use of the concept of decision tree, see the discussion of concept learning by E. B. Hunt (1962, pp. 224-38).]

The concept of a tree of possible future behaviors is much older than the modern theory of games, being traceable back at least to 1893 (Simon, 1957a, p. xxvii). Of the five separate and distinct concepts important in modern game theory, it is the only one which also plays a central role in Simon's model of administrative man. Indeed, the concept of a tree not only is important both for economic man and for administrative man, but also is central to the recent development of information theory by Shannon (Shannon and Weaver, 1949) and others. Simon has written (1957a, p. xxix):

The fact that this concept has been seized upon independently in such a variety of contexts to provide a framework for a theory of behavior suggests that it represents the real core of the new behavioral *Zeitgeist*.

The degree of difficulty of solving complex problems is dependent upon at least two variables: The size of the set of possible solutions that must be searched and the task of determining whether a proposed solution actually satisfies the conditions of the problem. In a given type of problem solving, either or both of these may be sources of difficulty. By using the maze as a model of problem solving, one may obtain some estimate of the difficulty of a particular class of problems. One asks essentially: How large is the maze that must be searched?

Newell, Shaw and Simon (1962) have made estimates of the size of the space of possible solutions for problems handled by the *Logic Theorist*. If no limit is imposed upon the length or other characteristics of sequences of symbolic expressions generated in the attempt to discover proofs, then, as they point out, the size of the maze is literally infinite. If, however,  $P$  is restricted,

for example, to proofs consisting of sequences of not more than twenty logic expressions, with each expression not more than twenty-three symbols in length and involving only the variables  $p, q, r, s$  and  $t$  and the connectives 'or' and 'implies', the number of possible proofs meeting these restrictions is about  $10^{235}$  – one followed by 235 zeros! (p. 73).

Even at the speed of a computer, either the random or the exhaustive search of such a maze is clearly unthinkable.

The number  $10^{235}$  is not only very large but also somewhat arbitrary, for it depends upon the restrictions placed upon sequences included within  $P$ . For this reason, Newell, Shaw and Simon propose an alternative approach to determine the size of the set,  $P$ . This involves considering a solution generator that produces members of the set in a specified order, and asking how many members the generator would have to produce, on the average, to obtain solutions to problems of a given class. Thus, they suggest consideration of generation of elements of  $P$  by the British Museum algorithm, so called after the monkeys credited with employing it:

1. We consider only sequences of logic expressions that are valid proofs – that is, whose initial expressions are axioms – and each of whose expressions is derived from prior ones by valid rules of inference. By generating only sequences that are proofs (of something), we eliminate the major part of the task of verification.
2. We generate first those proofs that consist of a single expression (the axioms themselves), then proofs two expressions long, and so on, limiting the alphabet of symbols as before. Given all the proofs of length  $k$ , we generate those of length  $(k + 1)$  by applying the rules of inference in all permissible ways to the former to generate new derived expressions that can be added to the sequences. That is, we generate a maze (see again, Figure 1), each choice point ( $a_1, b_1, b_2$ , etc.) representing the legitimate ways of deriving new expressions as immediate consequences of the expressions contained in the proof. Thus in the figure,  $d_4$  is a

proof that can be derived as an immediate consequence of  $c_2$ , using path 2 (Newell, Shaw and Simon, 1962, p. 74-5).

It is estimated that if this algorithm were employed, not less than a hundred million proofs would have to be generated to obtain all of the some sixty theorems that appear in chapter 2 of *Principia Mathematica*. The actual number may be much greater for it is difficult to estimate with any accuracy (Newell, Shaw and Simon, 1962, p. 75). Although small when compared with  $10^{235}$ , a hundred million ( $10^8$ ) is still a large number. Clearly, some procedure much more effective than the British Museum algorithm is required if proofs for theorems in symbolic logic are to be discovered by man or computer in a reasonable time. The *Logic Theorist*, a heuristic program, represents at least one such alternative.

The maze may be employed as a model in estimating the difficulty in many other classes of problems. Reference was made previously to the exceedingly large amount of time which would be required to search all of the possible continuations of a chess game to termination, and to the practical impossibility of employing such an algorithm. Suppose, however, that one considers only the maze that would be generated by considering the number of continuations not to termination, but only five moves deep by each player, assuming an average of twenty five legal continuations at each stage. Under these conditions the number of move sequences would be about one hundred million million ( $10^{14}$ ). Although even good amateur chess players may sometimes look as many as five moves deep in making a choice, it is clear that no human chess player employs the procedure of examining all possible continuations even five moves deep before choosing a move. Instead, even the best chess player employs heuristic procedures which simplify the task of searching the maze.

### *Other simulations*

In addition to the *Logic Theorist* and the *General Problem Solver*, a number of other programs have been written simulating various kinds of human problem solving. In fact, the number is now so large that an adequate review of them is beyond the scope of this discussion. For more information, the reader may wish to consult, in addition to the papers cited here, the relevant parts of the books

by Miller, Galanter and Pribram (1960), E. B. Hunt (1962), Borko (1962) and Green (1963). He may also find of interest the special section, 'Computers in behavioral science', which since April 1959 has been included regularly in the journal *Behavioral Science*. A number of articles concerning simulation of various aspects of human thinking have already appeared in this section and more may be expected in the future.

The discovery of proofs in plane geometry is a kind of problem solving familiar to high-school sophomores. It is thought to require what is often called ingenuity, imagination or intuition. Two examples were given above of heuristics useful in such problem solving. They were described to illustrate that heuristics may be specific to a given class of problems. Another example of a heuristic specific to geometry would be: 'If the figure has one axis of symmetry and it is not drawn, then draw it' (Gelernter and Rochester, 1958, p. 340). Both this and the two examples given earlier illustrate a common characteristic of heuristics in geometry; they involve the observation or manipulation of diagrams. If one were searching for a type of problem solving which would appear to be impossible to simulate by writing a computer program, one might well think of geometry because of its concern with spatial relationships. Hence, it is of particular interest that a heuristic program has been constructed which is successful in discovering proofs for many theorems in geometry (Gelernter, 1960; Gelernter, Hansen and Loveland, 1960; Gelernter and Rochester, 1958). In effect, the program behaves much as if it could draw figures, scan them, and deal intelligently with the results. Although, in fact, the original objective was not specifically to simulate the behavior of high-school sophomores, the resulting program contains some very plausible hypotheses about the ways in which humans do solve this kind of problem.

Can a computer be used to compose a symphony? An article published some years ago in the *Scientific American* (Hiller, 1959) began with this question and then went on to describe work being carried on at the University of Illinois. One program had been written employing the entire set of fourteen rules of first-species counterpoint. When run on the Illiac computer, it produced music strongly reminiscent of Palestrina. Another program in contrast produced music more like that of a Bartok string quartet. One



composition of the computer, the 'Illiac suite for string quartet', has been published. In closing, the article answered the question with which it began by arguing that, although the program would have to be far more elaborate than any yet devised, in principle there seems to be no reason why a computer cannot compose a symphony. The book *Experimental Music* (Hiller and Isaacson, 1959) provides a much more extended account of this same work. The authors point out that the process of musical composition involves a series of choices of musical elements from an essentially limitless variety of musical raw materials. They note that since music is a sensible form governed by laws of organization which permit fairly exact codification, it follows that meaningful computer-produced music is conceivable to the extent to which the laws of musical organization are codifiable. The primary interest of these authors was not in simulation. In so far, however, as the elements of the style of a Bartok can be expressed in a computer program, an important contribution would appear to have been made to the understanding of processes involved in composing music.

Work on programming a computer to compose music is also in progress at the Carnegie Institute of Technology (Reitman, 1961). This work has as its explicit objective the simulation of the processes of a composer. The work in fact began by tape recording over several months everything a particular composer said or played while composing a fugue. From these protocols the attempt was made to infer the processes which would 'account for the sequence of transformations and modifications the composer makes as he works, talks and plays' (Reitman, 1961, p. 28). The task in part is to identify the heuristics which are involved in such activity. It is of particular interest that the effort is being made to incorporate a modification of the *General Problem Solver* as the 'thinking part' of the composing system. Should this effort be successful, it would demonstrate even greater generality for the heuristics central to that program than had previously been anticipated.

The size of the maze or game tree involved in playing chess is so large that, as previously pointed out, choice of a move by considering all possible continuations of the game to termination is simply not feasible. Indeed, as also previously noted, choice of a

move by considering all possible continuations even five moves deep is out of the question, at least for the human player. Several attempts have been made to program a computer to play chess (Shannon, 1950; Kister *et al.*, 1957; Bernstein and Roberts, 1958; Newell, Shaw and Simon, 1958a). In reviewing these attempts Newell, Shaw and Simon comment:

There is clearly evident in this succession of efforts a steady development toward the use of more and more complex programs and more and more selective heuristics; and toward the use of principles of play similar to those used by human players. Partly, this trend represents – at least in our case – a deliberate attempt to simulate human thought processes. In even larger part, however, it reflects the constraints that the task itself imposes upon any information processing system that undertakes to perform it. We believe that any information processing system – a human, a computer, or any other – that plays chess successfully will use heuristics generically similar to those used by humans (1958a, p. 334).

Some of the heuristics important in chess were mentioned above. A more recent paper (Simon and Simon, 1962) explores the role of other heuristics in accounting for the discovery of ‘deep’ mating combinations by expert chess players. Since such combinations may involve continuations as many as eight moves deep, they might appear to require prodigious memory and ultra-rapid processing capacities. But this paper describes a program involving relatively simple heuristics which so simplifies the tree to be considered that the amounts of search and the processing speeds required do not appear extravagant. The paper concludes: ‘The evidence suggests strongly that expert chess players discover combinations because their programs incorporate powerful selective heuristics and not because they think faster or memorize better than other people’ (Simon and Simon, 1962, p. 429).

### *Heuristic decision making*

Administrative man makes decisions by searching until he finds an alternative which satisfices with respect to whatever values are important to him. The similarity of this model of decision making to the model of process in problem solving described thus far should be apparent. This similarity is perhaps most easily seen in terms of the playing of chess. In undertaking to simulate chess

playing, Newell, Shaw and Simon (1958a) organized their program in terms of a set of goals. Among these goals were the following: king safety, material balance, center control, development, kingside attack, promotion. Associated with each goal are various heuristics which guide the chess player in his search for and choice of a move. Alternatively, this same behavior might be described in terms of a search for and choice of a move which satisfies with respect to several values. The ultimate value for the chess player is to checkmate his opponent's king. But this single value is not sufficient to enable him to choose an alternative from among the very large number of sequences of moves available to him at any given point of the game; it would be sufficient only if it were feasible for him to consider all possible continuations of the game to termination. Instead, he makes his choice in terms of a number of intermediate values. The goals just listed represent clear examples of such intermediate values. The heuristics associated with any one of these goals may in turn be conceptualized as values intermediate in the service of that goal. One may think either in terms of a hierarchy of values, or in terms of a hierarchy of goals and/or heuristics. Heuristics commonly imply values. Consider for example: 'Protect your king', 'Try to control the center of the board', etc. In discussing the heuristics associated with the goal of 'material balance', Newell, Shaw and Simon (1958a, p. 331) comment: 'They incorporate a number of implicit assumptions about what is important, and what isn't, on the chess board.'

Thus far the discussion of simulation of heuristic problem solving has been concerned with types of problems which may appear relatively remote from the kinds which confront administrators or managers. There have been, in fact, a number of programs written which employ heuristics in solving problems or making decisions of various kinds important in business or industry. Included among the tasks for each of which a heuristic program has been written are: balancing an assembly line (Tonge, 1961; see also 1960); solving multi-product, single-machine scheduling and inventory problems (Maxwell, 1961); dealing with the trust investment problem of portfolio selection (Clarkson, 1962; see also Clarkson and Meltzer, 1960); locating warehouses (Kuehn and Hamburger, 1962); solving the so-called traveling

salesman problem (Karg and Thompson, 1962); scheduling a job shop (Gere, 1962). Each of these represents a type of problem for which an algorithm does not exist, or for the solution of which available algorithms are either not computationally or economically feasible. Each also involves kinds of decisions which managers do make with at least some degree of practical success. The primary objective in writing many of these programs was probably that of artificial intelligence rather than of simulation. Nevertheless, those developing such programs found fruitful leads by examining the behavior of individuals successful in solving such problems. Moreover, the heuristic programs produced include many plausible hypotheses about how managers do go about solving such problems or making such decisions.

The task which Tonge (1961) chose to investigate was that of balancing an assembly line. In many industries, the product is assembled on a continuous conveyor line. The tasks making up the assembly operation must be assigned to work stations along the line. In the simplest case, each elemental task requires a known operation time per unit, independent of when performed, and constraints exist as to the order in which the tasks can be performed. The problem consists in assigning tasks to work stations in such a way that 'each elemental task is assigned to one and only one work station . . . the sum of the times of all elemental tasks assigned to any one station does not exceed some maximum . . . the stations thus formed can be ordered such that the partial orderings among elemental tasks are not violated . . . the number of work stations thus formed is minimized (Tonge, 1961, p. 3). Efforts have been made to develop algorithms for solving this problem, but the computational time required by those thus far available prohibit their use. What Tonge did was to construct a heuristic program which, though presently more costly per balance produced than an industrial engineer, nevertheless appears to offer promise of further development which will be economically useful. In any case, his program appears to contribute much to the understanding of the procedures which industrial engineers employ implicitly or explicitly in solving such problems.

The investigator whose objective is that of artificial intelligence may often find fruitful the exploration of the heuristic procedures

employed by human beings expert in solving the kind of problem in which he is interested. Simon and Newell (1958) indeed have argued that 'the next advance in operations research' will come through the exploration of heuristic problem solving. They pointed out that operations research thus far has demonstrated its effectiveness in dealing with the kinds of management problems which may be called 'well structured'. However, many management problems, including perhaps most of the more important ones, are 'ill structured'. Well-structured problems are those which satisfy the following criteria:

1. They can be described in terms of numerical variables, scalar and vector quantities.
2. The goals to be attained can be specified in terms of a well-defined objective function – for example, the maximization of profit or the minimization of cost.
3. There exist computational routines (*algorithms*) that permit the solution to be found and stated in actual numerical terms (Simon and Newell, 1958, pp. 4–5).

Ill-structured problems are those that are not well structured. The task of balancing an assembly line is an example of an ill-structured problem. As a matter of fact, Tonge (1961) devotes a chapter to a discussion of the general question of the usefulness of a computer for the solution of ill-structured problems. Noting that the aim of his study was broader than that of producing a method for balancing assembly lines, he continued:

We set out to test the feasibility of a heuristic approach to a particular industrial decision and to examine the use of information processing languages in implementing such an approach. . . . But based on the experience reported in this paper, we conclude that the combination of a heuristic approach and these methods of computer utilization is a useful research tool for treating complex industrial management problems (Tonge, 1961, p. 63).

### *Postscript*

To make decisions well or to solve problems is to behave intelligently. But what is the nature of intelligence? Is it a single unitary capacity, as Spearman (1904, 1927) or Terman (1916) believed, or is it composed of a number of relatively independent factors? The technique of factor analysis has served as an important tool in

attempts to answer these questions. Among those who contributed most to the early development of this technique was Thurstone (1935). Employing it in investigating thinking, he concluded that intelligence is best conceived as made up of a number of primary mental abilities, including verbal comprehension, word fluency, number, space, memory, perception and reasoning (Thurstone, 1938). Within recent years, Guilford and his associates at the University of Southern California have been the most active in pursuing this approach. The questions with which they have been concerned are: 'What are the phenomena that exist in the domain of human thinking? What are the different kinds of operations or processes?' (Guilford, 1960, p. 6). Thus far, their work has led to the identification of more than fifty different intellectual factors. A brief introduction to this work is presented by Taylor (1963); a more complete summary is available in either of two papers by Guilford (1959, 1960).

How is a theory which regards intelligence as being composed of a limited number of factors to be reconciled with a theory which views the thinker as an information processing system? In a recent book, *Intelligence and Experience*, J. McV. Hunt (1961) argues that the developments in problem solving which have been described at length in this chapter, together with certain other recent developments in psychology, both demand and are contributing to a radical revision in the answer to the question: What is the nature of intelligence? Indeed, it may be anticipated that more adequate description of the thinker as an information processing system will provide a more adequate answer to the question.

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## **Part Two**

# **Non-Programmed Decision Making**

Four field studies of non-programmed decisions are described in the essays that follow. To varying degrees they all show that the economic model does not explain the managerial decision-making procedures that are observed. They all indicate the need for a new theory of managerial decision making that reflects those procedures and activities that managers actually engage in in the business world.

The Cyert–Simon–Trow (Reading 3) paper describes how a particular company decided upon the feasibility of installing a computer. It demonstrates the deficiencies of the economic model for explaining decision processes in the firm. For example, a problem is a ‘given’ in the economic model. However, as we read the observations of the first study, we become aware of the circumstances leading to the evolution of the problem of computer feasibility: first, as we note the expectation of the comptroller that there is a possibility of an application of the computer to accounting processes, then, as the staff member is assigned to keep up with EDP equipment, next, as the two computer companies initiate proposals and draw attention to the decision area, and so on. The observations lead away from consideration of a ‘given’ problem as in the economic model to questions of how problems arise, what triggers attention to them, and what the relations of present performance and level of aspiration are to their evolution.

Moreover, actors in the world of the economic model have access to all alternatives and their consequences in solving a problem. The managers observed in this study, once the problem has claimed attention, must seek alternatives and information concerning the consequences of such alternatives themselves.

Note that these decisions occur in an environment of uncertainty and the concept of an optimum or a maximum cannot be easily defined. The managers do not compare alternatives in terms of a single criterion, nor are the criteria comparable from one choice to another.

The second paper by Cyert–Dill–March (Reading 4) discusses two decisions: the first, a decision to accelerate the replacement of crane controllers, and the second, a decision to find new working quarters for a department in a firm. In neither case are there any computations to provide data showing that the decision is optimal. There are crude estimates made of costs, but none of returns. Both decisions concern feasibility rather than consideration of return and cost. Neither comes as a result of continued planning; both, rather, are results of short-range situations within the firm. Part of the difficulty the firms experience in their calculations is in the awkwardness of comparing units of differing dimensions, such as dollar savings, accuracy, safety, quality, reputation and so forth.

The Dufty–Taylor study (Reading 5) concerns a decision to transfer a number of personnel to a relatively unpopular location. This example demonstrates the influence of the decision maker's value system on the alternatives he considers and finally chooses. In this case, for example, it is pointed out that a simple alternative of transfer which would have complied with legal restraints was not considered, while alternatives which required considerably more effort on the part of the decision makers were adopted.

Non-programmed decision models cannot be tested. Models must be tested with data other than that used to construct the model. Such data can be obtained only if the decisions are repeated. Therefore, non-programmed decision models, being one-shot decisions, cannot be tested by classical statistical methods.

#### Observation of a Business Decision

R. M. Cyert, H. A. Simon and D. B. Trow, 'Observation of a business decision', *Journal of Business*, vol. 29, 1956, pp. 237-48.

Decision making – choosing one course of action rather than another, finding an appropriate solution to a new problem posed by a changing world – is commonly asserted to be the heart of executive activity in business. If this is so, a realistic description and theory of the decision-making process are of central importance to business administration and organization theory. Moreover, it is extremely doubtful whether the only considerable body of decision-making theory that has been available in the past – that provided by economics – does in fact provide a realistic account of decision making in large organizations operating in a complex world.

In economics and statistics the rational choice process is described somewhat as follows:

1. An individual is confronted with a number of different, specified alternative courses of action.
2. To each of these alternatives is attached a set of consequences that will ensue if that alternative is chosen.
3. The individual has a system of preferences or 'utilities' that permit him to rank all sets of consequences according to preference and to choose that alternative that has the preferred consequences. In the case of business decisions the criterion for ranking is generally assumed to be profit.

If we try to use this framework to describe how real human beings go about making choices in a real world, we soon recognize that we need to incorporate in our description of the choice process several elements that are missing from the economic model:

1. The alternatives are not usually 'given' but must be sought,

## Non-Programmed Decision Making

and hence it is necessary to include the search for alternatives as an important part of the process.

2. The information as to what consequences are attached to which alternatives is seldom a 'given', but, instead, the search for consequences is another important segment of the decision-making task.

3. The comparisons among alternatives are not usually made in terms of a simple, single criterion like profit. One reason is that there are often important consequences that are so intangible as to make an evaluation in terms of profit difficult or impossible. In place of searching for the 'best' alternative, the decision maker is usually concerned with finding a *satisfactory* alternative – one that will attain a specified goal and at the same time satisfy a number of auxiliary conditions.

4. Often, in the real world, the problem itself is not a 'given', but, instead, searching for significant problems to which organizational attention should be turned becomes an important organizational task.

Decisions in organizations vary widely with respect to the extent to which the decision-making process is *programmed*. At one extreme we have repetitive, well-defined problems (e.g. quality control or production lot-size problems) involving tangible considerations, to which the economic models that call for finding the best among a set of pre-established alternatives can be applied rather literally. In contrast to these highly programmed and usually rather detailed decisions are problems of a non-repetitive sort, often involving basic long-range questions about the whole strategy of the firm or some part of it, arising initially in a highly unstructured form and requiring a great deal of the kinds of search processes listed above. In this whole continuum, from great specificity and repetition to extreme vagueness and uniqueness, we will call decisions that lie towards the former extreme *programmed*, and those lying towards the latter end *non-programmed*. This simple dichotomy is just a shorthand for the range of possibilities we have indicated.

It is our aim in the present paper to illustrate the distinctions we have introduced between the traditional theory of decision, which appears applicable only to highly programmed decision

problems, and a revised theory, which will have to take account of the search processes and other information processes that are so prominent in and characteristic of non-programmed decision making. We shall do this by recounting the stages through which an actual problem proceeded in an actual company and then commenting upon the significance of various items in this narrative for future decision-making theory.

The decision was captured and recorded by securing the company's permission to have a member of the research team present as an observer in the company's offices on substantially a full-time basis during the most active phases of the decision process. The observer spent most of his time with the executive who had been assigned the principal responsibility for handling this particular problem. In addition, he had full access to the files for information about events that preceded his period of observation and also interviewed all the participants who were involved to a major degree in the decision.

### **The Electronic Data-Processing Decision**

The decision process to be described here concerns the feasibility of using electronic data-processing equipment in a medium-size corporation that engages both in manufacturing and in selling through its own widely scattered outlets. In July 1952 the company's controller assigned to Ronald Middleton, an assistant who was handling several special studies in the accounting department, the task of keeping abreast of electronic developments. The controller, and other accounting executives, thought that some of the current developments in electronic equipment might have application to the company's accounting processes. He gave Middleton the task of investigation, because the latter had a good background for understanding the technical aspects of computers.

Middleton used three procedures to obtain information: letters to persons in established computer firms, discussions with computer salesmen, and discussions with persons in other companies that were experimenting with the use of electronic equipment in accounting. He also read the current journal literature about computer developments. He informed the controller about these matters principally through memorandums that described the current status of equipment and some of the procedures that

would be necessary for an applications study in the company. Memorandums were written in November 1952, October 1953 and January 1954. In them, in addition to summarizing developments, he recommended that two computer companies be asked to propose possible installations in the company and that the company begin to adapt its accounting procedures to future electronic processing.

In the spring of 1954 a computer company representative took the initiative to propose and make a brief equipment application study. In August he submitted a report to the company recommending an installation, but this was not acted upon – doubt as to the adequacy of the computer company's experience and knowledge in application being a major factor in the decision. A similar approach was made by another computer company in September 1954, but terminated at an early stage without positive action. These experiences convinced Middleton and other executives, including the controller, that outside help was needed to develop and evaluate possible applications of electronic equipment.

Middleton drew up a list of potential consultants and, by checking outside sources and using his own information, selected Alpha as the most suitable. After preliminary meetings in October and November 1954, between representatives of Alpha and the company accounting executives, Alpha was asked to develop a plan for a study of the application of electronic data-processing to sales accounting. Additional meetings between Alpha and company personnel were held in February 1955, and the proposal for the study was submitted to the controller in March.

Although the proposal seemed competent and the price reasonable, it was felt that proposals should be obtained from another consulting firm as a double check. The controller agreed to this and himself selected Beta from Middleton's list. Subsequently representatives of Beta met with Middleton and other department executives. Middleton, in a memorandum to the controller, listed criteria for choosing between the two consultants. On the assumption that the written report from Beta was similar to the oral proposal made, the comparison indicated several advantages for Beta over Alpha.

After the written report was received, on 2 May, the company's



management committee authorized a consulting agreement with Beta, and work began in July 1955. The controller established a committee, headed by Middleton, to work on the project. Middleton was to devote full time to the assignment; the other two committee members, one from sales accounting and one from auditing, were to devote one-third time.

The consulting firm assigned two staff members, Drs Able and Baker, to the study. Their initial meetings with Middleton served the purpose of outlining a general approach to the problem and planning the first few steps. Twenty-three information-gathering studies were defined, which Middleton agreed to carry out, and it was also decided that the consultants would spend some time in field observation of the actual activities that the computer might replace.

During July, Middleton devoted most of his time to the twenty-three studies on volume of transactions and information flow, obtaining data from the sales department and from the field staffs of the other two committee members. Simultaneously, steps were taken to secure the co-operation of the field personnel who would be visited by the consultants early in August.

On 22 July Middleton submitted a progress report to the controller, describing the data-gathering studies, estimating completion dates, and summarizing the program's objectives. On 25 July the consultants met with Middleton and discussed a method of approach to the design of the data-processing system. The field trip took place early in August. The consultants obtained from field personnel information as to how accounting tasks were actually handled and as to the use actually made of information generated by the existing system.

On 8 August Middleton submitted another progress report, giving the status of the data-gathering studies and recording some ideas originating in the field trip for possible changes in the existing information-processing system. On 10 August he arranged with the assistant controller to obtain clerical assistance on the data-gathering studies, so that the consultants would not be held up by lack of this information, and on 17 August this work was completed.

On the following day the consultants met with the company committee to review the results of the twenty-three studies. They

then listed the outputs, files, and inputs required by any sales accounting system the company might adopt and drew a diagram showing the flow of the accounting information. The group also met with the assistant controller and with the controller. The latter took the opportunity to emphasize his basic decentralization philosophy.

Upon returning from his vacation early in September, Middleton discussed the flow diagram in greater detail with Able and Baker, and revisions were made on the basis of information Middleton supplied about the present accounting system. Baker pointed out that all the alternative systems available to the company could be defined by the location of seven principal functions and records. Further analysis reduced this number to three: stock records, pricing of orders, and accounts receivable. The possible combinations of locations of these gave eighteen basic alternative systems, of which eight that were obviously undesirable were eliminated. Middleton was to make a cost analysis of the existing system and the most decentralized of the proposed systems, while the consultants were to begin costing the most centralized system.

Middleton reviewed these tentative decisions with the other members of the company committee, and the group divided up the work of costing. Middleton also reported to the controller on the conference, and the latter expressed his attitudes about the location of the various functions and the resulting implications for the development of executive responsibility.

During the next week, in addition to working on his current assignments, Middleton gave an equipment salesman a preliminary overview of the probable requirements of a new system. Next, there was a two-day meeting of the consultants and the company's committee to discuss the form and implications of a centralized electronic system. The consultants presented a method of organizing the records for electronic processing and together with the committee calculated the requirements which this organization and company's volume of transactions would impose on a computer. The group then discussed several problems raised by the system, including the auditing problems, and then met with the assistant controller to review the areas they had discussed.

On the following day, Middleton summarized progress to date for the controller, emphasizing particularly the work that had been done on the centralized system. The controller expressed satisfaction with several new procedures that would be made possible by an electronic computer. During the next several days the committee members continued to gather the information necessary to determine the cost of the present system. Middleton also checked with the assistant controller on the proposed solutions for certain problems that the consultants had indicated could not be handled readily by a computer and relayed his reactions to the consultants.

A week later the consultants returned for another series of meetings. They discussed changes that might be necessary in current practices to make centralized electronic processing possible and the way in which they would compare the centralized and decentralized proposals. The comparison presented some difficulties, since the data provided by the two systems would not be identical. A general form for a preliminary report was cleared with the assistant controller, and a date was set for its submission. The processing, outputs and costs for the two alternatives would be described, so that additional information required for a final report could be determined.

During the next week Middleton continued collecting cost data. He phoned to the consultants to provide them with important new figures and to inform them of the controller's favorable reaction to certain proposed changes in the system that had implications for the company's policies.

On 17 October Baker met with Middleton to review the content of the accounting reports that would be produced by the centralized system, to discuss plans for the preliminary report, and to discuss the relative advantages and disadvantages of the centralized and decentralized systems. On the next day, Middleton checked on their decisions relative to the report with the controller and assistant controller and raised the possibility of an outside expert being retained by the company to review the final report submitted by Beta. During the last days of this week, Middleton attended the national meeting of a management society, where he obtained information about the availability of computers and computer personnel and the existence of other

installations comparable to that contemplated for the company.

Work continued on the planning and costing of the two systems – Middleton worked primarily on the decentralized plan, and the consultants on the centralized. On 27 October the two consultants met with Middleton and they informed each other of the status of their work. Baker discussed methods for evaluating system reliability. Plans for the preliminary report were discussed with the company committee and the assistant controller. Since the controller strongly favored decentralization of authority, the question was raised of the compatibility of this with electronic processing in general and with the centralized system in particular. The groups concluded, however, that centralization of purely clerical data-processing operations was compatible with decentralization of responsibility and authority.

After several meetings between the committee and the consultants to iron out details, the preliminary report was presented to the company committee, the controller, and the assistant controller on 3 November. The report was devoted primarily to the centralized system. The following points were made in the oral presentation:

1. That both the centralized and decentralized proposals would yield substantial and roughly equivalent savings but that the centralized system would provide more and better accounting data.
2. That the alternatives had been costed conservatively.
3. That the centralized system involved centralization of paper work, not of management.
4. That not all problems raised by the centralized system had been worked out in detail but that these did not appear insurmountable.
5. That the centralized system would facilitate improved inventory control.
6. That its installation would require nine to twelve months at a specified cost.

At this meeting the group decided that in the final report only the two systems already considered would be costed, that the final report would be submitted on 1 December, and that investigation

of other accounting applications of the system would be postponed.

In informal conversations after the meeting the controller told Middleton he had the impression that the consultants strongly favored the centralized system and that he believed the cost considerations were relatively minor compared with the impact the system would have on executives' operating philosophies. The assistant controller told Middleton he thought the preliminary report did not adequately support the conclusions. The committee then reviewed with the assistant controller the reasons for analysing in detail only the two extreme systems: the others either produced less information or were more costly.

The next day the committee met with the controller and assistant controller to determine what additional information should be requested for the final report. The controller outlined certain questions of practicability that the final report should answer and expressed the view that the report should contain a section summarizing the specific changes that the system would bring about at various levels of the organization. He thought the comparison between systems in the preliminary report had emphasized equivalence of savings, without detailing other less tangible benefits of the centralized system.

Middleton reported these discussions to the consultants and with them developed flow charts and organization charts for inclusion in the final report, settled on some intermediate deadlines, and worked up an outline of the report. Within the company he discussed with the controller and assistant controller the personnel and organizational requirements for installation on an electronic system and for operation after installation. Discussion focused on the general character and organizational location of the eventual electronic-data-processing group, its relation to the sales accounting division, and long-term relations with manufacturing accounting and with a possible operations research group.

On 14 November the controller, on recommendation of Middleton, attended a conference on automation for company senior executives. There he expressed the view that three to five years would be required for full installation of a centralized electronic system but that the fear of obsolescence of equipment

should not deter the company in making the investment. He also concluded that a computer installation would not reverse his long-range program for decentralizing information and responsibility.

Middleton, his suggestion being accepted, made tentative arrangements with an independent expert and with two large computer companies for the review of the consultants' report. Middleton presented to the controller and assistant controller a memorandum he had prepared at the latter's request, establishing a new comparison of the centralized and a modified decentralized system. The modification made the two systems more nearly comparable in data-processing capacity, hence clarified the cost comparison, which was now in favor of the centralized system. Consideration of the possibility of starting with a partially electronic decentralized system as a step towards a completely electronic system led to the decision that this procedure had no special advantages. The controller reported that conversations with the sales manager and the president had secured agreement with the concept of removal of stock record-keeping from field locations – an aspect of the plan to which it had been assumed there would be sales department opposition. The group discussed several other specific topics and reaffirmed that the final report should discuss more fully the relative advantages and disadvantages of centralized and decentralized systems.

Towards the end of November there was further consultation on the report, and final arrangements for its review were made with the two equipment companies and the independent expert. Each equipment company was expected to determine the method for setting up the proposed system on its computer and to check the consultants' estimates of computer capacity. During this week the controller informed the company's management committee that the report from the consultants would be submitted shortly and would recommend a rather radical change to electronic data-processing.

The final report, which recommended installation of the centralized system, was submitted on 1 December. The report consisted of a summary of recommendations, general description of the centralized system, discussion of the installation program, and six appendixes: statistics on volume of transactions (the

twenty-three studies); costs of the present system; requirements of a fully centralized system; changes in allocation of functions required by the system; outline of the alternative decentralized system; and a description of the existing system in verbal and flow-chart form. When the report was received and reviewed initially, the company's committee members and the consultants made some further computations on installation costs.

At a meeting the following Monday the assistant controller proposed an action program: send copies of the report to equipment companies, send copies to the sales department, and await the report of the independent expert. The controller decided that the second and third steps should be taken before giving the report to the machine companies, and the assistant controller indicated to Middleton some points requiring further clarification and elaboration.

By 7 January Middleton had prepared an outline for a presentation of the report to the sales department. This was revised on the basis of a meeting with the other interested accounting executives. A final outline was agreed upon after two more revisions and three more meetings. The report was presented on 28 January to the president and to six of the top executives of the sales department. The presentation discussed large-scale computers briefly, described with flow charts the proposed system, emphasized the completeness and accuracy of the information produced, discussed costs and savings, and mentioned the current trend in other companies towards electronic data-processing.

At Middleton's recommendation the same presentation was made subsequently to top members of the accounting department and still later to a group from the manufacturing department. At the same time the preliminary report of the independent expert was received, agreeing that the electronic installation seemed justifiable and stating that there might not be any cost savings but that it would make possible numerous other profitable applications of the computer. The consultants' report was then distributed to the computer companies, and Middleton began more detailed planning of the installation.

Middleton, the assistant controller, and the controller now met with the independent expert, who reported his conclusions: the feasibility study was excellent, the estimates of processing

time were probably optimistic, the installation program should provide for an early test run, and the two principal available computers were highly competitive. Independent confirmation had been obtained on the last two points from another outside source. Middleton now proposed that the company proceed with its planning while awaiting the final written report from the independent expert and the proposals of the equipment companies. The assistant controller preferred to wait until these reports were actually in hand.

During the next week the equipment companies proceeded with their analysis, meeting several times with Middleton. Baker sent a memorandum on his estimates of processing time to meet the criticism of the independent expert. Middleton prepared two charts, one proposing a schedule and the staffing requirements for the installation phase, the other proposing organizational arrangements for the computer center. Middleton and the assistant controller presented these to the controller at the beginning of February, discussion centering responsibility for accuracy of input information.

Middleton and the assistant controller also had a meeting with sales executives who reported that on the basis of their own internal departmental discussions of the consultants' report they were in general agreement with the program. Middleton and one of the other committee members then spent two days inspecting computer installations in two other companies.

In the middle of February the two equipment companies presented their reports, each bringing a team of three or four men to present their recommendations orally. The two recommendations were substantially alike (except for the brand of the machine recommended!), but one report emphasized the availability of its personnel to give help during the installation planning stage.

Discussions were held in the accounting department and with consultant Baker about these reports and the next steps to be taken. The question was debated whether a commitment should be made to one equipment company or whether a small group should continue planning the system in detail, postponing the equipment decision until fall. Most of the group preferred the former alternative.



On 15 February the controller, in conference with the assistant controller and Middleton, dictated a letter to the company's president summarizing the conclusions and recommendations of the study and requesting that the accounting department be authorized to proceed with the electronics program.

On the following day the controller read the letter to the management committee. The letter reviewed briefly the history of the project and summarized the conclusions contained in the consultants' report: that there was ample justification for an electronic-data-processing installation; that the installation would warrant use of the largest computers; and that it would produce savings, many intangible benefits, and excess computer capacity for other applications. The letter quoted the consultants' estimate of the cost of the installation and their recommendation that the company proceed at once to make such a conversion and to acquire the necessary equipment. It then cited the various cross-checks that had been made of the consultants' report and concluded with a repetition of the conclusions of the report – but estimating more conservatively the operating and installation costs – and a request for favorable management committee action. Supplementary information presented included a comparison of consultant and equipment company cost estimates and a list of present and proposed computer installations in other companies. After a few questions and brief discussion, the management committee voted favorably on the recommendation, and the controller informed Middleton of the decision when the meeting ended.

### **The Anatomy of the Decision**

From this narrative, or more specifically from the actual data on which the narrative is based, one can list chronologically the various activities of which the decision process is composed. If we wish to describe a program for making a decision of this kind, each of these activities might be taken as one of the steps of the program. If the rules that determined when action would switch from one program step to another were specified, and if the program steps were described in enough detail, it would be possible to replicate the decision process.

The program steps taken together define in retrospect, then, a

## Non-Programmed Decision Making

program for an originally unprogrammed decision. The program would be an inefficient one because it would contain all the false starts and blind alleys of the original process, and some of these could presumably be avoided if the process were repeated. However, describing the process that took place in terms of such a program is a useful way of organizing the data for purposes of analysis.

In order to make very specific what is meant here by a 'program', the chart below has been prepared to show the broad outlines of the actual program for the first stages of the decision process (through the first seven paragraphs of the narrative).

### *Program steps from inception of the problem to selection of a consultant*

#### *Keeping-up program* (paragraphs 1 and 2 of narrative):

Search for and correspond with experts;  
Discuss with salesmen and with equipment users;  
Search for and read journals;

#### *Procurement program* (paragraph 3):

Discuss applications study with salesmen who propose it;  
Choice: accept or reject proposed study;  
(If accepted) transfer control to salesmen;  
Choice: accept or reject applications proposal;  
(If rejected) switch to consultant program;

#### *Consultant program* (paragraphs 4 through 7):

Search for consultants;  
Choice: best consultant of several;  
Transfer control to chosen consultant;  
Choice: accept or reject proposal;  
(If accepted): begin double-check routine;  
Request expenditure of funds;  
(If authorized) transfer control to consultants;  
And so on.

#### *Subprograms*

The various program steps of the decision process fall into several subprograms some of which have been indicated in the chart above. These subprograms are ways of organizing the activities

*post factum*, and in the chart the organizing principle is the method of approach taken by the company to the total problem. It remains a question as to whether this organizing principle will be useful in all cases. As in the present example, these subprograms may sometimes be false starts, but these must be regarded as parts of the total program, for they may contribute information for later use, and their outcomes determine the switching of activity to new subprograms.

In this particular case the reasons for switching from one subprogram to another were either the proved inadequacy of the first one or a redefinition of the problem. Other reasons for switching can be imagined, and a complete theory of the decision process will have to specify the conditions under which the switch from one line of attack to another will occur.

### *Common processes*

In the whole decision-making program there are certain steps or 'routines' that recur within several of the subprograms; they represent the basic activities of which the whole decision process is composed. For purposes of discussion we have classified these common processes in two categories: the first comprises processes relating to the communication requirements of the organization; the second comprises processes relating directly to the solution of the decisional problem.

### *Communication processes*

Organizational decision making requires a variety of communication activities that are absent when a decision is made in a single human head. If we had written out the program steps in greater detail, many more instances of contacts among different members of the organization would be recorded than are now explicit in the narrative. The contacts may be oral or written. Oral contacts are used for such purposes as giving orders, transmitting information, obtaining approval or criticism of proposed action; written communications generally take the form of memorandums having the purpose of transmitting information or proposing action.

The information-transmitting function is crucial to organizational decision making, for it almost always involves acts of

selection or 'filtering' by the information source. In the present instance, which is rather typical in this respect, the consultants and subordinate executives are principal information sources; and the controller and other top executives must depend upon them for most of their technical information. Hence, the subordinate acts as an information filter and in this way secures a large influence over the decisions the superior can and does reach.

The influence of the information source over communications is partly controlled by checking processes – for example, retaining an independent expert to check consultants – which give the recipient an independent information source. This reduces, but by no means eliminates, filtering. The great differences in the amounts and kinds of information available to the various participants in the decision process described here emphasize the significance of filtering. It will be important to determine the relationship of the characteristics of the information to the resultant information change and to explore the effects of personal relations between people on the filtering process and hence upon the transmission of information.

### *Problem-solving processes*

Alongside the organizational communication processes, we find in the narrative a number of important processes directed towards the decision problem itself. One of the most prominent of these is the search for alternative courses of action. The first activities recounted in the narrative – writing letters, reading journals and so on – were attempts to discover possible action alternatives. At subsequent points in the process searches were conducted to obtain lists of qualified consultants and experts. In addition to these, there were numerous searches – most of them only implicit in the condensed narrative – to find action alternatives that would overcome specific difficulties that emerged as detail was added to the broader alternatives.

The data support strongly the assertion made in the introduction that searches for alternative courses of action constitute a significant part of non-programmed decision making – a part that is neglected by the classical theory of rational choice. In the present case the only alternatives that became available to the

company without the expenditure of time and effort were the systems proposals made early in the process by representatives of two equipment companies, and these were both rejected. An important reason for the prominent role of search in the decision process is that the 'problem' to be solved was in fact a whole series of 'nested' problems, each alternative solution to a problem at one level leading to a new set of problems at the next level. In addition, the process of solving the substantive problems created many procedural problems for the organization: allocating time and work, planning agendas and report presentations and so on.

Examination of the narrative shows that there is a rich variety of search processes. Many questions remain to be answered as to what determines the particular character of the search at a particular stage in the decision process: the possible differences between searches for procedural alternatives, on the one hand, and for substantive alternatives, on the other; the factors that determine how many alternatives will be sought before a choice is made; the conditions under which an alternative that has tentatively been chosen will be subjected to further check; the general types of search strategies.

The neglect of the search for alternatives in the classical theory of decision would be inconsequential if the search were so extensive that most of the alternatives available 'in principle' were generally discovered and considered. In that case the search process would have no influence upon the alternative finally selected for action. The narrative suggests that this is very far from the truth – that, in fact, the search for alternatives terminates when a satisfactory solution has been discovered even though the field of possibilities has not been exhausted. Hence, we have reason to suppose that changes in the search process or its outcome will actually have major effects on the final decision.

A second class of common processes encompasses information-gathering and similar activity aimed at determining the consequences of each of several alternatives. In many decisions, certainly in the one we observed, these activities account for the largest share of man-hours, and it is through them that subproblems are discovered. The narrative suggests that there is an inverse relation between the cost or difficulty of this investigational

task and the number of alternative courses of action that are examined carefully. Further work will be needed to determine if this relation holds up in a broader range of situations. The record also raises numerous questions about the *kinds* of consequences that are examined most closely or at all and about the conditions under which selection of criteria for choice is prior to, or subsequent to, the examination of consequences.

Another set of common processes are those concerned with the choices among alternatives. Such processes appear at many points in the narrative: the selection of a particular consulting firm from a list, the choice between centralized and decentralized electronic-data-processing systems, as well as numerous more detailed choices. These are the processes most closely allied to the classical theory of choice, but even here it is notable that traditional kinds of 'maximizing' procedures appear only rarely.

In some situations the choice is between competing alternatives, but in many others it is one of acceptance or rejection of a single course of action – really a choice between doing *something* at this time and doing nothing. The first such occasion was the decision by the controller to assign Middleton to the task of watching developments in electronics, a decision that initiated the whole sequence of later choices. In decisions of this type the consequences of the single alternative are judged against some kind of explicit or implicit 'level of aspiration' – perhaps expressed in terms of an amount of improvement over the existing situation – while in the multiple-alternative situations, the consequences of the several alternatives are compared with each other. This observation raises a host of new questions relating to the circumstances under which the decision will be formulated in terms of the one or the other of these frameworks and the personal and organizational factors that determine the aspiration levels that will be applied in the one-alternative case.

Another observation derivable from our data – though it is not obvious from the condensed narrative given here – is that comparability and non-comparability of the criteria of choice affects the decision processes in significant ways. For one thing, the criteria are not the same from one choice to another: one choice may be made on the basis of relative costs and savings, while the next may be based entirely on non-monetary criteria. Further,

few, if any, of the choices were based on a single criterion. Middleton and the others recognized and struggled with this problem of comparing consequences that were sometimes measured in different, and incomparable, units, and even more often involved completely intangible considerations. The narrative raises, but does not answer, the question of how choices are made in the face of these incommensurabilities and the degree to which tangible considerations are overemphasized or underemphasized as compared with intangibles as a result.

## Conclusion

We do not wish to try to transform one swallow into a summer by generalizing too far from a single example of a decision process. We have tried to illustrate, however, using a large relatively non-programmed decision in a business firm, some of the processes that are involved in business decision making and to indicate the sort of theory of the choice mechanism that is needed to accommodate these processes. Our illustration suggests that search processes and information-gathering processes constitute significant parts of decision making and must be incorporated in a theory of decision if it is to be adequate. While the framework employed here – and particularly the analysis of a decision in terms of a hierarchical structure of *programs* – is far from a complete or finished theory, it appears to provide a useful technique of analysis for researchers interested in the theory of decision as well as for business executives who may wish to review the decision-making procedures of their own companies.

### The Role of Expectations in Business Decision Making

R. M. Cyert, W. R. Dill and J. G. March, 'The role of expectations in business decision making', in M. Alexis and C. Z. Wilson (eds.), *Organizational Decision Making*, pp. 134-47, Prentice-Hall, 1967. (Adapted with permission from *Administrative Science Quarterly*, vol. 3, no. 3, December 1958, pp. 307-40.)

Theories of organizational decision making have ordinarily made rather sharp distinctions between business and public organizations. Particularly striking is the contrast between the best-developed theories of business decision – the economic theory of price and administrative theory – and the portrayal of public bureaucracies to be found in recent sociological and political theory. The contrast rests, rather explicitly, on two fundamental differences: the treatment of goals and the treatment of expected returns and costs.<sup>2</sup>

The theories of business behavior assume that an organizational goal is given: organizations attempt to maximize profit. They assume that the goal is operational: organizations know when they are and when they are not fulfilling that goal and what course of action will satisfy the goal. Although we believe this conception of organization goals to be fundamentally wrong in some important respects, we consider it in this paper only parenthetically.

We wish to examine here the treatment of expected return and expected costs in the classical description of business behavior and to consider in the light of the classical theory and some recently proposed revisions of it two specific decisions involving estimates of cost and return made by business organizations. Although the data are hardly conclusive, we think the case studies suggest rather strongly some important modifications in our views of the functions of expectations in organizational behavior.

1. The authors wish to acknowledge their indebtedness to C. J. Haberstroh and D. B. Trow, who, along with W. R. Dill, made the original empirical observations on which these analyses are based, and to H. A. Simon, who was also a member of the research group.

2. Compare, for example, Stigler (1946) and Gaus (1947).



## Expectations in Theories of Business Behavior

Theories of business decision making generally assume that estimates of cost and return *in some form* are made by the firm and that investment behavior depends heavily on such estimates. For example, the standard theory of price treats investment and internal resource allocation as hypersimple problems in maximization. The firm invests in each available alternative to the extent that the marginal return from each alternative will equal the opportunity cost. Except in so far as sunk costs are involved, the firm makes no fundamental distinction between internal and external investment; that is, all marginal returns are equal to the best alternative return available. Under these conditions, 'efficiency' – the ratio of obtained to potential return – is equal to one (Stigler, 1946).

What conception of organizational decision making is implicit in such theories? They assume that the organization scans all alternatives continuously and just as continuously adjusts its portfolio of investments to changes in the pattern of alternatives available. They assume that firms have accurate information on the costs to be incurred and returns to be received from alternatives and that decisions are made on the basis of this information. As will be noted below, these assumptions have been attacked both by economists and by organization theorists.

Attempts to revise the standard theories have been designed primarily to modify these assumptions through the introduction of probability distributions and the substitution of expected profit (or utility) for the profit (or utility) originally specified (Friedman, 1953).

The 'modern entrepreneur' is probabilistically omniscient. He knows (with certainty) the probability distribution of outcomes from all alternatives. He can, therefore, compute the expected value of any particular alternative and equate expected marginal return with expected opportunity cost.

At the same time, the assumption of infinite search has been replaced by a theory of search that recognizes certain costs to search and thus makes allocation of resources for securing information one of the investment decisions to be made. The modern entrepreneur does not scan all alternatives nor does he have all

information about all alternatives. He invests in information only so long as the marginal expected return from the information gained exceeds the expected opportunity cost (Koopman, 1956).

There is general consensus that these theories, and specifically the economic versions of them, have been rather valuable in both normative and empirical analyses of aggregate behavior. Since this has been the major traditional interest of economic analysis, aggregate economic theorists have found no pressing reasons for re-examining the assumptions of the standard theories.

On the other hand, economists and others interested in the behavior of the individual firm have not been entirely satisfied with the classic assumptions, which have been subject to criticism on two major grounds.<sup>3</sup> As normative theory, they have been challenged for accepting too easily Bernoullian expected utility. Alternative formulations, arising primarily from game theory considerations, are preferred by a vocal, but apparently minority, group (Luce and Raiffa, 1957). The normative uses of the theories, however, are tangential to our main interest here. We are more concerned with the challenges to these theories as explanations of business behavior. Because we wish to consider some empirical studies of business decision making, we will specify these challenges in somewhat greater detail.

There have been four major objections to the more or less 'pure' theory of expectations in so far as it has been applied to the behavior of individual firms.

First, the theories assume continuous competition among all alternatives for all resources. As Coase (1937) has pointed out, the perfectly competitive market for internal resources is a major implicit assumption of the standard theory of the firm. Such a description of organizational behavior is distinctly different from that implicit in many treatments of other organizations. For example, public administration models seem to emphasize local adaptation to specific problems; they stress problem solving much more than planning (Devons, 1950).

Second, the theories make search activity (and thus information) simply one of the several claimants for resources to be evaluated in terms of calculable costs and expected returns. Simon (1955) and others have questioned this treatment of search

3. For a thoughtful statement, see Koopmans (1957).

behavior. They have placed considerable emphasis on dissatisfaction as a stimulant to search, on the 'conspicuousness' of alternatives as a factor in their consideration, on external effects on the generation of information, and on the sequential characteristics of alternative evaluation.

Third, the theories require substantial computational activity on the part of the organization. Shackle (1949) and others have argued that the theory grossly exaggerates both the computational ability and, more important, the usual computational precision of human beings. A number of suggestions for constraining the amount of information that must be digested have been made. For example, the heart of Shackle's theory (still completely untested) lies in the  $\phi$ -functions by which the attention value of a particular outcome is determined.

Fourth, the theory treats expectations as exogenous variables. They are given, not explained. But such an eminently logical extension of certainty theory to the treatment of uncertainty ignores a major psychological aspect of uncertain situations, the interaction of expectation and desire. Quite aside from such an interaction, taking expectations as given in a theory of business behavior seems similar to taking the outcomes of all individual games as given in a theory of baseball championship.

Patently, it is not easy to test the validity of either what we have called standard theories or the proposed revisions we have mentioned. However, this paper reports detailed studies of two major decisions in two firms. On the basis of an analysis of these two decisions, we arrive at some tentative hypotheses about the problems mentioned above with respect to the theories of investment and internal resource allocation. In particular we will raise some questions about the usual notions of the role of expectations in organizational decision making.

### Methods of Observation

The two firms are . . . well-established, successful organizations: one a large, heavy manufacturing concern, the other a medium-sized construction firm. . . . Each of the firms gave the research group full access to files and to the activities of the organization. The decisions and the studies were made during 1953-6. Three basic techniques of observation were used: (i) detailed analysis of

memorandums, letters, and other written file material; (ii) intensive interviews with participants in the decisions; (iii) direct observation of the decision process. The first two techniques were used in every case. All pertinent documents in the companies' files were examined. All participating members of the organization were interviewed at least once; key members were interviewed repeatedly. In one case . . . an observer from the research team was present virtually full-time in the organization during the time the decision was being made. He was attached directly to a staff member in the organization and attended staff meetings.

The data on the decisions are, therefore, as complete as the limits of memory (both organizational and personal), interview technique, and observer ability permitted. Since those limits can be surprisingly restrictive, some questions of detail could not be answered. Nevertheless, the case studies described below are based on substantial information, direct and indirect. For purposes of presentation they have been condensed considerably, and emphasis has been placed on one aspect of the situation – the role of expectations. We are well aware of the dangers in such an abstraction, and we scarcely hope that the case studies, however detailed, will allay the skepticism of critical readers. The justification lies in our belief that the key propositions we want to make are conspicuous in the data and in our hope that the data will provide a start for empirical research in an area of extensive *ad hoc* theory.

### The Decisions

#### *Decision I: a problem in accelerated renovation of old equipment*

The first decision problem we shall analyse arose in a branch plant of a heavy manufacturing corporation employing several thousand workers and divided into semi-autonomous operating divisions – seven major divisions and several smaller ones. Auxiliary service departments such as safety reported to the plant manager and his assistants, but most such departments had liaison personnel assigned to the operating divisions.

An important goal of management was to achieve a better safety record than other plants in the corporation and in the

industry. Particular stress was placed on eliminating fatal accidents and on achieving annual reductions in the frequency of 'lost-time' injuries. Making the plant as safe a place to work as possible was more than a plant goal; it was a personal objective of most members of top management in the industry.

All the large divisions and most of the small ones made extensive use of overhead cranes. The movement of most cranes was governed by an old type of controller. Most cranemen and supervisors preferred magnetic controllers, a newer type that had been installed on many cranes in the plant. Because magnetic controllers operated on low-voltage control circuits, there was less danger of severe shock or of 'flash' – visible arcing of current across contact points – than with the old type, which operated on full-line voltage. Magnetic controllers also allowed operators to direct crane movements more precisely: there was less danger of 'drift', or unanticipated movements. Since they used less cab space than some older controllers, they offered the cranemen better visibility and more work space. They were also supposedly cooler and less fatiguing to operate, as well as easier to maintain.

The actual safety benefits that would accrue from the replacement of old-type controllers with magnetic controllers were hard to estimate. Burns, shocks, and eye injuries resulted from 'flash' in the older controller circuits, but they were infrequent and were not often disabling. Injuries caused by movements of cranes were more frequently attributable to human error by cranemen or ground crews than to mechanical failure of the controllers or to 'drift'.

Change-overs to magnetic controllers were being made only as the older controllers wore out, until a fatal accident in the plant triggered recommendations for an accelerated replacement program. A worker was killed when the unexpected movement of a crane load pinned him against a wall. Investigation by top management and by the safety department led to recommendations for a general review of problems of crane safety. The plant manager appointed a special committee to recommend steps that could be taken to improve a craneman's view of his working area and to give him better control over crane movements. The committee consisted of the director of safety, the superintendents of two operating divisions, and a man from the plant engineering department.

At the initial investigation of the accident, the crane man had been asked the type of controller with which the crane was equipped; but no links had been suggested between type of controller and the accident. Blame was assigned to the victim for standing in an unsafe position, to the crane man for moving a lift when his view was obscured, and to management for improper stacking of materials on the floor.

The special crane-safety committee did not mention magnetic controllers in its first report of recommendations for the division where the accident had occurred. Not until their seventh meeting, several weeks after the accident, while investigating conditions in a second division, did the committee discuss a suggestion for accelerated change-over of magnetic controllers. The change would 'save space in the crane cab' and provide better control levers, but the committees feared initially that 'the cost would be excessive'.

Apparently the committee changed its evaluation of the costs of the change, although minutes of the meetings do not report any further discussion. In its final report to the plant manager, the committee recommended as one of several changes that the controllers then in use 'should be replaced by magnetic controllers as quickly as feasible'. The plant manager circulated the entire list of recommendations without change to the division superintendents and asked that they all be adopted and implemented promptly.

After the order for implementation, specific questions of cost were raised and searches for information were initiated. Most division superintendents individually made quick estimates of the minimum cash outlays required for purchase and installation of the new controllers and checked with the plant manager to see if these expenditures would be approved. Their estimates ranged from \$27,000 to \$50,000 per division and were described by the safety director as 'an absolute minimum' since they did not cover all expected costs of installation.

To supplement the divisional estimates and to fit the accelerated replacement program into operating budgets, the plant manager asked the chief engineer to make a plant-wide survey of requirements and installation costs. Four months after the accident the chief engineer asked the special crane-safety committee

to draw up detailed plans for the replacement program and suggested that the program be included in the following year's budget. He wrote, 'It may be an expenditure between \$150,000 and \$200,000.'

Seven months later, in another memorandum to division superintendents, the chief engineer was still asking for an itemized list of cranes that needed the new controllers and of the number of replacements each such crane would need. At this time he described the program as a five-year job with budgeted expenditures of \$100,000 a year.

The chief engineer was not the only one exploring costs and benefits of the program. In the meantime one of the division superintendents had announced the program to a plant-wide conference of management personnel. He said that with the installation of magnetic controllers they would 'virtually eliminate' injuries to cranemen from flashes and burns. Several other division superintendents prepared a memorandum summarizing their objections to the old-type controllers. The chief industrial engineer reported to management that for the new magnetic controllers 'any increased costs in operation will be negligible'. He mentioned the old-type controllers as a 'cause' of the fatality which had initiated the program.<sup>4</sup>

Early in the second year of the program the plant manager asked the superintendent of maintenance to co-ordinate the replacement program over the next several years. By the ninetieth week after the accident the superintendent of maintenance had developed a revised plan for replacements. The estimated number of replacements had been decreased from 344 to 250, the estimated total cost increased from \$500,000 to \$600,000, and the estimated time for completion of the program increased from five to six or seven years. He reported costs in terms of the program's encroachment on men and facilities needed for other projects to which the maintenance division was committed. This was the first time in the written memoranda on the program that an estimate of available man power to install the controllers was cited as a limit to the completion of the program.

Initially, then, the program for accelerated replacement of

4. If this had been the case, it definitely had not been brought out in the detailed records of the inquiries following the accident.

controllers had been judged expensive but feasible. The original recommendation for the program had been promulgated along with a number of other suggestions for increasing crane safety that could be implemented less expensively in the short run.

The first year and a half after the program was approved by the plant manager were used to explore the scope of the decision and to plan for its implementation. Specific estimates of cost quadrupled in that time (rising from \$150,000 to over \$600,000); and the estimated time for completion changed by about two years to seven or more. Apparently the firm's commitment to an accelerated replacement program was made before the cost of new installations and the impact of the project on other commitments for maintenance and expansion were fully known. The development of cost information is summarized in Table 1.

In the end the commitment proved vulnerable, not to revised estimates of cost, but to short-run declines in available resources. At the end of two years two divisions stopped work on the program because a decline in operations had reduced their funds. One year later almost all divisions had reverted, for similar reasons, to the policy they were following before the accident; they were installing magnetic controllers only as the older control systems wore out.

Three major features of this decision process are particularly interesting from the point of view of the place of expectations in a theory of business decision making. First, it is clear that search behavior by the firm was apparently initiated by an exogenous event, was severely constrained, and was distinguished by 'local' rather than 'general' scanning procedures. Second, the non-comparability of cost expectations and expected returns led to estimates that were vague or easily changed and made the decision exceptionally susceptible to the factors of attention focus and available organizational slack. Third, the firm considered resources as fixed and imposed feasibility tests rather than optimality tests on the proposed expenditure.

The search behavior is difficult to interpret. The apparent sequence is quite simple: accident, concern for safety, and focus (among other foci) on magnetic controllers. As a view of top management, such a sequence seems to be reasonably accurate. Underlying this sequence, however, are a number of factors that



make too simple a theory of organizational search unwarranted. Most conspicuous is the fact that the connection between the stimulus (fatal accident) and the organizational reaction (new controllers) is remote. There is no evidence that the fatal accident depended in any way on the type of controller used on the crane. At the same time there is little doubt that the accident had made members of management give greater priority to any device that would improve crane safety and that the possibility of new controllers was well known to parts of the organization. Thus organization search for safety alternatives at the level of top management can be viewed at lower levels as the promotion of favored projects under the impetus of a crisis. The alternative of magnetic controllers was discovered not so much because the organization at this time searched everywhere for solutions to a problem but because some parts of the organization were already (for whatever reason) predisposed towards the project and (a) thought of it as relevant and (b) were able to present it as relevant to the perceived problem in safety.

The decentralized characteristics of information gathering in this case are particularly striking in the pursuit of cost information. Cost information was not readily available, especially to the men who were charged with investigating crane safety. Each knew something about the costs of a single installation since some of these had already been made. But none of the four had the information needed for even a rough approximation of the overall costs of an accelerated replacement program; and, as later searches showed, many people and much time would have been needed to gather such information. Even after the decision to make the plant-wide installations, when detailed cost and return data were sought, every new group brought in costs and advantages that other groups had not considered (see Table 1).

One of the reasons why detailed information on costs seems to play such an insignificant role in all but the final stages of the process is that at no time did the organization make a conscious calculation of costs and return in comparable figures. This feature of the decision is conspicuous in Table 1. Information about costs was not necessary to persuade members of management to order the installation of the controllers. All members of management apparently favored the new controls, and they were

**Table 1** The Sources and Uses of Cost Information in Crane Control Decision

| <i>Time since fatality (weeks)</i> | <i>Evaluation expressed in available correspondence</i>                                                                | <i>Source of evaluation</i> | <i>Context of evaluation</i>                                                             |
|------------------------------------|------------------------------------------------------------------------------------------------------------------------|-----------------------------|------------------------------------------------------------------------------------------|
| 6-11                               | New controls would save space in cabs and offer better control levers; cost of plant-wide program might be 'excessive' | Crane-safety committee      | Series of meetings to find ways to increase the safety of crane operations               |
| 11                                 | Accelerated, plant-wide installation of new controls is feasible                                                       | Plant manager               | Directive to division superintendents to carry out such a program                        |
| 13-19                              | 'Absolute minimum' costs for purchase and basic installation would be \$27,000 to \$50,000 per division                | Division superintendents    | Individual requests to plant manager for approval of expenditures                        |
| 20                                 | Program will take at least a year and may mean expenditure of \$150,000 to \$200,000                                   | Chief engineer              | Guide to plant manager for fitting program into next budget                              |
| 22                                 | New controls will virtually eliminate injuries to cranemen from flashes and burns                                      | Division superintendents    | Speech at annual management safety conference on his division's progress                 |
| 49                                 | Program will take 5 years and will involve budgeted expenditures of \$100,000 a year                                   | Chief engineer              | A request to division superintendents for more precise information on their requirements |

| <i>Time since fatality (weeks)</i> | <i>Evaluation expressed in available correspondence</i>                                                                                            | <i>Source of evaluation</i>         | <i>Context of evaluation</i>                                 |
|------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------|--------------------------------------------------------------|
| 52                                 | Increased costs of operation with new controls will be negligible                                                                                  | Chief industrial engineer           | Memorandum to the plant manager and division superintendents |
| 55                                 | New controls will be safer, easier to use, and cheaper to maintain                                                                                 | Group of division superintendents   | Memorandum to inform others in management                    |
| 95                                 | Program will take 6-7 years, will require 250 installations, and will cost \$650,000; rate of progress is limited by other maintenance commitments | Maintenance division superintendent | Report of plans to the chief engineer                        |
| 106-12                             | Lack of funds prevents further work on program                                                                                                     | 2 division superintendents          | Report to director of safety on progress of program          |

supported by non-company technical literature. They had been putting the new controllers in as the old systems wore out. Statements made by the division superintendents indicated that they were placing strong positive emphasis on the safety advantages of the new controls. These gains were usually expressed in absolute rather than relative terms. None of the safety advantages and few of the operating advantages were ever formally expressed in dollar terms. There was consensus that the program would be beneficial and evidence that the benefits - whatever their size - would apply in several departments: safety, maintenance, and operating divisions.

Under these conditions it is not surprising that the early cost estimates were too optimistic (at least if we can assume later

ones were more accurate). It is also not surprising to discover that variations in cost expectations had little impact on the basic decision until the focus on safety became less intense.

Measurable expectations entered in the decision only in the feasibility test. Do we have money for the controls? Initially agreement by various groups in management that the step was a good one and an estimate that costs – while unknown – would not be unreasonable were apparently sufficient to carry the decision. For costs to be reasonable under the standard theory of investment, they must be better (relative to the gain) than other available alternatives. This was not, however, how the issue was formulated here. Rather the question of 'reasonableness' hinged on whether the expenditure could be made without appreciably affecting existing organizational arrangements adversely (e.g. profits, dividends, wages, output).

As long as estimated costs were modest and output high, the costs were reasonable. As the costs grew and business activity declined, accelerated installation of the magnetic controllers became less 'reasonable'. This was obviously not because they became suboptimal whereas they had previously been optimal but simply because the supply of uncommitted resources (one form of organizational slack) had been substantially reduced. The later stages of the decision were dominated by the necessity of making specific provision for the program in the plant budgets and of preparing tentative time schedules for installation. When, at this stage, there was not enough money for all of the approved projects, some comparisons of the relative merits were made. At that time the hierarchy of preferred projects seemed to reflect such considerations as the tangibility of their expected return, the importance of their major supporters, and the conspicuousness of the problem for which they were designed. It is of course possible that such a process would also generate the optimum set of investments. We will note only that the explicit decisions made by two divisions to abandon the program seemed to be timed specifically in relation to declines in their level of operations. When it became apparent that cash would not be available to meet more than the bare minimum of repair and maintenance commitments, the two divisions stopped work on the accelerated program completely and returned to preaccident policies.

*Decision 2: A problem of new working quarters for a department with a doubtful future*

The second decision was an attempt in a medium-sized construction firm to find new working and storage quarters for its Home Specialities Department, which held a unique and somewhat insecure position in the firm. Its customers were not often shared by other departments. It used union labor like other departments of the firm but unlike most of its competitors; therefore, its labor costs were too high to enable it to bid successfully on many projects. Its labor costs and changes in style and technology in the construction industry were causing the department's market to shrink, though it had shared with other departments in the growth from new construction activity during and after the Korean War. Top management expected its sales to decline, and its members outside the Home Specialities Department had negative feelings towards the department for two reasons:

1. The head of the department was a senior man in the firm and his earnings under a profit-sharing contract were higher than the earnings of almost all other department heads.
2. Other departments were also expanding, and some of these were anxious to take over space that was being used by Home Specialities.

The problem of making a decision about the long-run importance of Home Specialities operations and of providing plant facilities to accommodate expanded operations had been current for at least two years. Management had long been aware of the need for some kind of action. However, there was no consensus about what the critical problem was or about what alternative would be satisfactory. The president, who believed centralized operations were most efficient, initially viewed the problem as one of finding a way to expand facilities at (or in the immediate vicinity of) the current site. The head of the Home Specialities Department wanted to move the department to a new location, where it would not be in conflict with the operations of other units. Some members of general management thought that the department should be dropped from the firm in order to release working capital for units that had a brighter future. The president and the branch manager had talked of maintaining the

department but of limiting it to a size that fitted the existing site, of reducing the share of profits going to departmental personnel, and of forcing the head of the department to take a cut in earnings. Some years earlier, a few men had almost managed to force the department manager out of the firm.

The president's show of interest when a local plot of land became available, coupled with continuing pressure from departmental management to investigate possible new sites, resulted in a decision to concentrate on the search for a new site. Study of the feasibility of moving the department may have seemed timely, too, because of the president's independent decision to renegotiate profit-sharing contracts with departmental management. Since the department manager and his assistant wanted to move, a decision to support their search for a new location might have been regarded as an inducement to them to accept a cut in earnings. In addition, the move might make it easier to follow the cut in earnings with a later decision to curtail departmental operations or to ease the department out of the firm.

Requirements for the new site were set forth in a conference attended by the branch manager, the department head for Home Specialities, his assistant, and a specialist in estimation of costs of building alterations. The pressures on current facilities, at least, were not expected to increase greatly over the next year or two: and in fact, the space requirements of Home Specialities were expected to decline. The Home Specialities facilities were probably not grossly unsuited to their operations; in defining the requirements for a new site, the head men in the department were merely trying, on most measures, to find something that would be equivalent to what they already had. The assistant head of the Home Specialities Department initiated most suggestions for site requirements. He worked from a memorandum he had prepared earlier. The final set of requirements was drafted by the branch manager after the meeting. The key specifications are set forth in Table 2.<sup>5</sup>

The conference was notable for the absence of real debate about or explicit consideration of the relative importance of different kinds of requirements. The discussion was oriented towards

5. Other specifications were discussed initially, but they did not figure explicitly in the later evaluations of actual sites.

Table 2 Selected Site Characteristics: Aspirations versus Actions

| Features of site                    | Existing facilities | Proposed requirements |                        |                          | Characteristics of 3 best sites |                           |                          |
|-------------------------------------|---------------------|-----------------------|------------------------|--------------------------|---------------------------------|---------------------------|--------------------------|
|                                     |                     | Requested by Dept     | Agreed on in meeting   | Listed by branch mgr     | No. 2                           | No. 14                    | No. 10                   |
| Total space, sq. ft.                | 25,000              | 25,000+               | 24,000                 | 26,000                   | 24,000+                         | 18,500                    | 15,500                   |
| Yard storage space                  | 8,850               | 8,850                 | 8,850                  | 9,000                    | Available                       | Not available             | Available separately     |
| Heating facilities                  | —                   | —                     | Work area to 60°       | Work area to 60°         | —                               | Will cost \$150/yr        | Will cost \$183/yr       |
| Location (minutes from main office) | 0                   | —                     | 10                     | 10                       | 9                               | More than 10              | About 10                 |
| Dock-height unloading space         | —                   | Desired               | Desired                | Desired                  | Has                             | Has                       | Does not have            |
| R. R. siding                        | —                   | Not mentioned         | Worth \$500 extra rent | Worth \$1,000 extra rent | No                              | No                        | 1½ blocks from R. R.     |
| Annual rent                         | \$6-7,000           | —                     | \$10,000               | \$10,000                 | Bid of \$10,000 submitted       | Bid of \$12,025 submitted | Bid of \$17,000 proposed |

making sure that the new site would offer the same facilities as the old one at no greater cash outlay for rent rather than towards determining what would be a 'most efficient' site for the Home Specialties Department. The most intensive discussion for several requirements centered on reaching an agreement as to what facilities the department had in its current location. The question of the flexibility of various requirements was hardly raised, although it was unreasonable to expect to find a site that corresponded to all of the committee's specifications.

An intensive search for sites followed the conference and lasted for four months. The evaluation of each site about which information was received was a three-phase process. First, the branch manager or another member of the central management group looked at the initial information that was available from advertisements, phone calls, or cursory visits to the site to decide whether the site was worth further inspection. As Table 3 indicates, at least eighteen sites were rejected at this stage because

they failed to meet one of a small set of requirements. The most important considerations at this stage were whether the site could be rented (the company did not want to purchase), whether the site was located near the company's existing facilities (something within ten minutes' driving distance was preferred), and whether the site was approximately the right size (sites with 15,000 to 25,000 square feet were preferred). One or more of these three factors underlay the rejection of eleven of the eighteen sites in this early phase. (Of the remaining seven, one was rejected because of problems of access, one because of an unsatisfactory layout, and five for unknown reasons.)

*Table 3 The Consideration and Disposition of Possible Sites*

| <i>Site no.</i> | <i>Period of consideration</i> | <i>Disposition of site</i>                                                      |
|-----------------|--------------------------------|---------------------------------------------------------------------------------|
| 1               | 14 June                        | Rejected: Inadequate access                                                     |
| 2               | 20 June–13 Sept.               | Bid upon: Bid of \$10,000+ not accepted                                         |
| 3               | 23 June–12 July                | Rejected: Considered in detail but too large and too liable to flood damage     |
| 4               | 6 July                         | Rejected: Too small, too far away                                               |
| 5               | 12 July                        | Rejected: Would have to be purchased                                            |
| 6               | 12 July                        | Rejected: Too far away                                                          |
| 7               | 12 July                        | Rejected: Too far away                                                          |
| 8               | 17 July                        | Rejected: Too large                                                             |
| 9               | 9 Aug.                         | Rejected: Unsatisfactory layout                                                 |
| 10              | 18 Aug.–24 Oct.                | Rejected: Bid prepared but not submitted: considered too expensive by president |
| 11              | 24 Aug.                        | Rejected: Reason unknown                                                        |
| 12              | 24 Aug.                        | Rejected: Reason unknown                                                        |
| 13              | 30 Aug.                        | Rejected: Too small (13,000 sq. ft)                                             |
| 14              | 30 Aug.–25 Sept.               | Bid upon: Bid not accepted by owner, who preferred commercial use of property   |
| 15              | 7 Sept.                        | Rejected: Too far away                                                          |
| 16              | 7 Sept.                        | Rejected: Too far away                                                          |
| 17              | 12 Sept.                       | Rejected: Would have to be purchased                                            |
| 18              | 12 Sept.                       | Rejected: Would have to be purchased                                            |
| 19              | 12 Sept.                       | Rejected: Too far away, wrong size                                              |
| 20              | 17 Sept.                       | Rejected: Reason unknown                                                        |
| 21              | 18 Sept.                       | Rejected: Reason unknown                                                        |
| 22              | 21 Sept.                       | Rejected: Reason unknown                                                        |



The second phase consisted of a more detailed evaluation of the site's potentialities. Four sites were given detailed consideration. Members of the Home Specialities Department staff estimated the expenditures required to make the necessary heating, lighting, and ventilating installations. One of the four sites was rejected after the detailed inspection because the branch manager found it liable to frequent flood damage and because the company would have had to buy other leases on the property.

There were, then, three sites that management thought good enough to prepare bids on. Looking at the major criteria of space, price, and nearness to existing facilities, we note in Table 2 that management relaxed its requirements as time went on. Site no. 2, the first one for which a bid was prepared, had an area about the same as the specifications called for; but sites no. 14 and no. 10 were both smaller than the specifications required. Site no. 10 was at and site no. 14 was beyond the distance limits set by management. Management expected to get by on site no. 2 with a bid of \$10,000 to \$15,000 for 24,000 square feet of space; the bid on site no. 14 was \$12,000 for 18,500 square feet. On site no. 10, the third one for which a bid was prepared, management considered offering \$17,000 for 15,500 square feet of space (excluding yard space which had to be obtained separately).

The bids on sites no. 2 and no. 14 were turned down by the agents for the properties, but the bid on site no. 10 was never submitted. The president refused to approve the bid because he thought it offered too much money for too little space. The search for a new site for the Home Specialities Department apparently ended with the president's refusal to approve a bid for site no. 10.

Why were other sites not considered? Among the reasons for ending the search, the following were probably most important:

1. The branch manager and the others who had been most active in the search probably felt that they had explored most of the available possibilities. They had even resorted to driving around the neighbourhood looking for 'for rent' signs.
2. The earnings contracts of the departmental managers had been renegotiated – most of them successfully. Use of the search for a

new location as an inducement to counteract the negative effects of renegotiation was no longer of any importance, and, with renegotiation completed, one point of friction between Home Specialities and other departments had been eliminated.

3. Contrary to expectations, Home Specialities had continued to maintain a fairly high level of operations over the summer, while its most direct competitor for work space had suffered a decline in business.

The decision-making process here has some significant similarities to that connected with the purchase of automatic controllers. As before, search activity represented a response to some specific events rather than a form of continued planning. Second, detailed expectation data entered into the decision relatively late, after a conditional commitment to secure space had been made. Finally, most of the tests were primarily feasibility tests rather than checks on optimality.

From the present point of view, perhaps the most interesting aspect to this study is the fact that the organization focused on the problem of outside space for the department. Although the decision was contingent (and was in fact never executed because bids were rejected), it represented a commitment to a course of action. Yet the commitment was made not because it was shown to have the best return, in terms of organizational goals, of a number of alternatives. Quite the contrary, the decision to find new quarters was made because a number of important parts of the organization, for apparently quite different reasons, viewed such a step as desirable. Had there been agreement, for example, between the Home Specialities Department and other departments about the probable long-run consequences of this step, one or the other of those groups would probably have opposed the move. Since this was an important aspect of the decision situation, some of the more important expectations were not discussed in open meetings, and hopes and expectations appear to have become substantially intertwined. The role of ambiguity of expectations in securing agreement where there is a conflict of interests has previously been noted with respect to political and labor-management decision making. There is some suggestion here that it is also important for the formation of business policy.

Once the decision to secure additional space had been made, data on alternatives were organized around a set of more or less independent criteria. These criteria are interesting in two respects:

1. They represent for the most part a simple statement of current facilities. The adequacy of some aspects of these facilities was discussed, but the general question of what would constitute an ideal site was not raised.
2. With one or two exceptions (e.g. an attempt to place a rental value on the existence of a railroad siding) the specifications represented a check list. Sites that were unsatisfactory on one or more of the major criteria were rejected immediately. Only among the more or less 'satisfactory' alternatives was there an attempt to compare the utility of an increment on one dimension of the criteria with a different dimension. And even at that point this comparison was somewhat halting and not always easily understood. Some of the sites rejected at an early stage might have been considered more thoroughly later, after management's aspirations declined.

In one conspicuous feature the site purchase decision was different from the decision to purchase the automatic controllers. The search for alternative sites was much more exhaustive than the search for alternatives in the first case. The organization did not have a ready-made site alternative but had to look. Although it is conceivable that the organization did not discover all the alternatives that were within ten minutes of the central office, it seems unlikely that they missed any that would have been suitable. To be sure, the use of the ten-minute criterion as a device for defining the range within which one would search made that criterion into an absolute one, in the sense in which the others (e.g. the size requirement) were not. But the difference between the number of alternatives considered in this instance and in the crane case is substantial. Similarly, the specific cost estimates reflected in proposed bids for sites and the decisions on whether to make the bids seem, in this case, to be more attempts to determine the intrinsic worth of the property to the organization and less a function of available resources than they were in the previous case.

## Discussion

The analysis of the . . . two . . . decisions suggests some problems with both the neoclassical conception of organizational use of expectations and some recent suggestions for revision. On balance, however, it suggests that each of the four criticisms of the conventional theory of decision making is warranted, at least in part.

*Resource allocation* within the firm reflects only gross comparisons of marginal advantages of alternatives. All the decisions were made within budgetary constraints and to that extent reflected any marginal calculations that entered into the formation of a general budget. When the rising estimates of costs for the crane controllers (Decision 1) and the decline of business created an internal problem of scarce resources, there were some attempts to compare the advantages of the safety devices with alternative investments. These attempts, however, focused on such considerations as prior commitment rather than marginal return.

In the other cases, there were distinct conceptions of 'appropriate' costs or net return. Undoubtedly these were related in a relatively unsystematic way to the comparable statistics (e.g. 'pay-off period') on other acceptable alternatives. Ignoring for the moment the problem of bias in estimates, the studies indicate that rules of thumb for evaluating alternatives provide some constraints on resource allocation even though it is substantially decentralized and there is no conscious comparison of specific alternative investments. Thus a theory that predicts grotesquely large deviations from a return on investment norm is probably not accurate.

On the other hand, it seems clear that the constraints do not guarantee very close adjustment, particularly where business conditions permit organizational slack. Any alternative that satisfies the constraints and secures suitably powerful support within the organization is likely to be adopted. This means that decision making is likely to reflect a response to local problems of apparent pressing need as much as it will reflect continuing planning on the part of the organization.

In a rough sense we can say that the . . . two decisions considered here arose primarily as responses to 'crisis' situations. . . . The organization was stimulated to search for solutions to con-

spicuously unsatisfactory conditions. In each case, once an alternative was evoked, it was accepted if it satisfied the general cost and return constraints and enjoyed the support of key people in management. The support in turn came about through a rather complex mixture of personal, suborganizational, and general organizational goals. In Decision no. 2 the support came for mutually contradictory reasons from two or three different parts of the organization. In Decision no. 1 the support from top management came for reasons that were not directly relevant to the events that had triggered the search. . . .

*Search activity* is not viewed as simply another use of internal resources. In general these studies suggest that there are several stages to motivated search activity on the part of an organization. If a problem area is recognized, there is ordinarily a search for possible alternatives. At this stage only rough expectation data are used to screen obviously inappropriate actions. In each case considered here this early scanning generated only a few suitable possibilities, which were then considered in greater detail. In most cases a rather firm commitment to an action was taken before the search for information proceeded very far, but the search became more and more intensive as the decision approached implementation. This was particularly obvious in the case of the crane controls.

One major reason why this seems to be true is that organizational 'search' consists in large part in evoking from various parts of the organization considerations that are important to the individual subunits, and the relevance of such considerations, and the impetus to insist on them, are not manifest until the implications of the decision are made specific through implementation. An obvious corollary of such a conception of the search process is the proposition that search will be much more intensive where organizational slack is small than where it is large. Where there are enough excess resources in the organization, the interdependence of allocation decisions is uncertain: search consequently becomes relatively routine.

At the same time a conspicuous factor in these cases is frequently ignored in search theory. Whether in its classical form or in the level of aspiration form, the theory of search is basically a prospecting theory. It assumes that the objects of search are

passive elements distributed in some fashion throughout the environment. Alternatives and information about them are obtained as a result of deliberate activities directed towards that end. Not all information comes to an organization in this way, however. Many of the events in these studies suggest a mating theory of search. Not only are organizations looking for alternatives; alternatives are also looking for organizations. . . . In Decision no. 1, . . . many efforts had presumably been made by producers of magnetic controllers to 'sell' management on a change. In fact, the timing of the major spurts of activity on those decisions was as much a function of the pressure from such outside groups as it was from internal factors.

The *computations* of anticipated consequences used by the organizations seem to be quite simple. Although there is no particularly strong evidence for Shackle's specific concept of what computations are made, at most only a half-dozen criteria were used explicitly in making the decisions. There appear to be two main reasons for the simplicity. First, in one form or another the major initial question asked of a proposed action was not how it compared with other alternatives but whether it was feasible. In the decisions discussed here there were two varieties of feasibility. The first was a budgetary constraint: Is money available for the project? The second was an improvement criterion: Is the project clearly better than existing procedures? In one form or another these questions were extremely important in all of the decisions discussed here. In some cases they were rather hard to answer, but they were almost always considerably easier than the question required by the classical theory of expectations: Does the expected net return on this investment equal or exceed the expected return on all alternative investments?

The second apparent reason for simplicity in establishing decision criteria was the awkwardness of developing a single dimension on which all relevant considerations could be measured. In each of the decisions described above costs in dollars were factors; so were dollar savings. But so also were such considerations as speed and accuracy of work, safety of personnel, distance from railroad transportation, quality of performance, and reputation of company. Unless one is prepared to make explicit the dollar value of such diverse factors, and neither of these firms

did so to any great extent, they must be treated substantially as independent constraints. Detailed expectations on these dimensions seemed substantially irrelevant to efforts to estimate costs because the organization had no way of using such information.

*Expectations* were by no means independent of such things as hopes, wishes, and the internal bargaining needs of subunits in the organization. Information about the consequences of particular courses of action in a business organization are frequently hard to obtain and of uncertain reliability. As a result, both conscious and unconscious bias in expectations is introduced. In each of the cases there is some suggestion of unconscious or semi-conscious adjustment of perceptions to hopes. The initial estimates of cost for the crane controllers appear to have been fairly optimistic. The expectations about the consequences of moving the Home Specialities Department seem to have been substantially a function of subunit goals. . . .

In addition, there is some evidence of more conscious manipulation of expectations. The classic statement came from a staff member involved in one of the decisions. He told a group of men outside the company: 'In the final analysis, if anybody brings up an item of cost we haven't thought of, we can balance it by making another source of savings tangible.'

It would be a mistake to picture the biases introduced in either of these fashions as exceptionally great. In almost every case there are some reasonably severe reality constraints on bias. But where the decision involves choice between two reasonably equal alternatives, small biases will be critical. Consequently, research on selective perception and recall is of substantial importance to an empirical theory of business decision making.

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### The Implementation of a Decision

N. F. Dufty and P. M. Taylor, 'The implementation of a decision', *Administrative Science Quarterly*, vol. 7, June 1962, pp. 110-19.

Following their analysis of a business decision, Cyert, Simon and Trow concluded, 'We do not wish to try to transform one swallow into a summer by generalizing too far from a single example of a decision process' (Reading 3). Our intention here is to add another swallow in the hope that eventually a sufficient number of them accumulate to justify calling it a summer.

March and Simon (1958, ch. 6) have substantially revised the traditional theory of decision making, and the decision described and discussed here will be analysed in the framework they have suggested. Unlike the decision studied by Cyert *et al.*, which was analysed by having a member of the research team present as an observer during the active phases of decision process, in the decision reported here, one of the authors<sup>1</sup> played a prominent role in the implementation of the decision made – to transfer personnel from one part of an organization to another. The transfer process was of short duration (thirteen days) compared to the case discussed by Cyert, Simon and Trow. It is not the decision to transfer the personnel that is analysed here; we are concerned largely with the subsequent decisions.

#### The Problem of Transfer of Personnel

The organization concerned was the Metropolitan Transport Trust (hereafter MTT) in the city of Perth, Western Australia. It had about 420 buses and 1500 personnel in the early part of 1960. In July of that year it acquired another organization known as the Western Australian Government Tramways (hereafter WAGT), comprising one large depot, 206 buses, and over 800 employees. Soon after the merger, it was decided that the efficiency of the whole organization could be improved by transferring certain

1. P. M. Taylor.

services from the former main depot of the WAGT to an MTT depot at Claremont, some miles away.

On Friday 2 September 1960 the chief executive, the chairman of the MTT, informed the personnel superintendent that it had been decided to transfer certain services to the Claremont depot. This involved the movement of buses, which was no problem, and the more difficult question of transferring personnel. On Monday 5 September, at the suggestion of the chairman, a conference was held which was attended by the personnel superintendent, the traffic manager and the assistant traffic manager. It was decided that the new service should start on 27 September and that eleven bus drivers and eleven fare collectors would have to be transferred to the Claremont depot to maintain it. The task of obtaining the required number of people who would be willing to transfer from the former WAGT depot to Claremont was given to the personnel superintendent. He was to arrange with the assistant traffic manager for the training of new staff to operate the other routes already operating from the Claremont depot. As the arbitration court award (equivalent to the collective bargaining contract) required 'reasonable' rotation through the rosters at any depot, the personnel transferred could not be confined to any one route.

Immediately following this conference, the personnel superintendent sent for the employment and training officer and the staff records officer to discuss the implementation of the decision. They agreed that it would not be easy to get the necessary volunteers to transfer to Claremont because when applications had been called in August to fill a driver's vacancy then existing at Claremont, only two licensed conductors (having driving licenses) applied, even though the transfer meant considerable financial gain. One of the applicants subsequently withdrew without giving any reason. In addition, the personnel at the former WAGT depot, who had been government employees for many years, tended to view with suspicion MTT personnel from other depots, all of whom had formerly worked for private employers. Their general belief was that working conditions were inferior in MTT depots, that discipline was stricter, and that there was a tendency for the MTT depot masters to 'sweat' their drivers in order to maintain tight schedules. Another factor was that the Tramways

Union had no members at MTT depots, most of the latter's employees being in the Transport and Motor Operators' Union. These anxieties had recently been expressed in the State Arbitration Court by witnesses for the Tramways Union in a hearing on the issue of a contract covering all MTT traffic employees.

In the August issue of the MTT staff newsletter the policy of inter-depot transfers had been explained in detail for the benefit of former WAGT personnel. Briefly, those interested in transfers were to make written application to the personnel department, giving their reasons for requesting transfers. If the reasons were judged to be satisfactory, the application was filed in the transfer register. Whenever vacancies occurred the employment officer first consulted the transfer register before taking any other action to fill a vacancy. This policy had operated quite well for some time – ever since the responsibility for transfers had been passed to the personnel department. The employment officer reported that despite this publicity, he had received only one transfer application from the former WAGT depot and this was not for a transfer to Claremont.

The personnel superintendent and his colleagues considered that the task of persuading eleven fare collectors to transfer to Claremont would be even more difficult. Very few of the former WAGT depot fare collectors lived within reasonable distance of the Claremont depot. This was important because the fare collectors, being women and on considerably lower rates of pay than the drivers, were picked up by the MTT when they were rostered on early shifts and taken home when they were on late finishing shifts. After some discussion it was agreed that the immediate program should be as follows:

1. The personnel superintendent was to issue a notice calling for applications from qualified drivers, conductors and fare collectors who were prepared to transfer to Claremont.
2. The staff records officer was to produce a list showing all former WAGT personnel living within a four-mile radius of the Claremont depot.
3. The employment officer was to consider all applications on the transfer register to see if alternative transfers could be made, e.g. Perth to Claremont and the WAGT depot to Perth.

4. A further meeting to discuss progress was scheduled for 8 September.

Immediately after the meeting the personnel superintendent discussed a tentative training program with the assistant traffic manager. It was thought that conductors not qualified as drivers would have to be considered for the driving positions and that this would throw a heavy burden on the instructional staff. It was felt that two instructors could handle the problem of training up to six men for their licenses as well as for route and fare instruction. The problem of training the fare collectors could be overcome by adding a competent and experienced fare collector to the training staff during the emergency.

The assistant traffic manager and the personnel superintendent then conferred with the traffic manager, who agreed to the following proposals:

1. Unlicensed conductors would be accepted for transfer and training, provided that an adequate response was not obtained from the notice that had been issued.
2. The most suitable fare collector should be added to full-time training duties and she should be trained in these duties by the chief instructor.

On 6 September, applications were received from three fare collectors who shared an apartment and who were prepared to move to another apartment near Claremont. Despite the fact that two of these girls had high absentee records and the other had a history of cash shortages, their transfers were approved, and the training arrangements were completed. The next day an inquiry was made by a driver who had been reduced to a conductor because of a high accident record, but this application was rejected. On the same day two employees from the former WAGT depot gave notice that they were quitting. It was decided not to replace them but to engage two new men to be trained as drivers for the Claremont depot.

On 8 September the superintendent of another depot reported that an adjustment of the rosters had left him with a surplus driver. The addresses of the drivers at this depot were examined, and one was located living near Claremont. No difficulty was

experienced in persuading him to transfer. That afternoon the employment officer, staff records officer, and personnel superintendent met to discuss progress, and it was decided to interview the twenty three people located within four miles of the Claremont depot and attempt to persuade some of them to transfer. The employment officer reported that his examination of the transfer register had been unfruitful so far as drivers were concerned, but that two fare collectors from the Perth depot were willing to transfer. They were easily replaced by transfers from the former WAGT depot. Another meeting was scheduled for 12 September.

Later that day the secretary of the Tramways Union saw the personnel superintendent about other matters and mentioned his concern about the notice and rumors that members would be compelled to transfer. He thought it most unlikely that volunteers would be obtained, and he was afraid that any members transferred would be lost to his union. The personnel superintendent pointed out that he could use any transferred members as ambassadors to help him in his struggle with the Transport and Motor Operators' Union. This idea appealed to the secretary, and he even suggested that he might help by persuading likely candidates to transfer. It seemed from this conversation that union opposition was not likely to continue, and this opposition may have been an important factor in hindering transfers.

On 9 September the employment officer began his interview program. By the end of the day seven drivers had been interviewed; two had agreed to transfer, one said that he would consider it, and the other four rejected the proposal completely. One fare collector was seen and agreed to consider the transfer, and the two licensed conductors interviewed were willing to move. One unlicensed conductor was interviewed but was considered to be unsuitable for training as a driver.

On Monday 12 September the employment officer completed his interviewing program. This yielded the following: five bus drivers, two licensed conductors, two unlicensed conductors, and one fare collector. In addition, the superintendent of the former WAGT depot reported that one bus driver was giving up his job because of a medical disability.

That afternoon the scheduled meeting of the personnel super-

intendent, employment officer, and staff records officer took place to consider the situation. It was decided to submit the two unlicensed conductors to the standard driving test to ascertain their fitness for training as drivers, before making a final decision. The next day, when the test was given, one was found to be satisfactory, and the other was classed as unsuitable. This made the number of drivers and potential drivers for the Claremont depot ten; the eleventh was provided by the replacement of the medically unfit driver at the former WAGT depot by promotion and by engaging a new driver for Claremont. The driver requirements were now filled, subject to the training of the conductor who had passed the selection test. The quota of fare collectors was still four short of its target, and it was considered that all reasonable alternatives had been explored. The recommendation was made to the assistant traffic manager that four new fare collectors should be recruited in the Claremont area despite the fact that this would leave four surplus fare collectors at the former WAGT depot. It was felt, however, that changes in the leave program could be made to utilize one or more of the fare collectors temporarily and that labor turnover, normally high in this class of worker, would soon account for the rest. Discussions were held with the assistant traffic manager, who agreed with the recommendations. Arrangements were made to alter the leave program to absorb one fare collector temporarily, and the other three, pending their absorption through labor turnover, were scheduled to city queue fare collecting to improve the efficiency of one-man bus services during the peak periods.

On 14 September the personnel superintendent notified the chairman that the required personnel would be available at the Claremont depot in time to start the newly scheduled service on 27 September.

### **Analysis of the Decisions**

As indicated, the analysis here is not an analysis of the decision to transfer the personnel, but rather an analysis of the several decisions made by the personnel superintendent in order to implement the transfer. As March and Simon (1958, p. 150) point out, the programs of members of higher levels of an organization

have as their main output the modification or initiation of programs for people at lower levels.

The organizational goals of efficiency and decentralization, which led to the original transfer decision, were not questioned by the personnel superintendent at any stage, nor were they questioned by any other person concerned with the implementation of the decision. It might have been thought that the acceptance of this 'logic of efficiency' would also have implied an acceptance of the machine model of organization, in which the employee is an instrument. This thesis ignores many of the motivational aspects of modern organization theory, of which the personnel superintendent and his staff were well aware. No attempt was made to take the simplest course of action – to select eleven drivers and eleven fare collectors and transfer them arbitrarily, complying only with the legal requirement of giving them the appropriate notice. Indeed, there was no evidence that this course of action was even considered. So far as the personnel superintendent was concerned, he was not only fully aware of the probable dysfunctional consequences of such action, but he would also have found it to conflict with his personal value system.

In this case the step initiating the program was taken by the chief executive, but he specified only the outcome or ends, i.e. that twenty-two people be provided for certain jobs at a certain place at a certain time. It was left to the personnel superintendent to supply the means-ends connections; he was given wide discretionary powers to use both the standard programs in his repertoire and to develop new programs or modify old ones through problem solving and learning processes.

If the implementation of the transfer decision had involved only the movement of one or two drivers, the stimulus would have evoked a routine response, namely, consultation of the transfer register. In the circumstances, it was obvious to the personnel superintendent that this step alone would not be adequate, and the first action taken was to initiate problem-solving activity by calling a conference of those people whom he thought could help solve the problem. The aim of the conference was to define the situation and then develop a number of performance programs, including the routine program of consulting the transfer register. The programs developed were as follows:

## Non-Programmed Decision Making

1. The issue of a special notice calling for transfer applications.
2. The production of a list showing all WAGT staff living within a four-mile radius of Claremont.
3. An extension of the normal program of consulting the transfer register by examining the possibility of making complex transfers, e.g. Perth to Claremont, WAGT depot to Perth.

This initial planning may be classified as substantive – developing new programs or modifying old ones – rather than procedural – developing programs for problem solving. Much of the narrative emphasizes the importance of communication processes when the decision making involved more than one person in the organization. These procedures included conferences, face-to-face or telephone communication between those participating in the performance programs, written notices to employees, interview programs, and discussion with an external organization – the union. The following five types of communication mentioned by March and Simon (1958, p. 161) were all represented.

1. Communication for non-programmed activity, e.g. discussion with the official of the union, which apparently resulted in a change in the union's attitude and a reduction in its opposition to the transfer of its members to Claremont.
2. Communication to establish programs, including their adjustment and co-ordination. Examples would be the conference between the personnel superintendent and his colleagues to establish the programs mentioned and that between the personnel superintendent and the assistant traffic manager leading to the widening of acceptance standards for drivers.
3. Communications to provide data required for the execution of programs, such as the interview program to find out who would be willing to transfer to Claremont.
4. Communications to initiate programs. The communication to the personnel superintendent of the chief executive's decision to transfer personnel to Claremont would be one example. Another would be that from the personnel superintendent to the chief instructor to give the standard driving test to the two un-licensed conductors.
5. Communications to provide information on the results of



activities. Examples of this would be the communication of the result of the interviews to the personnel superintendent and the latter's final report to the chief executive.

In the model of March and Simon (1958, p. 141), the decision maker is concerned with the discovery of satisfactory rather than optimal alternatives (see also Simon, 1955, pp. 99-118). In the case considered here, there was no attempt to define what was meant by optimal even though a less than optimal solution could have been attempted by treating the transfer as an assignment problem. This method, however, assumes that the effectiveness of the various personnel available for transfer can be measured (Churchman, Ackoff, and Arnoff, 1957). Such a procedure was obviously impractical under the circumstances. A 'satisfactory' level of performance in this particular case was the transfer of eleven drivers and eleven fare collectors to the Claremont depot in time for the newly scheduled service to begin on 27 September. Almost at the outset, however, this definition of what was satisfactory was reformulated in the light of what was known of the difficulty in persuading people to transfer to the Claremont depot. The relaxation took the form of accepting unlicensed conductors, who would require training. This alternative initiated routine subprograms, such as those for testing potential drivers and for training those who were suitable. A further adjustment to the desired level of satisfactoriness occurred when, because of the problems of transferring fare collectors, a surplus of four collectors at the former WAGT depot was considered a lesser evil than the inability to provide sufficient collectors at Claremont on the date set. The chief executive had specified the main task as the transfer of a particular bus service to the Claremont depot. An inferred subgoal was the elimination of the organizational slack (March and Simon, 1958, p. 126) which would develop at the old WAGT depot if the surplus personnel were allowed to remain there. This subgoal was to some extent abandoned. Lack of optimization was also evidenced by the acceptance of two fare collectors with past records of high absenteeism.

In the former WAGT depot, the staff generally was strongly identified with its union. In the opinion of the personnel superintendent, they were more concerned with the goals of the union,

an external organization, than those of the organization which presumed that it had purchased their allegiance by the payment of wages. The union's attitude was predominantly defensive. It perceived the MTT as a hard taskmaster whose primary goal was efficiency, probably because the chief executive had formerly held a similar position in a privately owned bus company. The union officials felt that working conditions had been easy for their organization and their members when the depot had been under the control of the WAGT; i.e. when there had been some organizational slack. They saw any action on the part of the MTT as a move to eliminate this organizational slack with a consequent tightening up of working conditions for their members. Their members saw it in this light too, and the ensuing feedback loops served to reinforce this impression. It was not surprising, therefore, that all communications from the MTT on the transfer issue were filtered, so that they fitted the established perceptions of this organization. This was almost entirely due to the fact that most of the communicators, both within the suborganization and the union, had similar frames of reference. All this was known to the personnel superintendent, who took two steps to remedy the situation. One was an attempt to change the union's attitude by discussing the situation with the union secretary – a step which seemed to have been quite successful, at least superficially. The other step was an effort to change the attitudes of those union members who lived close to the Claremont depot by means of the interview program. This also was successful in some cases.

## Conclusion

We have tried to analyse an organizational decision of a largely non-programmed type within the framework laid down by March and Simon. This framework, similar to that developed by Simon, Cyert and Trow, seems to be considerably more fruitful than the conventional one of classical rational choice, which leaves many questions unanswered. Even in such a relatively minor decision and short time span as this, the hierarchical structure of programs is apparent, and the importance of search programs, communications, perceptions and value systems can be seen. It is our conviction that the deeper understanding of decision-making

processes made possible by this type of analysis will lead to an improvement in those processes.

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## Part Three Programmed Decision Making

Unlike the non-repetitive decisions illustrated in Part Two, certain decisions need to be made over and over again. Prices must be established for the products a firm is selling. Supplies must be ordered by store buyers. Budgets must be set for various departments in a firm. Work schedules must be arranged to accommodate new projects. This section presents three field studies of such routine or programmed decisions.

The Cyert–March–Moore paper (Reading 6) concerns the decisions made in a large department store and develops simulation models for sales estimates, advance orders, reorders, mark-ups, sales prices and mark-downs. All but the reorder model were tested to determine how well they predict. The Weber paper (Reading 7) evolves five decision models based on observations of the manner in which projects were initiated and scheduled for the computer. In addition the paper illustrates the process by which an EDP budget was developed, reviewed and accepted. Weber tested all five of his models. A model for pricing in an oligopolistic market is delineated and tested in the Howard–Morgenroth paper (Reading 8).

The objective of all three studies is to develop models which have general application. The Cyert–March–Moore simulations were based on observations made in one department of a department store of over a hundred departments. The authors claim that with slight modifications, their models could be generalized so that they would simulate the decisions of a number of departments in the store. Howard and Morgenroth showed that their pricing model predicted not only the decisions of the manager observed but also predicted accurately the decisions of three other managers in diverse company locations. It is evident that

considerably more work needs to be done in this area to evolve generalized models.

The nature of the studies in this section appears to be quite different from that of the previous four. The decision models developed from observations were sufficiently explicit to be programmed for computer simulation. It may also be noted that while the non-programmed decision descriptions depict the manner in which problems come to the decision maker's attention, the search for alternatives and the choice among them, the programmed decision write-ups focus mainly upon the choice procedure. Of course, there was a time before the latter decisions became routine, when they were, in effect, non-programmed decisions. Then the decision makers went through all three steps of the decision process. However, as the decisions were repeated, fixed programs were developed for dealing with the problems. Problems came to the attention of decision makers in a predetermined way. For example, the need to make a price decision was triggered when a certain competitor changed his price. Or the need to make a sales estimate in a department store was set by the time of the year, January or July. Because the decision makers were satisfied with the choice procedure they had learned with experience, the models show no search for alternatives. The choice procedure is fixed and new problem-solving procedures are not considered unless the decision model fails in providing a satisfactory solution.

### A Model of Retail Ordering and Pricing by a Department Store

R. M. Cyert, J. G. March and C. G. Moore, 'A model of retail ordering and pricing by a department store', in R. E. Frank, A. A. Kuehn and W. F. Massey (eds.), *Quantitative Techniques in Marketing Analysis*, pp. 502-22, Irwin, 1962. Based on a chapter in R. M. Cyert and J. G. March, *A Behavioral Theory of the Firm*, Prentice-Hall, 1963, pp. 128-48.

The methods and practices by which retail firms make ordering and pricing decisions are discussed in most retailing books and in many introductory marketing texts. For the most part, however, the descriptions outlined are of a general nature. The focus has been on the broad aspects of the problems rather than the specifics of any given ordering pricing process. This paper describes a simulation model of ordering and pricing behavior in a specific department of a large retail department store. The predictions generated by the model are shown to bear a close relation to the actual observed behavior.

The organization chosen for intensive study is one department in a large retail department store. The firm involved is part of an oligopolistic market consisting (for most purposes) of three large downtown stores. Each of the firms involved also operates one or more suburban stores; but the focus of this study, and the bulk of the sales for each store, is the downtown market. The firm is organized into several merchandising groups. Each of these groups has several departments. The firm, in total, has more than a hundred major departments. We have studied, with varying degrees of intensity, the price and ordering decisions in about a dozen of the firm's departments. From these dozen we have chosen one for intensive investigation, and the specific model reported here is literally a model of decision making in that specific department. In our judgement, the decision processes we report for the one department could be generalized with trivial changes to other departments in the same merchandising group and could be generalized with relatively modest changes to most other departments outside the immediate group. Because of the great similarity in operation among department stores, the model

probably represents most aspects of decision making in a retail department store in general.

We present the model at two levels of specificity. In the first section we outline the decision process in the organization in rather general terms. In the second section we elaborate some of the specific decision rules in order to provide specific, explicit predictions of decisions.

### **General View of Pricing and Ordering in a Retail Department Store**

The organization studied makes relatively independent pricing and ordering decisions. There are loose connections between them, but for the most part they are made with reference to different goals and different stimuli. Although we will want to elaborate the goals of the organization somewhat when we turn to specific decision rules, we can describe two general goals that the department pursues. (a) The department expects (and is expected by the firm) to achieve an annual sales objective. (b) The department attempts to realize a specified average mark-up on the goods sold. Organizational decision making occurs in response to problems (or perceived potential problems) with respect to one or the other of these goals.

#### *Sales goal*

The general flow chart for decision making with respect to the sales goal is indicated in Figure 1. The organization forms sales 'estimates' that are consistent with its sales goal and develops a routine ordering plan for advance orders.<sup>1</sup> These orders are designed to avoid overcommitment, pending feedback on sales. As feedback on sales is provided, results are checked against the sales objective. If the objective is being achieved, reorders are made according to standard rules. This is the usual route of decisions. We will elaborate it further below.

Suppose, however, that the sales goal is not being achieved. Under such circumstances a series of steps are taken. First, the

1. This statement may not portray the process accurately. During the period we observed it was not possible to determine the interactions between the sales estimates and the goals. They always tended to be consistent with each other but it was difficult to determine the extent to which an implicit goal of 'equal or exceed last year's sales' influenced the estimates.

department attempts to change its environment by negotiating revised agreements with either its suppliers or other parts of its own firm or both. Within the firm, it seeks a change in the promotional budget that will provide greater promotional resources for the goods sold by the department. Outside the firm, the department seeks price concessions from manufacturers that will permit a reduction in retail price. If either of these attempts to relax external constraints is successful, reorders are made according to appropriately revised rules.

Second, the department considers a routine mark-down to stimulate sales generally and to make room for new items in the inventory. As we will indicate below, the department ordinarily has a pool of stock available for mark-downs and expects to have to reduce mark-up in this way on some of the goods sold. It will

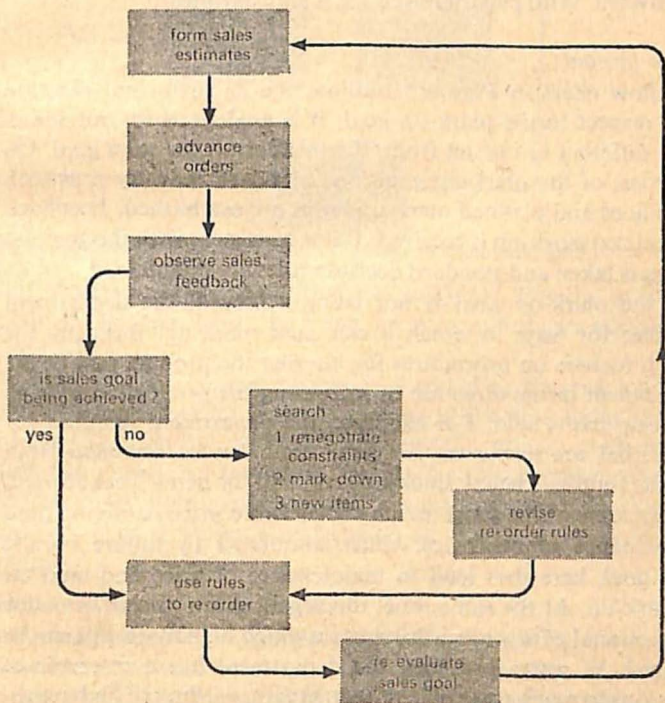


Figure 1 General form of reaction to sales goal indicators



attempt to stimulate all sales by taking some of these anticipated mark-downs. Once again, if the tactic is successful in stimulating sales, reorders are made according to slightly revised rules.

Third, the department searches for new items that can be sold at relatively low price (but with standard mark-up). Most commonly, such items are found when domestic suppliers are eliminating lines or are in financial trouble. A second major source is in foreign markets.

In general, the department continues to search for solutions to its sales problems until it finds them. If the search procedures are successful, all goes well. In the long run, however, it may find a solution in another way. The feedback on sales not only triggers action, it also leads to the re-evaluation of the sales goal. In the face of persistent failure to achieve the sales goal, the goal adjusts downward. With persistent success it adjusts upward.

### *Mark-up goal*

The flow chart in Figure 2 outlines the departmental reaction with respect to the mark-up goal. It is analogous to, but somewhat different in impact from, the reaction to the sales goal. On the basis of the mark-up goal (and standard industry practice), price lines and planned mark-up levels are established. Feedback on realized mark-up is received. If it is consistent with the goal, no action is taken and standard decision rules are maintained.

If the mark-up goal is not being achieved, the department searches for ways in which it can raise mark-up. Basically the search focuses on procedures for altering the product mix of the department in the direction of increasing the proportion of high mark-up items sold. For example, the department searches for items that are exclusive, for items that can be obtained from regular suppliers below standard cost, and for items from abroad. Where some of the same search efforts led to price reduction (and maintenance of mark-up), when stimulated by failure on the sales goal, here they lead to maintenance of price and increase in mark-up. At the same time, the organization directs its major promotional efforts towards items on which high mark-ups can be realized. In some instances, the department has a reservoir of solutions to mark-up problems (e.g. pressure selling of high mark-up items). Such solutions are generally reserved for crises and are

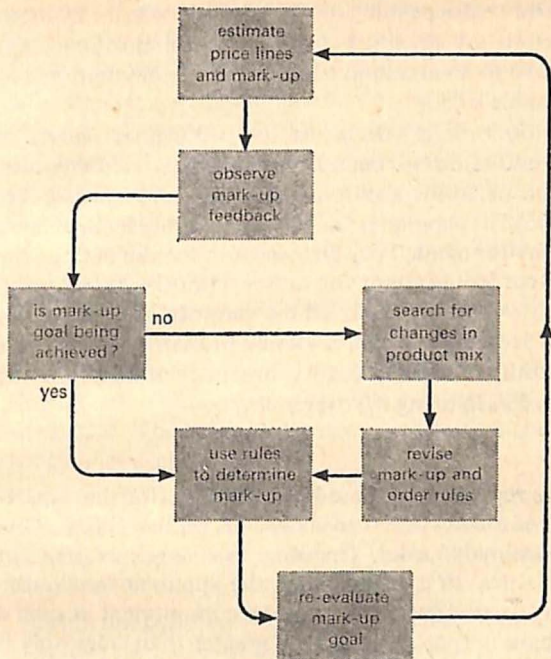


Figure 2 General form of reaction to mark-up goal indicators

not viewed as appropriate long run solutions. Finally, as in the case of the sales goal, the mark-up goal adjusts to experience gradually.

We think the general processes reflected in Figures 1 and 2 correctly represent the decision process in the firm under examination. They do not, however, yield specific, precise predictions. Detailed models for most (but not all) of major decisions need to be developed and compared with output from the organization studied. This is the task undertaken in the next section of this paper.

### Details of the Ordering Process

As has already been suggested, the ordering decision is essentially based on feedback from sales experience. Virtually no explicit calculation of the probable behavior of competitors is made; and although expectations with respect to sales are formed, every

effort is made to avoid depending on any kind of long run forecast. Ordering decisions are designed to satisfy two major goals: (a) limit mark-downs to an acceptable level; and (b) maintain inventory at a reasonable level.

The firm divides ordering decisions into two classes – advance (initial) orders and reorders. Each is dependent on a different set of variables and performs a different function. Advance orders allow the firm (and its suppliers) to avoid uncertainty by providing a contractual environment. They also account for the bulk of the total orders. Reorders account for only a minority of the total orders; but they provide virtually all the variance in total orders. In so far as the ordering decision is viewed primarily with respect to the total quantity of orders, reorders are much more important than advance orders in fixing the overall level.

### *Advance orders*

Advance orders represent the base level of orders for the department. The size of the advance order depends on two things. One of these is the estimated sales. The other is a simple estimate of the variance in sales. In a general way, the apparent motivation with respect to advance orders is to set the commitment at such a level that the base output alone will be greater than sales only if extreme estimation errors have been made. Thus, refinements in estimation are not attempted and simple estimating procedures are used, modified somewhat by special organizational needs only remotely related to the issue of accuracy.

*The estimation of sales.* The store operates on a six-month planning period. The individual department estimates dollar sales expected during the next six months. At the same time, sales are estimated on a monthly basis for each product class over the six-month period. Since the accuracy of the estimate is not particularly critical (at least within rather broad limits) for the overall level of orders, we consider the organizational setting in which the estimate is made in order to understand the decision rules. A low forecast, within limits, carries no penalties. The forecast cannot, however, be so low relative to past history that it draws criticism (as being unrealistic) from top management. The major limit on the low side is simply that the forecast be within a reasonable

distance of past achievements. Limits on the high side are specified by two penalties for making a forecast that is not achieved. First, achievement of forecasts is one of the secondary criteria for judging the performance of the department. Although the department cannot significantly affect the sales goal by underestimation, it can to a limited extent soften criticism (for failure) by anticipating it. Second, an overestimate will result in over-allocation of funds to the buyer. If he is unable to use the funds, he is subject to criticism. As a result, the buyer's estimate tends to be biased downward.

The primary data used in estimating sales are the dollar sales (at retail prices) for the corresponding period in the immediately previous year. Although these data are commonly adjusted slightly for 'unique' events, the adjustments are not highly significant. The following naïve rule predicts the estimates with substantial accuracy:<sup>2</sup>

Rule 1: The estimate for the next six months is equal to the total of the corresponding six months of the previous year minus one-half of the sales achieved during the last month of the previous six-month period.

From the point of view of ordering decisions, the more critical estimates are those for the individual months. The monthly figures are used directly in determining advance orders for the individual seasons. The estimation procedure for a particular product class is as follows:

Rule 2: *For the months of February, March and April.* Use the weekly sales of the seven weeks before Easter of the previous year as the estimate of the seven weeks before Easter of this year. In the same way, extend the sales of last year for the weeks before and after the season to the corresponding weeks of this year.

Rule 3: *For the months of August and September.* The same basic procedure as in Rule 2 is followed with the date of the public schools' opening replacing the position of Easter. The opening dates of county and parochial schools also are significant. If these dates are far enough apart, the peak will be reduced, but

2. We do not mean to imply that the department consciously uses such a rule. Although the rule was inferred from a study of actual behavior, the head of the department did not describe his estimation rule in these terms.

the estimate for the two months will still represent the total sales of the corresponding two months of the previous year.

*Rule 4: For the months of May, June, October, November and December.* Estimated sales for this year equal last year's actual.

*Rule 5: For the months of January and July.* Estimated sales for this year equal one-half of last year's actual rounded to the nearest \$100.

This set of simple rules provides an estimate of sales that is tightly linked to the experience of the immediately previous year with a slight downward adjustment.

*The seasonal advance order fraction.* The department distinguishes four seasons – Easter, Summer, Autumn and Holiday. The seasons, in fact, do not account exhaustively for all months, but they account for most of the total sales. Estimates of sales are established on the basis of the monthly estimates. These estimates do not necessarily include all months in the season. The following estimation rules are used:

Easter: Cumulate sales for the seven weeks before Easter

Summer: Cumulate sales for April, May, June and half of July

Autumn: Cumulate sales for half of July, August and September

Holiday: Cumulate sales for October, November and December

These cumulations give a seasonal sales estimate for use in establishing advance orders. Once such an estimate is made, some fraction of the estimated sales are ordered.

Advance orders generally offer some concrete advantages to the department. Greater selection is possible (some goods may not be available later) and some side payments may be offered by the producer (e.g. credit terms, extra services). The department exploits these advantages by ordering a substantial fraction of its anticipated sales in advance. But an attempt is made to limit the advance order fraction to an amount that would be sold under even an extreme downward shift in demand.

The advance order fraction is subject to learning on the part of the organization and reflects primarily differences among the seasons with respect to sales variability and uniqueness. The greater the susceptibility of seasonal sales to exogenous variables (e.g. weather), the lower the fraction. The more specialized the

merchandise sold during a season (i.e. the greater the difficulty of carrying it over to another season), the lower the fraction. At the point in time at which we observed the organization, the fraction (estimated from interviews and analysis of data) and the timing of advance orders for the four seasons were as follows:

| <i>Seasons</i> | <i>Per cent of estimated sales placed in advance orders</i> | <i>Time order made</i> |
|----------------|-------------------------------------------------------------|------------------------|
| Easter         | 50                                                          | 15–20 January          |
| Summer         | 60                                                          | 10–15 March            |
| Back-to-school | 75                                                          | 20–25 May              |
| Holiday        | 65                                                          | 20–25 September        |

In general we expect this simple model to predict quite well, being off only when the buyer makes *ad hoc* adjustments. Our observations lead us to believe this will not happen frequently.

### *Reorders*

For all practical purposes, reorders control the total orders of the department. As the word implies, a reorder is an order for merchandise made on the basis of feedback from inventory and sales. Because of leadtime problems, much of the feedback is based on early season sales information. Thus, the timing of a reorder depends on the length of time to the peak sales period as compared with the manufacturing leadtime required.

*Reorder rules.* Reorders are based on a re-estimate of probable sales. Data on current sales are used in a simple way to adjust 'normal' sales. The reorder program specifies reorders for a given type of product class as a result of a simple algebraic adjustment.

Let  $T$  = the total period of the season

$\tau$  = the period of the season covered by the analysis

$S_{i\tau}$  = this year's sales of product class  $i$  over  $\tau$

$S'_{i\tau}$  = last year's sales of product class  $i$  over  $\tau$

$S'_{i(T-\tau)}$  = last year's sales of product class  $i$  over  $T-\tau$

$I_i$  = available stock of  $i$  at time of analysis including stock ordered

$M$  = minimum amount of stock of  $i$  desired at all times

$O_{i(T-\tau)}$  = reorder estimate

Then

$$O_{i(T-\tau)} = \left[ \frac{S_{i\tau}}{S'_{i\tau}} S'_{i(T-\tau)} + M \right] - I_i$$

If  $O_{i(T-\tau)} \leq 0$  no reorders will be made. In addition, orders already made may be cancelled, prices may be lowered, etc. to reduce the presumed overstocking. Such an analysis would be made for each product class. The figure that results is a tentative one subject to minor modifications in the light of anticipated special events.

### *Open-to-buy constraint*

The firm constrains the enthusiasms of its departments by maintaining a number of records relevant to ordering decisions. One of the more conspicuous of such records is the 'open-to-buy'. The open-to-buy is, in effect, the capital made available to each department for purchases. The open-to-buy for any month is calculated from the following equation:

$$B_\tau = (I_{\tau+1}^* - I_\tau) + S_\tau^*$$

where  $B_\tau$  = open-to-buy for month  $\tau$

$I_{\tau+1}^*$  = expected inventory (based on seasonal plans) for beginning of month  $(\tau + 1)$

$I_\tau$  = actual inventory at beginning of month

$S_\tau^*$  = expected sales

The department starts each month with this calculated amount ( $B_\tau$ ) minus any advance orders that have already been charged against the month. Any surplus or deficit from the preceding month will increase or decrease the current account, as will cancellation of back orders or stock price changes.

While the open-to-buy is a constraint on ordering, the exact constraint is hard to specify. On the one hand, so long as the rules above are followed and the environment stays more or less stable, the open-to-buy constraint rarely will be violated. From this point of view, the open-to-buy is simply a long run control device enforcing the standard reorder procedure and alerting higher levels in the organization to significant deviations from such procedure. On the other hand, the constraint is a flexible one. It is possible for a department to have a negative open-to-buy (up to

a limit of approximately average monthly sales). Negative values for the open-to-buy are tolerated when they can be justified in terms of special reasons for optimistic sales expectations (e.g. when feedback has been affected by a transit strike).

The open-to-buy, thus, is less a constraint than a signal – to both higher management and the department – indicating a possible need for some sort of remedial action.

### **Details of the Pricing Process**

The firm recognizes three different pricing situations: normal pricing, sales pricing and mark-down pricing. The first two situations occur at regularly planned times. The third situation is a contingent situation, produced by failure or anticipated failure with respect to organizational goals. In each pricing situation the basic procedure is the same, the application of a mark-up to a cost to determine an appropriate price (subject to some rounding to provide convenient prices).

The bulk of sales occur at prices set by either of the regular standard procedures (normal and sales pricing). Mark-down pricing is one of the main strategies considered when search is stimulated. During the time period we observed, the demand was strong enough to permit fairly consistent achievement of the department's pricing goal – an average realized mark-up in the neighbourhood of 40 per cent. As a result, we did not observe actual situations in which the pressure to reduce prices stemming from inventory feedback conflicted with the pressure to maintain or raise mark-up stemming from overall mark-up feedback.

#### *Normal pricing*

Normal pricing is used when new output is accepted by the department for sale. As has already been observed, the problem of pricing is simplified considerably by the practice of price lining. In effect, the retail price is determined first and then output that can be priced (with the appropriate mark-up) at that price is obtained. Since manufacturers are also aware of the standard price lines, their products are also standardized at appropriate costs.

For each product group in the firm there is a normal mark-up. Like the seasonal advance order fraction, mark-up is probably



subject to long run learning. It varies in a general way from product group to product group according to the apparent risks involved, the costs of promotion or handling, the extent of competition, and the price elasticity. But in any short run the normal mark-up is remarkably stable. The statement is frequently made in the industry that mark-ups have remained the same for the last forty or fifty years.

*Standard items.* In the particular department under study, normal mark-up is 40 per cent. By industry practice, standard costs (wholesale prices) ordinarily end in \$0.75. By firm policy, standard prices (retail prices) ordinarily end in \$0.95. Thus, all but two of the price levels are in accord with the following rule:

'Divide each cost by 0.60 (i.e. 1 - mark-up) and move the result to the nearest 95¢.' The results of this rule and the effective mark-ups are shown in Table 1.

Table 1 Standard Prices

| <i>Standard costs<br/>(dollars)</i> | <i>Standard price<br/>(dollars)</i> | <i>Effective mark-up<br/>(per cent)</i> |
|-------------------------------------|-------------------------------------|-----------------------------------------|
| 3.00                                | 5.00                                | 40.0                                    |
| 3.75                                | 5.95                                | 37.0                                    |
| 4.75                                | 7.95                                | 40.2                                    |
| 5.50                                | 8.95                                | 38.5                                    |
| 6.75                                | 10.95                               | 38.3                                    |
| 7.75                                | 12.95                               | 40.1                                    |
| 8.75                                | 14.95                               | 41.5                                    |
| 10.75                               | 17.95                               | 40.0                                    |
| 11.75                               | 19.95                               | 41.0                                    |
| 13.75                               | 22.95                               | 40.0                                    |
| 14.75                               | 25.00                               | 41.0                                    |
| 18.75                               | 29.95                               | 37.4                                    |

*Exclusive items.* In some cases, the department obtains items that are not made available to competition. For such products and especially where quality is difficult to measure, the buyer prices higher than the standard. The pricing rule is as follows:

When merchandise is received on an exclusive basis, calculate the standard price from the cost, then use the next highest price on the standard schedule.

*Import items.* Presumably because they are frequently exclusive items, because of somewhat greater risks associated with foreign suppliers, and because of the generally lower costs of items of foreign manufacture for equal quality, the department increases the mark-up for imported items. For the product class studied the standard accepted increase over normal is 50 per cent (which gives a target mark-up of 60 per cent). This leads to the following rule for pricing imports:

Divide the cost by 0.40 (i.e.  $1 - \text{mark-up}$ ) and move the result to the nearest standard price. If this necessitates a change of more than 50 cents, create a new price at the nearest appropriate ending (that is, \$0.95 or \$0.00).

#### *Regular sale pricing*

We can distinguish two situations in which normal pricing is not used. One is during the regular sales held by the firm a few times during the year. The other is when the department concludes a mark-down is needed to stimulate purchases, or to reduce inventory levels. In this section we consider the first case. As in the case of normal pricing, sales pricing depends on a series of relatively simple rules. In almost all cases sales pricing is a direct function of either the normal price (i.e. there is a standard sales reduction in price) or the cost (i.e. there is a sales mark-up rule). Both figures on reduction and the sales mark-up are conventional, subject perhaps to long-run learning but invariant during our observations. The general pricing rules for sales operate within a series of constraints that serve to enforce minor changes either to ensure consistency within the pricing (e.g. maintain price differentials between items, maintain price consistency across departments), or to provide attractive prices (e.g. use prices a few cents below the dollar level or, when feasible, 'alliterative' prices such as \$3.30, \$4.40, etc.).

*General constraints.* The department sets its sales prices within the framework of five policy constraints. These constraints have not

changed in recent years and are viewed by the organization as basic firm policy. They are only rarely subject to review.

1. If normal price falls at one of the following lines, the corresponding sale price will be used:

| <i>Normal price</i> | <i>Sale price</i> |
|---------------------|-------------------|
| \$1.00              | \$0.85            |
| 1.95                | 1.65              |
| 2.50                | 2.10              |
| 2.95                | 2.45              |
| 3.50                | 2.90              |
| 3.95                | 3.30              |
| 4.95                | 3.90              |
| 5.00                | 3.90              |

2. For all other merchandise, there must be a reduction of *at least* 15 per cent on items retailing regularly for \$3.00 or less and *at least* 16 $\frac{2}{3}$  per cent on higher priced items.

3. All sales prices must end with 0 or 5.

4. No sales prices are allowed to fall on any of the price lines normal for the product group concerned.

5. Whenever there is a choice between an ending of 0.85 and 0.90, the latter ending will prevail.

*Departmental decision rules.* Subject to the general policy constraints, the department is allowed a relatively free hand. Since the policy constraints do not uniquely define sales pricing, it is necessary to determine the departmental decision rules. These rules are indicated in detail in the flow charts in Figures 3 and 4.

### *Mark-down pricing*

In our earlier discussions of organizational decision making, we have suggested that a general model of pricing and ordering must distinguish between the ordinary procedures (that account for much of the bulk of the actual decisions made) and the special search procedures that are triggered by special circumstances. We have already seen how such procedures enter into the determination of orders for the organization studied. We turn now to search and 'emergency' behavior on the price side. Price is the

major adaptive device open to the department in its efforts to meet its mark-up goal, maintain sales, maintain inventory control, and in general meet the demands of other parts of the organization. We have already indicated how an increase in mark-up (e.g. on imports and special items) is used by the department. We turn now to mark-downs.

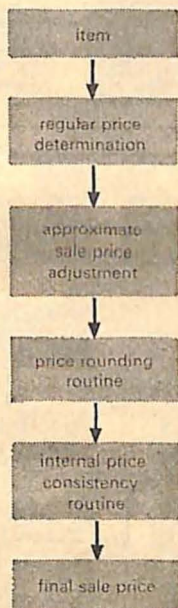


Figure 3 Major subroutine of sale pricing decision

With respect to mark-downs, the department has two decisions to make: When? And how much? In a general sense, the answer to the first question – the question of timing – is simple. The organization reduces price when feedback indicates an unsatisfactory sales or inventory position. The indicators include the inventory records, sales records, or physical inventory reports on competitive prices, and the open-to-buy report. Of secondary importance are mark-downs because of product properties (e.g. defective items). With respect to the amount of mark-down, the

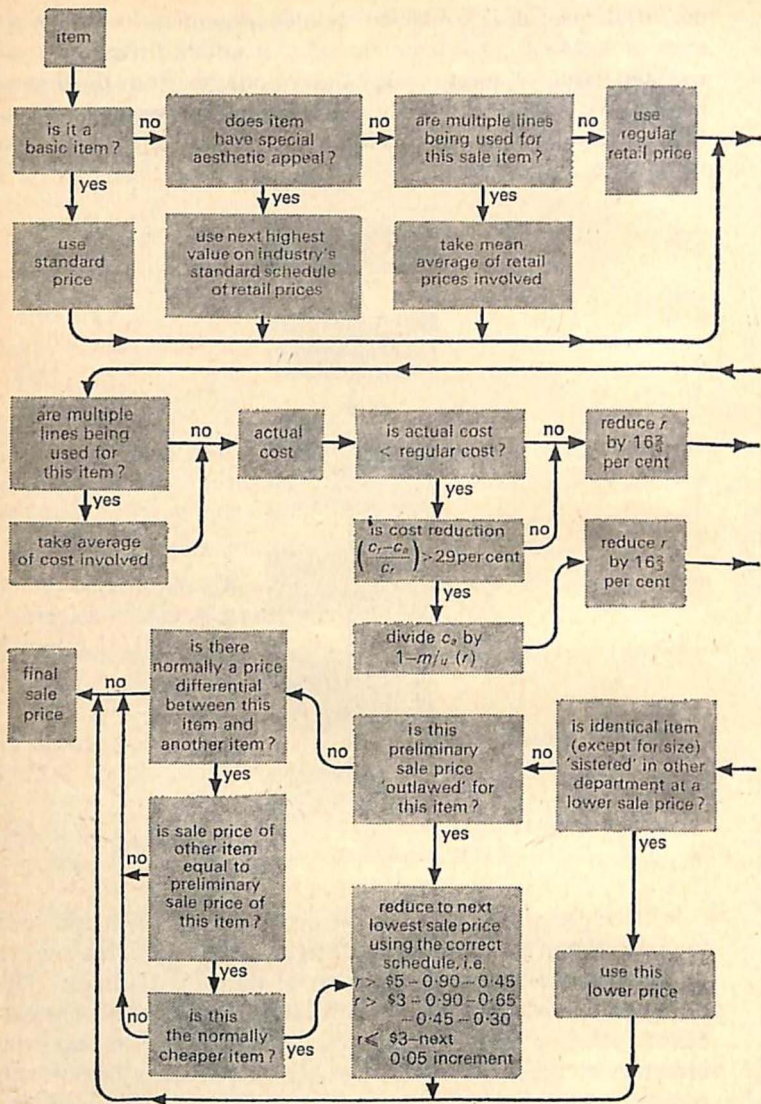
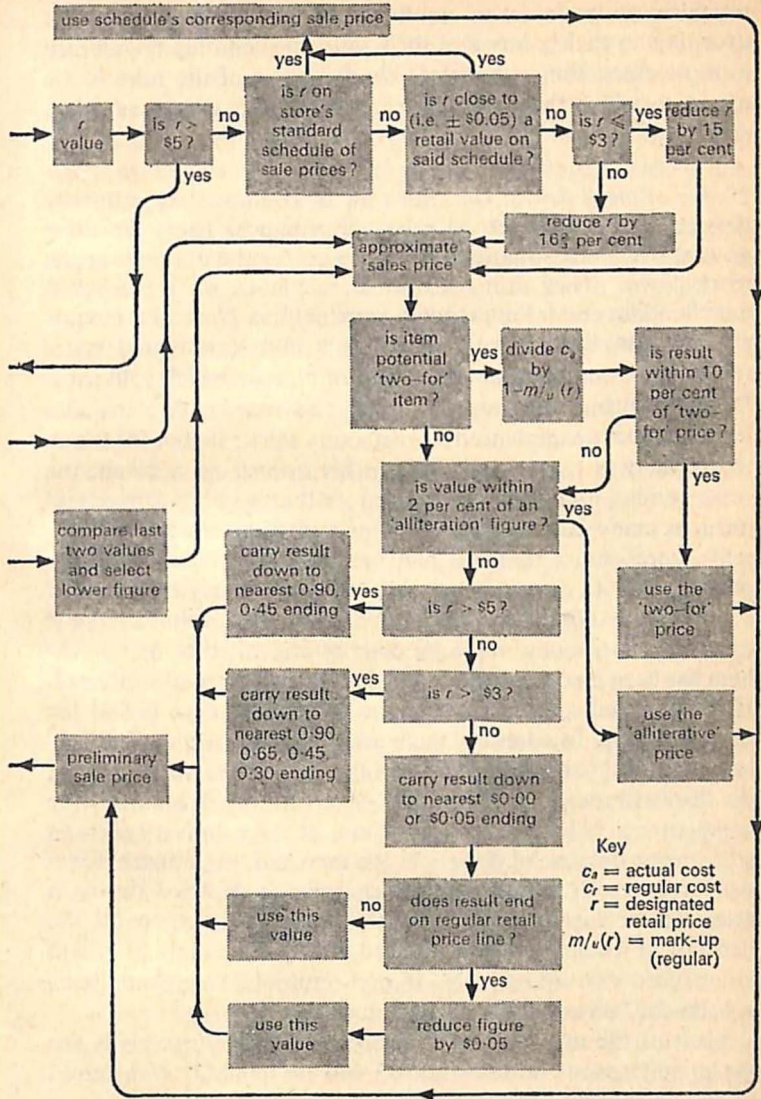


Figure 4 Flow chart for sale pricing decision





organization has a set of standard rules. They have developed over time in such a way that their rationale can only be inferred in most cases. But a consistent characteristic of the rules is the extent to which they avoid pricing below cost except as a last resort.

*Timing of mark-downs.* Occasions for mark-downs are primarily determined by feedback on sales performance. There are three general overstock situations that account for the majority of the mark-downs. They are: (a) normal remnants, (b) overstocked merchandise, and (c) unaccepted merchandise. Normal remnants are the odd sizes, less-popular colors and less-favored styles remaining from the total assortment of an item which sold satisfactorily during the season. Overstocked merchandise includes items that have experienced a satisfactory sales rate but for which the buyer was overly optimistic in his orders. As a result, the season ends with a significant inventory that is well balanced and includes many acceptable items. Unaccepted merchandise represents merchandise that has had unsatisfactory sales. The sales personnel try to determine during the season whether the lack of acceptance is due to overpricing or poor style, color, etc. The distinction is usually made by determining whether or not the item has been ignored. If it has, the latter cause is usually inferred. If the item gets attention but low sales, the inference is that the price is wrong. In addition, there are a number of quantitatively less important reasons for considering mark-downs. For example, the firm will meet competition on price (if a check indicates the competitor's price is not a mistake). If a customer seeks an adjustment because of defects in the merchandise, a mark-down will be taken. If special sale merchandise is depleted during a sale, regular merchandise will be reduced in price to fill the demand. If wholesale cost is reduced during the season, price will be reduced correspondingly. If non-returnable merchandise is substandard on arrival, it will be reduced.

Most of the merchandise that becomes excess (especially for the major reasons outlined above) will be mentally transferred to an 'availability pool'. When a particular opportunity arises or when certain conditions develop necessitating a mark-down, items are drawn out of this pool and marked down for the particular

occasion involved. Store-wide clearances are planned by the merchandise manager on non-recurring dates throughout the year (except the pre-Fourth-of-July period and the after-Christmas period) to provide all departments an opportunity to clear out their excess stocks. The buyers receive a tentative schedule of these events ahead of time from the publicity department in a six-month's promotion plan bulletin.

However, there may be times during the year when the department cannot wait for the next scheduled clearance for reasons of limited space capacity or of limited funds. If, for example, the department is expecting a large shipment of new merchandise and display and storage facilities do not have at the time the extra capacity to accommodate this additional inventory, there is no other choice but to clear some of the present stock by means of mark-downs.

The department may take mark-downs when its open-to-buy is too deep in the red. (The interpretation of 'too deep' is somewhat arbitrary but whenever the open-to-buy falls to the minus \$15,000 level it would be judged to be in unsatisfactory condition.) The department will not necessarily take mark-downs as the principal means of rectifying this state of affairs *per se* but instead will attempt to cancel merchandise on order or charge back merchandise already received *if* it cannot expect any relief from an increased sales rate within the immediate future or if the present average mark-up is low. But if a situation arises where the department has an urgent need to purchase additional merchandise and the open-to-buy at the time is in the red to the extent that the division merchandise manager will probably not approve any additional orders from the department, the department will then look to its availability pool and take mark-downs for the amount necessary to permit the particular purchase to take place.

*Amount of mark-down.* The complete model for predicting actual mark-down prices is given in Figure 5. The general rule for first mark-downs is to reduce the retail price by one third and carry the result down to the nearest mark-down ending (i.e. to the nearest \$0.85). There are some exceptions. Where the ending constraint forces too great a deviation from the one-third rule (e.g. where regular price is \$5.00 or less), *ad hoc* procedures are



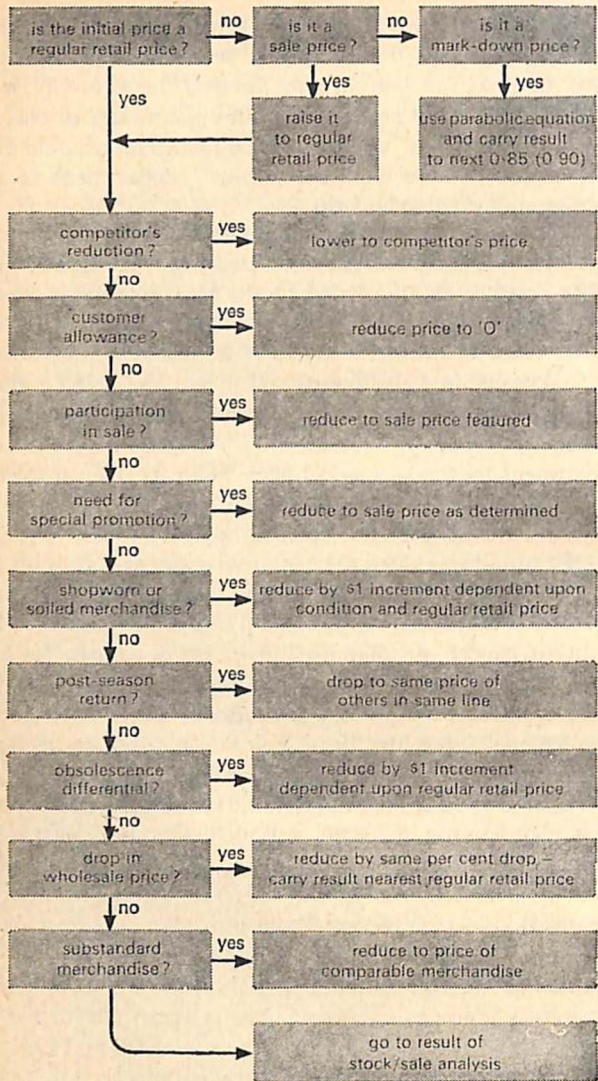
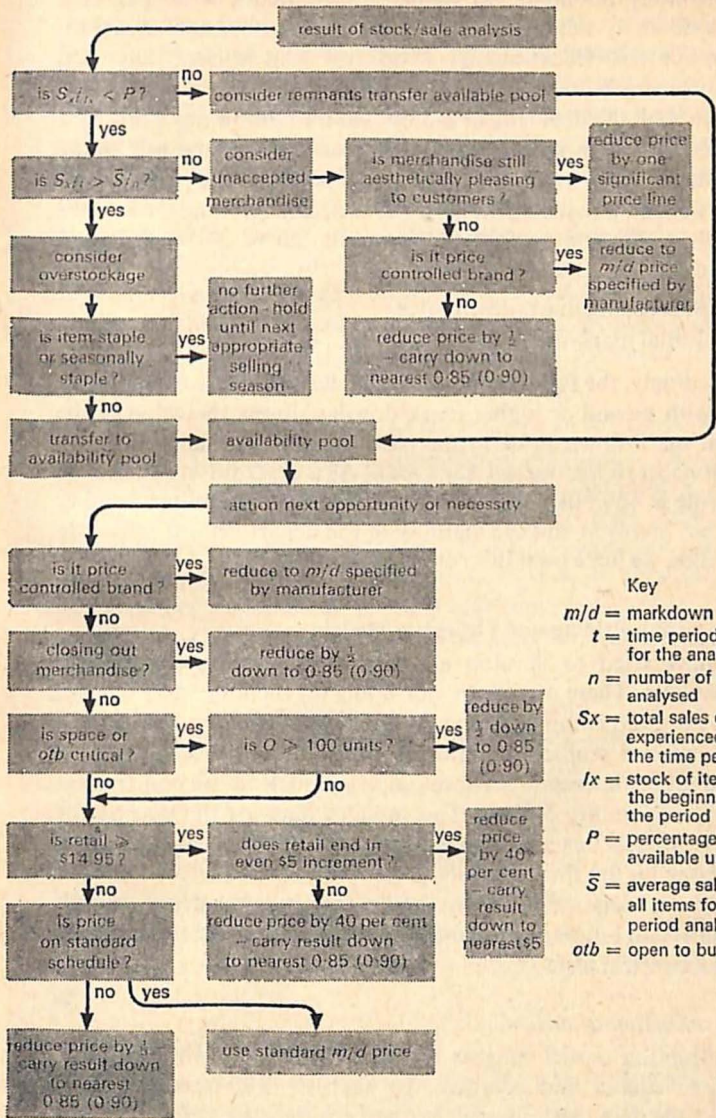


Figure 5 Flow chart for mark-down routine



occasionally adopted. On higher priced items, a 40 per cent mark-down is taken. On a few items manufacturers maintain price control. Occasionally, items represent a close out of a manufacturer's line and a greater mark-down is taken.

Although the department did not seem to follow any particular explicit rule with second or greater mark-downs, the higher the first mark-down value the greater tended to be the reduction to the succeeding mark-down price. In fact, this relationship seemed to follow the top half of the parabolic curve  $Y^2 = 5(X-2)$  where:

$Y$  = Succeeding mark-down price.

$X$  = Initial mark-down price.

Accordingly, the following empirically derived rule seems to work well with second or higher mark-downs: 'Insert the value of the initial mark-down price in the parabolic formula and carry the result *down* to the nearest 85¢ (90¢).' As a description of process, this rule is obviously deficient. But in view of the limited number of cases involved and the inability of the department to articulate the rules, we have used this rough surrogate.

### Tests of the Pricing and Ordering Models

We have tried to develop a model that would yield testable predictions. There are two major limits on such a goal. First, we have not been completely successful in defining a model that will make precise predictions in every decision area. Second, where we have been successful in developing a model, we are constrained by the availability of data. The value of data for the purpose of testing models has not always been controlling in data-retention decisions by the firm. Despite these limits, we have been able to develop models for the major price and ordering decisions and to subject all but one of the major components of those models to some empirical test.

#### *Determination of orders*

The ordering model consists of three segments – sales estimate, advance orders and reorders. In each of the tests described below, the data used are new and are not the data with which the model was developed.

*Sales estimation.* The sales estimation model is composed of the rule for estimating sales for the six-month period and of the rules for the estimation of the sales of individual months. The data available were for a two-year period so that the test is far from conclusive. However, there is no reason to believe that the model would not be valid for a larger sample of data. The first part of the model, the estimation of total sales for a six-month period, predicts the total within 5 per cent in each of the four test instances. With the set of monthly rules, we can predict about 95 per cent of the monthly sales estimates within 5 per cent. There is no question that the predictive power could be increased still further by additional refinement of the rules. However, at this point it does not seem desirable to expend resources in that direction.

*Advance orders.* This segment of the model and the sales estimation segment are related as we have shown previously. Therefore, discrepancies between predicted and actual are difficult to allocate precisely between the two segments although we have some clues from the above testing. Unfortunately the firm does not keep its records of advance orders any length of time so no extensive test of the model was possible. We were able to accumulate only four instances in which the predictions of the model could be compared with the actual.

| <i>Season</i> | <i>Predicted<br/>advance orders</i> | <i>Actual<br/>advance orders</i> |
|---------------|-------------------------------------|----------------------------------|
| 1             | 18,050                              | 16,453                           |
| 2             | 26,550                              | 24,278                           |
| 3             | 36,200                              | 35,922                           |
| 4             | 43,000                              | 35,648                           |

*Reorders.* This segment is one that it is most important to test. The fact is, however, that the data on reorders are not kept in any systematic fashion, and we have not been able to make any kind of test.

#### *Determination of prices*

The situation with regard to adequate data is much better for the pricing models. In each case the model was subjected to a large sample and performed adequately.

*Mark-up.* In order to test the ability of the model to predict the price decisions that will be made by the buyer on new merchandise, an unrestricted random sample of 197 invoices was drawn. The cost data and classification of the item were given as inputs to the computer model. The output was in the form of a predicted price. Since the sample consisted of items that had already been priced, it was possible to make a comparison of the predicted price with the actual.

The definition of a correct prediction was made as stringent as possible. Unless the predicted price matched the actual to the exact penny, the prediction was classified as incorrect. The results of the test were encouraging; of the 197 predicted prices 188 were correct and 9 were incorrect. Thus 95.4 per cent of the predictions were correct. An investigation of the incorrect predictions showed that with minor modifications the model could be made to handle the deviant cases. However, at this point it was felt that the predictive power was good enough so that a further expenditure of resources in this direction was not justified.

*Sale pricing.* In order to test the model a random sample of sales items was selected from the available records. A sample of fifty-eight items was selected. For each item the appropriate information as determined by the model was used as an input to the computer. The output was in the form of a price which was a prediction of the price that would be set by the buyer. Again we used the criterion that to be correct the predicted price must match the actual price to the penny. Out of the fifty eight predictions made by the model, fifty six were correct.

*Mark-downs.* In testing this part of the model the basic data were taken from 'mark-down slips', the primary document of this firm. Naturally such slips do not show the information which would enable us to categorize the items for use in the model. It was necessary, therefore, to use direct methods such as the interrogation of the buyer and sales personnel to get the information necessary to classify the items so that the model could be tested. All of the data used were from the previous six-month period. It would be possible on a current basis to get the information which

would enable the model to make the classifications itself as part of the pricing process.

The test for a correct prediction was the same as before, complete prediction, complete correspondence to the penny of the predicted and the actual price. A total sample of 159 items was selected and predictions made of the mark-down price for each item. Of the 159 prices predicted, 140 were correct predictions by our criterion and 19 were wrong. This gives a record of 88 per cent correct – the poorest record of the three models. Though this model does not do as well as the other two, the record is, in our view, adequate enough to allow reliance to be placed on the model.

### Summary

The tests that have been made of the model tend to support it. Clearly some of the tests are inadequate because of the paucity of the data. Also we have not attempted to build alternative models and compare predictive ability. No doubt that alternative models can be built and can be made to predict well. However, our primary interest has been in building a model which embodies the actual decision-making process. We do not believe a radically different model can be built which captures the actual decision process. Because our objective is to understand the actual process, we have not attempted to minimize the number of assumptions, the number of variables, or the number of inputs to the model.

The department store model outlined in this paper is supported by the ordering and pricing evidence collected in the field study. We would not argue that the evidence is conclusive with respect to the organization's decision-making process. It is not. It is, however, consistent with the model. The model, in turn, lends itself to further elaboration and testing. And the world is full of firms for further empirical study.

### Intraorganizational Decision Processes Influencing the EDP Staff Budget

C. E. Weber, 'Intraorganizational decision processes influencing the EDP staff budget', *Management Science*, vol. 12, no. 4, December 1965, pp. B69-93.

#### Introduction

The paper reports the results of a field study and suggests implications for a behavioral theory of the firm. *The Behavioral Theory of the Firm* and related works provide a conceptual framework for analysing management decision making (Cyert and March, 1963; Frank, 1958-9; Lindbloom, 1959; Thompson and Tuden, 1959; Williamson, 1963). Within this framework, managing can be viewed as a process involving the interaction of the decision strategies of the members of the organization; and a strategy can be defined as a set of constraints, rules or relations among variables that govern the sequence of responses to information (March and Simon, 1958; Shelly and Bryan, 1964; Simon, 1960).<sup>1</sup>

Budgeting, the primary orientation of the paper, is hypothesized in *The Behavioral Theory of the Firm* to be part of the more general process of setting goals (Cyert and March, 1963, pp. 26-38). The firm is considered to be a coalition in which members bargain about policy commitments; and then they use the budgeting process to bargain about the specific content of the commitments. Policy matters, it is argued, are exceedingly complex and defy exact definition in advance of implementation.

Major aspects of a behavioral theory of the firm, accordingly, are that the budgeting of resources is the outcome of the interaction of the decision strategies of several individuals and that

1. Herbert Simon, for example, defines strategy as a detailed prescription that governs the sequence of responses of a system to a complex task environment (Simon, 1960, p. 6). In a paper, 'Deliberation and judgement' (Shelly and Bryan, 1964, p. 49), C. West Churchman defines personal logic as the process by which the information processor transforms inputs into decisions.

this interaction can be characterized as a bargaining process. However, there are few field studies which address themselves to the content and interaction of decision strategies in ongoing business firms.<sup>2</sup>

The field study reported here is intended to contribute to a behavioral theory of the firm in several ways. First, it shows the constraints entering into the strategies of managers in a specific situation. Secondly, the analysis of these strategies suggests how organization goals are woven into the decisions of individual managers; and, thirdly, the analysis suggests the character of the interaction of decision strategies. I found less bargaining in the field situation than the above aspects of the behavioral theory of the firm would lead me to expect. There were conflict and 'politics', but these appeared to be due to differences in judgments about goal expectations of others, especially superiors.

The field study focused on several managers whose strategies influenced the budgeted size and composition of the staff of an electronic data processing department in a company. Two of the managers were directly responsible for proposing the salary budget of the electronic data processing department (EDP), but their decisions were influenced by the goal statement of their superiors, by the 'demand for service' from their most dynamic user, and by corporate staff members who had formal advisory positions.<sup>3</sup>

### *Method of analysis*

Five computer decision models were developed to describe the strategies of the managers studied. To test the models, simulated decisions were used to predict actual decisions; and comparisons were made between the predicted and actual decisions.

The analysis of budgeting and related strategies in an ongoing organization can be approached in different ways. My approach was to formulate hypotheses about the strategies from interviews, to construct models from the hypotheses, and then to test the models with different data. The models assert that certain data are the inputs for the decision strategies and that decisions are

2. For examples of two field studies, one by Cyert, March and Moore and the other by Clarkson, see Cyert and March (1963, chs. 7 and 10).

3. Goss (1961) provides an example in another context of how control is exercised through formal advisory positions.



reached on the basis of these inputs and on the basis of specific relations between the inputs and the decisions.

Computer programs have the value of allowing one to describe decision strategies more rigorously and to test these descriptions more systematically. Ambiguity in the results of a field study is difficult to avoid in any event, but the ambiguity can be reduced by the effort to translate prose descriptions or schematic representations of behavior into computer program statements. Essentially, this is a reduction in the ambiguity of the hypotheses proposed by the researcher. Various interpretations still remain of what relationships were observed, but this is the nature of field study where one can make limited observations of complex open systems. The reported research is no exception; but I submit that, despite the 'curve fitting', systematic field study provides insight for theory construction and added confidence for the design of laboratory experiments.

Approximately fifty interviews were conducted with the persons involved in the budget and related processes. These interviews were conducted to develop the computer programs and to obtain data for simulation. In addition, questionnaires were used to obtain other data for simulation.

It was necessary to use past decisions in the study. Since decisions on budgets are made only once a year in the company, the time required to wait for future decisions was too great to accumulate such data. Widespread reassignments of personnel which were made after the collection of past data further complicated the problem of follow-up.

Separate computer programs were developed for the decision strategies of the participants. Five programs were written in total. These programs had to be developed and tested as separate entities because the interviews were confidential. To test the programs as an integrated model would have required that I ask directed questions about situations described by the other participants, and this would have revealed sources of information.

Although the confidential nature of the data made it more appropriate that the decision strategies of the participants be written and tested as separate programs, integration of the strategies may bring out the character of their interaction more clearly. To do this, hypotheses were gleaned from the interviews

on how the programs of the participants were related to each other.

The five models are described in the next section, along with suggested hypotheses for their connections to each other. In the following section, data for testing the models are summarized. As indicated above, comparisons were made between predicted decisions and actual decisions. In the final section, the characteristics of the interaction of the strategies and other implications are discussed.

### **Models of Decision Strategies**

Models were developed for the decision strategies of the following participants:

1. Manager of market research.
2. Management of EDP (electronic data processing department).
3. Staff member of systems department.
4. Superior of EDP management.

The organizational structure of these managers and others whose judgements they considered is shown in Figure 1.

The market research department was the largest user of electronic data processing services outside of accounting and absorbed 30 per cent of EDP's processing time. The manager of market research reported to the vice president of the sales division. In the course of implementing the projects of his department, he communicated with EDP management and their superiors.

The management of EDP (Figure 1) consisted of the supervisor of EDP and his manager who was also responsible for other kinds of administrative service departments. They worked as a team, making decisions on what projects were to be done by EDP and what staff budgets to propose for EDP. In the process of making their decisions, the supervisor gathered routine and technical information and his manager maintained liaison with other departments. The manager over the EDP supervisor reported to the assistant vice president of the service division.

In the systems department, the strategy of a senior staff member was studied. He, of course, reported to the manager of the

systems department; and the manager of the systems department reported to the assistant vice president of the service division.

The superior of EDP management as shown in Figure 1 was the assistant vice president of the service division. Although he was also the superior of the manager of the systems department, the assistant vice president of the service division is referred to simply as the superior of EDP management in the paper because

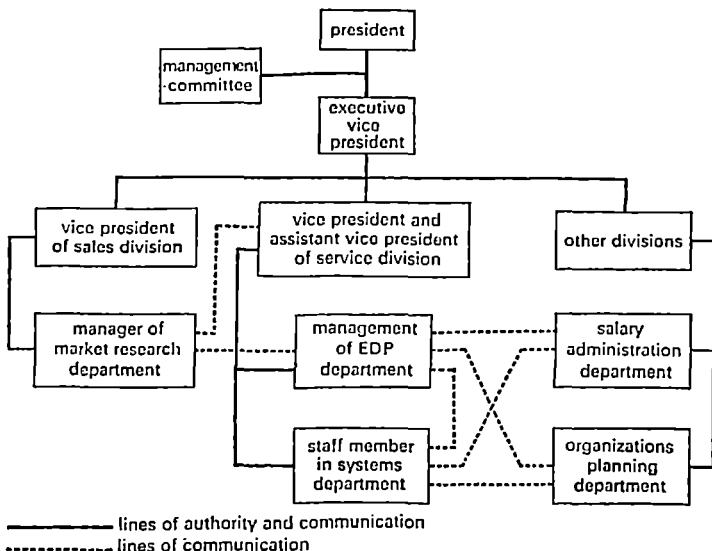


Figure 1 Organization

this was the role he played in the decision processes under consideration. The assistant vice president of the service division appeared to be the internal operating head of the division, while his superior, the vice president, appeared to handle certain external company relations and to participate in the deliberations of the management committee. The vice president appeared to interpret company policies discussed by the management committee to his subordinates. It is important to note that the manager of market research also participated in management committee deliberations.

*Model I: Manager of market research*

The work done by market research involved the analysis of information and ranged from elaborate, routine and repetitive projects to high priority 'one-shot' projects. The manager of market research received project suggestions from the chairman of the board, the president, the executive vice president, the management of the sales department, his own department and companies with which they dealt. Market research, for example, estimated the demand for new products, analysed information gathered by company salesmen, and appraised the feasibility of plant locations.

The model for the manager of market research was developed to simulate a sequence of decisions on initiating projects. His decisions which were simulated included the following:

1. Whether market research should undertake specific project proposals for the analysis of information.
2. Whether market research should request assistance in the processing of data from EDP in the event that market research decided to undertake a project.
3. Whether market research should press its request if EDP did not agree to give assistance when requested initially.
4. What, if any, alternative method should be selected to accomplish the project if EDP continued to reject their request.
5. Whether to ask EDP to modify its decision to postpone the completion of a report in the event that EDP agreed to undertake a project and later felt that the agreed deadline should be extended.

These decisions influenced the EDP staff budget (Model III). It is hypothesized in Model III that EDP management would make a judgement on the need to expand service in developing its proposed budget, and this judgement appeared to depend upon the interaction between market research and EDP in the scheduling of projects. There were, of course, other users of EDP's services, but their requirements were stable and did not enter into the budget decisions of EDP management. In effect, the interaction between EDP and market research created political pressures which EDP management did not choose to ignore.

Figure 2 represents the computer model of the strategy which the manager of market research appeared to use in order to initiate projects. The flow diagram is a condensation of the complete program and is intended only to convey the major constraints in the manager's strategy. The complete programs are available to the reader who wishes to pursue the analysis in greater depth. Not all of the types of decisions outlined above are explicitly shown in this figure, but they are implicit in its structure.

The market research manager's strategy consisted of a sequence of constraints, and his choice depended upon whether a specific project satisfied these constraints. This can be readily observed in Figure 2 by scanning it from top to bottom, without tracing through the flow of the arrows. The constraints and other elements in the strategy are numbered and are referred to as no. 1, no. 2, etc., in the paper.

The constraints entering into his strategy were of two types. One type is related to the technical feasibility of the project while the other type is related to his judgements of the objectives of other managers, especially superiors.<sup>4</sup> Both types of constraints were found in the decision strategies of the other participants as well.

Hopefully, the flow charts can convey the decision strategies without an extensive description accompanying them; but it may be helpful to describe the first one in some detail. The first major constraint (Figure 2, no. 1) considered by the manager of market research involved the usefulness of the information for corporate strategy. The usefulness of the information was evaluated in terms of four overlapping guides. Information was considered to be useful if it pertained to the productivity of salesmen, pricing, competitive position, and sales volume. Another guideline implicit in no. 1 and included in the program was the availability of the data to carry out the project. Whether a proposal satisfied one or more of these guidelines contained in no. 1 was a judgement by the manager of market research which entered into the program as an input. In general, the research was an endeavor to simulate how the managers combined or weighed their many technical and

4. The concept of organizational objectives as constraints in the strategy of the decision maker is elaborated by Simon (1960).

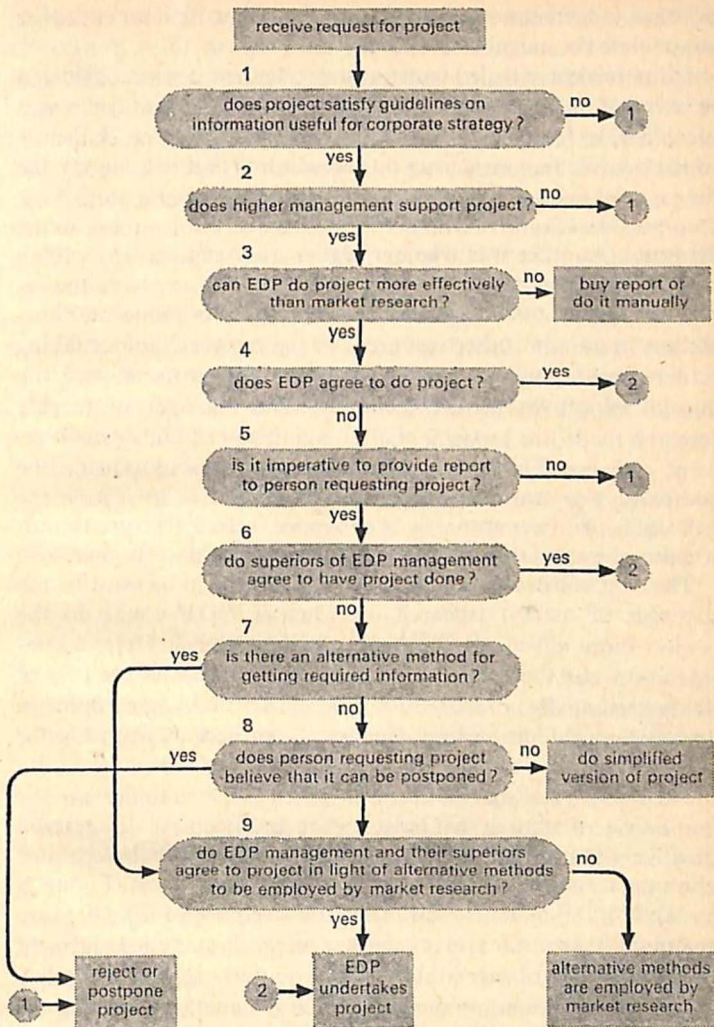


Figure 2 Model I: manager of market research project initiation strategy

political judgements to reach a decision rather than an endeavor to simulate the judgements themselves.

If the project satisfied constraint no. 1, then it was considered in terms of its likely support from higher management (sales vice president, executive vice president, president, and/or chairman of the board). In considering this constraint (Figure 2, no. 2), the manager of market research took into account several guidelines. One consideration was whether he had resources to commit to the proposal. Another was whether higher management was willing to commit resources to the proposal if he did not have the resources. He did not commit his own resources or request authorization to commit other resources to the proposal before taking into account potential conflict between the proposal and the current objectives of the company. The manager of market research made this judgement after sounding out higher management and possibly individuals from organizations outside the company. For example, one proposal, which was to request the collection of information by a customer, raised the question of whether the request would harm relations with this customer.

The next constraint (Figure 2, no. 3) was the judgement by the manager of market research on whether EDP could do the project more effectively than his own department. Here, a consideration was the cost of purchasing the report and the cost of doing it manually compared to using data processing equipment. Another consideration was whether the project was too big for EDP.

The manager of market research asked EDP to undertake the processing of data if he judged that EDP could do it more effectively than his own department. His strategy then depended upon the response of EDP management to his request (Figure 2, no. 4). If EDP management rejected his request or asked him to postpone it, the manager of market research made a judgement on the necessity of providing the information (no. 5). The judgement involved sounding out the person originally requesting the information from market research.

The manager of market research took his request to the assistant vice president and then to the vice president of the service division if he judged it imperative to provide the report. Information that they rejected the request (Figure 2, no. 6) caused the manager of

market research to consider alternative ways (no. 7) of processing information for the project. These alternatives included having the project done on equipment located in divisions of the company not responsible for this type of work, having the project done by an outside agency, and enlarging his own staff to undertake the project. It is important to note that he did not directly undertake an alternative method of processing the information but simply proposed such action. He then waited for a response from EDP (no. 9). EDP management and their superiors might offer to process the information when alternative methods were proposed as shown in Figure 2. They apparently had an interest in maintaining their position as the department which serviced the divisions located at company headquarters. The way in which they responded to requests and suggestions from the manager of market research is shown in later flow charts.

The strategy used by the manager of market research to reach his decisions on his requests that EDP management modify its postponement of the report deadline is not shown in Figure 2. However, the constraints entering into this decision were similar to those shown in Figure 2.

### *Model II: EDP management – scheduling*

Model II represents the decision strategy of EDP management in considering requests from the manager of market research and other users. At the time of the study, however, only market research was requesting additional data processing service.

Figure 3 shows the major constraints included in the model. The decision strategy for accepting or rejecting projects seems to be straightforward. Projects were accepted if slack existed (Figure 3, nos. 1, 3 and 4). Even if slack did not exist, projects could be accepted. This depended, first, on whether ongoing projects could be postponed (no. 5). Processing payroll, for example, was a project that could not be postponed. Secondly, it depended on whether the superior of EDP management was judged to support the project (no. 6). EDP management apparently made this judgement after sounding out their superiors. Again, we find that the constraints were about either technical matters or the objectives of superiors.

One might expect that agreement would be reached easily



## Programmed Decision Making

between market research and EDP since the participants were oriented towards the same considerations, but such was not the case. The objectives were apparently interpreted differently by the participants in the early stages of the decision process, and

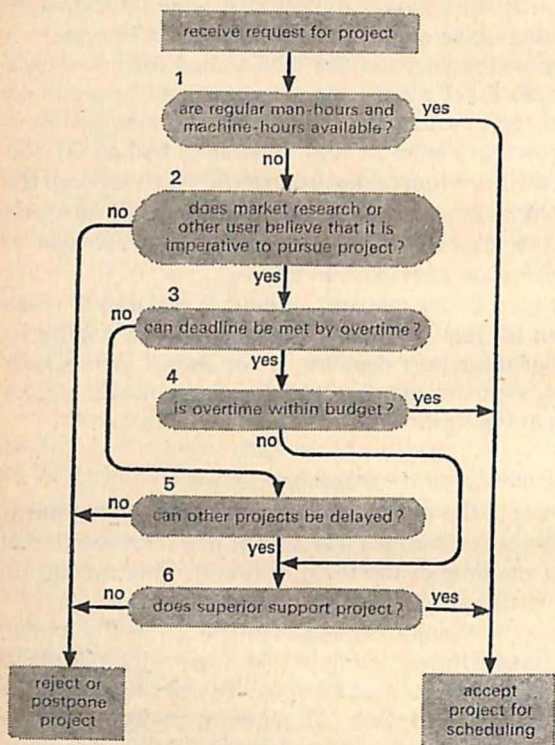


Figure 3 Model II: EDP management strategy on accepting projects for scheduling

the interpretations apparently converged only later. Possible explanations are discussed in the section on implications. It is interesting to note, however, that the deliberations of the management committee appeared to be the common source of these interpretations.

*Model III: EDP management – budgeting strategy*

EDP management proposed a staff budget at the end of the third quarter of the year for the following year. The proposed budget showed the number of persons for each of thirteen job grades. The critical decisions in constructing the staff budget were the number of persons to propose in each of the thirteen grades. In making these decisions, EDP management weighed the feasibility of specific proposals for changing the existing composition and size of staff. Model III describes the strategy which EDP management apparently employed in deciding the size and composition of its staff budget, and the constraints for this strategy are shown in Figure 4. There are four major aspects of EDP management's strategy described by this model. First, there are constraints set by the objectives which EDP management was expected to meet in their budget. Secondly, there is a list of proposals for modifying the size and composition of the staff, and there are accompanying rules for the search or recall of these proposals. Thirdly, there are technical and 'political' constraints used to evaluate proposed changes; and fourthly, there are rules for calculating the budget.

The first aspect described by Model III involves the constraints set by the objectives which EDP management was expected to meet in their budget (Figure 4, no. 1). These constraints consisted of the need to expand staff in order to meet requests for service and the need to reduce cost. EDP made judgements on the appropriate values to be taken by these constraints, and these judgements entered into their decision strategy (and the model) to determine their approach to revising the staff budget. As indicated above, such judgements were inputs for the model and set the values of the constraints since the purposes of the research were to determine the constraints in the decision strategies and to determine the relations among these strategies. The judgements were obtained by interviews and questionnaires.

The constraint on whether there was an imperative need to expand service (no. 1) seemed to result from conflictual interaction between EDP management and the manager of market research over the scheduling of projects. Their strategies for scheduling projects are shown in Figures 2 and 3 and are described above. The constraint on whether there was an imperative

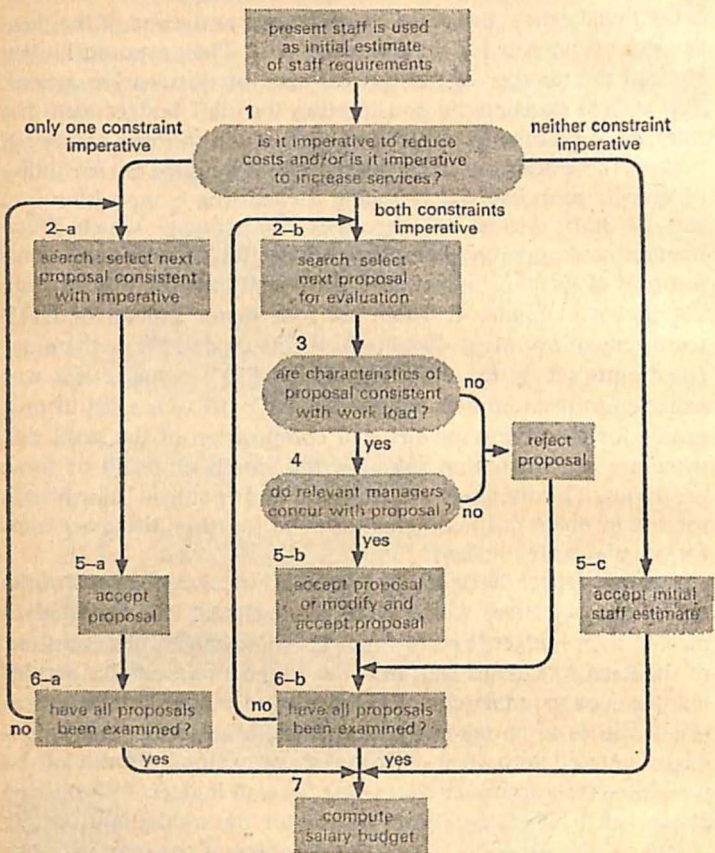


Figure 4 Model III: EDP management budgeting strategy

need to reduce cost (no. 1) seemed to result from communications with the superior of EDP management. The superior's strategy is shown in Figure 5 and is described below.

The second aspect of Model III is the list of proposals for modifying the size and composition of the staff with the accompanying search rules (Figure 4, no. 2). These proposals were received from Systems over the course of the year and were held for review

during the budget period. The proposals called for specific changes in the number of persons associated with specific grades. It is important to emphasize that the proposals were *not* designed to meet the constraints to expand service and/or reduce cost but to meet specific changes in the organization of the work. These constraints (no. 1) set the climate in which the proposals were

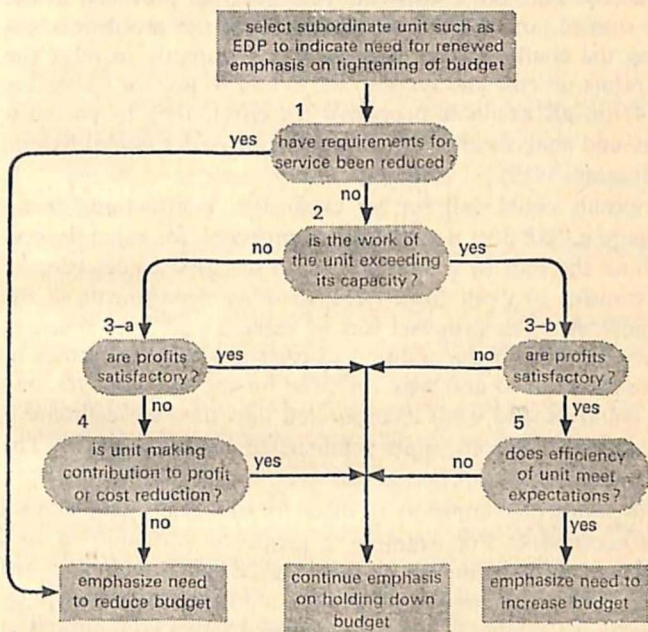


Figure 5 Model IV-a: superior of EDP management emphasis on tightening subordinates' budgets

evaluated. A proposal, for example, might be to transfer certain work from EDP to other locations and to reduce certain grades by specific amounts. Another example might be to increase the number in the higher grades by specific amounts and to reduce the number in lower grades by specific amounts because of the installation of a larger computer. The search or recall of proposals from the list of proposals was apparently straightforward. All proposals were considered if there were conflicting constraints

to expand service and to reduce cost; and only proposals consistent with these constraints were recalled for consideration if the constraints were not in conflict.

The third aspect described in Figure 4 is the set of technical and political constraints (nos. 3 and 4) used to evaluate specific proposals where the constraints (no. 1) to expand service and to reduce cost were not consistent. This situation prevailed in the years studied, and EDP management faced the problem of resolving the conflict. Their strategy was apparently to relax the constraints on cost and service (no. 1) and to test for consensus (no. 4) on all available proposals. In effect, they by-passed a means-end analysis and tested for agreement on specific changes (Lindbloom, 1959).

Proposals could call for an expansion, contraction, or no change (e.g. 'conduct a study'). One proposal, for example, was to reduce the staff by given numbers in specified grades because of a transfer of work from EDP to other departments in the company. Another proposal was to expand staff by a specified amount because of the addition of certain work. Both kinds of proposals could be and were reviewed for the same budget, and both could be and were incorporated into the staff estimate if they satisfied the constraints summarized in nos. 3 and 4. The characteristics of the proposal had to be consistent with the work load or changing complexity of the work (no. 3) for the proposal to be acceptable. For example, a proposed reduction in staff would need to be accompanied by a specific reduction in assigned work; or an upgrading of staff would need to be accompanied by new activities related to the operation of a larger computer. The relevant managers had to concur with the proposal (no. 4) for it to be acceptable. The managers whose consensus was relevant depended upon the characteristics of the proposal and could include the superiors of EDP management, managers of user departments, systems staff, salary administration staff, and organization planning staff.

The fourth aspect is about the rules for calculating the budget. The present staff is used as the initial estimate of staff requirements in making the calculations. Any proposed changes which are accepted, or modified and accepted, are used to modify the initial estimate (no. 5). For example, proposed reductions in staff



are halved under specified circumstances before being accepted. Total salaries are computed in the model by multiplying the number in a grade by the midpoint of the salary range of the grade and by summing the salaries for the grade (no. 7).

In sum, EDP management sought to propose a budget which reflected company objectives as these objectives were communicated by other participants to EDP management and were interpreted by EDP management.

#### *Model IV: Superior of EDP management*

Model IV was developed for the following types of decisions made by the superior of EDP management:

1. Whether to emphasize the tightening of subordinate units' budgets.
2. Whether to support proposals to change the size and mix of EDP staff.

These decisions relate to Model III on EDP management's strategy in proposing a staff budget. The decisions about the emphasis on tightening the budget (Model IV) are associated with the constraint in Model III on the need to reduce cost. The exact connection was seemingly the result of the judgement of EDP management on what the superior said and the context in which it was said. The decisions of the superior on supporting specific proposals (Model IV) were related to the constraint in Model III on the need for consensus among specified managers.

The major constraints contained in Model IV are shown in Figures 5 and 6. The constraints relate to the superior's judgement on the profit position of the company and on the overload and efficiency of the subordinate unit. The basis for his judgement on the profit position of the company was apparently the deliberation of the management committee.

#### *Model V: System's staff member*

The decisions included in Model V are the following:

1. Whether to make a specific proposal on the size and organization of EDP staff.
2. Whether to support proposals for which EDP management is checking for consensus.

The strategy for the first type of decision is shown in Figure 7. The strategy for the second is similar to that of the first type and is not shown. The first type of decision relates to how proposals get on the list of proposals in Model III, while the second relates to the check for consensus in the same model.

As indicated earlier, the timing of decisions by Systems to recommend changes was sporadic and was not confined to the same quarter of the year during which the budget was prepared. Systems was apparently the primary source of proposals for staff

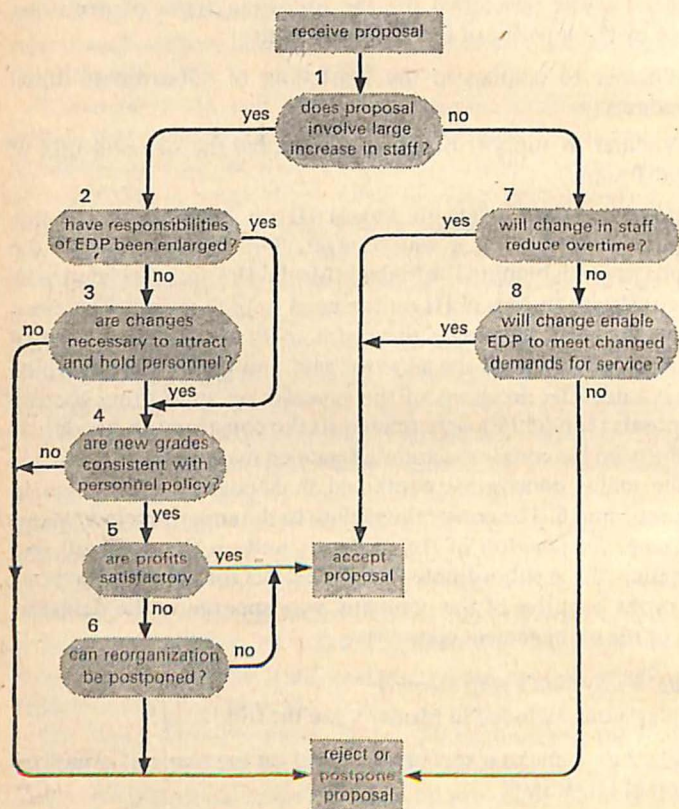


Figure 6 Model IV-b: superior of EDP management review of proposals to change EDP staff budget

changes, and it was a source that sometimes generated ideas independently of requests from EDP management.

Model V includes two occasions for which the staff member from Systems considered changes in the size or mix of EDP staff, and these are shown at the top of Figure 7. The staff member considered making recommendations either if his department felt that there was a need for such a change or if it received a request to make recommendations. Both types of occasions implied a responsiveness of Systems to the objectives of higher management. The felt need arose when System's own projects were being impeded by an inadequate organization or lack of staff in EDP. These were projects which Systems had been requested to design by higher management and to whose success Systems was committed. Requests to make recommendations came when there was a change in the mix of projects for programming and processing data.

If the staff member of Systems decided to make recommendations to EDP management, he developed a proposal for changing the organization of EDP (Figure 7, no. 3). The development of the proposal is enclosed in a broken line to indicate that this stage of the decision process is not included in the model. The proposals are treated as inputs for the model.

The major constraints for reviewing proposals are shown in Figure 7. The constraints are technical feasibility, consistency with personnel policy, and acceptability to other organizational units (nos. 1, 2, 5 and 6). Again, we can observe the same type of 'touching base' as was observed in the budget process and with the same results. In making their decisions, the participants took each others' attitudes into account. There seems to be a mutual exploration undertaken whenever it is necessary to determine how proposed changes relate to the corporate objectives.

## Simulation Results

The models were developed on the basis of information from one year and tested on the basis of information from the two previous years. Testing the models, as indicated above, involved the use of simulated decisions to predict actual decisions, and the comparison of the predicted and actual decisions.

Information for testing the models was obtained from budgets,



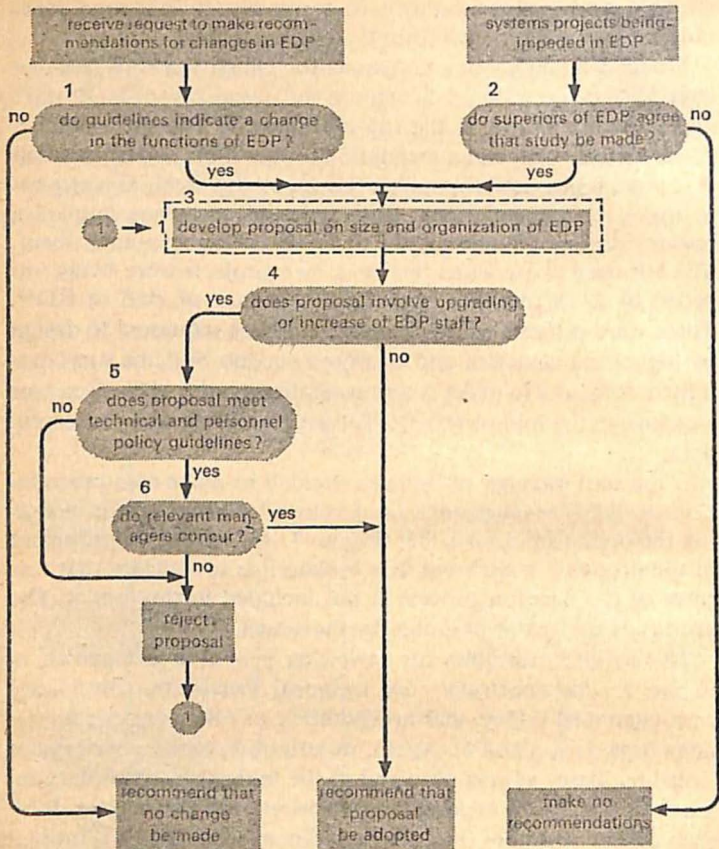


Figure 7 Model V: systems staff member proposing changes in size and organization of EDP staff

memoranda on budget guidelines, and questionnaires. Questionnaires were very heavily relied upon for testing because the greater part of the information hypothesized to be required for decision was not recorded. For example, Model II asserted that projects were accepted automatically if running time and manpower were available, but there were no records of manpower and running time. The information had to be obtained by questionnaire. Eleven different questionnaires were used to obtain the needed

information. The questions were randomly ordered to reduce influencing the responses by a 'logical' sequence. One of the questionnaires is shown in the Appendix.

The comparison of predicted and actual decisions for the two years for which the models were tested is summarized in Table 1. The table shows, for each type of decision, the number of predicted and actual decisions which were the same and the number of decisions which were not the same.

The comparison in Table 1 reveals that the predicted results were the same as the actual results for the predominate number of situations for some models and for a non-significant number of situations for other models.<sup>5</sup> I returned to the company to interview the managers in question and to examine the relevant documents for each instance in which the predicted results diverged from the actual results. An endeavor was made to reconstruct in each instance how the actual decision was made and to compare this with the simulated strategy. The differences where the divergence seems significant are examined in the remaining part of this section.

Model I predicted the actual decisions in almost every instance, except for the fourth type of decision (Table 1). In type 4 decision, the manager of market research was hypothesized to select *one* among alternative methods of processing data (e.g. enlarge his own staff) if EDP would not undertake the work. In fact, he

5. One test of the significance of the observed results is to use the normal approximation to the binomial distribution with  $\mu = \hat{p} = 0.50$  and  $\sigma_{\hat{p}} = \sqrt{\hat{p} \hat{q}/n}$  where  $\hat{p}$  is the observed proportion of the total decisions correctly chosen by the model. Using this test with a two-tail confidence interval and assuming the 0.50 level, Models I, III and V yield significant results; while Models II and IV yield non-significant results. The same results are obtained when the binomial distribution is used directly instead of the normal approximation. There are methodological questions in testing these models statistically. For example, the above test assumes that the types of decisions within a particular model are independent, but this does seem to be the case. The most serious question is how one weighs the evidence obtained from the interviews to construct the models against the sample displayed in Table 1 to test the models. The sample must be small because of the nature of the decision process. Statistical decision theory could, perhaps, be used if the interviewer were willing to attach probability statements to the hypotheses developed from the interviews. Perhaps consideration should be given to this possibility; but not in a situation as complex as the one contained in the study.

divided the work among the several alternatives in the four instances for which the predicted results differed from the actual results. In two of these four instances, he compromised with EDP management; and divided the work between EDP and another method such as contracting it out. The model assumed that at least one method was adequate for accomplishing the work, but this apparently was not correct. An interesting question is why testing for adequacy and combining methods did not occur earlier in the decision strategy. An earlier effort in this direction would have avoided extensive conflict. I submit that an earlier effort was not possible because of the participants' mutual expectation that EDP would undertake all such work. The constraints on EDP prevented them from meeting this expectation, and the conflict was necessary perhaps to make compromises among methods a legitimate solution.

Model II predicted only nine of the twelve instances correctly (Table 1). The three instances of incorrect predictions were actually situations in which the model was unable to make predictions. A hypothesis in the model was that EDP management would be certain about whether their superior supported the project and whether manpower was available during regular time. Uncertainty existed, however, in the three situations; and the model was not designed to process such inputs.

For Model III, the predicted results were the same as the actual results for a predominate number of situations (Table 1). The two discrepancies which did occur seemed to be attributable to clerical errors in the actual process. For Model IV, in contrast, the predicted and actual decisions (type 1) were the same in only two of the five instances. In one of the three incorrect predictions, the actual decision was to expand the department's budget because of an anticipated increase in work; but the model considered an overload only when it had already occurred. The model did not include *anticipated* changes because no data existed to support its inclusion during the time in which the model was being constructed. The other two incorrect predictions involved situations where the superior was uncertain about the values to be assigned to his constraints. The model was not designed to cope with this ambiguity. This divergence between predicted and actual results was similar to the one uncovered in Model II. Finally, the

**Table 1** Frequency with which Predicted and Actual Decisions were the Same and Frequency with which they were Different

| <i>Type of decision</i>                                                              | <i>Number of decisions in the two years for which models were tested</i> |                                     |              |
|--------------------------------------------------------------------------------------|--------------------------------------------------------------------------|-------------------------------------|--------------|
|                                                                                      | <i>Predicted same as actual</i>                                          | <i>Predicted not same as actual</i> | <i>Total</i> |
| <b>Model I: Manager of Market Research</b>                                           |                                                                          |                                     |              |
| 1. Decisions on undertaking proposals for analysis of information                    | 13                                                                       | 1                                   | 14           |
| 2. Decisions on requesting assistance from EDP                                       | 8                                                                        | 1                                   | 9            |
| 3. Decisions on pressing request if EDP did not agree to give assistance             | 3                                                                        | 0                                   | 3            |
| 4. Selection of alternative methods if EDP, again, rejects requests                  | 5                                                                        | 4                                   | 9            |
| 5. Decisions on requesting EDP to modify its postponement of report deadline         | 2                                                                        | 0                                   | 2            |
| Total                                                                                | 31                                                                       | 6                                   | 37           |
| <b>Model II: EDP Management</b>                                                      |                                                                          |                                     |              |
| 1. Decisions on accepting projects for scheduling                                    | 9                                                                        | 3                                   | 12           |
| Total                                                                                | 9                                                                        | 3                                   | 12           |
| <b>Model III: EDP Management</b>                                                     |                                                                          |                                     |              |
| 1. Decisions on feasibility of proposals for changing staff budgets                  | 5                                                                        | 0                                   | 5            |
| 2. Decisions on number of staff by job classes proposed in the budgets               | 24                                                                       | 2                                   | 26           |
| Total                                                                                | 29                                                                       | 2                                   | 31           |
| <b>Model IV: Superior of EDP Management</b>                                          |                                                                          |                                     |              |
| 1. Decisions about emphasis to place on the tightening of subordinate units' budgets | 2                                                                        | 3                                   | 5            |
| 2. Decisions about whether to approve proposals to increase EDP salary budgets       | 4                                                                        | 1                                   | 5            |
| Total                                                                                | 6                                                                        | 4                                   | 10           |
| <b>Model V: Systems Staff Member</b>                                                 |                                                                          |                                     |              |
| 1. Decisions on size and organization of EDP staff                                   | 6                                                                        | 1                                   | 7            |
| 2. Decisions on whether to support proposals                                         | 3                                                                        | 0                                   | 3            |
| Total                                                                                | 9                                                                        | 1                                   | 10           |

results for Model V included only one instance in which the predicted decision was not the same as the actual. In this one instance, the staff member relaxed the constraint of requiring consensus for the proposal.

### Implications

In the paper, the major constraints in the models were described, and some general relations among the models were suggested. Data for testing the models were summarized; but as pointed out above, it was not feasible to test the relations among the models.

The constraints and their interrelations which were apparently operative in the situation have implications for the behavioral theory of the firm and managerial effectiveness. These implications relate to characteristics of the constraints, the information used, and the decisions made.

#### *Characteristics of constraints*

The managers' decision strategies contain constraints which seem to have several dominant characteristics. These include the following:

1. Responsiveness by the participants to organizational goals.
2. Attention by the participants to cues from other participants.
3. Assignment of different weights to the importance of the cues.

The first characteristic is the responsiveness by the participants to statements of organizational goals. The chief executive and his management committee stated apparently whether projected profits were satisfactory, whether special emphasis should be placed upon cost reduction to obtain satisfactory profit and whether sales strategy should be changed. The changes in sales strategy involved innovation in the use of information. The new uses were technically feasible because of data processing technology. Changes in sales strategy resulted in added work for EDP; and the need to expand and reorganize the staff. It appears on the basis of the decision models that the participants accepted the statements on goals by top management as the relevant criteria for making their choices.

The participants did not directly bring to bear personal goals, contrary to my expectations. The individuals had personal values,

of course; but these values did not seem to be immediately relevant for the decisions which were studied. In other words, the participants did not appear to create values or norms for the organization, but they may have accepted the values of others 'in exchange' for career advancement and other rewards (Etzioni, 1961, pp. 3-67, and Simon, 1964).

The second characteristic is attention by the participants to cues from other participants. Responsiveness is insufficient for explaining the decision process. Why did the participants 'touch base' with each other? Why did they not know the nature of the goal statements without touching base? Various explanations can be put forward. For example, it can be argued that the participants did not want to 'rock the boat'; or it can be argued that they use this as a means to resolve conflicting goals or expectations about performance which were placed upon them by their superiors; or it can be argued that they were imitating similar behavior by their superiors.

Each of these explanations is plausible, but they relate to more fundamental phenomena. The goal statements did not appear to be operational, and the participants had to learn how a specific proposal related to profit, cost and service. As one of the participants said:

I think it is everyone's objective to reduce cost and only spend money (service) where it will pay for itself by providing tools to manage and increase profit. The problem is distinguishing between service that will result in greater profit and service that is just an increase in cost. It is too simple to say that one group wants to reduce cost and another group wants service.

The participants, as a group, did not perceive a direct way to 'calculate' the profitability of a proposal; but they perceived this to be a matter for subjective judgement. They sought to learn the meaning of the goals of the enterprise by probing the appropriateness of a concrete action or proposal. They sought to discover how the other participants interpreted goal statements. The participants attended to cues from the other participants to appraise the proposal.

'Touching base' is a way of learning the operational meaning of the goal statements. It is a way of transforming non-operational goals into operational goals.

Presumably, the participants would cease to be attentive after a while if the proposals were repetitive. The proposals were not repetitive for the most part, however, because they arose out of the newly introduced sales strategy.

The third characteristic is the assignment of different weights to the importance of cues from different sources. Greater weight seems to be given to cues within divisions of the company than between them and to be given to cues from superiors than from lateral participants. These different weights appear in the decision models in several ways. A negative attitude by certain participants would lead to dropping a proposal, while a negative attitude by others would only lead to its modification. In some stages of the decision process, choices were made without consulting all of the participants. Finally, the requirement for consensus gave veto power to participants within an organizational unit since they were not the ones initiating the change.

Two explanations seem plausible for the different weights, and evidence existed for both. The authority structure provided a reason for assigning greater weight to cues from within the organizational division than to those from other divisions. The superior seemed to have extensive influence over the career advancement of subordinates, and one would expect that cues from the superior would be attended to very closely under this circumstance. Also cues from others reporting to a common superior would be attended to since these persons are more likely to be cognizant of the attitudes of the common superior than those outside the division.

The frequency of communication is another explanation for the greater weight given to some cues. One may expect to find more occasions for communicating with other participants within an organizational unit than with those in another organizational unit. Indeed, there appeared to be no ongoing mechanism for communicating between divisions except at the top level of the hierarchy. Communication between participants in different divisions at the lower levels of the hierarchy appeared to be sporadic and to be evoked by disagreements over the scheduling of projects.

The models are, of course, a simplification of the situation and are perhaps an oversimplification, and the data were limited for

testing them. The information or cues received by participants is assumed to be known with certainty in the models; but, in reality, a participant may not be able to judge the position of another participant with certainty. The models also assume that the participants would have the required information. Sometimes, the assumptions did not correspond to the situation, and some of the failures to simulate the situation seemed to result from this lack of correspondence. My impression is that the constraints were ignored usually when the information or cues were not available, and the choice would be made on the available information. However, the lack of information or cues was not always ignored, and then its lack seemed to result in a decision not to act or to take a negative action.

### *Characteristics of information and decisions*

The decisions seem to have two general characteristics. One is whether they involve disagreement or agreement. Disagreement can arise during the scheduling of projects or whenever one of the participants seeks consensus on a proposal.

The second characteristic is the relation of the decisions to the growth of EDP staff. For example, market research may press to have EDP undertake additional work, and the senior staff member in Systems may approve proposals involving the expansion of EDP staff.

On the information side, two characteristics also seem to be pervasive: profit and innovation. Whether profit is satisfactory characterizes the information required by many of the constraints either directly or indirectly. The participants either directly interpreted the statements of the chief executive and his management committee or looked for support and agreement from those who made such interpretations.

The proposals to process data are items of information which obviously are essential for the strategies of the participants, and these proposals can be characterized by the company's commitments to innovation. The stimulus for those proposals was apparently a commitment of the chief executive and his management committee to a new sales strategy. This sales strategy involved innovation in the use of information technology. Their previous sales strategy used information which resulted from the



routinized processing of standardized data. The new sales strategy used additional kinds of information. The additional information, itself, was not specified; but only the general purposes of the information were specified. It was the responsibility of the management to innovate informational projects. Although innovation in the use of information was associated with sales strategy, it could be associated with any decision strategy, such as production scheduling, capital budgeting, and so forth. The essential notion is a commitment to innovation in the use of information.

Implications on the relations among the characteristics of the information and decisions are summarized in Table 2. If the combination occurs which is represented in the upper entry of the central column of Table 2,<sup>6</sup> this combination is unsatisfactory

*Table 2*

|                                                  | Unsatisfactory profit                        | Satisfactory profit                |
|--------------------------------------------------|----------------------------------------------|------------------------------------|
| No innovation made of information technology     | Agreement<br>Static or decline in staff      | Agreement<br>Static staff          |
|                                                  | Conflict                                     | Agreement                          |
| Innovation in use made of information technology | Small upward adjustment and growth postponed | Growth reflects rate of innovation |

profit and no innovation. The models would suggest that there would be no requests from market research to EDP for the undertaking of data processing projects since such projects would not facilitate company sales strategy. No alternatives to increase the size of EDP would be proposed since there would be no felt need by Systems or the superior of EDP management for the expansion of EDP. Proposals would be made to decrease the staff of EDP if the existing functions were making no tangible contribution to profit (as perceived by the superior of EDP management) or if there were a decrease in the functions of EDP (as perceived by Systems). In the budget process, there would be a demand to cut

6. This assumption is not intended to suggest that profit and innovation in sales are independent of each other but that they can characterize a situation separately or together.

cost if EDP were making no tangible contribution to profit (as perceived by superior of EDP management). In this situation, any proposal by Systems to reduce staff would be accepted. If the superior of EDP management perceived that the department were making a tangible contribution to profit, there would be neither an imperative to reduce cost nor expand service; and the current budget would be maintained. At no point in the decision process would there be disagreement among the participants, and the staff would remain the same or decline.

The combination of satisfactory profits and no innovation is represented in the top right entry of Table 2. The lack of commitment to innovation would again result in no requests by market research for new data processing projects to be undertaken by EDP; and there would be no demand for the increased use of EDP services. No proposals to change the size of EDP staff would be proposed by Systems since neither the superior of EDP management nor Systems would be prompted to look into the efficiency of EDP and since the work activities of EDP would not be increasing. Under these conditions, there would be no imperative to reduce costs or to expand service; and the current budget would be proposed for next year. Accordingly, there would be no disagreement among the participants and the size of the staff would not change.

Innovation and unsatisfactory profits are represented in the lower center of Table 2. Under these conditions, Market Research would propose that new data processing projects be undertaken by EDP. EDP management would schedule these projects until they reached their budget constraints. After the budget limit was reached, EDP management would continue to schedule projects, which they perceived as achieving the objectives of top management, until the limits of their capacity were reached. Otherwise they would refuse. Since project proposals were received from lateral units, there was no automatic connection established between the proposals and the objectives of top management. The need to learn the operational meaning of these objectives by trial and error would mean that some projects would be refused that met these objectives. These projects would then be referred to the superior of EDP management by Market Research in an endeavor to have the projects scheduled. These

projects would be scheduled if it became apparent in discussions with the superior of EDP management that they met the objectives of the chief executive and his management committee. Accordingly, there would be disagreement over the scheduling of projects and delay in the expansion of the work of EDP.

This expansion, however, would eventually occur and would bring about a need to expand EDP staff. The increasing EDP work load would bring about the realization by Systems that there was a need to expand and/or upgrade EDP. Systems, however, would be slow to make proposals to EDP management because their superior would delay approval of any proposals because of the unsatisfactory profit. In constructing its budget, EDP management would be faced with inconsistency between the constraints of expanding service and reducing costs. They would relax these constraints and search for consensus on all existing proposals to change the size of the staff. There would be approval for small upward adjustments, but the superior of EDP management would postpone approval of any major changes. Accordingly, there would be disagreement throughout the decision process and only small upward adjustments would be allowed.

Innovation and satisfactory profits are represented in the lower left of Table 2. Under these conditions, Market Research would make proposals for data processing projects to EDP. These projects would be scheduled by EDP management until EDP's capacity was reached. The expansion of EDP work would result in the proposals to expand EDP staff. Systems would be able to make these proposals without delay. They would touch base and obtain approval quickly because profits were satisfactory. In the budget process, the constraint on the performance of EDP management would be to expand service. Accordingly, all legitimate proposals involving an increase and/or upgrading in the staff would be incorporated into the proposed budget. Throughout the decision process there would be no disagreement among the participants on the need to schedule projects or on the expansion of the staff. The growth of the staff would reflect the amount of data processing requested by Market Research.

In sum, major growth is inferred from the decision strategies only when innovation occurs and profits are satisfactory. The

size of the staff is static or increases at a very small rate, it is argued, although profits are satisfactory if no innovation occurs. This is contrary to the traditional empire building hypothesis. The explanation for the lack of empire building may be in the manner in which slack is conserved. In the behavioral theory of the firm, it is purported that organizational units build up slack when profits are satisfactory. A major reason for doing this is the need to meet contingencies that could hamper the manager's responsiveness to organizational goals. The slack-building hypothesis leaves the question unsettled on *the form* in which slack is conserved. The manager can be more effective, perhaps, if he chooses a form that allows flexibility in its use (e.g. 'overtime'). This flexibility implies that the funds are relatively uncommitted, and this reduces the manager's ability to defend his slack against 'budget officers', etc. The manager may respond by making a relatively permanent commitment of his slack, and adding to the staff is a form of conserving slack which is relatively permanent. Accordingly, empire building may be a response to inappropriate budget procedures which were apparently absent with respect to the participants of the study. In support of this observation, it was noted in the study that funds were budgeted in forms which left them uncommitted.

## Appendix

### *A Sample Questionnaire for Model II*

1. Briefly describe project.
2. Was this one of the following:  
regularly scheduled project  
newly proposed repetitive project  
project for reprogramming to new equipment  
special request?
3. Did you have occasion to reconsider project?

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|                                                                                                                                            | Yes | No | Uncertain<br>or not<br>relevant |
|--------------------------------------------------------------------------------------------------------------------------------------------|-----|----|---------------------------------|
| 1. Was project scheduled to meet completion date requested by sponsor?                                                                     |     |    |                                 |
| 2. Did sponsor of project believe that imperative to do project?                                                                           |     |    |                                 |
| 3. Did sponsor of project request that project be discontinued?                                                                            |     |    |                                 |
| 4. Was manpower (key punchers, operators, programmers) available during regular time?                                                      |     |    |                                 |
| 5. Could sufficient manpower and running time for this project be obtained by delaying currently scheduled programming for other projects? |     |    |                                 |
| 6. Was overtime within budget constraints if needed to schedule project?                                                                   |     |    |                                 |
| 7. Was project scheduled to be done at date later than completion date requested by sponsor?                                               |     |    |                                 |
| 8. Did you discontinue project?                                                                                                            |     |    |                                 |
| 9. Was running time available on equipment?                                                                                                |     |    |                                 |
| 10. Did you delay currently scheduled programming for other projects and schedule this project?                                            |     |    |                                 |
| 11. Was overtime sufficient to provide the needed running time and manpower?                                                               |     |    |                                 |
| 12. Did you request project be postponed or redesigned?                                                                                    |     |    |                                 |
| 13. Were project requirements small for manpower and running time on equipment?                                                            |     |    |                                 |
| 14. Did superior believe that imperative to do project?                                                                                    |     |    |                                 |

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### Information Processing Model of Executive Decision

J. A. Howard and W. M. Morgenroth, 'Information processing model of executive decision', *Management Science*, vol. 14, no. 7, March 1968, pp. 416-28.

#### Introduction

Anyone attempting to construct a company information system quickly discovers that little is known about the precise nature of the executive decision process in spite of the plethora of management literature. Without the help of some general principles of the executive decision process the information technician – management scientist, market researcher, operations researcher, etc. – is seriously handicapped in determining the company's information requirements. It is not difficult when formal optimizing models can be used, but in many instances, perhaps even most, the information technician will find it necessary to work in terms of a much less general description of the decision process for which he is developing the information requirements. Further, we believe that largely to the extent he fully articulates his view (constructs a model) of this decision process he will be effective in carrying out his task. Hence the type of model set forth here can be extremely useful to the large number of people who are now attempting to provide optimum information to executives.

Communicating with the executive in the attempt to specify his information requirements is a much more difficult assignment than is usually expected as every information technician quickly finds.

Much current discussion of designing information systems reveals a naïve view of the difficulty of eliciting executive decision rules. It is our belief that serious mistakes are now being made in a too ready acceptance of the executive's statement about how he makes his decisions and what information he requires. One need only recall the many footless scholarly debates that have ensued

in economics about empirical pricing decision rules to disabuse his mind of this naïveté.

Isolating the information required is complicated by the executive's view of the matter which usually reflects two contradictory attitudes. Since decision making has become second nature to him and he does it with such ease, to him the act cannot be very significant, and he is a little surprised that anyone should be interested in knowing about it. On the other hand, he is quite sure that no amount of analysis will be able to reproduce it. His phrase is, 'It is intuitive!' with the implication that it is innately unknowable, with the further implication that it is fruitless to attempt to specify the information he uses. Hence, he is typically not a very lucid source for a statement of the information that he must have to carry out his decision-making activities.

Information processing models provide a way to identify these information requirements. An essential characteristic of the models is that they specify the information used by the decision maker and what he does with it in order to arrive at a decision. The term 'information processing model'<sup>1</sup> is applied both to systems of artificial intelligence and to the description of human decisions: We are concerned only with the latter here.

In the few instances where these models have been constructed, the results display a surprising degree of simplicity, a simplicity imposed by the limitations of man's intellectual capacity. It is sometimes asserted that the executive's inability to make extensive calculations is solved by utilizing the high-speed computer, but this solution merely gives rise to still another problem which is to determine the optimum relation between the man and the machine (computer) in making the decision. It seems clear that to obtain this optimum man-machine relation and to meet the non-computational requirements of the decision such as the search for alternative courses of action and the sociological or organizational influences, a deeper understanding of human behavior in an organizational setting has become essential. It is our belief that the model presented here contributes to that understanding partly because it focuses on the organizational factors that underlie high-level decisions. Further, models of this nature for the same

1. For a discussion of the nature of information processing models and how they apply to human thought processes, see Reitman (1965).



levels in different organizations whose products compete in the same market might be compared for insights into differing strategies. Finally, models similar to this for adjacent levels of the same organization might be 'hooked' together to simulate the organization's decision processes on a computer, and the aggregate process could then be tested for its consistency with relevant company objectives.

The background of the study will first be presented, followed by an exposition of the model and its terminology. The next stage is a careful discussion of how the model was validated ending with a summary of the conclusions of its significance and implications.

### **Background**

Here we describe the setting of and procedure used in simulating a pricing decision in a typical market: a few large producers along with a number of small ones, all selling a slightly differentiated product. The research was begun in 1959 and extended over a three-year period of observation, interviewing and analysis in one company which must remain anonymous because of the sensitive nature of the data. The company is listed among the fifty largest manufacturing firms in the United States as measured by volume of sales. The product is one where the prices are frequently changed and are constantly visible enough to permit the documentation of the pattern of prices at any time. Further, execution of the decision follows the decision so quickly in this case that it is easier to infer causality. These factors all combined to facilitate the model building process.

A number of sources of information were used. Interviews with the decision maker came first. He attempted to identify the variables and to explain how they were manipulated. From the interview data the researchers constructed flow charts to describe the process. The flow chart was found to be a splendid vehicle for communicating to the executive how the interviewer interpreted his statements and what inferences had been made from these interpretations. The chart was also valuable in the analysis of the relevant communication networks in the organization.

Second, the executive was observed in the process of making decisions. This provided a check, for example, on whether the

data that he allegedly used were actually available and on how they were transmitted and processed in the organization's communication system.

Third, records of past decisions and their supporting data were analysed and the resulting conclusions were reviewed with the executive. Because of anti-trust problems more detailed records of past decisions are maintained in the company than is probably true in most firms.

Fourth, the flow chart was tested against the recorded behavior of the decision maker and against the verbal statements of other executives at the same level, but in different regions of the country.

## **Model**

Here we deal with the scope, structure, function and rationale of the model. The scope of the model provides some evidence of its importance as a description of decision activity. The executive estimated that the model incorporates about 95 per cent of the company's pricing decisions. The model's output of price decisions includes all prices affecting less than a whole state. Price decisions involving a whole state or more are made at the executive committee level.

The reference marketer's pricing actions play an important role in the structure of the model. 'Reference marketer' is the label generally applied to the firm which has the largest share in that state. Although having the largest market share may have resulted from initial capture of and subsequent leadership in the market, a reference marketer may no longer be accepted by the other large firms as major initiator of price changes if it fails to interpret market conditions correctly. The reference marketer's price activity is watched by the other firms. This tendency for Company X to look primarily to the reference marketer for a stimulus to contemplate a price change as shown in the graphic description of the structure of the model in Figure 1 arises partly because the industry is made up of two distinct segments: a few large firms ('majors') and several quite small firms ('private branders'). As will be explained later, the nature of the pricing behavior differs sharply between these two segments. In addition, Company X initially contemplates the price behavior of the reference competitor, but, it as well as other large competitors,

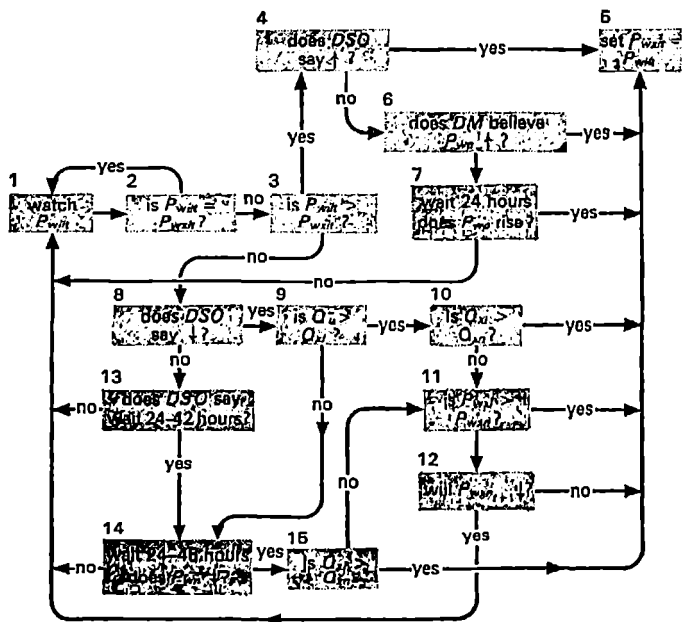


Figure 1 Model of pricing decision process

### Symbols

- $P$  = price
- $w$  = wholesale
- $i$  = initiator
- $l$  = local market
- $n$  = near-by market
- $t$  = time
- $DSO$  = district sales office
- $DM$  = decision maker
- $x$  = decision-maker's company
- $o$  = other major competitors (neither  $i$  nor  $x$ )
- $Q$  = expected physical volume of sales

acts with differing degrees of independence at different times. Company X quickly follows a price decrease by the reference marketer, but it follows his price increase more slowly.

For subsequent testing considerations it is important to distinguish between the structure and function of the model. The

structure of the model is a *set of rules* governing what actions are to be taken and as a consequence of the input of *certain pieces of information*. Obviously not all the objectively available information is used, which raises fascinating questions on the motivation underlying the decision to use certain pieces of information, and not others. These questions relate to problems of search: the search for alternative courses of action, the search for information about goals, and the search for information on the consequences of given actions for these different goals.

This structure has a *function* which is to generate the output of the process. The output is the decision which has a number of dimensions such as amount of price change, direction of change, and latency, the length of time that elapses between the triggering of the decision process and the actual decision.

The descriptive decision model derived from the research is shown in flow chart form in Figure 1 with price as its output. It depicts a sequential binary choice process. The cue or triggering element of the process is Box 1 in the upper left-hand corner of Figure 1, labeled 'Watch  $P_{wit}$ ', which means, 'Watch the wholesale ( $w$ ) price ( $P$ ), of the initiator ( $i$ ) in each local ( $l$ ) market at each point in time ( $t$ ).'

For administrative convenience the management of the firm divides the United States into geographic areas labeled regions, territories and zones, roughly aligned with population concentrations and structured by such criteria as natural geographic boundaries, roads and buying patterns. The zone is the smallest of the three units and is often termed 'local market'. Pricing activity is largely in terms of this local market unit, and the decision maker focuses his attention upon it.

The direction of the price change, whether upwards or downwards, makes a great difference in the decision process. Figure 1 quickly reveals that upward price moves are much simpler than downward price moves. When Box 3 differentiates between the wholesale price of the initiator and that of Company X, it separates the model into two price directions: upward and downward. The upward move comprises only three steps, evidenced by Boxes, 4, 6 and 7, before a decision is reached. The downward move may require up to 8 steps, as shown by Boxes 8 through 15.

This asymmetrical characteristic of the decision process serves

to introduce the rationale for the structure. This asymmetry can be explained by the nature of the decision environment and by the executive's motivation: if all competitors follow, the nature of the market is such that it is always profitable to raise prices, since purchases of the generic product are relatively unaffected by price changes. In economic terminology, the market demand is highly inelastic in the short-term. If the executive's motivating criterion is profit, he will always desire a higher price if he does not lose market share in attempting to attain the higher price.

Profit, however, is only one of the organization's goals. Different levels of the organization have different goals. An interesting point is the nature of the goals at the next lower level, the District Sales Office which appears as '*DSO*' in Boxes 4, 8 and 13. In order to motivate properly the activities of the next lower level, the decision maker strives to make decisions that are approved by that lower level (*DSO*). Much more important, however, is that the goals at the *DSO* and lower levels are biased against a price increase because the organizational incentive system is structured at these levels to favor volume of sales instead of profit. This point of view exists, because to the extent that competitors do not also decrease *their* prices, a price decrease is a way of increasing sales volume. Hence, if the lower level agrees to a price increase (Box 4), the higher level with its profit goal, 'jumps at the opportunity' to raise the price. Where the lower level consistently fails to report competitive price increases in the field because of the conflict of goals, the executive can place his staff in the field to report directly to him and in this way temporarily correct the deficiency in his communication system.

When Company X is responding to the initiator's *decreased* price, the greater complexity of the decision process is a result of two elements. The first element is the relative strength of Company X versus that of the initiator as indicated by market share. If X's share of market is less, X is more inclined to follow in the price decline than to maintain his current price. Second, a distinction is made between the local market and the near-by market, the latter being the most significant adjacent market. The near-by market becomes relevant because a price decline in the local market may spread to the near-by market causing the prices of competitors there to decline. Like fighting a forest fire, efforts are

directed towards 'containing' the price decline. This tendency for a price decline in one market to drag down the prices in contiguous markets is called a 'funnel' effect. The possibility of this dependent relation between the local and near-by market is a deterrent to price reduction in the local market. Hence, on a price decline, the influence of the lower level's bias in favor of price cutting is offset by (a) the complicating elements of intercompetitor differences in market share and (b) the distinction between local and near-by markets.

So far we have referred to only one dimension of the model's output, the direction of price change, but the distinction between decisions to increase price and those to decrease price introduces the latency dimension. The decision is made more rapidly on the upward movements in the sense that unless the others increase within twenty-four hours, X decides to do nothing, but when the decision involves a price decrease, X will delay as long as forty-eight hours before deciding to do nothing. The supporting evidence for this conclusion is from the thirty-one decisions shown in Table 1.

Company X's behavior differs, however, according to which competitor initiates the move. With respect to the reference marketer's nine upward moves, X's mean lag is three days and the median and modal lags are two days. For the reference marketer's eight downward moves, the mean lag is one day, the modal lag is either zero days or one day, and the median lag is one day. In short, Company X delays more in following the reference marketer up, than in following it down possibly indicating an attempt to steal the reference marketer's market, an attempt to avoid the loss of market share to a lagging competitor, or indicating goal conflicts between the reporting district, whose goal is mainly market volume, and division headquarters, whose goals include profit. Downward the lag is less, implying haste to avoid loss of market share, and loss of profit. On one downward decision<sup>2</sup> where the lag was four days, all the delay was in the district office.

The other majors originated ten moves: one up and nine down. These facts suggest lack of optimism on the other majors' part in initiating upward moves that others will follow. The solitary

2. See no. 20, Table 1.

successful upward move was made simultaneously by four majors including Company X. On the downward moves the range in latency exhibited by X is impressive: zero to nineteen days. Over

**Table 1** A Comparison of the Observed and Predicted Outcomes of Thirty-One Decisions

| Decisions | Box 3 | Box 4 | Box 6 | Box 7 | Box 8 | Box 9 | Box 10 | Additional elements of decision    | Box PD | OD |
|-----------|-------|-------|-------|-------|-------|-------|--------|------------------------------------|--------|----|
| 1         | y     | y     |       |       |       |       |        |                                    | 5      | u  |
| 2         | y     | n     | y     |       |       |       |        |                                    | 5      | u  |
| 3         | y     | n     | y     |       |       |       |        |                                    | 5      | u  |
| 4         | n     |       |       |       | n     |       |        | (13-y) (14-y) (15-y)*              | 5      | d  |
| 5         | y     | n     | y     |       |       |       |        |                                    | 5      | u  |
| 6         | y     | n     | y     |       |       |       |        |                                    | 5      | u  |
| 7         | y     | y     |       |       |       |       |        |                                    | 5      | u  |
| 8         | n     |       |       |       | y     | y     | y      |                                    | 5      | d  |
| 9         | n     |       |       |       | n     |       |        | (13-y) (14-y) (15-n) (11-y)        | 5      | d  |
| 10        | n     |       |       |       | n     |       |        | (13-y) (14-y) (15-n) (11-y)        | 5      | d  |
| 11        | y     | n     | y     |       |       |       |        |                                    | 5      | u  |
| 12        | y     | n     | n     | y     |       |       |        |                                    | 5      | u  |
| 13        | n     |       |       |       | y     | y     | y      |                                    | 5      | d  |
| 14        | n     |       |       |       | n     |       |        | (13-y) (14-y) (15-y)               | 5      | d  |
| 15        | n     |       |       |       | y     | y     | y      |                                    | 5      | d  |
| 16        | n     |       |       |       | n     |       |        | (13-y) (14-y) (15-y)               | 5      | d  |
| 17        | n     |       |       |       | y     | y     | y      |                                    | 5      | d  |
| 18        | y     | n     | n     | y     |       |       |        |                                    | 5      | u  |
| 19        | n     |       |       |       | n     |       |        | (13-y) (14-y) (15-n) (11-n) (12-y) | 1      | =  |
| 20        | n     |       |       |       | n     |       |        | (13-y) (14-y) (15-y)               | 5      | d  |
| 21        | y     | n     | y     |       |       |       |        |                                    | 5      | u  |
| 22        | y     |       |       |       | n     |       |        | (13-y) (14-y) (15-y)               | 5      | d  |
| 23        | n     |       |       |       | y     | y     | y      |                                    | 5      | d  |
| 24        | y     | y     |       |       |       |       |        |                                    | 5      | u  |
| 25        | y     | n     | n     | y     |       |       |        |                                    | 5      | u  |
| 26        | n     |       |       |       | y     | y     | y      |                                    | 5      | d  |
| 27        | y     | y     |       |       |       |       |        |                                    | 5      | u  |
| 28        | n     |       |       |       | y     | y     | y      |                                    | 5      | d  |
| 29        | n     |       |       |       | y     | y     | y      |                                    | 5      | d  |
| 30        | n     |       |       |       | y     | y     | y      |                                    | 5      | d  |
| 31        | y     | y     |       |       |       |       |        |                                    | 5      | u  |

On decision 19 no price change occurred because of danger of 'funnel' effect

PD — Predicted decision

OD — Observed decision

y — yes

n — no

d — down

u — up

= — no change

\* — numbers in parentheses refer to flowchart boxes

half the delay in the nineteen-day lag occurred in the district office. Apparently the remaining majors were reluctant to follow down.

When the private branders led with their one downward<sup>3</sup> move,

3. See no. 19, Table 1.

X and other majors were unwilling to follow. In the case of the three upward moves by the private branders, X's lag averaged four days. How much of this delay was caused by the desire of the majors to discourage the private branders from cutting price in the future is not known.

A number of summary conclusions can be made. Although Company X's decision process is primarily that of a follower, and the leader's move is normally duplicated, price differences do exist between the leader and X, and these reflect the importance of organizational factors as they conflict with market factors in pricing. For example, time-lags in downward price moves as compared to upward moves are caused by the conflict of different goals in the decision maker's goal hierarchy. The lack of symmetry of the model shows the relative greater complexity of the downward move compared to the upward move. Even though more complex, the downward move occurs more rapidly than the upward move when the reference competitor initiates the move, but this is not so when some other major company initiates the downward move. Company X will follow the private brander's up independently of the moves of other majors, but it will not so follow a private brander down.

### Testing the Model

Only when the model of the executive's decision process has been tested does it deserve the label 'scientific'. In this section the two test criteria are described, the procedure for applying each criterion is explained, some of the limitations of the procedure are set forth, and the results of both tests are summarized.

The research was carried out under field conditions and involved the observation of a single subject, both of which make the testing more difficult. Also, there are two features of the model to be tested: the structure (process) and the output (decision) of the structure. Traditionally we have tested only the output of a theory; how well the model's output predicts the executive's terminal behavior is taken as the measure of the adequacy of the theory. The rules (structure) implied in Figure 1, however, also represent behavior, both overt and ideational. For example, in Box 4 overt behavior is implied in contacting the District Sales Office for its advice about which action should be taken.



Ideational behavior is implied in each of the boxes where the decision maker must make a judgement. Hence, even though the model appeared to predict the output correctly, the process (the rules and their sequence) could differ from that used by the executive in arriving at the decision.

### *Testing the output*

To test the accuracy of the model's output, a systematic, random sample of every tenth decision was taken from the files of the division of the company managed by the executive whose behavior was observed in deriving the model. The files containing the pricing decisions made over a six-year period were arranged in chronological order with the date on which the decision was triggered serving as the specific ordering criterion. This sample yielded the data of thirty-one decisions shown in Table 1 which were used to test the model systematically. In addition, 130 other decisions from three separate geographic divisions were used to test the model in a more casual way, which will be described subsequently.

The output test is presented in the last two columns of Table 1, in which PD refers to predicted decision, and OD, to observed decision. The thirty-one decisions were inserted as the inputs and each consequent output is compared with the observed decision. The predicted decision concerns only the price: whether it be changed to duplicate the leader's change or remain unchanged. No prediction is made of the amount of change nor the length of delay. The amount of change, because of tax reasons and custom, is always in standard units and almost always in terms of one unit at a time. The prediction of the amount would have contributed little. To predict the length of delay would probably have required the inclusion in the model of a much wider range of variables.

Each item in the predicted column (PD) in Table 1 is taken either from the Box 5 column (those cases in which Company X followed) or the Box 1 column (those cases in which Company X did not follow). Perfect agreement exists between the predicted and observed outputs as indicated in Table 1. Hence, the hypothesis that the model represents the executive's decision process is confirmed by the output test.

*Testing the process*

If the model also describes the *process* used by the executive in coming to his decision, as well as describing his terminal behavior, our belief would be strengthened that the executive's behavior has been adequately explained. The reader will recall that the process is described by the model's structure.

Turing's test (Simon and Newell, 1959) has been suggested for testing the information-processing types of model. A rigorous application of Turing's test to the pricing decision would require comparing the protocols of the executive with the structure of a model that was inferred from some data other than the protocol. A protocol is the executive's description of the thinking process that he is going through in making the decision *as he makes the decision*, instead of a *post hoc* reconstruction. The protocol method of collecting data on ideational behavior has been called 'the thinking aloud technique'. To the extent that these presumably independent descriptions of the process (the model and the protocols) are indistinguishable, the model is an accurate description of the decision pricer's process.

Some aspects of the interviews taken in the study closely resembled protocols. The interviews were at first conducted in terms of questions: 'How do you set prices?' As the research progressed, however, the procedure came to be more and more of the thinking-aloud technique, and specific decisions became the focal point of the interview as a means of illustrating the way in which the executive made the decision under certain specified conditions. Partially in this way, the general rules making up the process were elicited.

It is difficult to keep the protocols and model as distinctly separate in their origin as Turing's test implies. At a minimum, for example, discussion with the executive is essential to merely setting the limits on the general nature of the problem. From this point to extracting protocols is a matter of degree. Also, protocols may omit important details of the process. When the executive was asked to articulate the process, for example, he passed over a number of important rules that he was in fact using, and only when he was shown that logically he must be going through these additional steps, did he become aware of this fact.

The procedure used here was to construct the structure of the

model as shown in Figure 1 by inferring it from the interviews and then to test it against company records of the actual decisions. This method was facilitated because detailed data were recorded in Company X at the time of each decision and carefully filed.

These records contained much of the data specified by the model, such as the specific price set by the decision, the reference marketer's price activities, and data used as background, such as retail prices and the initial moves of the other majors and the private branders. Some data required in the model, however, were not in the records, such as market shares of the majors, location and price position of near-by markets, recommendations of the DSO's, and other elements of the telephone conversations of the DSO with the decision maker. These were obtained from the decision maker's memory.

When the data specified by the model are fed through the model box-by-box as shown in Figure 1, there is perfect agreement, which the reader can verify for himself by taking the information from the first ten columns of Table 1 and applying it to Figure 1. Hence, the model is further validated, this time by the process test.

### *Inter-divisional comparison*

Still another validating step was carried out in which the model was reviewed by the executives in three other regional divisions of the company. 130 decisions were selected at random from the files of these three different geographic regions. This more casual method of testing had two phases. In the first phase the executives were asked to check the accuracy of the elements of the model including their order. Each of the three regional decision makers agreed that the model portrayed the process. In the second phase the interviewer used the model while the decision maker sat facing him with records taken randomly from the files. The interviewer asked the questions implicit in the model, and based upon the records and his memory the executive answered these questions. From the answers the interviewer predicted the price decision. Then, he compared the predicted price decision with the output recorded in the files, and finally, he checked the records for any data not represented in the model. In each of the 130 decisions the prediction was accurate. The executives expressed surprise

that their mental processes could be so accurately and simply portrayed.

The purpose of this additional step was mainly to determine whether different decision makers in the same company developed different decision processes to carry out their task of setting prices. This conclusion is particularly interesting because no effort at all, such as published standard operating procedures or training courses, had been offered by the company to insure uniformity among the decision makers in the different geographic divisions. A tentative conclusion, then, is that similar decision environments will produce essentially the same decision processes.

### *Summary and significance of test results*

Both the output test and the process test show perfect agreement between the model and the data. This conformity between theory and fact indicates that the model is a good description of reality.

The general significance of the test results is that they show it is possible to describe accurately an important, complex executive decision with a relatively simple non-optimizing model that in light of the organizational constraints upon decision probably represents fairly rational behavior. The fact that the model was constructed and in such simple form gives encouragement to the information technician that he can identify the current informational requirements of the executive, but that to do so is by no means an easy task.

Aside from testing, two other aspects of the research should be mentioned. First, throughout the discussion the 'decision maker' has been referred to, but, in fact, he was two people: the chief executive for the geographic division and his price analyst. During the period of the study the analyst's position was a new position. He was more and more taking over the responsibility for pricing from the executive who had been doing it for many years. In addition, the analyst maintained the great amount of records required by the task. It was, however, an unusually close working relationship. The model was first inferred from interviews with the executive and then it was compared with the procedure elicited from the analyst. Neither at this time nor at any time during the research were there discrepancies between the executive's and the analyst's behavior.

Second, the point was made earlier that the executive articulated some of the steps in the decision process only when shown that logic demanded them. This suggests the obvious danger that the research process itself was an influence upon behavior; however, the model is validated by both tests, the output and the process test. That he was not aware of all the details of his behavior is not surprising. Under normal circumstances there was no need for him to articulate the process because it was never communicated to anyone except the price analyst, and here communication was carried on over a long period on an intimate, face-to-face relation. Under these conditions errors in articulating the process to the interviewers could be expected.

### Conclusions

This research provides additional evidence that it is possible to describe the decision process of a high level corporate executive making an important repetitive decision. The importance of the decision process is indicated by the magnitude of the price change, typically, 5 per cent or more with serious profit consequences, the amount of the actual time consumed in making a decision, and the number of decisions made annually. The assertion that the research offers evidence of our ability to describe such a decision process accurately is made with the same type of support that is accepted throughout science: the hypothesis was tested and confirmed. The simple model of the process is also plausible: the executive does not always follow it, and whether he does or not, the decision is made on the basis of objective evidence.

A number of these studies can give us an understanding of the nature of complex behavior on which traditional research techniques in the main have faltered. The extent to which the findings can be generalized is open to question. The model, however, was tested against the behavior of executives of the same company in four different geographic divisions, although in only one was the analysis highly systematic. The probable error of a sample of four is high. It can also be argued, for example, that this decision, being highly repetitive, was atypical of the total activity of high level executives, but one who has done this type of research is impressed by the fact that when he first approaches the executive

he is told how impossible it is to describe the decision process which is so terribly complex and intuitive. The experience persuades us that this sequential, binary choice process may describe a very wide range of the executive's activity. Two other studies (Cyert and March, 1963; Marschner, 1964), one of department store buying and another of the decision to allocate advertising funds to advertising media, support this view; still another study (Clarkson, 1962) indicates that it is possible to describe similarly a more complex decision process, one in which the rules were modified depending upon the decision maker's estimates of the future state of the environment.

Our study also suggests how it may be possible with this type of research to explicate the mechanisms by which decision makers generalize the behavior they have developed from one situation to new situations and from one type of decision to another.

In addition to the relevance of the model to an understanding of decision behavior generally, it has the obvious implication for company information systems of specifying an executive's information requirements. The simplicity of the model is encouraging to information technicians – management scientists, market researchers, operations researchers, systems people, etc. – faced with the task of specifying the executive's information requirements so that an adequate information system can be designed. It also offers a *general procedure* that the information technician can use in eliciting these information requirements.

The model has relevance to anti-trust. A safe conclusion from the study is that the major firms were inhibited somewhat by fear of anti-trust action from more closely co-ordinating their price moves with each other. In our opinion, however, it would be unwise to conclude that, even if they were permitted to collude, all price rivalry would be eliminated. Uncertainty about the future would cause some rivalry (Fellner, 1949). Also, the presence of the small price-cutting firms sets an upper limit to industry price. The model also suggests a new defense against charges of collusion in price setting: models depicting strategies and behavior in the market for the accused firms might be constructed, tested and contrasted to reflect honest significant differences. This approach was being considered by defense attorneys in a different industry in 1964, when the government dropped the case.

The model has other implications that we do not develop but merely mention here. Organization theory, for example, is confronted with the crucial question of what determines the level to which authority becomes delegated. The model represents authority being exercised at one level and describes how it relates to the level above and to the level below. Economic theory takes as one of its central tasks the explanation of price decisions: the model presented here deals with a pervasive empirical pricing situation. Management science, with its emphasis upon the normative, needs a fuller understanding of the human and organizational limitations upon decision in order to develop more effective models of how the pricing decision should be made. Finally, the training implications of this type of model have not at all been exploited.

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## Part Four Heuristic Models

Parts Two and Three were concerned with field studies of managerial decision making. Parts Four and Five consider normative studies. They apply operations research findings to managerial decision making and indicate how managers ought to make decisions. We have classified normative decisions into two types, heuristic and algorithmic. Algorithmic models are covered in Part Five, which follows this section. Part Four illustrates heuristic models.

Heuristic models are used when either no exact mathematical or algorithmic solutions exist, or the cost of obtaining such exact solutions is prohibitive. Therefore, the solutions used are rule of thumb procedures which do not guarantee optimality, but which provide solutions more quickly and/or possibly less expensively than other methods.

All three papers in this section deal with complex combinatorial problems, that is, problems of combining tasks, resources and events in such a manner as to optimize or minimize a particular function. Tonge's heuristic program (Reading 9) finds the least number of work stations in an assembly line, given a desired production rate and an assembly process (the ordering of elemental tasks and the unit time each task requires). Tonge's rules of thumb enable the decision makers to construct a hierarchy of problems based on the natural groupings of tasks, then to group the tasks into work stations, and finally to regroup the work stations to even out the distribution of work.

The Kuehn-Hamburger paper (Reading 10) presents a heuristic program for determining the geographical location of warehouses. The heuristic has two parts, a main program and a 'Bump and Shift' routine. The main program locates



## Heuristic Models

warehouses one at a time by searching only those areas where there is a concentration of demand (large cities), locating a warehouse in a place which produces the greatest cost savings for the system, and finally, looking for the next location where the largest local savings is indicated. The 'Bump and Shift' routine modifies the solutions in the main program by eliminating warehouses which are no longer economical and by shifting the remaining warehouses within their respective territories to an optimum location.

Wiest attempts (Reading 11) to solve the problem of scheduling of a number of jobs in a project, given the technological ordering and resources required for each job and a restriction on total resources available during each period of the project. The basic program allocates resources period by period to jobs according to a priority scheme. A number of modifying routines are available which consider crew size, augmenting critical jobs, multi-resource jobs, borrowing from active jobs and so on.

All three heuristic decision models have been tested. The indications are that the models perform better than other extant solutions. Of course, there is no way of comparing the heuristic solution to the optimum.

### Summary of a Heuristic Line Balancing Procedure

F. M. Tonge, 'Summary of a heuristic line balancing procedure'  
*Management Science*, vol. 7, no. 1, October 1960, pp. 21-42.

#### Introduction

This paper describes a heuristic program for assembly line balancing. We employ heuristic methods because the assembly line balancing problem, like many combinatorial problems, has not been solved in a practical sense by advanced mathematical techniques.

Because this approach does not guarantee an optimum solution, the ultimate measure of a heuristic program is whether it provides better solutions more quickly and/or less expensively than other methods. However, at this early stage in the development of heuristic procedures there is still much to be learned about both the specification and the mechanization on a computer of such procedures. The research reported here was undertaken to explore these questions. No special emphasis was placed on producing an economically competitive program; but the results are sufficiently interesting to report.

This paper summarizes the heuristic program developed for assembly line balancing and the operating results obtained with that program. A detailed description of the procedure and further comments on this approach to utilizing digital computers are presented in another paper (Tonge, 1960).

#### Assembly Line Balancing

In many industries (home appliances, automobiles) the product is assembled on a continuous conveyor line. The elemental tasks making up the assembly operation must be assigned to work stations along the line. (For our purposes, 'work station' and 'operator' are equivalent.) In the simplest case, each elemental task (also called 'task' or 'element') is characterized by an

operation time per unit of product and a partial ordering relationship with other elemental tasks.

Figure 1 represents one such assembly (taken from Mitchell, 1957).<sup>1</sup> Here, for example, elemental task U5 requires nine time units. It cannot be started until task U4 is completed, and must be completed before either U6 or U7 can be started. The constraint that task U5 must precede task U14 need not be represented explicitly; this information is implied by the sequence  $U5 \rightarrow U7 \rightarrow U14$ .

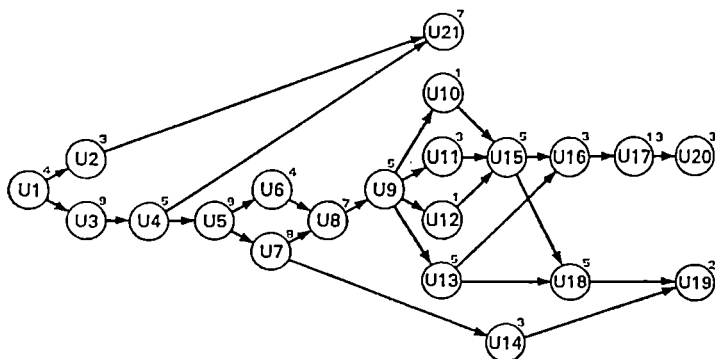


Figure 1

In industrial practice the ordering constraints are not explicitly stated. The industrial engineer works directly from bills of material and standard time data for the product and from his own knowledge of manufacturing technology.

A production rate set by management determines the maximum time (cycle time) to be assigned to any work station. That is, hours-per-shift divided by units-per-shift determine the maximum time an operator can spend on each unit.

The assembly line balancing problem<sup>2</sup> can be stated as: given a production rate (or, equivalent by a cycle time), what is the minimum number of work stations (operators) consistent with the time and ordering constraints of the product?

1. This directed graph representation of the assembly line balancing problem is due to Salveson (1955).

2. There are, of course, many variants of the balancing problem, introducing such factors as uncertainty of time values, varying operator capabilities, etc. None of these other constraints are treated here.

Table 1

| <i>Work station</i> | <i>Total time</i> | <i>Elemental tasks</i>  |
|---------------------|-------------------|-------------------------|
| 1                   | 18                | U1, U3, U4              |
| 2                   | 19                | U2, U5, U21             |
| 3                   | 15                | U6, U7, U14             |
| 4                   | 17                | U8, U9, U10, U11, U12   |
| 5                   | 20                | U13, U15, U16, U18, U19 |
| 6                   | 16                | U17, U20                |

A closely related problem is: given some number of men (work stations), what is the maximum production rate consistent with the time and ordering constraints of the product?

We shall consider the first formulation.

More explicitly, then, the assembly line balancing problem concerns a set of elemental tasks such that:

1. Each elemental task requires a known operation time per unit of product, independent of when performed.
2. A partial ordering exists among the elemental tasks.

An optimal solution of the problem consists of an assignment of elemental tasks to work stations such that:

1. Each elemental task is assigned to one and only one work station.
2. The sum of the times of all elemental tasks assigned to any one station does not exceed some maximum (the cycle time).
3. The stations thus formed can be ordered such that the partial orderings among elemental tasks are not violated.
4. The number of work stations thus formed is minimized.

A minimal work station solution to the problem of Figure 1 (given a cycle time of 20) is shown in Table 1.

Actual instances of the assembly line balancing problem are much more complex than the example given here. A representative problem from the appliance industry would contain nearly a hundred elemental tasks: the industrial engineer balancing a line

works from a sheet listing the elements and their operation times and from his knowledge of the manufacturing process. In the absence of any formal procedures, he must rely on judicious use of trial-and-error methods to find an acceptable grouping.

### **Exhaustive Procedures for Assembly Line Balancing**

Assembly line balancing techniques have received little attention in standard production management literature; most works merely acknowledge that the problem is a common one. However, several management scientists have studied the problem.

Salveson (1955) reviews the industrial setting of the problem and comments on several difficulties associated with line balancing; e.g. determining before solution the minimum number of operators, taking into account variances in operation times. He suggests application of limited combinatorial analysis, but the procedure rests upon previous enumeration of all possible work stations, an enormous task. However, many of Salveson's observations on the nature of the assembly line balancing problem are valid, and this article first brought the problem to the attention of the management science audience.

Jackson (1956) presents an algorithm for systematically enumerating and evaluating possible solutions. Comparisons of this exhaustive method with the heuristic procedure developed here are presented in a later section.

In commenting on Jackson's article, Helgeson and Kwo (1956) suggest an additional criterion – minimizing the variation in work load among stations – in evaluating possible solutions.

Bryton (unpublished thesis) develops a 'convergence' procedure for shifting elements among given work stations so as to increase the maximum attainable production rate. While not directly applicable to the problem stated here, this procedure is useful for equalizing the work load among stations once a solution has been found.

Mitchell (1957) extends Jackson's algorithm to include another common constraint, zoning. By zoning is meant the division of the set of elemental tasks into (possibly overlapping) subsets corresponding to physical constraints on the assembly operation. Zoning of an assembly line may be determined by the position of the product on the conveyor, the layout of the production

facility, or both. For example, certain elements may be performed only from the back of the product, or only while it is lying on its side; likewise, some elements may be carried out on a smaller sub-line joining the main conveyor. The constraint that all elemental tasks assigned to a work station must be in the same zone is added to the definition of a solution.

The methods mentioned above are not practical for large assembly line balancing problems because of their computational requirements. Indeed, no satisfactory general scheme for resolving large combinatorial problems involving partial ordering relations has yet been devised.<sup>3</sup>

### Heuristic Programs

Webster's *New International Dictionary of the English Language* (1959) defines the adjective 'heuristic' as 'serving to discover or reveal'. Thus, by heuristics we mean (after Newell, Shaw and Simon (1958b)) principles or devices that contribute, on the average, to reduction of search in problem-solving activity. The admonitions 'Draw a diagram' in geometry, 'Reduce everything to sines and cosines' in proving trigonometric identities, or 'Always take a check - it may be mate' in chess are all familiar heuristics.

Heuristic problem-solving procedures are procedures organized around such effort-saving devices. A heuristic program is the mechanization on a digital computer of some heuristic procedure. The computer attempts to solve the problem by carrying out the heuristic program. At present this use of digital computers is the only means we have of making explicit the behavior of a complex heuristic procedure in dealing with a large class of problems. The Logic Theorist (Newell, Shaw and Simon, 1957), the Chess Machine (Newell, Shaw and Simon, 1958a), and the Geometry Machine (Gelernter, 1958) are examples of working heuristic programs in other areas.

The distinction between heuristic and non-heuristic problem-solving procedures is often vague. Rather than attempt to specify a rule by which all procedures can be so categorized, we shall cite some common characteristics of existing heuristic procedures:

3. However, much unreported research is being done by industrial firms into assembly line balancing and related problems.

## Heuristic Models

1. Factorization of the problem into a number of 'smaller' problems and subproblems (often through means-end analysis), with a corresponding goal-subgoal organization of behavior. For example, the Chess Machine might realize that it cannot play P-K4 because it would lose an exchange on that square, and consequently set up the subgoal of first bringing another man to bear on its K4.
2. Use of cues in the environment to determine the particular behavior evoked from a wide set of possible alternatives available to the program. That is, a high degree of interdependence between the specific problem (from a more general class) being considered and the particular problem-solving methods used. Thus, the methods used by the assembly line balancing program for choosing elements to shift between groupings depend on the particular characteristics of those groupings.
3. Use of recursive procedures to bring to bear on subproblems the same repertoire of problem-solving techniques used on the original problem. Thus, the Logic Theorist can use the same 'bag of tricks' to prove a derived expression as to prove the initial statement from which the derived expression was produced.
4. No guarantee of a satisfactory solution or, often, of any solution. For example, the Chess Machine, because of time and space limitations, may not be able to consider some promising continuations, including the *a posteriori* optimum one.

Because a heuristic procedure substitutes the effort-reduction of its shortcuts for the guaranteed optimal solution of an exhaustive method, the justification of such a program as a problem-solver must be in terms of the number of cases successfully solved and the relative amount of effort involved. In a later section on operating results, the assembly balancing program presented here is compared with several exhaustive procedures.

The set of heuristics outlined here for balancing an assembly line evolved from several sources: discussions with industrial engineers of how they actually balance lines; study of the various papers cited above; explorations with several co-workers, particularly A. Newell, of possible techniques; and finally extensive experimentation with particular instances of the problem.

### **The Assembly Line Balancing Program**

This heuristic approach to assembly line balancing is based on simplification – sufficient simplification of a complex combinatorial problem that it becomes solvable (in most cases) by simple straightforward methods.

Two recursively defined routines form the essence of this procedure.<sup>4</sup> Phase 1 constructs a hierarchy of increasingly simpler line balancing problems by aggregating groups of elements into a single compound element. Each of these compound elements is itself a member of this same class of line balancing problems, since it is made up of elements requiring a given operation time and among whom partial ordering relationships exist.

Phase 2 solves a simple (small number of elements) line balancing problem by assigning groups of available workmen to elements and then taking as subproblems those compound elements (simple problems in themselves) which have been assigned more than one man.

This approach requires heuristics for aggregating groups of elements into compound elements, for solving the simplified problems thus created, and for reintroducing the detail of the original problem when the simplified version does not yield a solution.

A third phase of the problem-solving process, utilizing virtually the same heuristics as already required, involves 'smoothing' the final work load (assigned time) among work stations. Since the greatest total time assigned any work station limits the speed of the line, a smooth balance answers the problem 'What is the

4. Several other strategies could be suggested as bases for heuristic approaches to the problem:

(a) Division of the problem into relatively independent sub-problems, solution of these by optimizing techniques, and combination of the sub-solutions by heuristic methods.

(b) Solution of a problem abstracted from the original by replacing all times with one of a single large or a single small value, and then adjustment of the result to fit actual times.

(c) Development of stations in an order determined by the density of partial ordering constraints, first building in those regions of the problem where there is least freedom among elements. None of these alternative approaches are considered here in any further detail.



highest production rate achievable with a given number of men?' That is, since both men and time are measured in discrete units, a *non-smoothed* optimum solution of the problem 'given a production rate, minimize the number of men required' need not be an optimum solution of the dual problem 'given a number of men, maximize the production rate'.

Thus, the general problem-solving scheme calls for:

Phase 1. Repeated application of aggregative procedures, creating a hierarchy of simplified line balancing problems ranging in complexity from the initial problem to one containing a single compound element.

Phase 2. Recursive application to these simplified problems of a procedure for assigning men to tasks, down to the level of problems whose component tasks require one man each. When the compound elements making up a problem require more men than are available, these elements are broken up and their components regrouped to require fewer men.

Phase 3. Smoothing the resulting balance by transferring tasks among work stations until the distribution of assigned time is as even as possible.

The following sections discuss the heuristics entailed in each of these procedures.

Since this approach does not guarantee an optimum solution to the overall line balancing problem, we must have some notion of a satisfactory solution and accept or reject proposed solutions based on this notion. Also, since the solution of a problem does not guarantee that its subproblems will be solved, whatever process generates solutions must remain active until all subproblems have been solved, ready to generate another solution if necessary. The methods by which these requirements are met are indicated below.

### **Constructing the Hierarchy of Problems**

The ordering constraints present in the problem suggest two natural units of aggregation of elements. Either a completely ordered relationship exists between several elements – as, U3 must always precede U4 (Figure 1) – or no ordering is specified –

as, U10, U11, U12. We adopt the 'chain' and the 'set' as basic aggregative units in constructing a simplified problem:

1. A group of adjacent elements whose relative order is completely determined, each except the first having a single direct predecessor and each except the last having a single direct follower, can be replaced by a single compound element, called a *chain*.
2. A group of elements whose relative order is completely unspecified, all having the same direct predecessors and followers, can be replaced by a single compound element, called a *set*.

Thus, U10, U11, U12 in Figure 1 can be replaced by a set 'V2', and then V2, U15 can be replaced by a chain 'V3'. These aggregations can be indicated on the original problem, as in Figure 2a. However, it is convenient to represent the aggregations as a branching tree, with each compound element having beneath it the elements of which it is composed.

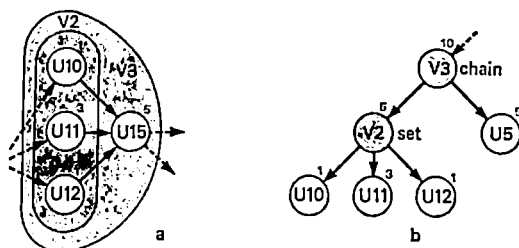


Figure 2

The tree of compound element V3 is shown in Figure 2b. Note that the time requirement of a compound element is the sum of the times of its components.

We use the term 'chain relationship' to indicate that some ordering (possibly indirect) exists between two elements and 'set relationship' to indicate that none exists.

While the solution strategy calls for repeated application of these aggregative operations to yield a hierarchy of simplified problems, these two types of aggregation are not sufficient to completely reduce (to a single compound element) most actual

problems. We can proceed by first defining more complex aggregative operations and then if necessary, by moving 'troublesome' ordering constraints. Proposed solutions must then be checked to see that these missing constraints are not violated.

The one additional compound element introduced to date is the 'Z'.

3. A Z is a group of four elements with the two front elements having common predecessors and the other two back elements having common followers. The single direct follower of one front element is one of the back elements; the two direct followers of the other front element are the back elements. The back elements have no other direct predecessors.

An example of a Z and its representation in tree form are given in Figures 3a and 3b. (Note that there is a canonical order of subelements in the tree representation of the chain and the Z.)

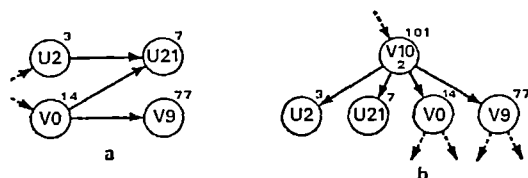


Figure 3

The recursive procedure carrying out this aggregating process may be applied to any assemblage of elements. By an assemblage of elements we here mean those given elements without predecessors within the assemblage (called the front elements) and their direct followers, and their followers' direct followers, and so forth, to and including those elements with no direct followers. Thus, the illustrative problem of Figure 1 is an assemblage with front element U1.

While there is not space here to present the full details of this procedure, a brief summary follows.

Given an assemblage of elements with a single front element, the routine attempts to create a chain. When an element having several direct followers is encountered, the program first sets up the subproblem of aggregating the assemblage with those several

front elements and then applies itself to that problem. (The routine is recursive, so that attempting to solve that subproblem may involve setting up and attempting to solve sub-subproblems and so forth.) If the subproblem is solved successfully, the higher level problem of creating a chain is continued. If the subproblem fails, or if an element is encountered with direct predecessors outside the assemblage (other than those of the front element), the higher level problem fails.

Given an assemblage of elements with several front elements, the routine attempts to create a set, or failing that, a  $Z$ . If this can be done, the problem becomes one of reducing an assemblage with a single front element. If not, the routine first sets up the independent subproblems of aggregating separate assemblages starting with each of the front elements, and applies itself to each of these subproblems in turn. When these subproblems are concluded, the higher level problem of creating a set or  $Z$  is resumed.

Trying to resolve these subproblems independently often reveals complex ordering constraints between them. A  $Z$  is then postulated incorporating such constraints. Further constraints that prevent completion of an already postulated  $Z$  are relaxed so that the  $Z$  can be completed, and the higher level problem is then continued.

Figure 4 is the tree of compound elements constructed by application of this recursive procedure to the problem of Figure 1. The running commentary of this routine is given in Appendix A; this is a dynamic statement of how the routine is proceeding. It is instructive to follow through this 'protocol' while viewing Figures 1 and 4. This first phase of the problem-solving process need be carried out only once for a given product (set of constraints). The resulting hierarchy is supplied as an input to the second phase of the process.

### **Grouping Tasks into Work Stations**

Inputs to the second phase, grouping tasks into work stations, are: the problem hierarchy as developed in Phase 1; a cycle time determined by the required production rate; and a 'per cent usable time' supplied as a guide for setting up and accepting potential work stations. Per cent usable time is an estimate (at

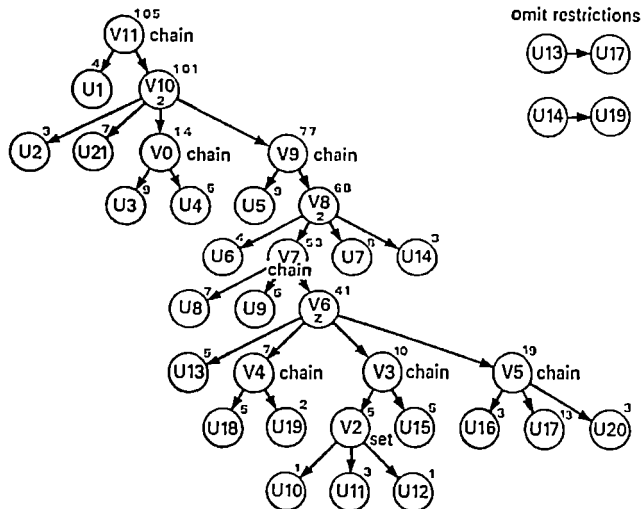


Figure 4

present made by the user) of how close to the required station the task elements can be grouped. This measure reflects the structure and time values of the particular problem being solved.

The assignment routine consists of a simple recursive procedure for allocating men (work stations) to groups of tasks and a set of procedures for regrouping the tasks when necessary. These regrouping heuristics are described in the following section.

The recursive routine for allocating men to groups of tasks proceeds as follows:

1. An initial estimate is made of the number of men required to meet the given production rate, given a per cent usable time (per cent effectiveness). This number of men is assigned to the 'top' compound element, representing a single grouping of all task elements. The recursive routine described in step 2 is then applied to that element. If the routine succeeds, the line has been balanced and Phase 2 ends. If the routine fails, the number of men assigned to the top element is increased and the procedure repeated.

- 2 (a). If the element being considered has been assigned more than one man, these available men are allocated among the direct

components of the element according to their time requirements. This recursive routine is then applied to each of these component elements in turn. If the routine successfully solves each of the sub-problems, then the problem of grouping tasks into work stations is also solved at this level and the routine terminates. If the available men cannot be allocated among the direct components of the element in question – if, considered independently, they require more men than are available – then regrouping procedures are called upon to shift tasks among these groupings so that they are independently solvable. If such a regrouping cannot be found, control is returned to the next higher level, signalling failure to solve the subproblem.

If the recursive routine should fail to handle one of the components below this level and report back failure, excess elements from the failing subproblems are shifted to another grouping or, failing that, the regrouping procedures are activated to produce another set of independent groupings. Again, if solvable sub-problems cannot be found, control is returned to the next higher level with a failure signal.

2 (b). If the element being considered has been assigned a single man, additional elements are added to it if necessary to bring it near the maximum allowable size and the grouping is marked as a work station. Control then returns to the next higher level, signalling success.

Thus, this recursive routine, like that of Phase 1, deals with examples of a particular class of problems. It solves a problem by setting up within it (and solving in the same way) other 'easier' problems of the same class whose solutions can be combined to solve the larger problem also. In particular, Phase 1 of the line balancing program makes use of natural groupings of the elemental tasks to build up a hierarchy of simplified problems, and Phase 2 attempts to balance the line using these groupings as complete units, transferring tasks among these groupings only when the simple allocation scheme fails.

### **Regrouping Procedures**

Five regrouping procedures – direct transfer, trading, sequential grouping, complete grouping, and exhaustive grouping – are

available to the Phase 2 recursive routine when its simple scheme for allocating available men fails. Which of these regrouping heuristics will be called upon, and in what order, is determined by characteristics of the compound elements being regrouped. These procedures are also used by Phase 3 of the assembly line balancing program in smoothing a proposed line balance.

All five methods make use of a single recursive routine that scans a given part of the hierarchy of elements (the 'problem tree') and generates a sequence of groups of elements lying within certain specifications (maximum total time of group, minimum total time of group, from front or from back). This routine proceeds by building a first group, always taking the largest element acceptable, and then constructs further groups by eliminating from consideration (or breaking down into components, if a compound element) successive elements of that group, and applying itself to the remaining elements of the given part of the hierarchy. Thus, if requested to produce groups totaling at least eight but not more than sixteen time units from the back of compound element V6 (see Figure 4), the routine would generate the sequence (V4, U13, U20) and (U20, U17). The routine generates each element of this sequence as requested, remembering where it is in the sequence to be able to generate the next one.

The first three methods – direct transfer, trading, and sequential grouping – are used to set up independently solvable subproblems which can then be handled by the Phase 2 recursive routine.

*Direct transfer* is applied when only two components are involved. This method tries simply to transfer elements from one component to the other and thus reduce the number of men required by a straightforward totaling of whole men.

Thus, if V11 in Figure 4 had been assigned six men (given a cycle time of twenty), the direct transfer procedure would first attempt to shift elements totaling at least one but not more than sixteen time units from V10 to U1, and would in fact shift V00 (fourteen time units).

*Trading* also applied only to two components, and assumes that direct transfer has been attempted without success. Trading tries to regroup by shifting an element larger than the acceptable limit

from one component in exchange for smaller elements (in a set relationship with the first element shifted) from the other component.

An example of this method is cited in the next section.

*Sequential grouping* is used when there are several components, and attempts to construct an acceptable work station from the front of the given group of components. If the remaining components can be handled by the remaining men available, the method is considered successful. If not, an attempt is made to construct another work station from the back of the component group, and a similar test is made.

Suppose, for example, that V7 in Figure 4 had been assigned three men (cycle time twenty). Since V7 is made up of three components requiring one, one, and three men, regrouping procedures would be evoked. Sequential grouping would first group together U8, U9, and V2 and then, since the remaining component V6 would now total 36 time units, requiring only the two remaining available men, the method would be successful.

The remaining two regrouping procedures, complete grouping and exhaustive grouping, try to completely solve the subproblems remaining. They may be regarded as 'last ditch' methods at any particular level.

*Complete grouping* attempts, first from the front of the component group and then from the back, to construct work stations until all task elements are grouped. If at any time the method cannot construct a station such that the remaining elements total less than can be handled by the remaining men, the method fails.

*Exhaustive grouping* generates all possible (independent) first work stations, then all possible following work stations for each of these. This method is, in fact, the exhaustive algorithm suggested by Jackson (1956). Because of the comparatively large amount of effort required to do an exhaustive grouping, this procedure is used only when two men are to be assigned. The method does furnish to the next higher level Phase 2 routine (on failure) the best groupings it was able to construct from the front and the back, as well as which elements were left ungrouped in those solutions.



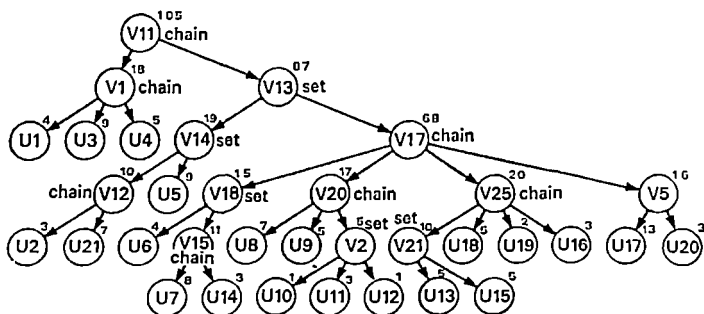


Figure 5

While these regrouping methods are clearly not foolproof, they have proven satisfactory for all problems attempted to date. Figure 5 shows the problem of Figures 1 and 4 after the Phase 2 recursive routine has been applied to it (cycle time twenty, 95 per cent usable time), and Figure 6 pictures the work stations thus created on the original problem. (See also Table 1). Appendix B lists the protocol produced during this assignment.

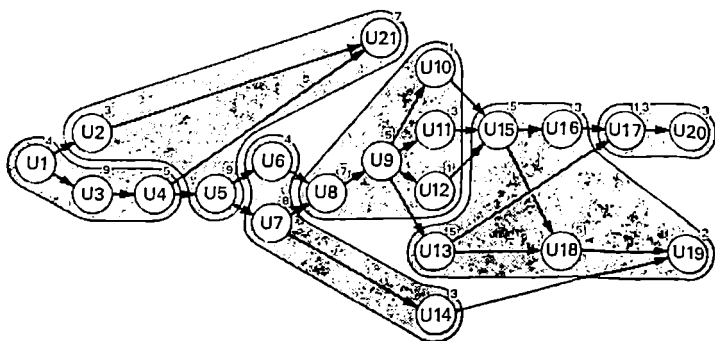


Figure 6

## Smoothing the Resulting Balance

Phase 3 of the assembly line balancing program seeks to even the distribution of work among work stations by repeatedly reducing the time requirement of the largest work station. Inputs to this

phase of the problem are a balanced line in hierarchical representation, such as would be produced by Phase 2, and a cycle time. This iterative routine uses the same regrouping heuristics used by the Phase 2 recursive routine.

The following steps comprise the Phase 3 procedure:

1. Calculate the least possible time value of the highest station (with the given cycle time). If the largest station's time value is not greater than this bound, no further smoothing is possible and the routine terminates.
2. Given the largest station, consider in turn, in increasing order of size, all 'adjacent' (in a set relationship or direct predecessors or followers) stations to that largest station. Try to even the distribution of work between them using the direct transfer heuristic. If successful, return to step 1. If not, go to step 3.
3. Consider again those stations adjacent to the largest station in increasing order of size. Try to reduce the work load of the larger using the trading heuristic. If successful, return to step 1. If not, proceed to step 4.
4. Once again, consider adjacent stations in increasing order of size. For each one, using first direct transfer and then trading, try to make any transfer that reduces the largest station, even if the formerly smaller station is now as large or larger. If some such transfer is found, set up the subproblem of reducing this new larger station and apply this routine to it (excepting that step 4, setting up further subproblems, cannot be used). If successful, return to step 1; if not, the Phase 3 routine terminates.

The procedure outlined above has not yet been coded (which should be a relatively easy task, as it relies so heavily on already-coded routines), but it has been hand-simulated for several cases. The results of this hand-simulation for the problem of Figures 1 and 4 is shown in Figure 7. The simulated output of this phase of the assembly line balancing program is given in Appendix C.

### **Operating Results**

Three sample problems were used in developing and testing this heuristic procedure. These are an 11 element problem taken from Jackson (1956), the twenty-one element problem used as an example here, taken from Mitchell (1957), and a 70 element

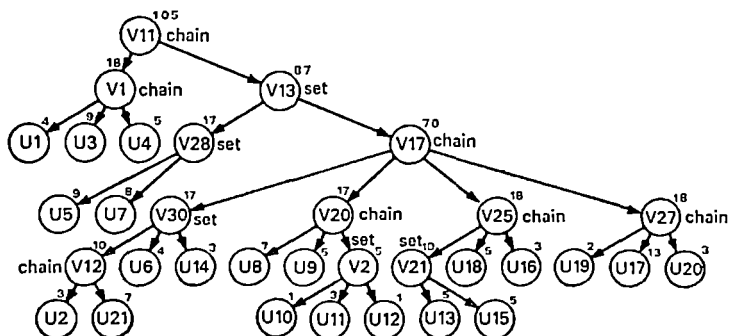


Figure 7

problem representing actual appliance industry data. While these few cases do not completely test the method's general validity,<sup>5</sup> we can extract some interesting measures of performance in different types of problems.

Data summarizing these problem-solving exercises are given in Table 2. Note the increase in computing effort with problem-size in both Phases 1 and 2. We also observe for the several cases of the twenty-one element problem an increase in effort per station as per cent idle time decreases. It appears that the amount of effort required to reach a balance depends upon the number of elements in the problem, number of stations desired and the per cent idle time available. Additional experience with actual problems will enable us to develop a method for estimating the effort required in particular cases.

To get some feeling for the effort required by exhaustive algorithms, we also attempted the eleven element problem with only the 'exhaustive grouping' method, thus solving the problem using Jackson's algorithm (1956). (This is only a rough comparison, since the algorithm is carried out here using list processes and would benefit more than the heuristic program as a whole from use of matrix representation. Also, since the method is imbedded in the midst of our procedure, some amount of processing not

5. It is necessary to test this procedure against other large problems not only to measure its economic efficiency but also to insure that the heuristics incorporated here have not been unconsciously adapted to meet the requirements of these particular test problems.

required by that algorithm *per se* is included in the measure.) Under these conditions the program required about 389,000 IPL instructions to reach a balance, a factor of 2.5 over the heuristic approach. While this difference is not striking in light of the above warnings, the disparity will grow rapidly with increasing problem size.

Table 2

| Problem    | Phase I              |               |               |                    | Phase II |           |                                     |
|------------|----------------------|---------------|---------------|--------------------|----------|-----------|-------------------------------------|
|            | effort<br>IPL instr. | cycle<br>time | pct<br>usable | no. of<br>stations | pct idle | effort    | effort per<br>station $\times 10^3$ |
| 11 element | 14,478               | 10            | 95            | 5                  | 8        | 153,075   | 30.6                                |
| 21 element | 51,386               | 20            | 90            | 6                  | 12       | 141,868   | 23.7                                |
|            |                      | 19            | 95            | 6                  | 8        | 143,183   | 23.8                                |
|            |                      | 14            | 95            | 8                  | 6        | 627,809   | 78.5                                |
|            |                      | 18            | 98            | 6                  | 3        | 483,458   | 80.5                                |
|            |                      | 21            | 100           | 5                  | 0        | 760,803   | 152.2                               |
| 70 element | 207,194              | 176           | 93            | 23                 | 9        | 2,495,118 | 108.5                               |

We also tested Salvesson's (1955) linear programming formulation of the assembly line balancing problem on our eleven element problem, using the RAND Simplex Code. The formulation required eleven equations in sixty-two unknowns (one unknown for each possible legal grouping, given a cycle time of ten). This program required fifteen iterations (starting from an artificial basis) to reach an optimum solution. As was expected, this answer contained groupings of fractional parts of elements. We must await an operating integer programming code in order to really test a linear programming approach.

The next areas we hope to analyse are the effort saving through incremental changes – that is, starting from a near-by balance as opposed to starting from scratch with each new cycle-time – and the usefulness of initially producing balances at a range of interesting production rates, thus providing an approximation to the labor cost function for the assembly operation.

### Adding the Zoning Constraint

One of the advantages sought from the heuristic approach to complex decision problems is the ability to redefine the problem, adding or deleting restrictions on a solution, with ease. As a specific example, we introduce the zoning restriction treated by

Mitchell (1957). Under this restriction each elemental task is assigned to one or more zones reflecting the physical limitations of the production process.

Table 3

| Zone | Elemental tasks                                           |
|------|-----------------------------------------------------------|
| 1    | U1, U2, U3, U4, U5, U7, U8, U21                           |
| 3    | U3, U4, U6, U7, U8, U9, U10, U11, U12, U13, U15, U16, U18 |
| 4    | U13, U14, U15, U16, U17, U18, U19, U20                    |

To incorporate this new restriction, the basic grouping generator (see *Regrouping Procedures*) is modified to produce only groupings within a specified zone or zones, and the routine that accepts work stations is modified to reject groups whose elements are not in a common zone. These modifications can be made relatively easily without affecting other parts of the overall program. These modifications have been hand-simulated for several problems. Table 3 indicates the zoning of elements in the sample problem of Figure 1. Figure 8 is the result of the modified Phase 2 operation on that problem (cycle time twenty).

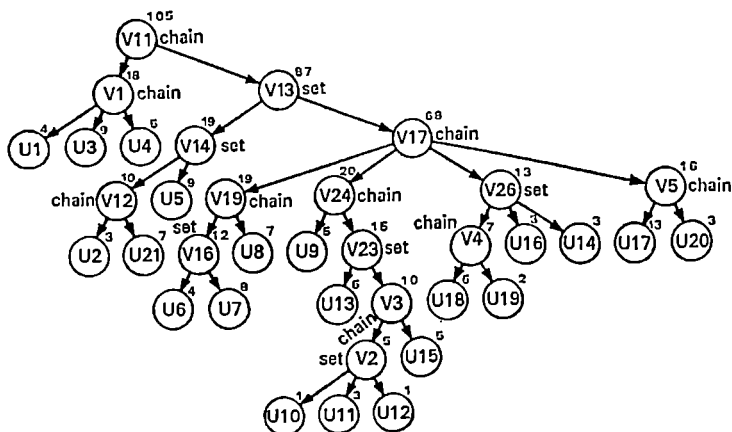


Figure 8

### Mechanizing the Assembly Line Balancing Program

The assembly line balancing program described here is programmed in an interpretative system, IPL-IV, on the RAND Corporation's digital computer, JOHNNIAC. The IPL-IV system uses about 1200 of the JOHNNIAC's 4096 words of high-speed core memory and about 650 words of the 12,288 word auxiliary drum memory. In running the line balancing problem, which makes heavy use of the drum for temporary storage of data, the system interprets at the rate of about 9000–10,000 IPL instructions per minute. While there has been no published account of IPL-IV, the closely related IPL-V for the IBM 650, 704 and 709 is fully documented (Newell and Tonge, 1960; Newell *et al.*, 1960a; Newell *et al.*, 1960b).

Why symbol manipulation languages<sup>6</sup> are extremely useful research tools for exploring techniques for problem solving in complex and ill-structured situations is examined in more detail in another paper (Tonge, 1960). The essential point is that the 'parameters' which the problem solver wishes to vary freely are policies – general principles, rules of thumb, or what have you. The diversity of these principles cannot be anticipated when the problem-solving process begins with the problem of finding a good problem-solving process for the problem at hand. Some system for using the computer is required which frees the problem solver from making early commitments (which he will later regret) about storage allocation, information to be carried, and so forth. This system must allow the user (possibly at the cost of machine speed and storage usage) to state his incompletely formulated problem and method of solution and start experimenting. List structure languages are a first step towards such a system.

The assembly line balancing program itself requires about 6700 machine locations, of which about 6100 are in auxiliary storage. In keeping with our preference for quick results rather than 'efficient' operation, the entire structure of the problem was encoded in list form. With a satisfactory program (from the performance standpoint) developed, savings in machine space and

6. Such programming languages include the IPL (Information Processing Language) series (Newell and Tonge, 1960; Newell *et al.*, 1960a; Newell *et al.*, 1960b), LISP (McCarthy, 1959), COMIT (Yngve, 1958), and FORTRAN List Processing Language (Gelernter, 1958).

speed could be made by encoding some structural information in matrix form. Bryton (unpublished thesis), Marimont (1959) and others have made interesting contributions in this direction. Such a recoding would require only changing those routines that locate the value of certain properties of elements. The rest of the code is independent and would remain unchanged. Other reductions in operating time can be obtained by recoding in basic machine language certain operations now in interpretive code. Using IPL-V on the 704, it will be possible to implement the program described in this paper at five times the speed achieved on the JOHNNIAC. At such speeds (about an hour maximum to balance an appliance line) this approach seems close to economic feasibility in treating some complex industrial decision problems.

### Final Remarks

The aims of this research have been broader than just trying to produce a method for solving the assembly line balancing problem. We have set out to test the feasibility of a heuristic approach to complex decision making in a particular industrial area and to examine the use of new computer techniques in implementing such an approach. As always, many interesting questions remain unexplored. But based on the experience reported here, we must conclude that the combination of a heuristic approach and these new methods of computer utilization are useful research tools in complex problem solving.

Our program is not economically competitive when measured against the dollar-per-hour cost of line balancing by the industrial engineer. However, a true evaluation of the method must also consider (i) the possibility of fewer men required along the line on the average (a subject not yet fully explored), (ii) the value of quick production of balances at a large number of production rates and (iii) the value of releasing industrial engineers to do other, more creative analytic work.

Also, our research has indicated that present symbol manipulation languages, while a great advance for these purposes over conventional programming techniques, are still relatively primitive. While it is difficult to conceive preparing this program in a less powerful language than IPL-IV, much effort is required in machine-oriented aspects of communicating the problem-solving

procedure to the computer. Further research in this area is needed before the heuristically-oriented problem solver will be free to expand his effort primarily on developing satisfactory problem-solving techniques, using the computer as a tool for spelling out the implications of his procedures.

## Appendix A

### *Phase 1 – 21 Element problem*

- 1 Propose Chain U1
- 2 Propose Set U2, U3
- 3 Propose Chain U2
- 4 Cannot Reduce U2 to U21
- 3 Propose Chain U3
- 4 Define Chain V0 = U3, U4
- 4 Propose Set U5, U21
- 5 Cannot Reduce U21
- 3 Propose Z V0, U2
- 4 Propose Chain U21
- 4 Propose Chain U5
- 5 Propose Set U6, U7
- 6 Propose Chain U6
- 7 Cannot Reduce U6 to U8
- 6 Propose Chain U7
- 7 Propose Set U8, U14
- 8 Cannot Reduce U8
- 6 Propose Z U7, U6
- 7 Delete Constraint U14 to U19
- 7 Propose Chain U8
- 8 Define Chain V1 = U8, U9
- 8 Propose Set U10, U11, U12, U13
- 9 Define Set V2 = U10, U11, U12
- 9 Propose Chain V2
- 10 Define Chain V3 = V2, U15
- 10 Propose Set U16, U18
- 11 Cannot Reduce U18
- 9 Propose Chain U13
- 10 Propose Set U17, U18
- 11 Cannot Reduce U17
- 11 Cannot Reduce U18



- 9 Propose  $Z$  U13, V3
- 10 Delete Constraint U13 to U17
- 10 Propose Chain U18
  - 11 Define Chain  $V4 = U18, U16$
- 10 Propose Chain U16
  - 11 Define Chain  $V5 = U16, U17, U20$
- 10 Define  $Z$  V6 = U13, V4, V3, V5
- 8 Propose Chain V6
- 8 Define Chain  $V7 = U8, U9, V6$
- 7 Propose Chain U14
- 7 Define  $Z$  V8 = U6, V7, U7, U14
- 5 Propose Chain V8
- 5 Define Chain  $V9 = U5, V8$
- 4 Define  $Z$  V10 = U2, U21, V0, V9
- 2 Propose Chain V10
- 2 Define Chain  $V11 = U1, V10$

## Appendix B

*Phase 2 – 21 Element problem – cycle time 20 – PCT usable 90*

- 1 Consider V11 – Components U1, V10 – 6 Men Available
  - 2 Activate Direct Transfer
  - 3 Combine V0, U1
    - 4 Redefine Chain  $V11 = V1, V13$
    - 4 Define Chain  $V1 = U1, U3, U4$
    - 4 Define Chain  $V12 = U2, U21$
    - 4 Define Set  $V13 = V12, V9$
- 2 Assign 1 Man to V1, 5 to V13
  - 3 Consider V1 – Components U1, U3, U4 – 1 Man Available
    - 4 Mark V1 as Work Station – Time = 18
  - 3 Consider V13 – Components V12, V9 – 5 Men Available
    - 4 Assign 1 Man to V12, 4 to V9
      - 5 Consider V12 – Components U2, U21 – 1 Man Available
    - 6 Combine U5, V12
      - 7 Redefine Set  $V13 = V14, V8$
      - 7 Define  $V14 = U5, V12$
    - 6 Mark V14 as Work Station – Time = 19
  - 5 Consider V8 – Components U6, V7, U7, U14
    - 6 Add U14, U6 to Waiting List

- 6 Assign 3 Men to V7, 1 to U7
- 7 Consider U7 – 1 Man Available
  - 8 Combine U7, U14, U6
    - 9 Define Set V18 = U6, V15
    - 9 Define Chain V17 = V18, V7
    - 9 Define Chain V15 = U7, U14
    - 9 Redefine Set V13 = V14, V17
  - 8 Mark V18 as Work Station – Time = 15
- 7 Consider V7 – Components U8, U9, V6 – 3 Men Available
  - 8 Activate Sequential Grouping
    - 9 Combine U8, U9, V2
      - 10 Redefine Chain V7 = V20, V6
      - 10 Define V20 = U8, U9, V2
      - 10 Redefine Z V6 = U13, V4, U15, V5
  - 8 Assign 1 Man to V20, 2 to V6
    - 9 Consider V20 – Components U8, U9, V2 – 1 Man Available
      - 10 Mark V20 as Work Station – Time = 17
    - 9 Consider V6 – Components U13, V4, U15, V5 – 2 Men Available
      - 10 Activate Sequential Grouping
        - 11 Combine U15, U13, V4, U16
          - 12 Define Chain V23 = V25, V5
          - 12 Define Chain V25 = V21, U18, U19, U16
          - 12 Redefine Chain V5 = U17, U20
          - 12 Define Set V21 = U13, U15
          - 12 Redefine Chain V7 = V20, V23
      - 10 Assign 1 Man to V25, 1 to V5
        - 11 Consider V5 – Components U17, U20 – 1 Man Available
          - 12 Mark V5 as Work Station – Time = 16
        - 11 Consider V25 – Components V21, U18, U19, U16 – 1 Man Available
          - 12 Mark V25 as Work Station – Time = 20
- 7 Define Chain V17 = V18, V20, V25, V5

## Appendix C

*Phase 3 – 21 Element problem – cycle time 20 – PCT usable 90*

1 Least Possible High Station =  $105/6 = 17\frac{1}{2} = 18$  Time Units

1 Consider V25 – Time = 20

2 Activate Direct Transfer, V25 to V5

3 Combine U19, V5

4 Redefine Chain V17 = V18, V20, V25, V27

4 Redefine Chain V25 = V21, U18, U16

4 Define Chain V27 = U19, U17, U20

1 Consider V14 – Time = 19

2 Activate Direct Transfer, V14 to V18

2 Activate Direct Transfer, V14 to V1

2 Activate Trade, V14 and V18

3 Combine V14, U7

4 Redefine Set V13 = V28, V17

4 Define Set V28 = V12, U5, U7

4 Redefine Set V18 = U6, U14

3 Combine V12, V18

4 Redefine Set V28 = U5, U7

4 Redefine Chain V17 = V30, V20, V25, V27

4 Define Set V30 = V12, U6, U14

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## A Heuristic Program for Locating Warehouses

A. A. Kuehn and M. J. Hamburger, 'A heuristic program for locating warehouses', *Management Science*, vol. 9, 1963, pp. 643-66.

### The Warehouse Location Problem

Regional warehouses may perform a variety of functions in the distribution of a manufacturer's products. These include: the reduction of transportation costs relative to direct shipment to customers by permitting bulk or quantity shipments from factory to warehouse; the reduction of delivery costs by combining products manufactured at several factories into single shipments to individual customers; and the improvement of customer relations by decreasing delivery time relative to direct factory shipment, thereby permitting customers to reduce their inventories. There are, however, substantial costs associated with the operation of a regional warehouse system.

The problem at issue may therefore be phrased as follows: determine the geographical pattern of warehouse locations which will be most profitable to the company by equating the marginal cost of warehouse operation with the transportation cost savings and incremental profits resulting from more rapid delivery. A heuristic computer program which appears to be capable of generating reasonably good solutions to this class of problems will be described in the following sections, after a brief discussion of the heuristic approach to problem solving. A mathematical formulation of the warehouse location problem is given in Appendix 1. A comparison of the heuristic program with several alternative approaches to the problem is contained in Appendix 2.

### The Heuristic Approach to Problem Solving

Simon (1961) has referred to heuristics as rules of thumb selected on the basis that they will aid in problem solving. In an earlier paper, Simon, in collaboration with Newell and Shaw, used the

term 'heuristic' to denote 'any principle or device that contributes to the reduction in the average search to a solution' (Newell, Shaw and Simon, 1958b, p. 22). Making use of the latter definition, a heuristic program can be defined (after Tonge, 1969b) as a problem-solving program organized around such principles or devices. Simon (1961) has distinguished between such programs and algorithms on the basis that *only* the latter guarantee solution of the problem to a desired degree of accuracy. We do not believe that this is the most appropriate way to characterize heuristic programs. There are many solution procedures referred to as algorithms which do not guarantee solutions to a desired degree of accuracy, but rather, as is possible with the heuristic warehouse location program, provide only upper and lower bounds to the solution (for example, the fictitious play method for solving matrix games, Kemeny and Thompson, 1958). Furthermore the definition of algorithm generally used by mathematicians (for example, Courant and Robbins, 1941, p. 44) is 'a systematic method for computation'. Such a definition would include all computer programs.

We prefer to look at heuristic programming as an approach to problem solving where the emphasis is on working towards *optimum solution procedures* rather than *optimum solutions*. This is not to say that we ever expect to obtain an optimum solution procedure. The requirement of optimality would, in fact, be contradictory to the concept of using heuristic techniques. Heuristic techniques are most often used when the goal is to solve a problem whose solution can be described in terms of acceptability characteristics rather than by optimizing rules (Tonge, 1961b, p. 232).<sup>1</sup> The traditional operations research approach has been to search for optimum solutions. The heuristic approach differs in the following ways:

1. Explicit consideration is given to a number of factors (for example, computer storage capacity and solution time) in addition to the quality of the solution produced.
2. The evaluation of heuristic techniques is usually done by inductive

1. These points have been discussed in more detail elsewhere in the context of a theory of human problem solving and choice (see, for example, Simon, 1957, pp. 196-207 and 241-74; March and Simon, 1958, chs 6 and 7; Cyert, Dill and March, 1958, Reading 4).

rather than deductive procedures. That is, specific heuristics are justified not because they attain an analytically derived solution (for example, an optimum) but rather because experimentation has proved that they are useful in practice (Simon, 1961, p. 11).

Recent interest in the heuristic approach to problem solving has led to the development of computer programs designed to: compose music (Hiller, 1959), play checkers (Samuel, 1959), play chess (Bernstein, Roberts, Arbuckle and Belsky, 1958; Kister, Stein, Ulam, Walden and Wells, 1957; Newell, Shaw and Simon, 1958a), discover proofs for theorems in logic and geometry (Newell and Simon, 1956; Gelernter and Rochester, 1958), design electric motors and transformers (Gomory, 1958), and balance assembly lines (Tonge, 1961b).

### A Heuristic Program for Locating Warehouses

The heuristic program which we propose for locating warehouses consists of two parts: (i) *the main program*, which locates warehouses one at a time until no additional warehouses can be added to the distribution network without increasing total costs, and (ii) *the bump and shift routine*, entered after processing in the main program is complete, which attempts to modify solutions arrived at in the main program by evaluating the profit implications of dropping individual warehouses or of shifting them from one location to another. The three principal heuristics used in the main program are:

1. *Most geographical locations are not promising sites for a regional warehouse; locations with promise will be at or near concentrations of demand.*<sup>2</sup> The use of this heuristic in searching for and screening potential warehouse locations permits us to concentrate upon substantially less than  $\frac{1}{100}$  of 1 per cent of the United States and thereby eliminate mountains, marshes, deserts, and other desolate areas from consideration. To be sure, the program may as a result miss a good location. In general, however, computer time is put to much better use in screening and

2. Baumol and Wolfe (1958) also consider only a limited number of places at which to obtain warehouse space. However, their problem considers only the leasing of warehouse space and consequently the number of available locations is already limited and no heuristic is required to restrict the alternatives to be considered.

evaluating a finite number of concentrations of demand than in searching blindly for a possible profitable desolate location. (If management or the program operator is interested in evaluating any specific locations of this type, they can be entered as alternatives.)

2. *Near optimum warehousing systems can be developed by locating warehouses one at a time, adding at each stage of the analysis that warehouse which produces the greatest cost savings for the entire system.* The use of this heuristic reduces the time and effort expended in evaluating patterns of warehouse sites. Thus, if there are  $M$  possible warehouse locations, the above heuristic would reduce the number of cost evaluations necessary from  $2^m$  to approximately  $N(M' + 1) < NM$  where  $N$  is the size of the intermediate buffer, discussed further below, and  $M'$  is the number of warehouses located. One can think of several classes of examples in which this heuristic would not work very well. However, such situations appear to occur only rarely in practice.

3. *Only a small subset of all possible warehouse locations need be evaluated in detail at each stage of the analysis to determine the next warehouse site to be added.* To insure adding that warehouse location producing the greatest cost savings we could evaluate completely each of the remaining potential warehouse sites. The time required by such an approach can, however, be reduced very substantially with the addition of only slight risk with a good, easily computed method of screening potential sites. The heuristic used for screening calls for  $N$  of the  $M$  potential warehouse locations ( $M > N > 1$ ) to be evaluated in detail at each stage (see step 3, Figure 1, Flow Diagram). The  $N$  potential warehouse sites chosen at each stage are those which, considering only local demand, would result in the greatest cost savings (or smallest increase in costs) if serviced by a local warehouse rather than by the system existing in the previous stage (see step 2, Flow Diagram). In other words, it is assumed that at any stage we can do reasonably well by locating the next warehouse in one of the  $N$  areas chosen on the basis of local demand and related warehousing and transportation costs.

In the detailed evaluation of each of the  $N$  locations placed in the buffer at each stage, the program either eliminates the site



from further consideration, assigns a warehouse to that location, or returns the location to the list of potential warehouse sites for reconsideration at later stages in the program (steps 4, 6 and 7, respectively, in the Flow Diagram). Any site whose addition would not reduce total distribution costs is eliminated from further analysis in the main program. Of those sites which reduce total costs, that location which affords the greatest savings is assigned a warehouse; all others are returned to the list of potential warehouse sites. When the list of potential warehouses is depleted, all sites having been either eliminated or assigned a warehouse, the program enters the Bump and Shift Routine.

The Bump and Shift Routine is designed to modify solutions reached in the main program in two ways. It first eliminates (bumps) any warehouse which is no longer economical because some of the customers originally assigned to it are now serviced by warehouses located subsequently. Then, to insure the servicing of each of the territories established above from a single warehouse within each territory in the most economical manner, the program considers shifting each warehouse from its currently assigned location to the other potential sites (original list) within its territory. It should be noted that this routine does not guarantee that each territory will in fact be serviced in the most economical manner (this deficiency is illustrated below with reference to several sample problems).

The basic steps in the heuristic program are summarized in the Flow Diagram, Figure 1. Before going on to examine the results obtained in applying this program to several sample problems, let us discuss briefly the heuristics used in handling the shipping cost data (see step 1d, Flow Diagram). The inclusion of lists of actual transportation costs and delay times (or distance) between all potential shipping points as data might appear to be unwieldy relative to the Shycon-Maffei approach (1960) outlined in Appendix II, since locating  $M$  customers and warehouses by longitude and latitude takes only  $M$  computer locations whereas up to  $M^2/2$  locations are required for recording all shipping costs. In practice the problem is not nearly so unwieldy and produces some compensations. For example, in many cases *a priori* judgements can be made that customers in certain geographical regions will not be serviced from potential warehouses in other regions. Thus, in

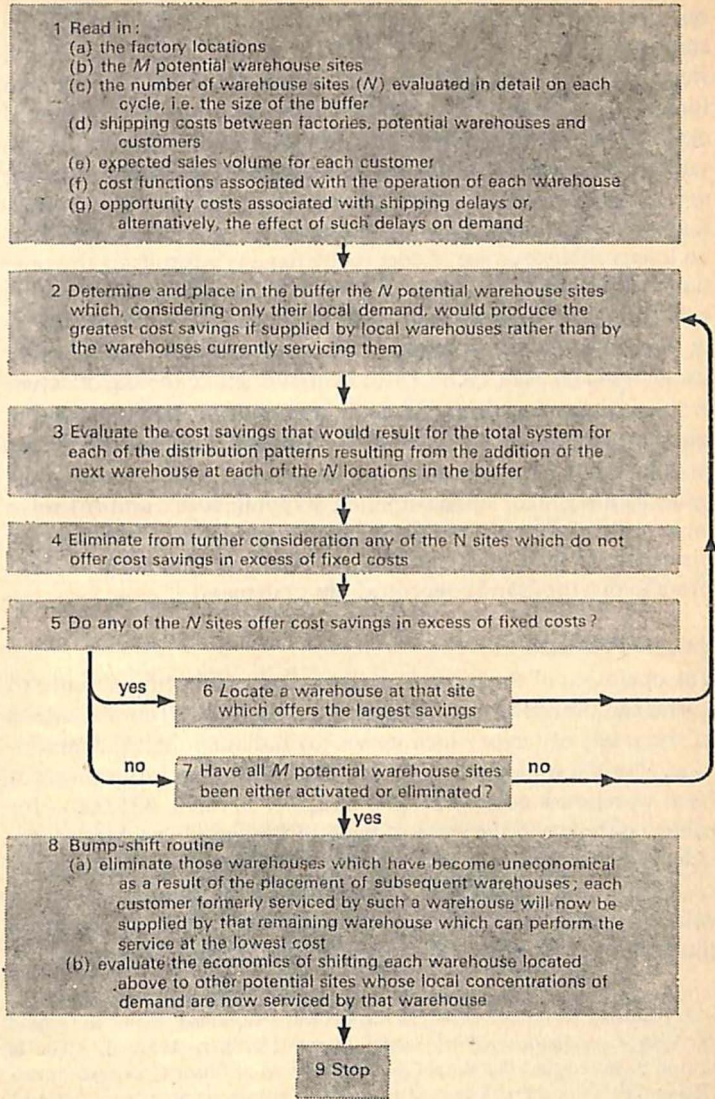


Figure 1 Flow diagram

one of the sample problems discussed below, we do not consider shipping from warehouses in Eastern cities to the West Coast since the factory is located in Indianapolis. In addition, customers can frequently be aggregated into concentrations of demand (for example, metropolitan chain grocery and wholesaler warehouses) because of close geographical proximity. The program also automatically eliminates from the search list potential warehouse sites and warehouse-customer combinations that no longer offer promise of cost reduction. As a result, by the time that the program has located two or three warehouses, the list being searched is frequently reduced by 90 per cent. The reduction in list size continues as more warehouses are added, speeding up the analysis on each cycle. These heuristics make the use of actual costs computationally efficient (computation times for twelve sample problems are outlined in the following section). They also permit us to: (i) avoid the errors associated with the use of air miles as a basis for approximating shipping costs; and (ii) solve large-scale problems, involving, for example, several factories, ten products, at least two hundred potential warehouse sites, and more than a thousand concentrations of demand.

### Sample Problems

The operation of the program will be illustrated with reference to twelve sample problems. The problems represent all combinations of three sets of factory locations – (a) Indianapolis, (b) Jacksonville, Florida, (c) Indianapolis and Baltimore – and four levels of fixed warehouse costs – \$7,500, \$12,500, \$17,500, \$25,000 – for each warehouse in the system. Each of the sample problems considers only a single product. Transportation costs and costs associated with shipping delays are assumed to be proportional to the railroad distance between shipping points.<sup>3</sup> For purposes of illustration, bulk shipping rates from the factory to warehouses

3. Railroad distances between cities were obtained from the *Rand McNally-Cosmopolitan World Atlas* (Rand McNally, 1951, p. 193). It should be noted that the simplifying assumption of linearity of transportation and delay costs with respect to railroad mileage is strictly a matter of convenience in making the cost data available to the reader. In practice, actual shipping costs and delay times would generally be read into the computer.

are evaluated at \$0.0125 per mile per unit, whereas the sum of the shipping and delay costs from warehouses to customers is considered to be \$0.0250 per mile per unit. To further simplify the twelve distribution problems analysed in this paper, the variable costs of operating the warehouses are assumed to be linear with respect to the volume of goods processed.<sup>4</sup> Consequently, these costs do not affect the optimal warehouse system and need not be further considered in the sample problems.<sup>5</sup> The size of the buffer ( $N$ ) was equal to five in each of the twelve sample problems.

The market structure considered in the sample problems consists of fifty concentrations of demand scattered throughout the United States. Twenty-four of these centers of demand are treated as potential warehouse sites. The metropolitan population of each of these areas was used to represent sales potential, a population of 1000 representing one unit of demand (see Table 4).

The results obtained for each of the twelve cases are shown in Tables 1 through 3. These tables summarize:

1. The warehouse locations selected by the main program, in the order of selection.
2. The modifications introduced into the main program solution by the bump-shift routine.
3. Alterations to the heuristic warehouse network which are known to lower total distribution costs.
4. The total distribution costs at each stage of the heuristic

4. The twelve sample problems were not specified so as to fully test the generality of the program. The simplification of linear warehousing cost functions was incorporated in the test problems so that the heuristic solutions obtained might subsequently be compared with optimal solutions developed by the application of integer programming. Such a comparison has not yet been made since we are not aware of the existence of an integer programming routine capable of solving a problem of this size.

5. It should be noted that the heuristic program, in addition to being able to treat the case where both shipping costs and the variable and fixed costs of warehousing vary throughout the country, can determine which of several different types of warehouses (some of which might include packaging facilities) and transportation systems should be used to service each concentration of demand. The program can also be employed to locate regional factories, choosing among alternative factory sites for which production costs are specified.

**Table 1** Heuristic Solutions to Sample Problems Factory Location: Indianapolis

*Fixed costs of warehouses*

| \$7500                                                 |                                     | \$12,500                                               |                                     | \$17,500                                               |                                     | \$25,000                                               |                                     |
|--------------------------------------------------------|-------------------------------------|--------------------------------------------------------|-------------------------------------|--------------------------------------------------------|-------------------------------------|--------------------------------------------------------|-------------------------------------|
| <i>warehouse located at each stage</i>                 | <i>cost of system at each stage</i> | <i>warehouse located at each stage</i>                 | <i>cost of system at each stage</i> | <i>warehouse located at each stage</i>                 | <i>cost of system at each stage</i> | <i>warehouse located at each stage</i>                 | <i>cost of system at each stage</i> |
| <i>Main program</i>                                    |                                     | <i>Main program</i>                                    |                                     | <i>Main program</i>                                    |                                     | <i>Main program</i>                                    |                                     |
| No warehouses                                          | \$1,248,688                         | No warehouses                                          | \$1,248,688                         | No warehouses                                          | \$1,248,688                         | No warehouses                                          | \$1,248,688                         |
| Philadelphia                                           | 1,075,120                           | Philadelphia                                           | 1,080,120                           | Philadelphia                                           | 1,085,120                           | Philadelphia                                           | 1,092,620                           |
| Los Angeles                                            | 910,514                             | Los Angeles                                            | 920,514                             | Los Angeles                                            | 930,514                             | Los Angeles                                            | 945,514                             |
| Seattle                                                | 876,429                             | Seattle                                                | 891,429                             | Seattle                                                | 906,429                             | Seattle                                                | 928,929                             |
| San Francisco                                          | 861,967                             | San Francisco                                          | 881,967                             | San Francisco                                          | 901,967                             |                                                        |                                     |
| Houston                                                | 850,645                             | Houston                                                | 875,645                             | Houston                                                | 900,645                             | <i>Bump-shift routine</i>                              |                                     |
| Chicago                                                | 839,853                             | Chicago                                                | 869,853                             | Chicago                                                | 899,853                             | No change                                              | \$928,929                           |
| New York                                               | 830,424                             | New York                                               | 865,424                             |                                                        |                                     | <i>Improvements not found by the heuristic program</i> |                                     |
| Detroit                                                | 824,721                             | Detroit                                                | 864,721                             | <i>Bump-shift routine</i>                              |                                     | <i>None known</i>                                      |                                     |
| Denver                                                 | 819,073                             | Kansas City                                            | 860,484                             | Replace Houston with Dallas                            | \$896,864                           |                                                        |                                     |
| Pittsburgh                                             | 815,818                             | Atlanta                                                | 859,125                             | <i>Improvements not found by the heuristic program</i> |                                     |                                                        |                                     |
| Washington, D.C.                                       | 813,321                             | Cleveland                                              | 858,764                             |                                                        |                                     |                                                        |                                     |
| Kansas City                                            | 809,827                             | <i>Bump-shift routine</i>                              |                                     |                                                        |                                     |                                                        |                                     |
| Boston                                                 | 808,203                             | Drop Detroit                                           | \$857,725                           |                                                        |                                     |                                                        |                                     |
| Atlanta                                                | 801,845                             | Replace Phila. with Wash.                              | 856,257                             |                                                        |                                     |                                                        |                                     |
| <i>Bump-shift routine</i>                              |                                     | <i>Improvements not found by the heuristic program</i> |                                     |                                                        |                                     |                                                        |                                     |
| Drop Denver                                            | \$801,748                           | Replace Houston with Dallas                            | \$854,672                           |                                                        |                                     |                                                        |                                     |
| <i>Improvements not found by the heuristic program</i> |                                     |                                                        |                                     |                                                        |                                     |                                                        |                                     |
| Replace Houston with Dallas                            | \$800,163                           |                                                        |                                     |                                                        |                                     |                                                        |                                     |

**Table 2** Heuristic Solutions to Sample Problems Factory Location: Jacksonville

*Fixed costs of warehouses*

| \$7500                                                 |                                     | \$12,500                                               |                                     | \$17,500                                               |                                     | \$25,000                                               |                                     |
|--------------------------------------------------------|-------------------------------------|--------------------------------------------------------|-------------------------------------|--------------------------------------------------------|-------------------------------------|--------------------------------------------------------|-------------------------------------|
| <i>warehouse located at each stage</i>                 | <i>cost of system at each stage</i> | <i>warehouse located at each stage</i>                 | <i>cost of system at each stage</i> | <i>warehouse located at each stage</i>                 | <i>cost of system at each stage</i> | <i>warehouse located at each stage</i>                 | <i>cost of system at each stage</i> |
| <i>Main program</i>                                    |                                     | <i>Main program</i>                                    |                                     | <i>Main program</i>                                    |                                     | <i>Main program</i>                                    |                                     |
| No warehouses                                          | \$1,832,861                         | No warehouses                                          | \$1,832,861                         | No warehouses                                          | \$1,832,861                         | No warehouses                                          | \$1,832,861                         |
| New York                                               | 1,602,504                           | New York                                               | 1,607,504                           | New York                                               | 1,612,504                           | New York                                               | 1,620,004                           |
| Los Angeles                                            | 1,376,900                           | Los Angeles                                            | 1,386,900                           | Los Angeles                                            | 1,396,900                           | Los Angeles                                            | 1,411,900                           |
| Chicago                                                | 1,239,864                           | Chicago                                                | 1,254,864                           | Chicago                                                | 1,269,864                           | Chicago                                                | 1,292,364                           |
| Seattle                                                | 1,211,687                           | Seattle                                                | 1,231,687                           | Seattle                                                | 1,251,687                           | Seattle                                                | 1,281,687                           |
| Washington, D.C.                                       | 1,169,916                           | Washington, D.C.                                       | 1,194,916                           | Washington, D.C.                                       | 1,219,916                           | Washington, D.C.                                       | 1,257,416                           |
| St Louis                                               | 1,143,998                           | St Louis                                               | 1,173,998                           | St Louis                                               | 1,203,998                           | St Louis                                               | 1,248,998                           |
| Cincinnati                                             | 1,123,224                           | Cincinnati                                             | 1,158,224                           | Cincinnati                                             | 1,193,224                           | Cincinnati                                             | 1,245,724                           |
| Houston                                                | 1,106,239                           | Houston                                                | 1,146,239                           | Houston                                                | 1,186,239                           |                                                        |                                     |
| San Francisco                                          | 1,098,949                           | San Francisco                                          | 1,143,949                           |                                                        |                                     |                                                        |                                     |
| Denver                                                 | 1,096,245                           | <i>Bump-shift routine</i>                              |                                     | <i>Bump-shift routine</i>                              |                                     | <i>Bump-shift routine</i>                              |                                     |
| Detroit                                                | 1,093,780                           | No change                                              | \$1,143,949                         | No change                                              | \$1,186,239                         | No change                                              | \$1,245,724                         |
| Pittsburgh                                             | 1,092,163                           | <i>Improvements not found by the heuristic program</i> |                                     | <i>Improvements not found by the heuristic program</i> |                                     | <i>Improvements not found by the heuristic program</i> |                                     |
| Atlanta                                                | 1,091,374                           | None known                                             |                                     | None known                                             |                                     | None known                                             |                                     |
| <i>Bump-shift routine</i>                              |                                     |                                                        |                                     |                                                        |                                     |                                                        |                                     |
| No change                                              | \$1,091,374                         |                                                        |                                     |                                                        |                                     |                                                        |                                     |
| <i>Improvements not found by the heuristic program</i> |                                     |                                                        |                                     |                                                        |                                     |                                                        |                                     |
| None known                                             |                                     |                                                        |                                     |                                                        |                                     |                                                        |                                     |

**Table 3** Heuristic Solutions to Sample Problems Factory Locations: Baltimore and Indianapolis

*Fixed costs of warehouses*

| \$7500                                                 |                                     | \$12,500                                               |                                     | \$17,500                                               |                                     | \$25,000                                               |                                     |
|--------------------------------------------------------|-------------------------------------|--------------------------------------------------------|-------------------------------------|--------------------------------------------------------|-------------------------------------|--------------------------------------------------------|-------------------------------------|
| <i>warehouse located at each stage</i>                 | <i>cost of system at each stage</i> | <i>warehouse located at each stage</i>                 | <i>cost of system at each stage</i> | <i>warehouse located at each stage</i>                 | <i>cost of system at each stage</i> | <i>warehouse located at each stage</i>                 | <i>cost of system at each stage</i> |
| <i>Main program</i>                                    |                                     | <i>Main program</i>                                    |                                     | <i>Main program</i>                                    |                                     | <i>Main program</i>                                    |                                     |
| No warehouses                                          | \$899,770                           | No warehouses                                          | \$899,770                           | No warehouses                                          | \$899,770                           | No warehouses                                          | \$899,770                           |
| Los Angeles                                            | 735,164                             | Los Angeles                                            | 740,164                             | Los Angeles                                            | 745,164                             | Los Angeles                                            | 752,664                             |
| Seattle                                                | 701,079                             | Seattle                                                | 711,079                             | Seattle                                                | 721,079                             | Seattle                                                | 736,079                             |
| New York                                               | 672,666                             | New York                                               | 687,666                             | New York                                               | 702,666                             | New York                                               | 725,166                             |
| San Francisco                                          | 658,205                             | San Francisco                                          | 678,205                             | San Francisco                                          | 698,205                             |                                                        |                                     |
| Houston                                                | 646,882                             | Houston                                                | 671,882                             | Dallas                                                 | 691,772                             | <i>Bump-shift routine</i>                              |                                     |
| Chicago                                                | 636,091                             | Chicago                                                | 666,091                             | Chicago                                                | 690,980                             | No change                                              | \$725,166                           |
| Denver                                                 | 630,442                             | Kansas City                                            | 661,853                             |                                                        |                                     | <i>Improvements not found by the heuristic program</i> |                                     |
| Detroit                                                | 626,481                             | <i>Bump-shift routine</i>                              |                                     | <i>Bump-shift routine</i>                              |                                     | <i>Improvements not found by the heuristic program</i> |                                     |
| Kansas City                                            | 623,114                             | No change                                              | \$661,853                           | No change                                              | \$690,980                           | None known                                             |                                     |
| Cleveland                                              | 620,405                             | <i>Improvements not found by the heuristic program</i> |                                     | <i>Improvements not found by the heuristic program</i> |                                     |                                                        |                                     |
| Atlanta                                                | 617,337                             | Replace Houston with Dallas                            |                                     | None known                                             |                                     |                                                        |                                     |
| <i>Bump-shift routine</i>                              |                                     |                                                        |                                     |                                                        |                                     |                                                        |                                     |
| Drop Denver                                            | \$617,116                           |                                                        |                                     |                                                        |                                     |                                                        |                                     |
| <i>Improvements not found by the heuristic program</i> |                                     |                                                        |                                     |                                                        |                                     |                                                        |                                     |
| Replace Houston with Dallas                            | \$615,531                           |                                                        |                                     |                                                        |                                     |                                                        |                                     |

solution and for the warehouse network which incorporates subsequent improvements.<sup>6</sup>

In each of the four cases in which an improvement upon the heuristic solution was discovered, the improvement consisted of replacing a warehouse in Houston with a warehouse in Dallas. This improvement was not found by the shift portion of the bump-shift routine since Dallas was not being serviced from the Houston warehouse. The shift routine as currently programed considers as alternatives only those warehouse sites which are located within the territory served by the warehouse under examination. The rationale for limiting the alternatives considered in this fashion was (a) it provided a convenient method of identifying most of the near-by unactivated warehouse sites, and (b) computation time would be minimized by not considering the realignment of regions at this point in the program.

The shift routine as specified above cannot be applied directly to multiple product systems in which different mixes of products might be shipped to the customer from different warehouses since the regions for the different product mixes will not necessarily be identical. A simple heuristic now being programed to treat the

6. The improvements upon the heuristic solutions tabulated for four of the twelve problems have been found by evaluating the modifications in the heuristic distribution network which, upon inspection, appeared most likely to result in lower distribution costs. Approximately twenty-five types of modifications were tested, but only one resulted in a minor improvement in four of the problems. To determine the optimal system by complete enumeration would require the evaluation of the  $2^{24}$  possible ways of locating up to twenty-four warehouses. With an IBM-704, which could perform approximately one such evaluation per second, this operation would take more than six months of continuous operation per problem. Testing all combinations of three and four warehouses, which would probably be sufficient to insure finding the optimal network for any one of the two least interesting cases (those problems in which, because of high fixed warehousing costs, the heuristic program locates only three warehouses) would require approximately four computer hours. The use of integer programming offers more promise. Once such a computer program is available, it should be feasible to test the sample problem solutions we have found for optimality in one iteration by using the heuristic solutions as the initial basis for the integer program. This points to another possible application for heuristic programming. In so far as heuristics can be used to develop an advanced starting basis for an integer programming problem, a substantial reduction in the total computation time required to reach an optimum may be possible.



**Table 4** Sales Potential of Concentrations of Demand Used in Sample Problems (Population in 1000s)

| <i>Concentrations of demand</i> | <i>Sales potential</i> | <i>Concentrations of demand</i> | <i>Sales potential</i> |
|---------------------------------|------------------------|---------------------------------|------------------------|
| Albuquerque, N. Mex.            | 146                    | Knoxville, Tenn.                | 337                    |
| Amarillo, Tex.                  | 87                     | Los Angeles, Calif.*            | 4368                   |
| Atlanta, Ga.*                   | 672                    | Louisville, Ky.                 | 577                    |
| Baltimore, Md.                  | 1337                   | Memphis, Tenn.*                 | 482                    |
| Billings, Mont.                 | 31                     | Miami, Fla.*                    | 495                    |
| Birmingham, Ala.                | 559                    | Mobile, Ala.                    | 231                    |
| Boston, Mass.*                  | 2370                   | Nashville, Tenn.                | 322                    |
| Buffalo, N.Y.*                  | 1089                   | New Orleans, La.*               | 685                    |
| Butte, Mont.                    | 33                     | New York, N.Y.*                 | 12912                  |
| Cheyenne, Wyo.                  | 32                     | Oklahoma City, Okla.            | 325                    |
| Chicago, Ill.*                  | 5495                   | Omaha, Nebr.                    | 366                    |
| Cincinnati, Ohio*               | 904                    | Philadelphia, Pa.*              | 3671                   |
| Cleveland, Ohio*                | 1466                   | Pittsburgh, Pa.*                | 2213                   |
| Columbia, S. C.                 | 143                    | Portland, Oreg.                 | 705                    |
| Dallas, Tex.*                   | 615                    | Richmond, Va.                   | 328                    |
| Denver, Colo.*                  | 564                    | St. Louis, Mo.*                 | 1681                   |
| Des Moines, Iowa                | 226                    | St. Paul, Minn.*                | 1117                   |
| Detroit, Mich.*                 | 3016                   | Salt Lake City, Utah*           | 275                    |
| Duluth, Minn.                   | 253                    | San Antonio, Tex.               | 500                    |
| El Paso, Tex.                   | 195                    | San Francisco, Calif.*          | 2241                   |
| Fargo, N. Dak.                  | 38                     | Seattle, Wash.*                 | 733                    |
| Houston, Tex.*                  | 807                    | Spokane, Wash.                  | 222                    |
| Indianapolis, Ind.              | 551                    | Tucson, Ariz.                   | 49                     |
| Jacksonville, Fla.              | 304                    | Washington, D. C.*              | 1464                   |
| Kansas City, Mo.*               | 814                    | Wichita, Kansas                 | 222                    |

\* Potential warehouse sites.

Source: *The World Almanac* (1960).

multiple product problem considers shifting the warehouses located by the main program to all sites specified in the input as 'neighboring warehouse sites'. That is, the neighboring warehouse sites of each potential warehouse location are specified in the input to the program and are evaluated as alternatives in the shift routine. Since this routine does not make use of the concept of warehouse territories, it will also correct errors of the Dallas-

Houston variety when applied to problems involving only a single product. (This routine will increase computation time in most cases.) It will not, however, correct for less-localized deviations of the main program solution from the optimal warehouse network.

In considering the development of new or more elaborate bump-shift routines (or, the inclusion of such devices in the main program to be performed after the addition of each warehouse) it is desirable to determine the improvements which might be expected. In the twelve sample problems discussed above, the improvements upon the main program solution developed in the bump-shift routine and through subsequent analysis never amounted to more than 0.5 per cent. If future research indicates that the main program solution is generally near-optimal, it would give strong support to the use of the three basic heuristics in the main program and limit the gain to be expected in searching for corrective routines.

Some support for the heuristic which selects warehouse sites to be placed in the buffer is obtained by reference to the frequency distribution of warehouses selected for activation in the twelve sample problems from each of the positions in the five-place buffer used in the analysis. This distribution is tabulated in Table 5, the buffer positions representing the rank of the potential warehouse sites in terms of their cost savings considering only local demand (Step 2, Figure 1, Flow Diagram).

*Table 5* Frequency distribution of warehouses selected for activation from each position in the buffer

| <i>Position in the buffer</i> | <i>Number of warehouses located from each position</i> | <i>Percentage of total warehouses located from each position</i> |
|-------------------------------|--------------------------------------------------------|------------------------------------------------------------------|
|                               |                                                        | per cent                                                         |
| 1                             | 48                                                     | 49.0                                                             |
| 2                             | 15                                                     | 15.3                                                             |
| 3                             | 15                                                     | 15.3                                                             |
| 4                             | 10                                                     | 10.2                                                             |
| 5                             | 10                                                     | 10.2                                                             |

### *Computation time*

The time required to reach a solution for the twelve sample problems in the main program totaled seventy-two minutes on an IBM-650 with RAMAC disc storage. The individual problems required an average of two minutes setup time and thirty seconds per warehouse located. Experimentation with and analysis of the heuristic program indicates that computation time increases at a much slower rate with increases in problem size than is the case with linear programming algorithms designed to handle fixed cost elements. It appears that the problem set up time increases linearly with the product of the number of warehouses, the number of products, and the number of customers (concentrations of demand). The time required for locating warehouses increases approximately linearly with the size of the buffer ( $N$ ), the number of products, and the number of customers, but almost negligibly with the number of potential warehouse sites. The effect of multiple factories on setup time is at most linear; if capacity constraints are not operative the effect is substantially less than linear. Surprisingly, increasing the number of factories actually tends to decrease the total warehouse location time since there is no effect upon the time required to locate individual warehouses and the total number of warehouses located will generally be reduced.

Accurate time estimates for the bump-shift routine are not available since only an inefficient routine was operating when the IBM-650 at Carnegie Tech was replaced. Processing the twelve sample problems with this version of the bump-shift routine required a total of one hour. We would expect an efficient computer routine to perform this operation in ten to fifteen minutes since comparable reductions in computer time were achieved in the revision of the main program.

### *Extensions and applications*

Improved heuristics in terms of reduced computation time and/or more nearly optimum solutions of the warehouse location problem will probably be forthcoming. The six-minute solution time on an IBM-650 in itself probably suggests to the reader that additional check and bump-shift routines might be interspersed between the location of individual warehouses; after all, the

difference in cost between six minutes and even six hours of computation time on an IBM-650 is negligible relative to the cost savings that might be achieved in the sample warehouse network problems studied. It is not clear, however, that such approaches will on the average improve upon the solutions generated by the existing heuristic program if at least four warehouses are located. Care must also be taken to avoid the chase for optimal solutions to simple problems and thereby miss the actual problem of business – the solution of large-scale problems containing many customers buying various mixes of a full product line, many potential warehouse sites, alternate warehouse types with different cost structures, several factories and, perhaps, a number of potential factory sites.<sup>7</sup>

Two warehouse network problems containing many of the above complexities are now being examined, one representing the distribution of a variety of grocery-drug type consumer products, the other a line of consumer appliances. In both cases the problem is of such magnitude that the solution time could easily come to several hours on an IBM-7090 computer unless the problem is simplified beyond the level now thought to be desirable. Furthermore, in view of some uncertainty as to the actual nature of warehousing costs, it appears prudent to make several runs with different warehousing cost functions to determine the sensitivity

7. It should be noted that the distribution of order-shipment mixes of products can be treated by considering each geographical concentration of demand as several concentrations at the same location, each concentration representing a given mix of products of a given total size. In so far as discrete distributions can be used to approximate the empirical distributions, the specification of the problem can be greatly simplified. The number of computer locations required to store each of these mixes would then be reduced substantially from that which would be required if each of the mixes were treated as the demand at an individual geographical location. An interesting aspect of this treatment of the problem is that the total warehouse network would be established with full recognition of the fact that customers will not necessarily receive all of their shipments from a single warehouse if all factories do not produce all products. An order of packaged detergents and toilet bar soap, for example, might be received from one warehouse if it consists largely of detergent and from another if the order is primarily composed of bar soaps. Similarly, not all products will necessarily be stocked at all warehouses. In the distribution of appliances, for example, yellow refrigerators, for which there is a relatively small demand, might be stocked in only the larger warehouses.

of the heuristic warehouse solutions to the cost functions. It is in this context that the advantages of improved solutions to test problems must be evaluated relative to increased computer time requirements. Additional check or bump-shift heuristics increasing computer time on test problems from six minutes to six hours would increase the IBM-7090 time per run from 3-6 hours to 180-360 hours, time which might well be better spent in testing the sensitivity of the solutions to variations in warehouse cost structures and in providing an improved model of demand through greater detail in the description of the product mix and size of customer orders.

It has been suggested that the heuristics might be applied by eliminating warehouses rather than adding them. That is, a warehouse is assumed to be operating at each potential site at the start of the program. Warehouses would then be eliminated one by one on the basis of cost savings. It is not clear how the quality of solutions produced in this manner would compare with those developed from the heuristic program outlined in this paper. In terms of computation time, however, it seems likely that the current program would be the more efficient when the number of warehouses located is less than half the number of potential sites being considered. This seems to be generally the case in industry although situations could, no doubt, be found where this is not true (for example, the firm which is interested only in considering the possibility of closing existing warehouses).

Once we know the optimal solutions to the test problems (through the application of integer programming, using the heuristic solution as a starting basis), we will be in a better position to evaluate the potential gains possible through the use of improved heuristics. In addition, knowledge of the optimal solution should provide sound direction as to the types of heuristics which offer most promise in correcting the deviations inherent in the current program.

## Summary

A heuristic program was developed and applied to several warehouse location problems. The results suggest that a heuristic approach to this class of problems may be quite profitable in

practice, producing near-optimal solutions within acceptable limits of computer time.

The use of heuristics in solving these problems has two prime advantages relative to the currently available linear programming formulations and solution procedures: (i) computational simplicity, which results in substantial reductions in solution times and permits the treatment of large-scale problems, and (ii) flexibility with respect to the underlying cost functions, eliminating the need for restrictive assumptions. It also represents an important extension to the simulation approach to locating warehouses in that it incorporates a systematic procedure designed to generate at least one near-optimal distribution system without reducing flexibility in the modeling of the problem.

The proposed heuristic program permits fast screening and evaluation of alternative types of warehouses, transportation systems, and warehouse locations. It should, however, be emphasized that this program is not the end of the road. It may some day become practical to solve large-scale warehouse location problems with optimizing algorithms given continued development of computer hardware and linear programming techniques. Heuristic programming, too, is capable of improvement and such developments will probably be forthcoming as a result of the large amount of research on heuristic models and computer programming now being carried on at the RAND Corporation, Carnegie Tech, and elsewhere.

## Appendix 1 Mathematical Formulation of the Warehouse Location Problem

The problem can be expressed mathematically as follows:

$X_{h,i,j,k}$  = the quantity of good  $h$  ( $h = 1, \dots, p$ ) shipped from factory  $i$  ( $i = 1, \dots, q$ ) via warehouse  $j$  ( $j = 1, \dots, r$ ) to customer  $k$  ( $k = 1, \dots, s$ ).

$A_{h,i,j}$  = the per unit transportation cost of shipping good  $h$  from factory  $i$  to warehouse  $j$ .

$B_{h,j,k}$  = the per unit transportation cost of shipping good  $h$  from warehouse  $j$  to customer  $k$ .

$C_{h,j} \left( \sum_{[i,k]} X_{h,i,j,k} \right)$  = total cost of warehouse operation associated with processing good  $h$  at warehouse  $j$ . Without loss of generality

we may express this function as the sum of  $S_{h,j}$  and  $F_j$  defined below.

$D_{h,k}(T_{h,k})$  = explicit or imputed cost due to a delay of  $T$  time units in delivery of good  $h$  to customer  $k$ . When the customer imposes a maximum delivery time (constraint),  $D$  becomes infinite whenever the indicated time limit is reached.<sup>8</sup>

$F_j$  = fixed cost per time period of operating warehouse  $j$ . Note that this is a planned fixed cost to be incurred and not a sunk cost.

$S_{h,j}(\sum_{i,k} X_{h,i,j,k})$  = semi-variable cost of operating warehouse  $j$  per unit of good  $h$  processed, including variable handling and administrative costs, storage costs, taxes, interest on investment, pilferage, and so on (the homogeneous portion of the very general function  $C_{h,j}$ ).

$Q_{h,k}$  = quantity of good  $h$  demanded by customer  $k$ .

$W_j$  = capacity of warehouse  $j$ .

$Y_{h,i}$  = capacity of factory  $i$  to produce good  $h$ .

$Z_j = 1$  if  $\sum_{h,i,k} X_{h,i,j,k} > 0$  and zero otherwise (that is,  $\sum Z_j$  = the number of warehouses used).

The problem then becomes one of minimizing total distribution costs, an objective function of the form

$$f(X) = \sum_{h,i,j,k} (A_{h,i,j,k} + B_{h,j,k}) X_{h,i,j,k} + \sum F_j \cdot Z_j + \sum_{h,j} S_{h,j} (\sum_{i,k} X_{h,i,j,k}) + \sum_{h,k} D_{h,k} (T_{h,k}),$$

subject to constraints of the following form:

$\sum_{i,j} X_{h,i,j,k} = Q_{h,k}$  (customer  $k$ 's demand for product  $h$  must be supplied),

$\sum_{j,k} X_{h,i,j,k} \leq Y_{h,i}$  (factory  $i$ 's capacity limit on good  $h$  cannot be exceeded),

$I_j(\sum_{h,i,k} X_{h,i,j,k}) \leq W_j$  (the capacity of warehouse  $j$  cannot be exceeded),

8. The effect of delay in supplying customers has been treated above as an 'opportunity cost' since this simplifies the notation and is consistent with current research practice. However, an alternative formulation which reflects management's view of the problem more accurately is to have delivery times affect demand.

where  $I_j \left( \sum_{h,i,j} X_{h,i,j,k} \right)$  is a function which denotes the maximum inventory level associated with the flow of all goods from all factories to all customers serviced through warehouse  $j$ .

## Appendix 2 A Comparative Study of Alternative Approaches to the Warehouse Location Problem

### *Linear programming*

In theory, a linear programming approach (for example, using Gomory's (1958) integer algorithm or other variations) could be used to solve the problem. In practice, however, the size and nonlinearities involved in many problems are such that application is not currently feasible.<sup>9</sup>

The most important types of nonlinearities generally encountered stem from the fixed costs associated with the operation of warehouses and variable warehousing and delivery costs which are nonlinear. Two types of warehousing and delivery cost functions have been suggested in the literature, strictly concave functions and piecewise linear functions. Figure 2 describes the strictly concave cost function proposed by Baumol and Wolfe (1958). Figure 3 represents the piecewise linear function which, apart from the fixed cost element, is equivalent to that illustrated by Balinski and Mills (1960). The fixed cost element is incorporated in Figure 3 for purposes of generality.<sup>10</sup>

Both of the above functions describe essentially the same types of cost structures, that is, cost structures where the transportation rates and the marginal cost of operating a warehouse decrease as the quantity of goods handled by the warehouse increases. The different functions reflect slightly different views of the total problem, Baumol and Wolfe focusing primarily upon the warehouse operating costs which, in a sample problem, they approxi-

9. The difficulties that have been encountered in applying linear programming directly to the warehouse location problem are similar to those encountered in the application of these algorithms to production scheduling problems. See, for example, Holt, Modigliani, Muth and Simon (1960, ch. 20).

10. In the previous formulation of the warehouse location problem the warehouse operating costs and the cost of delivering goods to warehouses were separated. However, these two types of costs may be combined into one function without any loss of generality.





Figure 2 A strictly concave function describing warehousing and delivery costs

mate by square root functions (see Baumol and Wolfe, 1958, p. 255) and Balinski and Mills concentrating upon freight and storage rates specified in terms of the volume of goods handled.

Let us now examine several other approaches to the warehouse location problem discussed in the literature, paying particular attention to the treatment of those aspects of the problem not handled adequately by linear programming in its current state of development.

## *The Baumol-Wolfe marginal cost approach*

Baumol and Wolfe (Baumol, 1961; Baumol and Wolfe, 1958) pose the problem as minimizing total distribution costs which, utilizing the symbols defined above, may be stated as follows:

$$\min f(X) =$$

$$\min \sum_{i,j,k} (A_{i,j} + B_{j,k}) X_{i,j,k} + \sum_j S_j \left( \sum_{i,k} X_{i,j,k} \right) + \sum_j F_j \cdot Z_j$$

subject to

$$I_j \left( \sum_{i,k} X_{i,j,k} \right) \leq W_j \quad (\text{the warehouse capacity constraint}),$$



Figure 3 A piecewise linear function describing warehousing and delivery costs

and  $\sum_{i,j} X_{i,j,k} = Q_k$  (customer demand constraint, that is, all demands must be satisfied).

The effects of delay in delivery times are not incorporated into the Baumol-Wolfe treatment of the problem although it is apparent that opportunity costs associated with such delays could be added to the shipping costs. It should also be noted that the above symbolic representation of the problem requires only three subscripts. The reason for this is that the Baumol and Wolfe method deals with only one product or, perhaps, a composite product (that is, a constant product mix). It is possible that the method can be extended to deal with the multiproduct case although Baumol and Wolfe do not indicate how this might be done.

The Baumol-Wolfe algorithm consists of an iterative procedure which requires the solution of an ordinary transportation problem at each stage. The steps involved in this procedure are as follows:

1. *The initial stage.* For each pair  $i, k$  of factory and retailer, find the least cost of shipment considering only the transportation costs:

$$C_{i,k}^0 = \min_j (A_{i,j} + B_{j,k}) - (A_{i,j_1,k}^0 + B_{j_1,k}^0)$$

where  $j_{i,k}$  denotes the routing between factory  $i$  and customer  $k$  via warehouse  $j$  as selected by this criterion. The superscripts refer to the stage in the solution process. Thus,  $C_{i,k}^0$  is the lowest unit cost of shipping the product from factory  $i$  to customer  $k$  considered over all warehouse possibilities at the initial stage. These  $C_{i,k}^0$  are then used to solve an ordinary transportation problem<sup>11</sup> involving shipments from factories with known availabilities to retailers with known demands so as to minimize the cost function  $\sum_{i,k} C_{i,k}^0 X_{i,k}$ .

2. *The  $n^{\text{th}}$  stage.* Thus starting at stage 0, the iterations are continued until a stage, say  $n-1$ , is reached. From the warehouse loadings computed at stage  $n-1$ ,  $(\sum_{i,k} X_{i,j,k}^{n-1})$ , the marginal warehousing costs are computed by means of the expression

11. Many efficient computing methods for solving this special form of linear programming are available (Dantzig, 1951; Charnes and Cooper, 1954; Ford and Fulkerson, 1956).

$$\frac{dS_j \left( \sum_{i,k} X_{i,j,k}^{n-1} \right)}{d \left( \sum_{i,k} X_{i,j,k}^{n-1} \right)}$$

the derivative of the operating costs of warehouse  $j$ .

The new set of transportation costs to be used in the transportation problem at this stage is defined as

$$C_{i,j,k}^n = \min_j A_{i,j} + B_{j,k} + \frac{dS_j \left( \sum_{i,k} X_{i,j,k}^{n-1} \right)}{d \left( \sum_{i,k} X_{i,j,k}^{n-1} \right)}$$

3. *Test for stopping.* Compare the warehouse loadings of the  $n^{\text{th}}$  stage with those of the previous stage. If the same stop, if different continue by returning to step 2.

The justification for this approach is contained in a set of proofs which Baumol and Wolfe present in their paper. They do not claim that the method will produce an optimal solution but rather that:

(a) 'this procedure will reduce the total cost . . . in each step.'<sup>12</sup>

(b) 'the procedure . . . will yield a solution that probably cannot be improved except by prohibitively expensive computation for large-scale problems.'<sup>13</sup> That is, the method determines a local optimum.<sup>14</sup>

The Baumol-Wolfe method may be satisfactory for solving certain special types of warehouse location problems. However as a general approach to this class of problems the method appears to be unsatisfactory. First, although the formulation of the problem permits fixed costs associated with the operation of warehouses, there appears to be no mechanism within the solution procedure itself designed to handle this aspect of the problem. That is, both the differential calculus as used in adjusting the transportation costs and the transportation model are not well designed to handle fixed-cost elements. Furthermore, even if fixed costs are neglected, the solutions to concave programming problems<sup>15</sup>

12. Baumol and Wolfe (1958), p. 257.

13. Ibid., p. 256.

14. Baumol (1961), p. 413, and Baumol and Wolfe (1958), p. 252.

15. That is, problems in which the cost function possesses the property that  $dC(x)/dx < C(x)/x$ . For a more precise definition see Charnes and Cooper (1961), p. 284.

produced by the Baumol-Wolfe method will frequently not be satisfactory. The quality of the solutions produced will in general depend on the degree of concavity of the cost function. To illustrate the impact which a concave cost function can have upon the solution to even a simple problem, let us consider the example used by Baumol and Wolfe to demonstrate their procedure.

The Baumol-Wolfe sample problem involves two factories, five potential warehouse sites and eight retailers. The problem involves no fixed costs in the operation of warehouses, warehousing costs being regarded as square root functions of warehouse volume. Table 6 shows the solutions derived by several procedures.

*Table 6*

| <i>Method of solution</i>             | <i>Warehouses used</i> | <i>Cost</i> |
|---------------------------------------|------------------------|-------------|
| Baumol-Wolfe*                         | 1, 2, 4, 5             | \$2362      |
| Heuristic program                     | 3                      | \$2047      |
| Arbitrary choice of single warehouses | 1                      | \$2452      |
|                                       | 2                      | \$2379      |
|                                       | 4                      | \$2194      |
|                                       | 5                      | \$2070      |

\* Baumol and Wolfe (1958) calculated the total cost associated with their warehouse network solution as \$2257, which is \$105 less than that tabulated above. This difference is due to an error in the computation of factory to warehouse costs. It should be noted, however, that this error does not in any way influence the Baumol-Wolfe solution with respect to warehouse locations or loadings.

The table shows that the Baumol-Wolfe warehouse location procedure has a strong bias in the direction of locating more than the optimal number of warehouses. Baumol and Wolfe recognized the existence of such a bias (1958, p. 262), but did not, in their paper, concern themselves with the extent of its impact. In fact, the Baumol-Wolfe solution is not even a local optimum in terms of changes in warehouse location patterns; a reduction in total costs can be accomplished by eliminating any one of the four warehouses in the solution set.<sup>16</sup> The heuristic solution, obtained

16. The Baumol-Wolfe solution is a local optimum in the sense that no individual unit of product can be shipped by an alternate route without increasing total distribution costs. Costs can be reduced, however, by transferring the total demand of a retailer (or a major portion thereof) from one warehouse to another or, as indicated above, by eliminating individual ware-

through application of the program discussed in this paper, has since been proven to be the optimal solution.

### *Balinski-Mills average cost method*

The Balinski-Mills approach to the warehouse location problem is similar to that of Baumol and Wolfe in that it requires the problem to be cast in the framework of the linear programming transportation model (Balinski and Mills, 1960). However, that is as far as the similarity goes. Baumol and Wolfe viewed the cost of delivering goods to warehouses and storing them as being described by a concave function whereas Balinski and Mills treated these costs as a piecewise linear function. Furthermore, Balinski and Mills specifically restrict their solution procedure to the case of a single factory (or vendor) and a single product (1960, p. 1).

In terms of the symbols defined above, Balinski and Mills pose the following problem:

Minimize,  $\sum_j C_j (\sum_k X_{j,k}) + \sum_{j,k} B_{j,k} X_{j,k}$  (total distribution costs)

subject to  $I_j (\sum_k X_{j,k}) \leq W_j$  (the warehouse capacity constraint),

and  $\sum_j X_{j,k} = Q_k$  (the customer demand constraint), where the variable portion of  $C_j (\sum_k X_{j,k})$  is a piecewise linear function (see Figure 3).

In principle, an optimal solution to this problem can be found by using integer programming. However as Balinski and Mills point out (1960 p. 6) even small sample problems often involve so many variables and constraints that they cannot now be handled on existing computing equipment. As a result of these restrictions on the current use of integer programming, they develop an approximation technique which they report has proven to be highly successful in certain cases. (Balinski and Mills, 1960, p. 6). This technique consists of approximating

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houses. Baumol (1961) did apparently believe that his solution was a local optimum in the latter sense when he wrote, 'No *minor* changes from this computed set of warehouse locations could yield any reduction in costs (the result was sure to be a local optimum).'

$C_J(\sum_k X_{J,k})$  by

$$\frac{C_J(a_J)}{a_J}$$

where  $a_J = \min_{j,k} (W_J \sum_{j,k} X_{j,k})$ . That is, the warehousing cost function for each warehouse is approximated by the average unit cost of operating that warehouse at some high level, such as the warehouse capacity ( $W_J$ ) or the total flow of goods passing through the system during the year.

By using the above approximation of the warehousing cost function all non-linearities are eliminated from the problem. As a result the problem is cast into the framework of a simple transportation problem. The solution to this transportation problem yields a distribution network which minimizes the objective function

$$f(X) = \sum_{j,k} \left( B_{j,k} + \frac{C_J(a_J)}{a_J} \right) X_{j,k}$$

subject to the constraints listed above. The value of this solution, denoted by  $\lambda_*$ , represents a lower bound to the cost of the optimal solution to the original problem. The  $X_{j,k}$  shipment routings arrived at through the use of this algorithm are regarded as the solution to the original problem. The value (cost) of this solution to the original problem designated by  $\lambda^*$  can then be calculated by substituting these  $X_{j,k}$  into the original cost functions. Balinski and Mills prove (1960, p. 8) that the cost of the actual optimal solution to the original problem (denoted by  $\lambda^0$ ) must lie between these two values, that is,  $\lambda_* < \lambda^0 < \lambda^*$ .

Thus we see that the Balinski-Mills method possesses the very desirable property of providing a lower bound to the optimal solution  $\lambda^0$  to help evaluate the quality of the solution  $\lambda^*$ . Such a property is desirable since it cautions one against accepting a poor solution as a good one. A large spread between  $\lambda_*$  and  $\lambda^*$  does not, however, necessarily indicate that  $\lambda^*$  is a poor solution. To be sure, the worst that can happen if  $\lambda^*$  is near-optimal and the spread between  $\lambda^*$  and  $\lambda_*$  is substantial is that one might continue to look for better solutions. More important, however, is the question of whether the technique does in fact produce near-optimal solutions.

Extensive examination of the Balinski-Mills method suggests that it is not well designed to handle the decreasing marginal cost functions generally postulated for the warehouse location problem. This can be illustrated by applying the method to the sample problem posed by Baumol and Wolfe. The Balinski-Mills solution calls for the use of all five warehouses at a cost of \$2499 which is 22 per cent above the optimal solution of \$2047.

The lower bound ( $\lambda_*$ ) to the solution of any problem provided by the Balinski-Mills method depends upon the quality of the solution used as a basis for calculation. The lower bound calculated on the basis of the Balinski-Mills solution to the Baumol-Wolfe problem is \$1655, some 19 per cent below the optimal solution. In contrast, the lower bound that would be calculated if the optimal warehouse network (namely, using only warehouse 3) had been identified is \$2047, identical with the distribution cost of the warehouse network used as the basis for computing this value of the lower bound. Such an equality would insure that the optimal had indeed been attained. This pleasant state of affairs is not, however, guaranteed by the Balinski-Mills lower bound. In general the lower bound will be equal to the optimal solution only when each warehouse entering the solution is used to some predetermined capacity or alternatively, when the optimal solution consists of using only a single warehouse (that is, each warehouse in the optimal solution handles the volume  $a_j$ ).

Mills, in personal communication, has stated that the Baumol-Wolfe problem violates one of the conditions set forth in the Balinski-Mills paper, namely, that the warehouse cost functions be 'piecewise linear but not concave' (1960, p. 3).<sup>17</sup> However, application of the method to such a problem does not seem inappropriate since the concave functions used in the Baumol-Wolfe problem can be closely approximated by piecewise linear functions containing the essential elements of the problem.

In comparing the Balinski-Mills and Baumol-Wolfe methods

17. The piecewise linear function illustrated by Balinski and Mills (1960, p. 4) is similar to the cost function in Figure 3. This function, with or without a fixed cost element, is concave (even strictly concave) over suitably specified regions. (For definitions of concavity, convexity, and the related extreme-point optimization properties, see Charnes and Cooper, 1961, pp. 284-7.)

it should also be noted that the former permits the treatment of fixed costs whereas the latter appears to be unable to handle such cost elements. Comparing the two methods on a problem which does not contain fixed costs does not, therefore, fully test the Balinski-Mills method. However, the difficulty with the method appears to stem from its inability to cope with functions which deviate significantly from simple linear functions. Thus, adding fixed costs might appear to aggravate the situation. For example, if there were fixed costs associated with operating warehouses in the Baumol-Wolfe sample problem, and if these costs were equal for each warehouse, the Balinski-Mills solution would be independent of the level of fixed costs. In contrast, we might logically expect to make use of fewer warehouses in a distribution system if the fixed costs per warehouse were increased. Consequently, the existence of fixed costs tends to increase the deviation of the Balinski-Mills solution from optimality.

Balinski (1961) has applied this same average cost approximation technique to what he calls the fixed cost transportation problem. His results seem to show that the method, although not guaranteeing optimality, works fairly well in solving such problems. This problem is not the same, however, as the warehouse location problem. The essence of the difference between the two problems is that in the fixed cost transportation problem the function describing the fixed cost elements is a separable one. That is, the fixed cost associated with using any route (that is, any path from a source of supply to a point of demand) is independent of the other routes used. In the warehouse location problem, shipping and handling costs may take this form but, in addition, a fixed cost may be associated with the use of each warehouse. This cost is incurred if a warehouse is used, but is independent of the number of routes passing through that warehouse.

### *Simulation of a distribution system*

The use of simulation techniques in the modeling of warehouse networks has been proposed by Shycon and Maffei (1960) as a means of avoiding the approximations in problem specification required by the techniques outlined above.

The value of a simulation approach to solving the warehouse location problem, much as with the use of any other technique,



depends upon how well the model describes the essence of the system being studied and the time required in computation. As with the other approaches, some balance must be reached in terms of model detail and costs of computation. Once a model has been constructed containing the basic characteristics of the distribution system under study, it is used to evaluate the distribution costs associated with alternative sets of warehouse sites and customer ordering rates. The problem that remains is to devise an algorithm which can be used to generate at least one near-optimal warehouse system.

Shycon and Maffei do not outline a computational method for determining the sets of warehouse sites to be evaluated. Their approach requires that management or a consultant specify the warehouse systems (number of warehouses and their locations) to be evaluated. Maffei has stated that new warehouse systems can be generated from any given distribution network by moving individual warehouses fixed or random distances in random directions, but such a procedure does not appear to be an efficient method for searching for near-optimal warehouse location patterns (Marketing Theory Seminar, University of Vermont, August 1960).

One other aspect of the Shycon-Maffei approach differs with respect to the other methods outlined in this appendix and the heuristic program itself. To save computer storage space they locate factories, warehouses and customers in terms of longitude and latitude and subsequently approximate shipping costs between all of these points in terms of the computed air miles. The other methods outlined in this article would in general use actual costs, although a similar estimation technique could be used if actual data were not readily available. The use of air mile distances as approximations for shipping costs is an interesting approach to the problem and should be studied in more detail to determine the magnitude of error likely to result in cost data generated in this manner. If the error is within acceptable limits, it affords a means of reducing the time required in collecting and analysing the cost data.

In its most detailed application, a simulation approach to the warehouse problem would permit the processing of actual customer orders through the alternative warehouse distribution

systems being analysed and imputing costs to the various phases of the operation. This would be a desirable approach, particularly for seasonal products, since it would permit incorporation of the dynamic elements of warehousing and inventory costs. The Shycon-Maffei approach, like the other methods discussed in this paper, does not simulate the distribution system in that degree of detail but rather estimates the warehousing and inventory costs as functions of the total volume of each product routed through any given warehouse. (In the heuristic program, since the number of products considered can be increased with less than a linear effect on computation time, it is possible to describe customer demand in terms of discrete distributions of product mix and order size such that the program treats each order-size product-mix combination as a separate product, except insofar as it influences inventory levels.)

In summary, the linear programming approaches to the warehouse location problem outlined in this section have as a desirable feature a systematic routine for generating alternative warehouse systems for evaluation. However, they are inferior to the simulation approach in that there is less flexibility available in the modeling of the distribution system. The computer program described in this paper combines most of the desirable features of simulation with a set of heuristics designed to generate near-optimal warehouse systems.

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### A Heuristic Model for Scheduling Large Projects with Limited Resources

J. D. Wiest, 'A heuristic model for scheduling large projects with limited resources', *Management Science*, vol. 13, no. 6, February 1967, pp. B359-77.

#### Introduction

In recent years, much thought and study has been devoted to the problems and techniques of scheduling large projects. With the growing number of such projects, the increase in the size of project management organizations, and the developing need to examine operations from a 'systems approach', the problems of large project management have increased numerically and in complexity. Centralized scheduling of such projects is becoming more and more a necessity, and methods have been sought to make such a goal practical. It is with such a method and its associated heuristics that this paper deals.

#### *Large projects*

By a 'large project' we refer to an extensive, one-of-a-kind undertaking leading to a final, well-defined goal or product – such as the building of a dam, the development of a space vehicle, or a major maintenance project. Projects typically consist of several hundred or thousand separate activities or jobs, at least some of which must be done in a given sequence for technological reasons. Each job normally requires one or more resources (men, machines, money, etc.) and a given time for completion (which may vary with the rate at which resources are applied). As a rule, resources are limited, but may be varied over the scheduling period.

#### *The scheduling problem*

In its essence, the problem of scheduling large projects may be formulated as follows: given a project as defined above, and constraints in the form of limited resource availabilities, find a schedule of job start times and resource assignments that satisfies

the constraints and minimizes schedule-related project costs. Thus, the problem is representative of a class of combinatorial problems in which elements of a set (i.e. jobs in a project) are to be ordered or grouped according to some criterion (e.g. minimum project length, within technological and resource constraints).

Because even modest sized projects have an enormous number of possible schedules, optimal solutions are usually impossible to find by inspection or by complete enumeration of possible schedules. Analytic techniques, such as linear programming, may be useful in formulating the problem in a rigorous manner.<sup>1</sup> This can certainly supply theoretical help as well as insight into other (non-analytic) approaches, pending further progress in linear programming techniques for solving large programs. For the moment, however, such analytic approaches remain computationally impractical for many – perhaps most – real world problems, even with the aid of a powerful computer. It appears desirable, then, to consider other possible approaches.

At present, the large project scheduling problem seems most amenable to solution by means of heuristic programming. In common usage, a 'heuristic' is, essentially, a method of reducing search in a problem-solving situation – an aid to discovery of a solution (Karg and Thompson, 1964; Kuehn and Hamburger, 1963; Simon and Newell, 1958; Tonge, 1960). Actually, a heuristic is any systematic method for solving problems – e.g. systematic cut-and-try based on reasonable rules of thumb at one extreme, and algorithms with their supporting theories and known properties at another extreme. Here we shall be concerned with exploring various heuristics of the rule-of-thumb variety. A heuristic scheduling program in the present context, then, is a procedure for generating a project schedule on the basis of one or more scheduling rules. While such a program may not always result in an optimum solution, it often has the advantage over analytic techniques of arriving at a solution (hopefully a 'good' one) with much less computational effort.

1. Charnes and Cooper (1962), Kelley (1963) and Fulkerson (1964) among others, have given a linear programming formulation of the project scheduling problem, given unlimited resources. For an LP formulation incorporating resource constraints, see Wiest (1963), which in turn is developed from Bowman's model (1959) for the job scheduling problem.

*CPM and PERT*

PERT (Dewitte, 1964), CPM (Kelley, 1961), and a host of similar techniques used in scheduling large projects all employ a project graph (arrow diagram), which is useful for displaying and manipulating project jobs in their technological ordering. But the use of critical path analysis and the notion of criticality derived from it are based on the implicit assumption that unlimited resources are available for assignment to the project jobs (or at least that sufficient resources are available for each job to be scheduled sometime between its earliest and latest start dates).<sup>2</sup> While the assumption may be justified in some cases, most project schedulers are faced with the problem of limited resources, and the conventional critical path analysis must be modified.

The tool has been useful, however, as a basis for several scheduling methods which attempt to level or smooth resource requirements by shifting slack jobs beyond periods of peak resource requirements. (For example: Alpert and Orkard, 1962; Dewitte, 1964; Kelley, 1963; Levy, Thompson and Wiest, 1962; McGee and Markarian, 1961). The approach used here for developing a heuristic scheduling model, while it makes use of critical path slack notions, looks at the problem as a limited resource allocation problem, rather than as a smoothing problem. The solution routine consists, essentially, of a group of scheduling rules which determine when each job shall be started and with what assignment of resources. A brief description of the model and its major features follows.

**Heuristic Model: Basic Approach**

In its basic approach, the model focuses on available resources, which it serially allocates, period by period, to jobs listed in order of their early start times. Jobs are scheduled, starting with the first period, by selecting from the list of those currently available and ordered according to their total slack (which is based on technological constraints only and normal resource assignments). The most critical jobs have the highest probability of being

2. In some instances, estimates for individual activity times are influenced by a consideration of available resources; but such estimates are usually made independently of other activity estimates, and the possible competing claims for the same resources are not explicitly considered.

scheduled first,<sup>3</sup> and as many jobs are scheduled as available resources permit. If an available job fails to be scheduled in that period, an attempt is made to schedule it the next period. Eventually all jobs so postponed become critical and move to the top of the priority list of available jobs.

### *Modifying heuristics*

The basic program described above is modified by a number of additional scheduling heuristics or subroutines generally designed to increase the use of available resources and/or to decrease the length of the schedule. In the brief description of these heuristics that follows, we will refer to resources as men, to the amount of resources applied to a job as the crew size, to a group of homogeneous resources as a shop, and to the scheduling period as a day. (Any other units, of course, could be used in place of these.)

*Crew size.* With each job is associated a normal crew size, or the number of men or other resources normally assigned to the job, a maximum crew size, or the maximum number of men required for crashing the job, and a minimum crew size, or the smallest number of men which can be assigned to the job. Normally these three crew sizes will differ from each other, although in some cases two or all three of them may be equal when jobs cannot be stretched out or crashed. The rules for crew size selection are as follows: If a job to be scheduled is critical,<sup>4</sup> it is placed on a priority list and given special treatment. If sufficient men are available, the job is scheduled at its maximum crew size,<sup>5</sup> that is,

3. Jobs in the list are scanned sequentially. Each job has a probability  $r$  (where  $r$  is an input parameter) of being considered for scheduling. If a job is passed by, the next one is considered with probability  $r$ , and so on. All other jobs in the list are scanned before a by-passed job is reconsidered. Scanning is repeated until all jobs have been considered. A similar procedure is discussed in Levy, Thompson and Wiest, (1962). Probabilistic elements in the program provide some randomness of job assignments and the likely production of different schedules on repeated applications of the model to a project. Thus, a number of different schedules can be generated (depending on the size of the project and computer time available), and the best one chosen from among them.

4. A job is considered critical if its slack does not exceed some value  $k$ , where  $k$  is an input parameter.

5. Actually a 'critical' crew size is chosen—i.e. that which is sufficient to increase the job's slack to  $k + 1$  (if possible), with the maximum crew size as an upper bound.

it is crashed. If insufficient men are available to do so, or even to schedule the job at normal crew size, then an attempt is made to obtain the required men by means of 'Borrow and Reschedule' routines described below. If all efforts fail, however, and the job cannot be scheduled even at minimum crew size, then its early start date is delayed one period and an attempt is made to schedule the job on the following day. Non-critical jobs are scheduled at normal crew size if the required number of men are available, but if resources available are insufficient for scheduling even the minimum crew size, then the job is delayed for consideration until the next day.

*Augment critical jobs.* Repeated attempts are made to speed up critical jobs (including those which become critical after being scheduled) which have crew sizes less than their maximum crew size. Before any new jobs are scheduled on a given day, jobs previously scheduled and still active are examined. If any of these is critical and has a crew size assigned less than its maximum, and if resources are available, its crew size is increased as much as possible up to the maximum.<sup>6</sup>

*Multi-resource jobs.* Sometimes a job requires a number of different resources, such as men of different skills, machines, money, etc., each of which may be limited in quantity. For such multi-resource jobs, separate jobs are created for each resource and the jobs are constrained to start on the same day with the same level of resource assignment – that is, normal, minimum, or maximum crew size (or some intermediate level).

*Borrow from active jobs.* If resources available are insufficient for scheduling some critical job  $j$ , then the model enters into a procedure for searching currently active jobs to see if sufficient men might be borrowed from them for scheduling job  $j$  on that day. Men are borrowed from a job only when the resultant stretching of the job will not delay the entire project.

*Reschedule active jobs.* Sometimes a critical job  $j$  could be scheduled if other jobs previously scheduled which use the same resources had been postponed to start at a later time. The model

6. See previous footnote.



scans the list of currently active jobs and picks out those which could be postponed without delaying the project due date. If sufficient men could be obtained in this way and/or from the borrow routine described earlier, then job  $j$  is scheduled and the necessary adjustments are made in previous assignments.

The reschedule routine has much the same effect as a look-ahead feature. Instead of attempting to look ahead to future needs of critical jobs (difficult to do in the limited resource case since jobs are not always scheduled at their early start), the model schedules all jobs possible as it moves along from day to day, repenting, so to speak, of previous scheduling errors if jobs are encountered with more critical need of resources than those to which the resources were assigned at earlier dates.

*Add-on unused resources.* After as many jobs as possible are scheduled on a given day, there still may be unused resources in some of the shops for that day. The model compiles a list of active jobs to which these resources might be assigned and arranges them in ascending order of their total slack. Proceeding down the list, the model increases the crew size of these jobs until the unused resources or the list of jobs is exhausted. (The increment is temporary; jobs supplemented in this way return to their assigned crew size the next day, unless unused resources are available then also.)

After going through the above scheduling routines each day, the model then records the results in a manpower loading table which notes the number of men assigned on each job and in each shop, and it updates the critical path data for unscheduled jobs. (Note that several of the above routines may alter a job's criticality; for example, when the maximum crew size is assigned to a critical job, the shortening of the job may result in its gaining slack and perhaps some other job or jobs becoming critical.) The model thus proceeds from day to day until all jobs have been completed.

## Evaluation of Schedules

A schedule should be evaluated in terms of its effects upon schedule-related costs. Relevant costs are a function of the particular project being scheduled and its setting, but in general they include:

1. Resource costs (and in particular, costs of unused resources and premium or overtime resources which are affected by the schedule).
2. Overhead costs (directly related to the length of the schedule).
3. Costs of changing resource levels (including hiring and lay-off costs, etc.)

Two particular cost functions reflecting these items have been used in the model so far.

$$\text{Total cost} = cz + \sum_{s=1}^m q_s^* w_s z, \quad 1$$

where  $c$  is a daily cost (e.g. overhead expenses and/or due date penalties, charged on a per-day basis),  $z$  is the length of the schedule,  $q_s^*$  is the maximum number of men required in shop  $s$ ,  $w_s$  is the average daily wage in shop  $s$ , and  $m$  is the number of shops. The implicit assumption is that shop crews are maintained at peak loads and are paid whether active or idle. Should the circumstances of a specific project justify it, a non-linear cost function of  $z$  could be substituted for the linear one above – e.g. when penalties for exceeding the due date increase exponentially.

$$\text{Total cost} = cz + \sum_{s=1}^m a_s^* w_s z + \sum_{s=1}^m \sum_{d=1}^z (q_{sd} - a_s^*) v w_s \delta, \quad 2$$

where  $c$ ,  $z$  and  $w_s$  are as above,  $\delta = 0$  if  $(q_{sd} - a_s^*) \leq 0$  and  $= 1$  otherwise, and  $a_s^*$  is the optimum shop crew size based on a premium rate  $v w_s$  for overtime or subcontracting when manpower requirements exceed  $a_s^*$ . ( $v$  is the ratio between premium and regular pay rates; thus the hourly overtime rate would be  $v w_s / 8$ .) The assumption is made that regular crew sizes are maintained at  $a_s^*$ , even during slack periods. If we let  $n(a_s)$  represent the number of days out of  $z$  that manpower requirements in shop  $s$  equal or exceed  $a_s$ , then  $a_s^*$  is that manpower level for which  $n(a_s^*) v \geq z > n(a_s^* + 1) v$ . That is to say, if  $a_s$  is raised one unit above  $a_s^*$ , then the incremental costs of paying one more man the regular wage for  $z$  days ( $z w_s$ ) exceed the incremental savings on overtime pay – i.e. the costs of paying a man at overtime rates for  $n(a_s^* + 1)$  days ( $n(a_s^* + 1) v w_s$ ). Costs of changing resource levels can be included in both functions where relevant.

Various additional criteria functions for evaluating schedules have been suggested by Burgess (Burgess and Killebrew, 1962), Carruthers (Carruthers, Costain and Battersby, 1965) and others. Since schedule-related costs are likely to be influenced by the particular circumstances surrounding a given project, it will often be expedient for cost functions to be designed on an *ad hoc* basis.

### Search Routines

A given schedule is based on a pre-assigned set of shop limits which may either be constant over the scheduling period or may vary day by day. It is possible that in some cases, the cost of increasing shop resource limits above this initial set of levels would be more than offset by the resulting decrease in overhead charge and/or due date penalty, and the reverse situation might also be true. Hence, a search procedure – either manual or by means of the computer – should be employed to seek some optimum combination of shop resource levels and resulting finish date.

Two rather simple computer approaches have been explored. The first search routine starts with minimal resource levels or those just sufficient to insure that all jobs can be scheduled, serially if not in parallel. After a schedule has been generated and its costs calculated, the resource levels of all shops associated with critical jobs are increased by some increment, a new schedule is generated, and its costs are calculated. The process is repeated as long as some improvement in schedule cost is noted. The second search method starts at the other extreme. Ample resource levels are assumed; that is, levels high enough to permit starting all jobs at their early start. Then resource levels are incrementally decreased – first, all shops at once and later, one shop at a time, until no further improvements in scheduled costs are noted.

### The SPAR-1 Model

A computer program which incorporates the characteristics and features of the general model described above has been written and tested. Called SPAR-1 (for Scheduling Program for Allocation of Resources), it is displayed in Figure 1 in simple flow-diagram form. The basic program is able to handle single or multiple projects, fixed or variable crew sizes, constant or variable

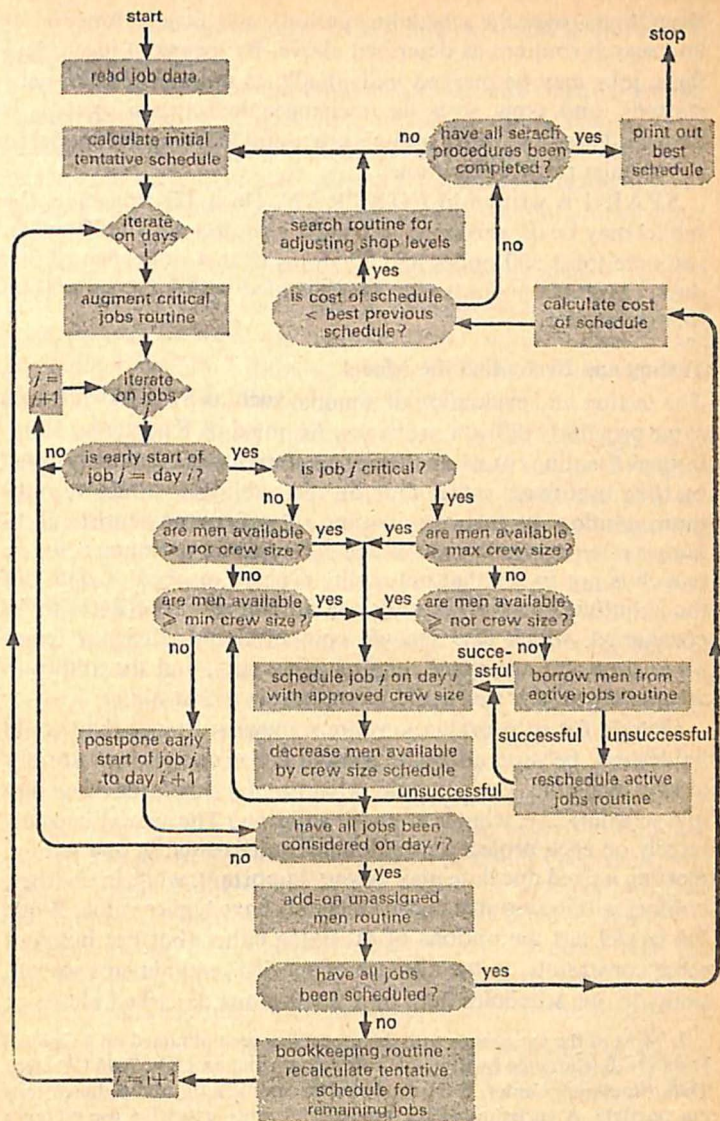


Figure 1 Flow diagram-SPAR-1

shop limits (over the scheduling period), and various functionals and search routines as described above. By means of input data flags, jobs may be marked individually as uninterruptible (once started), and crew sizes as unchangeable (once assigned), if desired. These and other options are useful in fitting the model to a particular project situation.

SPAR-1 is written in FORTRAN. On a 32K machine, the model may be dimensioned to handle a project with 1200 single-resource jobs, 500 nodes and 12 shops over a time span of 300 days.<sup>7</sup> Multiple projects may be scheduled within the same total jobs constraint.

### Testing and Evaluating the Model

The testing and evaluation of a model such as SPAR-1 presents some peculiarly difficult problems. As noted by Kuehn and Hamburger (Reading 10), evaluation of heuristic models is usually based on their usefulness rather than on their ability to attain an optimum solution. By their very nature, rule-of-thumb heuristic techniques often preclude a guarantee of finding an optimum solution (which is not to say that optimality is never reached). Quality of the solution, however, is only one among several criteria to be considered, which also include computational efficiency (computer time, storage space requirements, etc.), and the ability to adequately reflect 'real world' complexities (constraints).

Criteria for such evaluations are somewhat fuzzier than could be desired, because adequate standards for comparison are not always available. For example, what are the standards of quality of a schedule? i.e. what is a 'good' solution? The answer depends largely on each project's situational requirements; in one setting, meeting a fixed due date may be very important, while in another, holding within resource constraints may have higher value. While the model has the options of satisfying either (but not both) of these constraints, in the absence of specific requirements we will evaluate our schedules here by the functions described above or

7. Most of the experience with the model has been obtained on a Control Data G-20 (Carnegie Institute of Technology) and an IBM 7094 (Western Data Processing Center, UCLA). Some trade-offs in the above dimensions are possible. A variation of the model with more extensive use of tapes increases the job limitation to 1500, with practically no limit on shops or days.

in terms of the simple criterion, 'minimum schedule length within given resource limits'.

Evaluation of computational efficiency also lacks absolute standards, although some comparison may be made with 'current practice' or other proposed methods; or a rough calculation may be made of computational costs and a judgement made of what appears to be reasonable or unreasonable computational effort (as we have done below).

Several approaches to testing the model are possible:

1. 'Laboratory Tests.' Schedule projects small enough for hand solution and compare the model's output with pre-determined optimum schedules.<sup>8</sup> (Several trials of this nature are reported below, based on a number of fictitious projects.)
2. 'Field Tests.' Apply the model to a variety of real-world scheduling problems to study its behavior when subject to various scheduling environments and constraints. (A number of applications of this kind have been completed, including the scheduling of construction projects, a space-vehicle development program, a month-end closing of accounting records project, and job-shop like operations in a boiler manufacturing plant and in a military work center. Particular characteristics of these projects are described below, as a means of indicating the model's capabilities. Typical output and computer times are also included, as indicators of the model's computational feasibility.)
3. 'Comparative Tests.' Compare schedules generated by the model with those created by conventional means for the same projects, or with schedules generated by other heuristic computer models. (Much of this work remains to be done. Field data suitable for comparisons are difficult to obtain, as large projects that the author has encountered are usually not hand-scheduled in sufficient detail, or resource constraints are not considered (as with CPM-PERT schedules). Comparison with other heuristic models awaits exposure in the literature of work in this field.)<sup>9</sup>

8. Pascoe (1965) has undertaken an extensive evaluation of various heuristic scheduling rules as applied to a number of synthetic projects – in essence a 'laboratory test'.

9. In addition to the small projects included in this article, other larger projects (with SPAR-I schedules) are available from the author upon request, for purposes of comparative tests.

## *Project scheduling experience: 'laboratory tests'*

A number of fictitious projects, ranging from sixteen to one hundred jobs, were employed to test the various heuristics of the model. Some of them, when sufficiently constrained, were small enough so that optimal solutions (i.e. minimum length schedules within the resource limits) could be found by cut-and-try techniques.

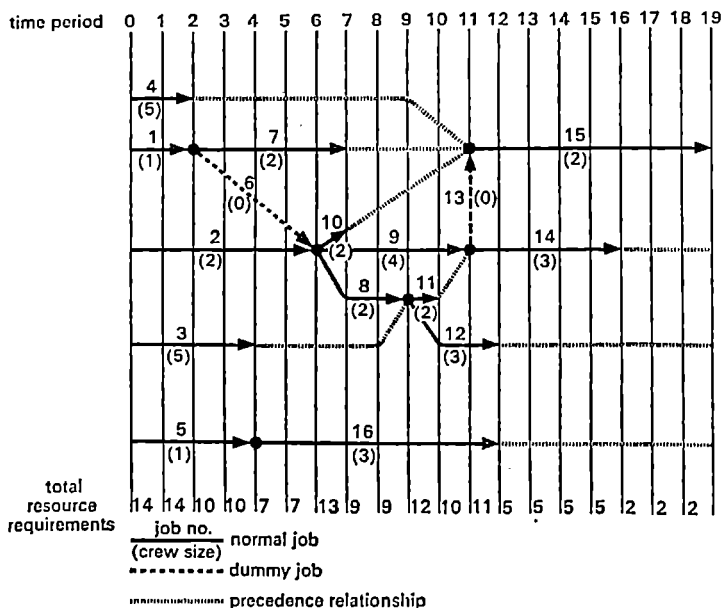


Figure 2 Schedule graph for Martino project, unlimited resources

A drawback of trial projects is that 'the deck may be loaded' – i.e. projects may be fabricated (and have been, by the author and others) which produce good or bad results, as desired, with any particular set of heuristics. One such project, proposed by Martino (1965), is an example of how total slack as a priority index would lead to non-optimal results. The project is shown in Figure 2, a schedule-graph based on unlimited availability of the single resource required.

With a resource limit of eight men, the optimum schedule is

nineteen days long.<sup>10</sup> A straightforward application of SPAR scheduling heuristics resulted, as expected, in a non-optimal, twenty-one day schedule (Figure 3). However, when the probabilistic feature in the job selection routine was utilized, job 4 was

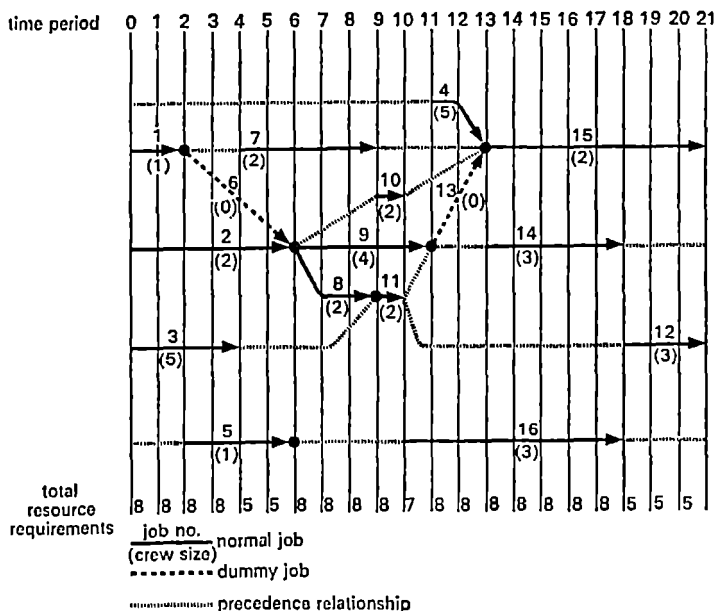


Figure 3 SPAR-1 schedule graph for Martino project, resource limit of eight men (deterministic job selection)

sometimes scheduled before job 7, with the optimal results shown in Figure 4.<sup>11</sup>

With a resource limit of seven men, the optimum schedule is twenty-five days long. The shortest SPAR-1 schedule – with no interruptions of jobs – was twenty-seven days long, although the model found a twenty-five day schedule by splitting one of the jobs. With a resource limit of nine men, SPAR-1 generated an optimum schedule of length of nineteen days. Nine men were

10. Several different nineteen-day schedules may be identified.

11. In ten trials, the optimal schedule was found twice.



## Heuristic Models

sufficient to reduce the schedule length to the point where technological constraints became limiting. (As indicated in Figure 2, the critical path is nineteen days long.)

Although the random selection device enabled the model to find optimum schedules in the above cases, other examples could probably be developed for which the location of an optimum

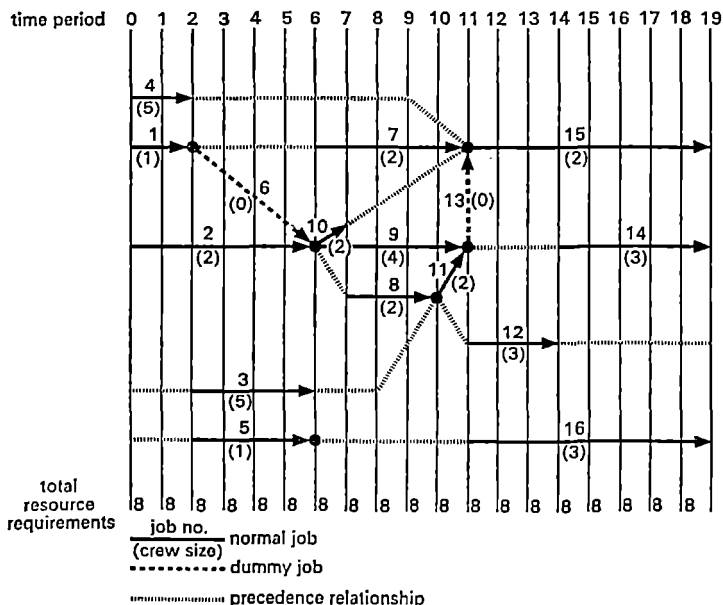


Figure 4 SPAR-1 schedule graph for Martino project, resource limit of eight men (probabilistic job selection)

solution would be unlikely in a reasonable number of iterations. (Counter-example projects, of course, could probably be found for any rule-of-thumb heuristic model.) A fairer test would be to schedule a number of projects not purposely 'loaded' to prove or disprove a given set of heuristics. A modest attempt was made in this direction. To avoid any intended bias, several projects were generated by a random process (crew sizes, job lengths, and resources required were randomly selected) and scheduled with various resource limits. One project was sufficiently constrained

to permit hand solutions for two sets of resource limits.<sup>12</sup> In one case, the SPAR schedule was optimal at thirty-four days; in the other, the SPAR schedule of thirty-nine days was two days longer than optimal. Unfortunately, the hand-solution method of finding an optimal schedule is sufficiently arduous to limit its usefulness as a means of evaluating the model with a large sample of 'neutral' projects, and especially with sizeable ones.

While none of the above results could be considered conclusive, they did indicate the model's capability of finding optimum schedules for the particular projects attempted. It should be noted, however, that the projects, by not allowing variations in job crew sizes, restrained the model from exercising several heuristics designed to increase the utilization of available resources. In large projects, especially, this flexibility in the assignment of crew sizes would likely be more important in minimizing idle resources than would the probabilistic feature. In large projects, not only are there more possible schedules to sample from (thus reducing the probability of finding an optimum schedule on a single trial), but the computational demands would lead to a smaller sampling from these schedules for a given computational effort. Hence, when computer time becomes a limiting factor, it is relatively more important to generate 'good' schedules on a single trial than to rely on a chance location of an optimum (or near optimum) solution on a sampling of schedules.

### *Project scheduling experience: 'field tests'*

To study the operation of the model with 'real world' data, a number of actual projects were scheduled by SPAR-1. The projects are described below, with relevant results.

*Small construction project.* The first was a small construction project which contained about one hundred multi-resource jobs (or 181 single resource jobs) requiring twelve different resource groups. SPAR-1 with the second search routine described above was applied to the project, using for the first iteration resource

12. Minimum, normal and maximum crew sizes were all the same, and resource limits were held constant throughout the scheduling period. The project contained fifty-five jobs, each requiring one of four different resources. For detailed results of this and other applications of SPAR, see Wiest (1963).

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levels adequate to meet the maximum crew size of any job. Table 1 summarizes schedule data for each of the ten iterations that resulted. A comparison of the best schedule (iteration 10) with the schedule which results from conventional CPM techniques is given in Table 2. (All jobs were scheduled at early start with normal crew sizes.) Table 2 lists the peak requirements in each of

**Table 1** SPAR-1 Applied to 181 Job Construction Project.  
Resource Limits Changed Iteratively (Search Routine No. 2)

| Iteration<br>no. | Resource number |   |    |   |   |    |    |   |    |    |    |    | Schedule<br>length<br>(days) | Total cost<br>(1,000's) |
|------------------|-----------------|---|----|---|---|----|----|---|----|----|----|----|------------------------------|-------------------------|
|                  | 1               | 2 | 3  | 4 | 5 | 6  | 7  | 8 | 9  | 10 | 11 | 12 |                              |                         |
| 1                | 12              | 3 | 20 | 7 | 8 | 12 | 14 | 8 | 10 | 2  | 4  | 1  | 71                           | 326                     |
| 2                | 11              | 3 | 19 | 6 | 7 | 11 | 13 | 7 | 9  | 2  | 3  | 1  | 77                           | 320                     |
| 3                | 10              | 3 | 18 | 5 | 7 | 10 | 12 | 6 | 8  | 2  | 2  | 1  | 79                           | 295                     |
| 4                | 9               | 3 | 17 | 4 | 7 | 9  | 12 | 5 | 7  | 2  | 2  | 1  | 78                           | 263                     |
| 5                | 8               | 3 | 16 | 4 | 7 | 8  | 12 | 4 | 6  | 2  | 2  | 1  | 76                           | 234                     |
| 6                | 7               | 3 | 15 | 4 | 7 | 7  | 12 | 4 | 5  | 2  | 2  | 1  | 80                           | 232                     |
| 7                | 7               | 3 | 14 | 4 | 7 | 7  | 12 | 4 | 4  | 2  | 2  | 1  | 99                           | 284                     |
| 8                | 7               | 3 | 14 | 4 | 7 | 7  | 12 | 4 | 5  | 2  | 2  | 1  | 80                           | 232                     |
| 9                | 7               | 3 | 13 | 4 | 7 | 7  | 12 | 4 | 4  | 2  | 2  | 1  | 99                           | 282                     |
| 10               | 7               | 3 | 13 | 4 | 7 | 7  | 12 | 4 | 5  | 2  | 2  | 1  | 80                           | 231                     |

For each iteration, the table lists the set of resource limits used in the scheduling model, with the length and cost of the resulting schedule. Total costs are based on overhead charges of \$200/day and resource hourly rates as follows (in order, beginning with resource 1): 4-50, 5-00, 2-50, 3-00, 2-25, 4-50, 4-50, 25-00, 4-50, 4-00, 4-00, 4-50. Eight-hour work days are assumed.

**Table 2** Peak Resource Requirements

| Resource number              | 1  | 2 | 3  | 4 | 5 | 6  | 7  | 8 | 9 | 10 | 11 | 12 |
|------------------------------|----|---|----|---|---|----|----|---|---|----|----|----|
| Unlimited resource schedule* | 12 | 3 | 20 | 7 | 8 | 12 | 14 | 8 | 4 | 2  | 4  | 1  |
| Limited resource schedule†   | 7  | 3 | 13 | 4 | 7 | 7  | 12 | 4 | 5 | 2  | 2  | 1  |

\* All jobs scheduled at early start times and with normal crew size.

† Based on resource limits from Iteration 10 in Table 1.

the schedules. The length of the project was reduced from ninety-three days in the CPM schedule to eighty days in the SPAR-1 schedule, with a considerable reduction in most of the resource limits. (The reduction in length of project resulted from the above-normal allocation of available resources to critical jobs.)

Hand smoothing of CPM schedules – by delaying slack jobs which occur on peak resource days – is possible, of course, and is

feasible for relatively small projects like the one above.<sup>13</sup> But the difficulties of manual smoothing increase exponentially with the number of jobs, and they greatly reduce the potential effectiveness of this approach on large projects. A computer is needed to explore, in a reasonable length of time, the many possible combinations of job start times and crew sizes for such projects. For the above project, the ten iterations were completed in about three minutes.<sup>14</sup>

*Large construction project.* The second construction project – from a company that designs and builds chemical and petroleum plants – contained approximately 600 jobs with fifteen resources. Scheduling was complicated by the requirement that some (but not all) jobs could not be interrupted once started, and that some (but not all) jobs must maintain a constant crew size once selected. Each of the fifteen resources was limited in supply; in addition, limitations were placed on the total men assigned from any of certain groups of resources. This constraint reflected a ‘congestion’ problem: certain work areas were so small as to physically limit the number of men present – regardless of their skill or craft. The schedules generated were from 280 to 350 periods long (depending upon the resource limits chosen) and required three to five minutes of computer time for each schedule. This gives us some measure of the economic feasibility of the model. At commercial rates, computer costs would thus be about \$30 to \$50 per schedule. Key punching of data would add about \$20.<sup>15</sup> Thus, the costs of applying the model are well within a reasonable range (and could no doubt be further reduced by more efficient coding of the program – perhaps in machine language).

*Month-end closing of accounting records.* The accounting project consisted of the elemental tasks required for the monthly closing

13. The contractor for the above project employed two or three schedulers who normally took two weeks to ‘hand-smooth’ jobs in such projects in order to reduce peak resource requirements.

14. Computer times are for the IBM 7094 (or estimated equivalents for the 7094 if another computer was used).

15. Since data would have to be collected for any scheduling procedure, costs of data gathering are not included here. New data (not used by present techniques), however, should be included as an incremental cost of applying the model.

of accounting records of a large steel company. The tasks ranged from one-half hour to forty-nine hours, were performed by eighteen different skill groups, and for the most part had to be completed by a single worker. Month-end closing was a major effort for the company, involving over 1500 man-hours of work and about 700 assignable tasks. The project had to be completed within six days, or 288 half-hour scheduling periods, and was complicated by variable resource limits due to shift work and other factors. Resource availabilities varied from day to day as well as from shift to shift, and sometimes within a shift. Under such circumstances, the concepts of critical path and slack lose their normal meaning; conventional PERT and CPM models are not applicable. The SPAR-1 model modifies slack and critical path calculations, however, to reflect the resource constraints imposed on jobs because of shift work. Job scheduling is done only if resources are available during the time period being considered. SPAR-1 generated an optimal schedule for the project in six minutes.<sup>16</sup>

*Space vehicle project.* The space vehicle program was similar in size to the previous projects, but it differed in that many jobs required multiple resources. 'Jobs' were rather large block engineering activities which required the talents of up to five different types of engineers.

The extent of resource smoothing for a project as a whole is well illustrated in Figure 5 which shows a composite manpower loading chart for the space vehicle program.<sup>17</sup> The dotted line indicates a conventional PERT-type schedule with all jobs at early start; the solid line is the SPAR-1 schedule. Peak manpower requirements were reduced considerably, the period of moderate usage was more extended, and the total schedule length was shortened by five months. The conventional schedule, of course, is both unrealistic and uneconomic; it implies that peak or near-peak resources are immediately available at the commencement of the program. In addition, resource requirements

16. Because of the special structure of the project, the minimum length schedule could be determined by inspection.

17. Nine separate classes of technical manpower were scheduled, but they are combined here to show total manpower requirements.

are highly unstable, dropping from very high to very low levels. High costs of hiring and layoffs are implicit in the schedule. Most companies would prefer to maintain more stable employment rolls, lower than the peak requirements but extended over longer periods of time. The SPAR-1 schedule comes close to this requirement.

One measure of the costs of changing resource levels is the number of unit increases in resource requirements – i.e. the

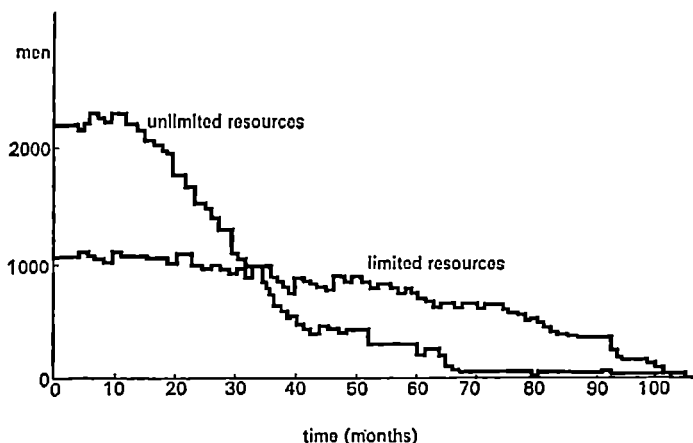


Figure 5 Manpower loading schedule–space vehicle project

month-to-month changes in the resource schedule. For the unlimited resource schedule, total positive changes numbered 2406;<sup>18</sup> for the limited resource schedule, this figure was 1683, a reduction of 30 per cent. Computer time for the 300-job project was under three minutes.

*Job-shop projects.* Two quite different problems were the military work center scheduling and the boiler plant scheduling projects. Both could be characterized as types of job-shop operations, as jobs to be scheduled arrived on a continuous basis and had to be

18. Positive changes represent gross hirings. Since the count was started and ended with an assumed zero resource level, then negative changes (representing layoffs) equaled positive changes.

fit into the schedules for completing previously received jobs. Each job, however, consisted of a number of sub-jobs or elements and could be looked upon as a separate, small project to be scheduled on a multi-project basis with other jobs. A schedule could be generated periodically (say once a week) for the set of jobs currently available – i.e. old jobs not yet completed plus newly arrived jobs. The jobs would compete for available resources and be scheduled on the basis of their criticality.

Priorities were imposed by means of a pseudo job appended to each compound job (project) with length sufficient to reduce the slack of project jobs to some appropriate level of criticality. For example, assume compound jobs *A* and *B* as represented in Figure 6.

For any due-date chosen (say day seven) sub-job five is more critical than sub-job one and hence would be scheduled first. If *A* has a higher priority, however, this can be reflected in slack values by appending a pseudo job of length three or greater to the end of *A*, reducing slack on all jobs in that project by an amount corresponding to the length of the pseudo job. By selecting pseudo jobs of appropriate lengths, each compound job may be 'assigned' slack according to several degrees of priority. Thus 'Rush' jobs might be given zero slack, 'Urgent' jobs five days

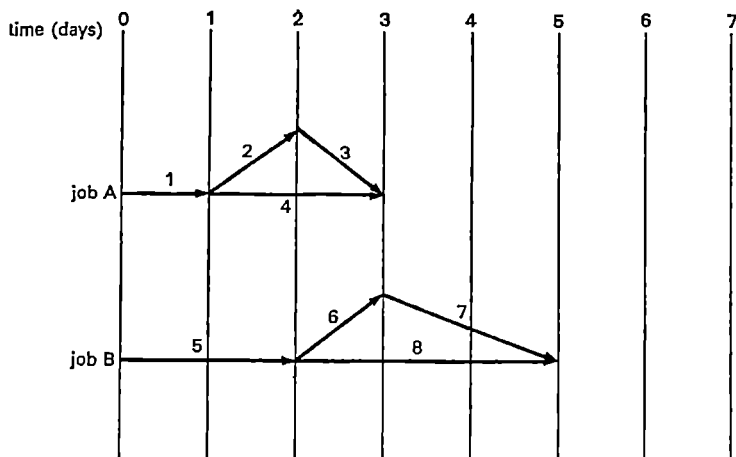


Figure 6

slack, 'Normal' jobs ten days slack, and so forth, where the numbers are chosen to reflect management's translation of descriptive priority terms to some quantitative scale of permissible slippage. The above numbers imply, for example, that an 'Urgent' job becomes 'Rush' if delayed five or more days beyond its initial early start time.<sup>19</sup>

This device for reflecting priority was used in both the boiler plant and work center projects. The former consisted of seventeen compound jobs, with a total of 459 sub-jobs or work elements, while the latter contained 107 compound jobs, with a total of 620 sub-jobs. These dimensions of the two job-shop projects give some clue to their nature, and explain a marked difference in their running times. In any one scheduling period, the work center project had from four to eight times as many sub-jobs available for scheduling (i.e. competing for available resources) as did the boiler plant project. Hence the time required for sorting and scanning available job lists was considerably increased. The boiler plant project required under five minutes of computer time, compared to the work center project's fifteen minutes.

Some reduction in list processing time would be accomplished by additional use of pseudo jobs, appended to the beginning of each of the compound jobs and with length inversely proportional to the priority of the jobs. Thus, less critical jobs would be postponed for consideration for several periods, allowing other jobs to be scheduled first and reducing the average length of the job availability list.

While a device of this kind can help reduce the problem of computer time, there remains the question of the appropriateness of job slack (however modified to reflect priority) as the sole criteria of job ordering in job-shop scheduling. Other heuristic scheduling models<sup>20</sup> specifically designed for job-shop scheduling and un-encumbered by the necessity for periodic recalculation of

19. Pseudo jobs may also be used to increase the criticality (and hence the priority for resources) of jobs leading up to certain milestone events in a network, thereby reflecting a desire to complete the milestones by certain due dates. Pseudo jobs may be provided manually – i.e. included with job data input cards – or they may be generated by a subroutine of the SPAR-I program.

20. See, for example, Gere (1962) and Reiter and Holstein (1964).



critical path and slack data may prove more efficient and effective than SPAR-1 in typical job-shop applications (although more experimentation and comparative evaluation is needed here). But for scheduling problems which – like the boiler plant – lay somewhere between large project and job-shop scheduling, specific recognition of job technological orderings, multi-resource requirements, variable crew sizes, etc., would seem desirable if not necessary, requiring a heuristic model with the capabilities of SPAR-1. And as noted above, the computational demands of the model are not unreasonable for projects of this kind.

### Experimentation with the Model

The solution routines as well as the associated model allow for some interesting experimentation. By changing a number of parameters in SPAR-1, for example, and specifying the use or non-use of certain of the modifying heuristics, one can simulate project scheduling under varying constraints and with different scheduling rules. The degree of criticality necessary for certain subroutines (like Borrow, Re-schedule, etc.) to be brought into play can be changed. Job splits may be allowed or disallowed for each job, as may crew size changes (after a given crew has been assigned initially). If desired, resource limits may be ignored (i.e. overtime allowed) in order not to delay critical jobs. These and other changes in the operation of the model may be specified by input parameters. With relatively minor changes in programming, the scheduling heuristics themselves may be changed and their effects on the scheduling process studied. Thus, the model may be used as a research tool as well as an operational scheduling program.

### Conclusion

Additional development and testing of the model – on a variety of project types and with a number of new scheduling heuristics – is underway. A major modification of the model (SPAR-2) based on concepts of ‘critical sequence’ and ‘conditional slack’ (Wiest, 1964) is being programmed.

Other models for scheduling large projects with limited resources are also being developed by a number of organizations

and individuals.<sup>21</sup> All of these models are adding to our knowledge and skill in project scheduling, and experience in their use will help to measure the worth of various scheduling rules that have been suggested.

On the whole, it seems fair to say that these models are fulfilling an immediate need and are also laying a basis for further progress in heuristic programming. While they demonstrate in a specific way that heuristic programming, aided by the computational power of a digital computer, helps to solve complex scheduling problems in large project management, in a broader view they contribute to our understanding of the use of this approach on a more general class of large combinatorial problems frequently met by managers and researchers, many of which have not previously yielded to analytic solutions.

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21. A notable example is RAMPS (for Resource Allocation and Multi-Project Scheduling), a proprietary program of CEIR, Inc., which has some rather interesting heuristics for determining job scheduling priorities (Lambourn, 1963; Moshman, Johnson and Larsen, 1963). The United States Steel Company has developed its own model called GRASP (for General Resource Allocation and Scheduling Program). Martino (1965) describes a model he has developed called MAP (Multiple Allocation Procedure) for resource leveling to achieve various desirable requirement profiles. Other heuristic approaches are suggested by Kelley (1963), Moder and Phillips (1964), Hooper (1965) and Pascoe (1965). Davis (1966) surveys a number of resource allocation models. Unfortunately, some of the models, for proprietary reasons, have been described in general terms only, and the underlying heuristics must be inferred from such literature as is available – e.g. literature of a promotional variety.

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## Part Five Algorithmic Models

An algorithmic model consists of that finite series of mathematical steps which will provide the optimum approach to a particular problem. Algorithmic models are normative, as were the heuristic models of the previous section.

In the first essay of Part One Simon offers some guidelines for using algorithmic models in managerial decision making.

1. Construct a mathematical model that satisfies the conditions of the tool to be used and which, at the same time, mirrors the important factors in the management situation to be analysed.
2. Define the criterion function, the measure that is to be used for comparing the relative merits of various possible courses of action.
3. Obtain empirical estimates of the numerical parameters in the model that specify the particular, concrete situation to which it is to be applied.
4. Carry through the mathematical process of finding the course of action which, for the specified parameter values, maximizes the criterion function.

The papers in Part Five apply this set of guidelines to marketing and production decisions.

The Charnes-Cooper-DeVoe-Learner study (Reading 12) provides an algorithmic model for decision making in marketing a new product. The model is based on research which established the data requirements and the relationships among the elements of the model and also on the development of new mathematics to exploit these data. The relationships stipulated in the model were tested with over three thousand measurements that accounted for 88 per cent of the brand to brand variability. In an eighteen-month test of this model and a conventional marketing plan, the

model provided a marked increase in profits over its conventional counterpart.

Rappaport's article (Reading 13) introduces the concept of 'sensitivity analysis'. He illustrates its application to an operating decision and to an information gathering decision. Sensitivity analysis, of course, may be applied to any situation where the solution resulting from parameters may influence the manager's decision.

## DEMON: A Management Model for Marketing New Products

A. Charnes, W. W. Cooper, J. K. DeVoe and D. B. Learner,  
'DEMON: a management model for marketing new products',  
*California Management Review*, Autumn 1968, pp. 31-46.

The function of new product marketing has become of major importance and concern to business management in response to consumer demand and also in response to expanding research and development activities. Its importance was already evident by 1961, when, as an article in *Business Week* (1961) reported, almost one out of every seven sales dollars was generated by products that did not even exist five years before. Some of the reasons for concern are illustrated in a recent survey (*Management of New Products*, 1965) which shows a high failure rate for new products, even in well-managed companies. In fact, a 60 per cent failure rate was experienced among new products that had progressed all the way through test marketing.

These data apply to well-managed companies; hence, it seems safe to assume that this failure rate was sustained in the face of the best that modern management could supply in the form of systematic procedures for assembling, combining, and exploiting marketing information. (This failure rate does not include lost opportunities occasioned by an erroneous decision not to market a product.) Collecting such marketing information, usually in the form of elaborate, detailed manuals that are maintained along with checklists, formulae, electronic computer codes, checking, and verification procedures, can be expensive. These activities are often justified on the grounds that the results will aid in the important decision to 'market nationally' – where many millions of dollars may be expended – or the equally important decision to stop further efforts at commercialization and absorb the penalties.

The volume of marketing information can reach a point where full exploitation cannot reasonably be expected, even when

electronic computing aids are available. Something more than volumes of data and high-speed computers are apparently required for analysing and exploiting such data.

Consider, for instance, a development sequence in which one marketing study may point only to the (apparently frustrating) need for further study. Under these circumstances, as might be expected, only the most recent study in such a sequence is considered – generally to the neglect of previously collected data. That is, data from previous studies are ignored or considered at best in perfunctory and unsatisfactory ways difficult to relate to the marketing decisions at hand. This would seem to raise some question as to whether some or all of the previous studies involved substantial wastes of funds and time in order to assemble data that were not wholly relevant or, perhaps worse, whether relevant and valuable data were wasted because of inadequacies in the available tools of analysis.

Other problems can be cited, of course, besides those involving data assembly and treatment. Among these problems might be included the need for better ways of ascertaining how the proposed marketing endeavor might affect other (non-marketing) aspects of company policies and activities.

## Marketing New Products

These problems and others will be noted or elaborated in this report on our nearly four years of research which have resulted in a management model called DEMON (DEcision Mapping via Optimum Networks) for marketing new products (DeVoe, 1965; Learner, 1964a, 1964b, 1965). This model is composed of two major components:

1. Detailed study and analysis of some 200 actual cases, plus interviews with experienced marketers, to establish the pertinent data requirements and relationships among marketing elements, with special reference to consumer packaged goods.
2. The other component addresses the need for developing new mathematics to exploit these data and relationships with the flexibility and power that are required for dealing in a more profitable manner with the ever-changing world of new product marketing.



As a marketing management system, DEMON :

1. Focuses on a clear-cut consistent objective for marketing new products – maximum profits.
2. Integrates financial, marketing, and production considerations into a comprehensive, practical plan for action.
3. Develops marketing plans in a flexible, dynamic fashion, constantly responding to changing priorities that result from the way the world changes.
4. Considers the way all these factors interact in a simultaneous manner, thereby eliminating that old saw – ‘all other things being equal’ – when we know they never are.

### Managerial Aspects

#### *The DEMON network*

We will discuss the managerial rather than the mathematical aspects (Charnes, Cooper, DeVoe, and Learner, 1966, 1968a, 1968b; and Charnes, Cooper, DeVoe, Learner, Light, Snow and Pringle, 1968) of DEMON. Figure 1 depicts the possibilities for marketing activities and decisions for a new product. There are, of course, many reasons motivating new product introduction, such as: profit potential, protecting the market position of established products, forestalling competition, utilizing excess capacity, or establishing an outlet for by-products that would otherwise go to waste.

These motivating considerations and the available marketing evidence are reviewed and evaluated at the stage labeled evaluation (eval.) I in Figure 1 and may be so compelling that a decision to ‘GO National’ should be reached. This is the intended significance of the arrow, or line, pointing from eval. I to the node labeled ‘GO’. GO abbreviates the decision GO National, i.e. commence marketing on a national scale – with all its attendant cost of implementation. Such costs, although not shown in Figure 1, form an integral part of the model and bear on the decisions made through its use.

Evidence may also, of course, be overpowering on the negative side. The label ‘NO’ represents the alternative NO-GO decision which then halts further program development and expenditures.

As a third alternative, the evidence may not be sufficiently

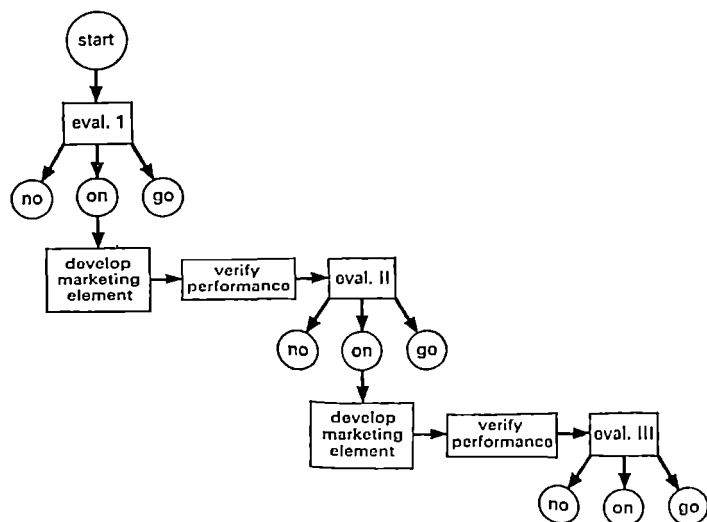


Figure 1 Possibilities for marketing activities and decisions for a new product

decisive to warrant a NO or GO decision, although continued development of a marketing program is warranted. Note that such a continuation may be warranted even when already available information suggests that marketing of the product will be profitable. For instance, if merely minimum acceptable profit prospects are in view there may be development opportunities for achieving greater profits. Such increased profit prospects will, in general, be attainable only by changing and improving the performance of some aspect of the marketing plan. Ascertainment of those aspects which should be changed in the marketing plan may require some collection of additional data, but this only raises a question of the best study sequence in the light of already assembled data as well as the still further study possibilities, and so on.

Suppose, for instance, that the profit possibilities are acceptable even at eval. I. Taking this into account, DEMON might nevertheless signal movement to the ON stage of eval. I, rather than GO national. This occurs because changing the performance

of one or more elements of the marketing program is likely to open new, better, and previously hidden profit possibilities. Such changes can be time-consuming. For example, profit possibilities might improve by changing the product formulation or by changing advertising effectiveness through a different copy. The development of products promotions and copy requires expending time – time during which the marketing world and various marketing elements may change. These changes are not ordinarily reflected in the marketing plan developed at eval. I. Thus, the results of these changes on profit prospects must be determined if continued planning is to have real meaning.

The marketplace performance of each changed marketing element can be verified by market research. If a product formulation is changed, the resulting change in consumer behavior estimates is useful in adjusting other marketing plan elements to strive for maximum profits, thus capitalizing on the newly revised product performance.

This new perspective for market research underscores its role in providing market performance feedback for management planning. Subsequent evaluations using verified performance of other marketing elements can uncover marketing opportunities unforeseen when the initial plan was developed. So the DEMON network overcomes one of the major shortcomings of traditional new product planning – viz. the long time-lag between developing and implementing a new product plan which often leads to obsolescence in the implemented plan. DEMON sidesteps this problem through the use of continued verification of the likely performance accomplishment of each marketing element. These current performance accomplishments are then fed back to modify other plan components – always with maximum profit as the objective.

In short, via the ON alternative we move through the stage labeled 'develop marketing element' to the stage labeled 'verify performance' where DEMON selects the best from among the available market research study possibilities. This selection considers both the costs and quality of the data that are likely to be secured by each study alternative.

Figure 1, then, illustrates the sequential development and assembly of marketing programs. In a flexible manner DEMON

proceeds to consider all marketing program possibilities and their profit-cost prospects in the context of accumulated study data. On this basis it contingently selects the marketing elements that should be improved and specifies market research required to verify that improvement.

It is important to emphasize that DEMON is not a static, one-time-only analysis. As each marketing element is developed and its performance verified, additional evaluations take place. In this manner, DEMON integrates the most recent market performance with accumulated data and evaluates the result in the context of changing market conditions. The process of developing the maximum profit marketing plan is one of continuous adaptation to the changing world, until a GO or NO-GO decision can be reached with some reasonable degree of assurance.

## Elements of Program

### *The marketing relations*

The other major component of this system is the marketing relationships uncovered by studying 200 or so actual cases. Figure 2, also portrayed in the form of a network, indicates how relationships between advertising expenditures, advertising copy, product performance, distribution, etc., are employed. Thus adv. \$ (dollars of advertising expenditures) give rise to media audiences (gross impressions) and so on, until triers (of the product) are converted to users and then, via a unit price, the actual quantity of consumer sales is derived. Here adv. \$ are viewed as directed towards generation of product trial (or triers). Other routes to developing product trial are also possible. See, for instance, 'promotion' which also has a link leading to 'triers'.

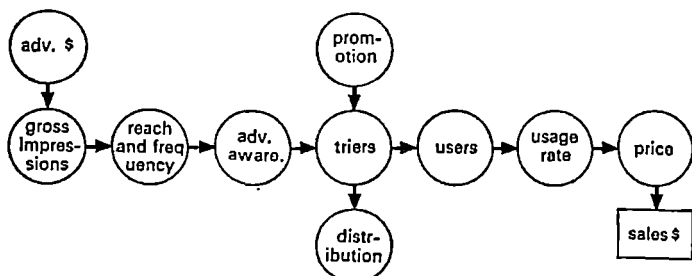


Figure 2 How relationships are employed

Differing expenditures may be allocated to promotion and advertising and, in concert with other factors, such as distribution, audience composition, and copy content and execution, can affect trial and usage rates. Each of these factors is an important element of a marketing program. Using the relationships between these elements, as estimated from the case studies, DEMON determines, at each evaluation, the combination of values for each of these elements required to maximize profits. Note that this implies optimal expenditure levels for both advertising and promotion activities.

Changing any element of a marketing program in response to an ON decision is intended to influence market behavior. Thus, the verified performance results of some alteration may serve to open prospects of still further profit improvement in the marketing program. DEMON and its associated mathematics are designed to consider such contingent prospects by systematically exploiting all accumulated marketing information to obtain improved profit possibilities; this is in contrast to traditional methods which simply react to the most recently available information. In this way the dynamics of a changing market are explicitly considered and evaluated to obtain an optimal marketing program.

These marketing relations have both an evaluative and diagnostic planning value. In the eval. I stage, the average relation (based on the case histories) is used to forecast profit expectations. In subsequent evaluations, as marketing element performance is verified, these average relations are replaced by the current measurements provided by marketing research studies.

For example, the case history relationships might indicate that 40 per cent of those aware of the advertising are likely to try the product. This 40 per cent advertising awareness to trial ratio would serve as the benchmark. An advertising test measuring actual purchase behavior might show that 50 per cent of those aware of the advertising have tried the product. The average awareness to trial ratio (40 per cent) would be replaced by the actual ratio (50 per cent) describing the performance of the tested advertising. In this manner average performance expectations for each marketing element are replaced by performance ratios unique and specific to the marketing plan under development. In

this manner the marketing relations serve to evaluate performance; they can also be useful in diagnosing why events occurred the way they have.

Let us suppose, for example, that test results show that 60 per cent of the target market can recall the advertising. This is a rather high awareness achieved. Similarly, let us suppose that 20 per cent of the target market try the product – a low trial rate. Diagnosis of these two results shows that execution of the advertising is sufficiently powerful to bring under the sales tent for this product almost two out of three persons in the target market. However, the content of the advertising – its motivating power – is feeble, since only two of ten in the target group try the brand. Creative effort should thus be directed to improving the meaningfulness of the sales message, without concern for improving the stopping power of the advertising. Reverse results of awareness and trial ratios would point out the need to get more consumers under the tent, perhaps by creative use of a black eye or a white tornado. Additional creative concern over the content of the sales message would then be unnecessary, since 60 per cent of those who display this awareness of the advertising find it sufficiently compelling to try the product.

Product performance can be diagnosed from the trial to usage performance ratio. High trial and low repeat (usage) are indicative of products that promise performance but do not deliver it. Low trial levels coupled with high repeat purchase describe highly successful product performance on a promise that is inadequately communicated to the target market.

In a similar fashion, the other performance ratios serve for re-evaluative and diagnostic uses: expenditures to promotion redemption, salesmen to distribution, and price to triers. These ratios tell how well the marketing plan may perform and the reason for such performance. The critical notion in DEMON's use of these data is the manner in which current information is used to replace obsolescent information that might lead to erroneous forecasts and decisions.

### *Corporate objectives, policies, and constraints*

The market and its dynamics are important. So are corporate objectives, policies, and constraints. It has not always been easy

to ensure that general management policies are adequately reflected in marketing programs which are evolved mainly in response to changes in market behavior. Hence, as already noted, there is a problem of fitting the product's marketing strategy (and its consequences) to other aspects of corporate policy as well as vice versa. This does not mean, however, that these policies should be regarded as fixed and static in contrast to the dynamic marketing phenomena that are encountered. DEMON provides ample opportunities; indeed it requires systematic review and revaluation of existing new product policies and objectives as can be illustrated by reference to the often-used concept of a payback period.

Payback, or breakeven analyses, are often used as criteria, along with requirements such as minimum profit potential to guide and evaluate the prospects for any product's potential. For example, marketing policy may require that no new product should be marketed unless the anticipated profits pay back the initial marketing outlays within a prescribed time period (except in extraordinary circumstances, e.g. if it became apparent that a competitor was on the verge of a new marketing venture). Caution should be exercised in the use of such formulas, however, because they very likely represent oversimplifications resulting from an inability to deal effectively with all the pertinent corporate policies and objectives. Payback as a desirable control on investment risk should be carefully distinguished from payback as an objective. Cast in the latter role, payback has generally achieved priority over all other considerations, including maximum profit, in so far as the latter requires considering prospects and actions which extend beyond the end of the payback period. Although the payback approach has become an almost universally accepted way to evaluate new product marketing prospects, this should not be permitted to obscure the deficiencies that accompany its use as an overriding criterion for planning.

Payback *versus* maximum profit is an issue of long standing in finance, capital budgeting, and related areas of study. Indeed, it is almost a classic exercise in finance textbooks and courses to show the many inadequacies of the former (payback) in contrast to the latter. The supposition, however, is that the choice of one

of these as a marketing (or finance) objective necessarily precludes any use whatsoever of the other.

But this is not the way in which the matter is treated by DEMON. The issue of payback *versus* maximum profit is resolved by DEMON in ways which allow both to come into focus for explicit consideration. Consider, for instance, the argument that planning via a payback approach inadequately deals with important factors in the introduction of a product and hence might better give way to some other objective, such as 'maximum profit'. On the other hand it must be admitted that the introduction of a new product is attended by significant marketing risks as well as data uncertainties arising from the studies that have been (or might be) conducted, and payback control may represent one way of dealing with these risks.

How then should the issue of payback and profit – especially maximum profit – be resolved? The DEMON model was designed so that both factors could be accounted for in decision making. When this is done, many possibilities emerge for combining risk control, via payback, with profit opportunities. One such possibility is to establish profit as the objective and to assign payback the status of a constraint that screens out unacceptable investment risks. For instance, suppose a company is unwilling to accept greater than nine to one odds that payback will not be achieved within two years after a GO decision. Marketing programs which have greater risks (longer payouts) are then screened out, irrespective of their profit potential. However, DEMON operates so that any significant profit prospects that may be uncovered are presented for management review, and policies may be revised if warranted.

Further attention should be given to the way in which this screening is accomplished. Suppose, for example, that the stipulated payout period is set at two years. Evidently, this cannot be absolutely guaranteed with probability one in most marketing contexts. Instead, such a context would appear to warrant an approach in which one specifies the acceptable odds that are implied by statements such as 'the probability of achieving a two-year payout is 0.9', while 'the probability of achieving payout in two and one-half years is 0.95', and so on.

The above ideas are accommodated via 'chance constraints'



which extend ordinary linear programming so as to make the optimizations (under constraints) applicable, even in situations where the data are uncertain. Hence, it follows that in such cases the constraints of ordinary linear programming must give way to those of 'chance constrained programming'<sup>1</sup> which allow the constraints to be violated, but only with specified probabilities such as are indicated by the statement that 'a two-year payout period will be achieved with 0.9 probability', and so on.

Bearing this use of risk constraints in mind we next turn to the objective that should be pursued after the specified too risky alternatives have been eliminated. The meaning of the DEMON objective MEMP (Maximum Expected Maximum Profit) can be explained by reference to Figure 1. For every marketing program that results in a GO decision because it exceeds some given profit level, DEMON adjusts the content of that program, the marketing elements, to obtain maximum profits. Further, DEMON selects the best (or maximum) of these GO marketing plans for implementation. This, then, is what is meant by the objective, Maximize Expected Maximum Profit – a maximum profit plan is arranged for each GO possibility and the maximum of all such GO possibilities is selected. MEMP is to be secured within the context of corporate policies, such as the already indicated payback. Other corporate policies or constraints such as budgets should, of course, also be included in DEMON as required.

Any arbitrary constraint or management control device may inadvertently conceal profit possibilities that come into view as the controls are removed. This notion applies to budgetary limitations as well as payback constraints. At each consecutive stage of DEMON the management constraints may be altered to explore opportunities that otherwise might be lost from view. This means that DEMON can reveal the nature of the policy alterations that would be required to produce a GO or NO decision at the earliest opportunity. By comparing these new policies and results with the original policy constraints, manage-

1. Chance constrained programming, itself a recent development in management mathematics, also required further extension for use in DEMON (see Charnes and Cooper, 1959, 1961, 1963).

ment is supplied with a systematic basis for evaluating profit potentials and altering its policies and objectives accordingly.

### **An Example**

#### *A case history illustration*

To make these notions more concrete, let us consider a corporation that desires to introduce a new brand into a drug product category. After receiving appropriate approvals for new drugs from the Food and Drug Administration, management initiates development of its marketing program via DEMON. Since DEMON is founded, in part, upon known relationships between various marketing elements (Figure 2), these relationships can be combined to produce an estimate of the most likely profit for a new brand in a product category. This maximum profit is then evaluated relative to corporate policies. Two kinds of information form the starting-point for DEMON's initial benchmark evaluation:

1. Management policies that reflect the way the company is supposed to behave.
2. Marketing data that reflect the way the world is behaving.

During this initial study and development phase, DEMON develops a marketing plan for implementation during a later planning period. The planning period serves as the basic time frame of reference for all marketing programs developed by the system. In this example, the manufacturer established five years (from the date of national introduction) as the planning period. Of course, the longer the planning period, the greater the uncertainty surrounding plan accomplishments. DEMON does specify the extent of this uncertainty to show how likely it is to affect management decisions.

The initial DEMON evaluation involves one assumption. The marketing plan that leads to the five-year accomplishment, noted in Figure 3, is based upon average performance of advertising, product, sales force, etc. Average performance is assumed at this point, simply because it is most likely to occur. The marketing plan in Figure 3 requires no data that would not ordinarily be available at the time the product is available for marketing commercialization.

Figure 3 shows that, were the decision to go national implemented (immediately), the likely sales accomplishment over the five-year planning period would be \$94.3 million. These sales would be achieved with a price of 9 cents per ounce; average product performance leading to 27 per cent users, and average advertising content and execution achieving awareness of 60 per cent among the market target. The cumulative five-year advertising expenditures in consumer media necessary to achieve these performances amounts to \$10 million. This case history does not include consumer promotion expenditures and distribution costs nor does it indicate in detail the rate at which the advertising funds will be expended. Of course, all these factors play an integral role and are indeed considered in normal practice, although not present here.

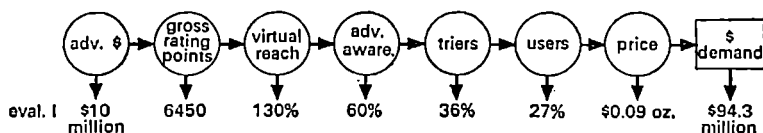


Figure 3 DEMON case history, based on average performance

The best advertising expenditure is determined by examining the range of expenditures to discover which level leads to the greatest profit at the end of the five-year planning period. The first benchmark evaluation asks:

What advertising and promotion expenditure is required, over the planning period, so that the five-year profits will be as large as possible, considering average performance on the part of all the elements in the marketing plan?

In this example, the answer is \$10 million. It should be noted that other performance levels of the marketing elements will, of course, require a different advertising expenditure in order to maximize the five-year profit. If an above-average product formulation were coupled with average advertising content and below-average sales force performance, the advertising expenditures (and values in Figure 3) required to maximize profits would in all likelihood be quite different. Assuming different product, advertising, and sales force performance is equivalent to assuming a

different marketing mix, it appears intuitively sound that different expenditures would be required to maximize profits from different marketing plans. What we seek in developing a marketing plan is the maximum profit, considering all levels of expenditure and all combinations of marketing mix.

Table 1 shows the profit implications of the marketing plan in Figure 3. The first column illustrates likely plan accomplishments, and the second column shows managerial requirements. The

*Table 1* DEMON Case History: Profit Implications

|                             | <i>Eval. I</i>   | <i>Results policies</i> |
|-----------------------------|------------------|-------------------------|
| Profit                      | \$24.8 million   | \$6.4 million           |
| Risk                        | ± \$62.0 million | —                       |
| Confidence of GO profit     | 43%              | 70%                     |
| Payout period               | 3.5 years        | 3.5 years               |
| Confidence of payout period | 36%              | 70%                     |
|                             | 12 yrs @ 70%     |                         |

maximum likely profit of \$24.8 million far exceeds management's requirements of \$6.4 million. If profitability were the only consideration, a GO national decision would be justified, the assumptions and quality of data notwithstanding.

In many similar circumstances, a basic question is the accuracy of information or 'how good are the data?' The figure in the second column of Table 1, labeled 'Risk', summarizes in one number just how good the data are. This data uncertainty arises from three different sources: errors in the sales forecast, errors in market research, or errors in the marketing relationships. Such unreliability has always existed, and it has indeed been difficult in the past to provide a realistic answer to the question of data quality. The notion of 'Risk' does not eliminate this uncertainty, but it does answer the question directly, in terms related to maximum profit. Thus, while the maximum profit might be \$24.8 million, the uncertainty or unreliability of that estimate is \$62 million. Risk does not mean that we should infer that there will actually be a loss of over \$37 million ( $62.0 - 24.8 = 37.2$ ), since obviously the venture would never be permitted to continue long

enough to incur such a loss. It does mean that the uncertainty of achieving the maximum profit is almost three times the amount of profit that can be achieved.

Additional insight concerning risk can be gained by referring to the confidence figure in the second column of Table 1. As indicated in the second column, management required odds somewhat better than two out of three (70 per cent) that they would achieve at least \$6.4 million before being willing to make a GO decision. These odds reflect the fact that very few things happen with certainty. The odds say, in essence, 'If we want to be absolutely certain of achieving \$6.4 million, we would probably do nothing, since in business we can be sure of nothing. As long as we are willing to gamble, with odds better than two-to-one in our favor, we'll GO national.'

The odds in the first column (43 per cent) reflect the effect of the risk and the likelihood of achieving the GO profit of \$6.4 million. Although the maximum profit may be \$24.8 million, because of data uncertainty the odds of achieving even \$6.4 million are little more than three out of five. So the accumulated uncertainty has effectively lowered the odds of achieving the target profit. These risks and uncertainties have always existed, as reflected by management's general reluctance to take action based upon market research data. DEMON uncovers the effects of these uncertainties and relates them to the decision at hand, making the decision itself more straightforward.

Referring again to Table 1, management policy requires that new products payout, or break even, at three and one-half years. Clearly, this does not mean that payouts of forty-four or thirty-eight months are unacceptable. It does mean that management wants to break even at forty-two months, with some reasonable degree of assurance. This required degree of assurance is indicated in the second column at 70 per cent. Once again, because of uncertainties surrounding the way in which profit will accumulate, the likelihood, or odds of achieving payout in three and one-half years are only slightly better than one in three (36 per cent). Upon seeing the odds of making a forty-two month payout, the marketing vice president asked, 'If I demanded seventy per cent odds, how long a payout period would be required to give me that confidence?' The answer in the last line of Table 1 prompted

the reply, 'No wonder we've introduced so many products with twelve-year payouts!'

The managerial implications of the marketing plan developed in Table 1 and Figure 3 show that the brand has great profit potential, although at this juncture, because of the uncertainties in the data and the implications of various management policies, the decision must be to continue ON. Such a decision affords the

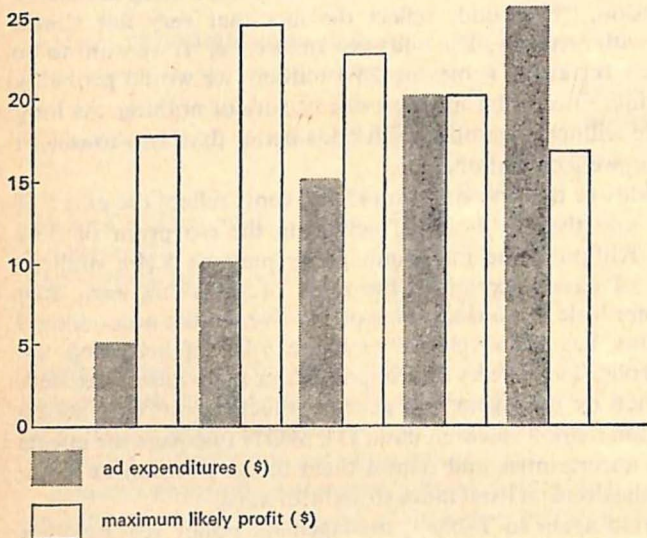


Figure 4 DEMON case history, evaluation 1

opportunity to examine the implications of alternative marketing actions that might be taken to improve profit potential. As a diagnostic aid it is possible, for example, to examine the expected relation of advertising expenditures with profit.

It is clear from Figure 4 that the greatest profit (\$24.8 million) occurs at \$10 million expenditure, and profit decreases as more or less funds are expended. The rates of drop in profits from over- or under-spending are not equal. For example, 50 per cent greater expenditure (\$15 million) results in about \$22.5 million profits, whereas 50 per cent less expenditure (\$5 million) turns up only \$17.5 million in profit. Thus, Figure 4 shows that it is more

profitable to overspend than underspend on this new product's advertising. This is hardly a world-shaking conclusion, since the same rule of thumb has generally been followed by knowledgeable marketing managers. The point of significance is that 'how much?' to over- or under-spend can now be answered with some degree of realism, by examining the managerial implications that may be associated with Figure 4.

Other examinations of leverage on profit by product performance, price, size of sales force, etc., can give the manager insight into the opportunities afforded by this ON decision.

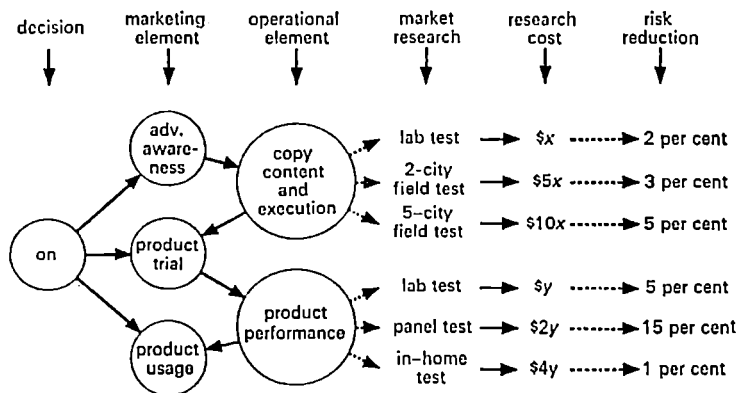


Figure 5 Performance testing

There are many possible ways of reaching a GO decision by arranging a better marketing program. A better plan refers to reduced risk, increased profit, or both. Profit depends in part upon the way each element in the marketing program performs in the market place. Risk depends in part upon the accuracy of measuring that performance. The selection of which element of the marketing program requires improvement is based upon their individual leverage on profit. The extent of that leverage is measured by market research which contributes better data, reducing uncertainty. Both these tasks must be accomplished in the least costly fashion.

These notions can be illustrated by referring to Figure 5. The ON decision has been specified. One or more of the three marketing

elements illustrated in the example in Figure 5 may be selected for improvement. As previously pointed out, the conversion of consumers from being aware of the advertising to trying the brand is due to the effectiveness of the creative content of the advertising. The conversion of consumers from triers (first purchase) to users (second purchase) depends upon the product's performance. It is the marketplace performance of this advertising or the product that must be improved, then verified through market research. There are clearly many ways of verifying the performance of each element. One market research tool may be more or less accurate and costly than another. Inaccuracies in the market research contribute to risk, while improved performance of the marketing element contributes to profit. The choice of which marketing element to alter is based upon the likely increase in profitability of the entire program.

In the case of this drug product, the ON analysis selected copy content and product performance as the marketing elements to be improved. Both elements were selected for parallel development and testing, because their profit opportunity and risk reduction per research dollar were virtually equivalent. The advertising agency developed advertising content, which was subsequently tested by measuring the proportion of television show viewers who could recall the advertising message (awareness) for each of three alternative advertising approaches.

While this creative development and copy research were being completed, the product group arranged an in-home product use test of two alternative product formulations. This project determined the proportion of persons in the test who purchased the brand after trying each formulation. In this manner, then, performance of the advertising and performance of the product were measured under realistic conditions. These actual field measurements of ad awareness and product usage were up-to-date replacements for the now-obsolete benchmark averages for these two marketing elements.

These new data were used as the starting-point for the second DEMON evaluation. The managerial policies were reviewed to assure that such factors as payout and profit requirements continued to reflect current management viewpoints. DEMON computations then adjusted the advertising and promotion expenditures to obtain a new maximum profit marketing plan.



Figure 6 illustrates this optimum marketing program. The asterisks identify the current measured values for the two newly developed marketing elements.

Inspection of Figure 6 shows that \$9 million spent on advertising over the five-year planning period produces slightly over \$21 million of profit. This is in contrast to the first evaluation which shows \$24.8 million of profit resulting from a \$10-million advertising expenditure. A comparison of Table 1 and Figure 6 shows that the main difference in the composition of the two

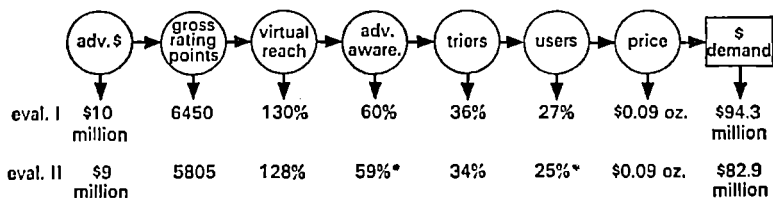


Figure 6 DEMON case history, optimum marketing program

marketing plans lies with the advertising appropriation. It is also quite apparent that the target values for the revised media plan are somewhat lower than those for the benchmark plan. The advertising awareness accomplishment, however, is virtually the same as that of the benchmark evaluation. This apparent discrepancy points out that the introduction of actual advertising content, in place of assuming average content, produced virtually the same advertising awareness for a million dollars less cost.

Table 2 shows the effects of the advertising and product development sequence completed prior to the development of the second evaluation DEMON marketing plan. It is quite apparent that the maximum expected maximum profit of \$21.2 million is far in excess of the \$6.4-million required profit target. Because we now deal with verified information (performance of the advertising and the product), the uncertainty or risk associated with the achievement of MEMP has been reduced to about \$8.5 million. This risk reduction markedly increases the assurance of achieving the objective and is reflected in the increased confidence of achieving the \$6.4-million profit target, which has jumped to 90 per cent, thus satisfying that management requirement.

*Table 2* DEMON Case History: Effects of Advertising and Development Sequence Prior to Second Evaluation

|                             | <i>Eval. I</i>   | <i>Results<br/>policies</i> | <i>Eval. II</i> |
|-----------------------------|------------------|-----------------------------|-----------------|
| Profit                      | \$24.8 million   | \$6.4 million               | \$21.2 million  |
| Risk                        | ± \$62.0 million | —                           | ± \$8.5 million |
| Confidence of go profit     | 43%              | 70%                         | 90%             |
| Payout period               | 3.5 years        | 3.5 years                   | 3.0 years       |
| Confidence of payout period | 36%              | 70%                         | 70%             |
|                             | 12 years @ 70%   |                             |                 |

The rate of profit accumulation results in achieving the break-even point at three years with odds of seven chances out of ten. This result exceeds the requirement laid down by management that payout occur within three and one-half years with odds of seven out of ten. Obviously if the payout odds are seven out of ten in three years, the odds will be even greater in favor of breaking even in three and one-half years.

On the basis of management requirements for profit, payout and confidence, the results of the second DEMON evaluation indicate that GO National is the best decision alternative. Though a GO decision has been reached and the marketing plan to implement this decision has been developed, numerous other diagnostic insights into the sensitivity of the marketing plan to changing circumstances can be explored.

For example, Figure 7 shows the relationship between gross income and gross profit as a function of various amounts of advertising expenditure. It is quite apparent that beyond \$9 million the revenue and profit curve part markedly from one another. So too, under normal circumstances, do the financial officer and marketing officer part company when discussing which plan to implement. Historically, marketing performance has been measured on the basis of market share. This criterion is in clear conflict with the objective of maximum profit, as illustrated in Figure 7. Sometimes there are sound and good reasons for trading off decreased profits against larger market shares. If, for example, the company had a variety of line extensions under development, a larger market share might provide a better platform for launching these other new products. Management might then be willing to sacrifice a relatively short-term profit in order to build up the market share so that the launch of the line extensions could take advantage of established products with a similar brand name.

The sensitivity of success odds to the sales forecast can be seen by referring to Figure 8. This graph shows sales volume increasing at a disproportionate rate, along with the odds of achieving the GO profit. This result is surely in line with the intuition most marketing men have held: If the sales volume is bigger, you can have more confidence in achieving the profit target. Once again DEMON shows how much the odds of achieving the target rise with an increase in sales volume.

## Algorithmic Models

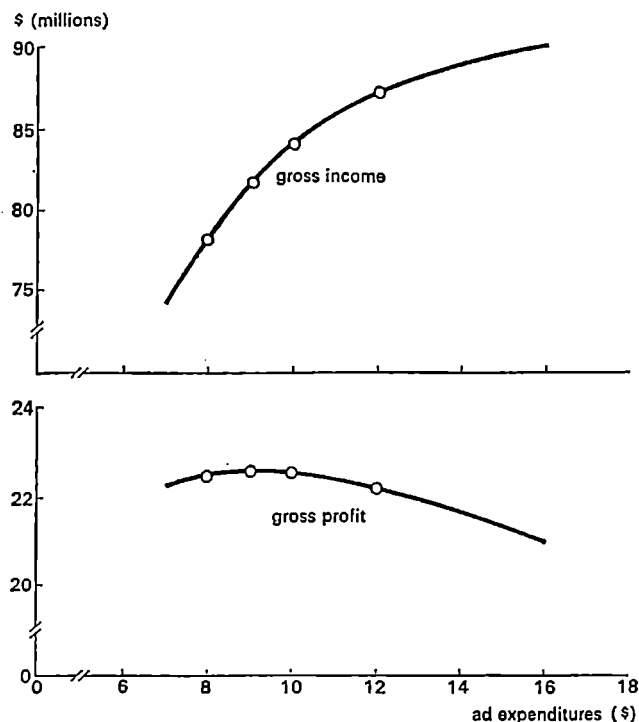


Figure 7 DEMON case history, relationship between gross income and gross profit

The initial management decision requirements were 70 per cent confidence in achieving the GO profit target. Eval. II results in a marketing plan that exceeds this 70 per cent level, providing 90 per cent confidence of achieving \$6.4 million profits. It is apparent in Figure 8 that the 90 per cent confidence is associated with the \$83-million sales estimate. The 70 per cent confidence level was adequate in management's initial judgement, and the curve in Figure 8 shows a sales volume of \$55 million associated with the 70 per cent confidence level. Thus, the difference between \$55 million and \$83 million (\$28 million) provides the additional 20 per cent confidence.

From another viewpoint, the profit forecast of \$83 million can

be in error by as much as a \$28-million overestimate and still be within the original confidence requirement of 70 per cent. Thus, it is quite apparent that the sales forecast might be in error, but exactly the same management decision would be made on the basis of the implications of the total marketing plan. It is also quite apparent from examining these data that, if management's confidence requirements are altered from time to time, so too

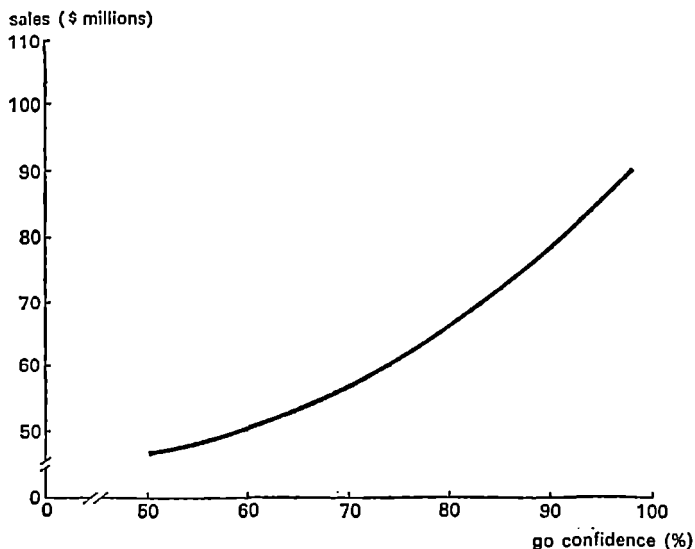


Figure 8 DEMON case history, sensitivity of success odds to the sales forecast

must the plan accomplishments be altered to maintain pace with expectations or requirements.

As a final illustration of the diagnostic capability of DEMON to examine the sensitivity of the marketing plan, Figure 9 shows the relationship between profit and the odds of exceeding such a profit. Thus \$6.4 million profit can be exceeded with odds of nine out of ten. The odds are better than eight out of ten of exceeding \$12 million, but merely 50-50 of exceeding \$18 million. Extending these results, it is apparent that there is virtually no assurance of exceeding \$21.8 million, because that is the maximum profit

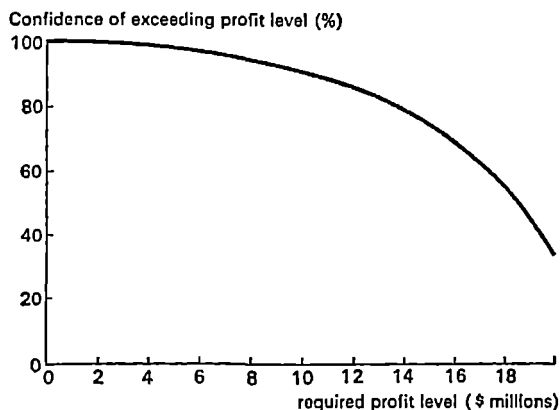


Figure 9 DEMON case history, relationship between profit and the odds of exceeding such a profit

level. It is appropriate to point out that, if the odds of exceeding \$18 million look attractive to management, then a new DEMON evaluation ought to explore the profit potential, if management's original requirement was 50-50 odds of exceeding \$18 million. It is quite possible that because of some presently unforeseen circumstance such a profit opportunity might exist, although it might not be apparent under the policy conditions stipulated at the beginning of eval. II. In this manner, then, DEMON has the potential to uncover profit opportunities that may not previously have existed and capitalize upon them via an optimum marketing plan. This type of flexibility is important, especially when overall policies and immediate marketing conditions must be jointly considered to allow further exploration of opportunities that might not have been apparent when planning was started.

### A Versatile Tool

#### *System validity*

In this case history, we have shown that the objective of maximum profit can be used to improve the profit status of an initially stipulated payback requirement. All parts of the system have been considered and evaluated when a change in a marketing component is effected. It is two years since DEMON was first

implemented, and so it is appropriate to raise the issue of whether such a planning system is valid. This question of validity can be answered from three different viewpoints. At the simplest level the system does indeed appear to look correct. It has face validity. Knowledgeable marketing men working with the system use it and react in much the same way they would to other kinds of managerial control information. The system has produced no anomalous results, at least in so far as this is attested to by acceptance on the part of marketing people.

The question of whether the component relationships of the marketing planning system are valid can also be examined. In such a validity test, the relationships developed on the original 200 or so cases were projected to forecast marketing achievement in new circumstances. In total more than 3000 measurements in over thirty-six different product categories were analysed. The relationships developed on the original data were used to predict results in a completely new setting. These predictions proved quite accurate. About 88 per cent of the brand-to-brand variability in the new situations was accounted for by the predictions from the old relationships. This statistical evidence shows that the properties of these marketing relationships are quite stable.

In addition, marketing data were collected in the United Kingdom and West Germany. Although those data were not originally collected for use in the development of the DEMON system, similar marketing relationships were found. Clearly, there were differences in the size of the economies involved, but the same structural relationships existed both in the United Kingdom and West Germany as previously found in the United States. This result also makes sense from a marketing point of view. For in these foreign countries, marketing managers use no different marketing tools and techniques than are used in the United States. Since these approaches work equally well (or equally poorly) in Europe, there is no reason to believe that basic differences in marketing exist.

The results of DEMON look right, and the components have the appropriate statistical validity when used in new situations, but the question remains whether the system as a whole has value. There is, of course, no unequivocal way of evaluating whether a

DEMON-derived marketing plan might alter the way in which the world behaves, producing more or less profit than some other marketing plan. The nearest approach to turning the world back and replaying it is to set up a parallel test in which the DEMON plan and a conventionally derived marketing plan were implemented and evaluated.

Such a test took place during the eighteen-month interval between January 1965 and June 1966. Two alternative marketing plans, one derived by DEMON and the other derived in a conventional manner, were implemented in two pairs of evenly matched test markets. The sole difference in the two marketing plans reflected advertising expenditure of the DEMON plan at one-half the amount of conventional plan. (Recall that the DEMON objective is maximum profit and not market penetration, market share, etc.) All other marketing costs and programs were identical.

During the eighteen-month test period, records of consumer sales were gathered, and various categories of costs were subtracted from the respective total sales volume to arrive at an approximate profit in each pair of test markets at the end of the test period. The cost in the two pairs of test markets were virtually identical. Thus, any resulting difference in profit could be attributed only to the difference in the two marketing plans (advertising expenditure level) in each pair of markets. At the end of the accounting period the DEMON plan resulted in 134 per cent of the profit of the conventional marketing plan. This means that \$1.340 million in profit accrued from the DEMON markets for every \$1 million in profit from the conventional markets. This 34 per cent profit premium points out that the advertising budget in the conventional markets was substantially beyond the optimum level. The performance discrepancy was so great that there was less than one chance in one hundred that the difference could have been recouped over the course of the five-year planning period. The 34 per cent gain is further enhanced by the fact that the 50 per cent overspent on advertising would have been available for other ventures, which might have provided significant return in their own right.

It is thus quite apparent that on an overall systems basis there is a substantial premium to the DEMON marketing plan. No



matter how optimistic these results may be, it is quite appropriate to point out that the system considers the odds of success, and it is indeed quite possible that in another application the DEMON system might not provide the optimum profit, for there is always some chance the system will be in error. However, on the basis of system results at the present time, it does appear that the promise of DEMON to provide maximum profit in a new product venture can be realized.

A variety of other results have accumulated in the course of utilizing this procedure. DEMON planning has pointed out the critical nature of integrating distribution coverage with the release dates of advertising. Although this point seems rather obvious, many managements either advertise in an area where they have no distribution or do not advertise in areas where distribution has been achieved. This timing of the distribution achievement with the release of advertising is critical for the accomplishment of the plan's sales objectives.

Another aspect of distribution planning that has come into sharp focus via the use of DEMON is the need for integrating the sales forecast with distribution coverage. In many cases marketing management assumes, through the normal sales forecast calculations, that distribution will be achieved virtually instantaneously in all sectors of the country, and the full market potential will immediately be available. In contrast to this assumption, DEMON clearly relates the sometimes agonizingly slow pace of distribution coverage to consumer availability. If only 50 per cent distribution has been achieved, DEMON considers that a maximum of only 50 per cent of the consumers will be able to purchase the brand, and so brand share targets may have to be doubled, if sales and profit targets are to be met on time. Although this example oversimplifies the case, the notion is that conventional sales forecasts do not account for the market not provided by lack of distribution. This discrepancy has a substantial impact on the likelihood of accomplishing the planned objective.

In the course of working with a number of manufacturers, differing organizational structures have evolved as a result of using DEMON. The integrated team approach, where representatives of production, finance, marketing, and R&D are

responsible for carrying the new product through its entire commercialization phase, has proved to be quite feasible and thoroughly desirable when using DEMON as a management system. A further side benefit that was entirely unexpected indicates that DEMON acts as a personnel multiplier on the skills of scarce product managers. Put simply, a product manager using DEMON to introduce a new product is quite capable of dealing with many more new product assignments.

Although the results of DEMON applications show it to be a versatile management tool, there are a variety of applications that would be inappropriate and of marginal value. As the system is currently structured, it cannot deal with consumer durable goods. Nor, for that matter, is it appropriate for packaged goods that have a long purchase cycle. Product categories such as anti-freeze, automobile wax, and other low use-up rate goods are inappropriate for DEMON application.

In a similar vein, many capital goods products such as aircraft and many industrial products are also out of bounds for DEMON at this point.

## A Total System

### *Conclusion*

By a case example, by diagrams, and by discussion, we have exhibited how the DEMON model operates when applied to marketing a new product. The machinery of DEMON relies heavily on new mathematics developed from research that was directed specifically to improving management methods for marketing new products. It would be a mistake, however, to regard this system solely in terms of mathematical research. The marketing aspects of this development played an important role, as did overall guides and controls obtained by reference to managerial requirements and considerations.

We have indicated how the model was developed so that pay-back and profit could both be accommodated. Overall corporate considerations as well as market behavior in its various dynamic and uncertain aspects are explicitly accommodated in DEMON. Information feedback is utilized to alter objectives or evaluate established corporate policies and controls whenever significant

new marketing opportunities are uncovered. The planning and risk implications of inaccurate and insufficient data are enumerated. In conclusion, we have also noted certain areas (e.g. consumer durables) where the current version of DEMON does not appear to be applicable. Of course, this does not preclude such extensions or other possibilities for further research since the basic DEMON concepts appear to be applicable to these areas also.

The need for each of these features was verified by extensive consultations with managers and marketers at various stages in the development of DEMON. With this in mind, we can now summarize the salient dimensions of DEMON as follows:

1. The model is composed of a planning subsystem and a decision subsystem.
2. Within the alternatives provided by these subsystems, the model determines a best way to proceed and systematically exploits all available data to this end.
3. DEMON brings all results together for review, examination, and exploration in a form suitable for managerial consideration.

Figure 1 provides a synopsis of these aspects of DEMON. Each box labelled EVALUATION represents the planning system, i.e. planning review and evaluation. These EVALUATIONS, it should be noted, are guided by the light DEMON can shed on future marketing alternatives. In short, any EVALUATION which is currently being undertaken is connected to all future EVALUATIONS, because each one is a step in an integrated and changing total planning system. Similar remarks apply to the GO, ON, and NO decisions which result from each EVALUATION. That is, each decision makes available new alternatives, which in turn are connected to still other decisions. Thus, again, it is the purpose of DEMON to supply a best course of action relative to the total new product system as well as to optimize at each stage where a decision must be made. The decision system and the planning system are, in addition, connected to other parts of a corporation's policies and objectives, and thus there, too, are accommodated or evaluated by the methods that DEMON supplies.

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## 13 A. Rappaport

### Sensitivity Analysis in Decision Making

A. Rappaport, 'Sensitivity analysis in decision making', *Accounting Review*, July 1967, pp. 441-56.

Freedom from uncertainty is a luxury rarely enjoyed by the contemporary manager. In a society characterized by change, uncertainty is an established and accepted fact of life. Notwithstanding the difficulties, the decision maker is expected to attain satisfactory results as measured by the goals of the organization.

In the face of uncertainty, the most recurring questions are of the form, 'What if . . .?'

What if our principal competitor successfully markets new product 'X' six months before us? Three months? One month?

What if we were to defer our planned expansion program for one year? Six months?

What if the proposed merger were disallowed by the Justice Department?

The 'what if' question may be viewed as an introduction to sensitivity analysis. In its mathematical sense, sensitivity analysis is a study to determine how possible changes or errors in parameter values affect model outputs. In its applied organizational setting, sensitivity analysis may be broadly defined as a study to determine the responsiveness of the conclusions of an analysis to changes or errors in parameter values used in the analysis.<sup>1</sup>

The principal objective of this article is to illustrate how sensitivity analysis can serve as an important aid in improving the basis for management decision making. The prime function of sensitivity analysis may be said to be to facilitate a better under-

1. The terms 'sensitivity analysis' and 'simulation' are often used interchangeably. They are not, however, synonymous. Sensitivity analysis may be performed by analytical techniques such as parametric linear programming, by experimental simulation approaches emphasizing numerous trials or iterations, or by a combination of these two approaches.

standing of risk.<sup>2</sup> Specifically, sensitivity analysis tests the responsiveness of model results to possible variations in parameter values, and thereby offers valuable information for appraising the relative risk among alternative courses of action. This technique is not only applicable to operating decisions,<sup>3</sup> but offers guidance for 'information decisions' as well. That is, sensitivity analysis can provide guidelines for allocating organizational resources to data collection and data refinement activities. Applications of sensitivity analysis for both operating and information decisions will be presented.

Implicitly or explicitly, managers have actively employed sensitivity tests for appraising relative risk of alternative courses of action from the earliest stages of business development. What is new is the increasing use of the term 'sensitivity analysis', the pervasiveness of its actual and potential applications with the

2. Contemporary literature by and large still maintains F. H. Knight's distinction between risk and uncertainty (Knight, 1921). Risk is characterized by situations in which the outcome is not known with certainty, but where the probabilities of alternative outcomes are either known or can be estimated. Uncertainty refers to situations for which probabilities of outcomes cannot even be predicted in probabilistic terms. While this distinction may be a useful pedagogical device, there is serious doubt about its applicability to decision makers in an organizational context. Here the distinction is blurred by the fact that decision makers generally have some feelings about the probabilities of future events. Admittedly, these feelings range from a degree of confidence bordering on certainty to ill-defined feelings approaching mysticism. The critical point remains that these feelings affect the judgements made by the decision maker. For this reason, the terms uncertainty and risk are here used interchangeably.

3. Sensitivity analysis is particularly adaptable to the evaluation of risk for investment decisions. See, for example, Hess and Quigley, 1963, pp. 55-63; Hertz, 1964, pp. 95-106; House, Jr, 1966, pp. 22-9. Readers interested in applications of sensitivity analysis to other decision models may wish to review the following references: Beranek, 1966, ch. 5. Beranek illustrates sensitivity analysis with an inventory-control model for working capital. A similar example for merchandise inventory can be found in 'Techniques in inventory management', *NAA Research Report No. 40* (National Association of Accountants, 1964, pp. 41-6). For an example of the sensitivity of the lease-or-purchase decision to alternative loan interest rates, see Bower, Herrington and Williamson, 1966, pp. 257-65. For an early article illustrating sensitivity for a plant-location problem, an optimum lot size ordering model, transportation-cost problem, and a capital goods replacement problem, see Maffei, 1958, pp. 177-86.

advent of high-speed computers and some recently developed mathematical techniques such as parametric linear programming<sup>4</sup> for testing sensitivity in complex, multi-variable decision models. The benefits of subjecting models to sensitivity analysis are succinctly summarized by Arnoff and Netzorg (1965, p. 46):

The use of an operations research model is especially important and advantageous in that it permits experimentation 'on paper', without manipulation of the actual system. In using the model, one can assess the *sensitivity* (response) of the system to a wide variety of conditions – without requiring either the time, expense, or risks associated with experimenting with the system itself (if such experimentation would, in fact, be possible and meaningful). Hidden relationships can be brought to light and brought to bear upon decisions and control of activity.

The importance of sensitivity analysis as an integral part of risk analysis varies with the degree of uncertainty. That is, the less certainty there is about values of model parameters, the more important it is to study the results of possible variations among parameter values.

A general model of a problem or decision situation can be expressed as follows (Ackoff, 1962):

$$V = f(X, Y)$$

where

$V$  = the measure of the value of the decision that is made.

$X$  = the variables which are subject to control by the decision maker, i.e. the decision variables.

$Y$  = the factors, variable or constant, which affect performance but which are not subject to control by the decision maker within the scope of the problem as defined.

$f$  = the functional relationship between the decision variables and performance factors, and the dependent variable  $V$ .

Consider the sensitivity of the value of a decision to changes in parameter estimates in the context of a linear programming model. The linear programming model is commonly referred to as an optimizing model. This label can be misleading, for it optimizes if and only if one assumes that all relevant variables have been properly incorporated and that values of the coefficients are sufficiently accurate. The ordinary linear programming

4. Parametric linear programming is discussed in detail later in the article.

model is deterministic, that is, it assumes that model data are known with certainty. To enhance the usefulness of linear programming to the planner the certainty assumption must in many cases be relaxed, for he is often faced with uncertainties regarding such factors as future demand, prices, technological change, and so forth. Stochastic linear programming models in which either coefficients of the objective function, technological coefficients, or coefficients of the requirements vector are treated as random variables have been employed under conditions of risk (see Hadley, 1964; Dantzig, 1963; Charnes and Cooper, 1959). Due to the computational burdens often associated with stochastic programming problems, applications to date have been limited.

Sensitivity analysis is another possible approach to risk evaluation when values of coefficients are subject to variation.

Actually, such coefficients are derived from analysis of data and usually represent *average* values or *best-estimate* values. Accordingly, it is most important to analyse the sensitivity of the solution to variations in these coefficients or in the estimates of these coefficients. Stated still another way, one seeks to determine the ranges of variation of the coefficients over which the solution will remain optimal. Sensitivity studies of this sort are known as *parametric linear programming* (Arnoff and Sengupta, 1961).

The stability of the optimal solution to changes in coefficients has important managerial implications. For example, in a given situation a modest variation in a coefficient may result in a new optimal solution with a significantly lower maximum value for the objective function. On the other hand, a relatively large variation in another coefficient may result in little or no difference in the value of the maximum.

### Case Study of an Operating Decision

To illustrate a sensitivity analysis for a linear programming solution, a case study is presented. Assume that during the recent surge of demand for color television sets a manufacturing company was considering how best to utilize its production facilities to maximize profits. The company produces three styles of black-and-white sets (standard, deluxe, and super) and a color set. The



company confidently believes it can sell as many sets as it can produce. Each set goes through the plant's three departments – sub-assembly, assembly, and testing. The number of man hours of labor required in each department is as follows:

|              | <i>Standard</i> | <i>Deluxe</i> | <i>Super</i> | <i>Color</i> |
|--------------|-----------------|---------------|--------------|--------------|
| Sub-assembly | 12              | 15            | 15           | 25           |
| Assembly     | 10              | 12            | 13           | 20           |
| Testing      | 0.5             | 0.6           | 0.6          | 2.0          |

The capacity of the plant allows no more than 3500, 3000, and 240 daily man-hours in the sub-assembly, assembly, and testing departments, respectively. Due to existing contractual agreements at least ten standard and ten deluxe models must be produced daily. The profit contribution (revenue minus variable costs) from the sale of each set is as follows:

|                     | <i>Standard</i> | <i>Deluxe</i> | <i>Super</i> | <i>Color</i> |
|---------------------|-----------------|---------------|--------------|--------------|
| Profit contribution | \$25            | \$30          | \$40         | \$100        |

The above can be expressed in conventional linear programming format as follows:

$$\begin{aligned}
 &\text{Maximize: } Z = 25x_1 + 30x_2 + 40x_3 + 100x_4 \\
 &\text{subject to: } \begin{aligned}
 &12x_1 + 15x_2 + 15x_3 + 25x_4 \leq 3500 \\
 &10x_1 + 12x_2 + 13x_3 + 20x_4 \leq 3000 \\
 &0.5x_1 + 0.6x_2 + 0.6x_3 + 2x_4 \leq 240 \\
 &x_1 \geq 10 \\
 &x_2 \geq 10 \\
 &x_3 \geq 0 \\
 &x_4 \geq 0
 \end{aligned}
 \end{aligned}$$

With the aid of a FORTRAN program for simplex linear programming we find the optimum daily production schedule to be as follows:

$$\begin{aligned}
 x_1 - \text{Standard} &- 10 \text{ units} \\
 x_2 - \text{Deluxe} &- 10 \\
 x_3 - \text{Super} &- 49 \\
 x_4 - \text{Color} &- 99
 \end{aligned}$$

This schedule yields an optimal profit of \$12,410.

The confidence of the decision maker in the optimal schedule

is necessarily related to the confidence he has in the values initially recorded in the model. Variations within the model may be classified as follows:

1. Variations in objective function coefficients.
2. Variations in technological coefficients.
3. Variations in requirements vector coefficients.
4. Addition or deletion of constraints.
5. Addition or deletion of variables.

Let us consider each of these variations to show how valuable management information can be derived from sensitivity studies. For each type of variation, examples of relevant analyses based on the television set product-mix problem are presented.

#### *Variations in objective function coefficients<sup>5</sup>*

How far in each direction can the unit profit contributions for standard, deluxe, super, and color models vary without causing any change in the present optimal solution?

Profit contribution per unit for each of the four set styles is a function of their average or best-estimate values for selling price, cost of materials, direct labor, and other variable costs associated with their respective production. Variability in the value of these factors may or may not affect the optimum schedule and profits, but it is important that the decision maker have this information if parameter variability can in fact be expected. This information may serve as a basis for departing from the initial optimum schedule, but in any case should increase the confidence of the decision maker in whatever optimum schedule is ultimately used.

For the above problem, the following are the indifference ranges for objective function coefficients:

| <i>Variable</i> | <i>Style</i> | <i>Original coefficient</i> | <i>Lower coefficient limit</i> | <i>Upper coefficient limit</i> |
|-----------------|--------------|-----------------------------|--------------------------------|--------------------------------|
| $x_1$           | Standard     | 25                          | $-\infty$                      | 32.67                          |
| $x_2$           | Deluxe       | 30                          | $-\infty$                      | 40.00                          |
| $x_3$           | Super        | 40                          | 30                             | 60.00                          |
| $x_4$           | Color        | 100                         | 66.67                          | 133.33                         |

5. The indifference ranges for objective function coefficients and requirements vector coefficients are an output of the computer program. All other inquiries in this section are solved by varying the input data and

On balance the optimal schedule appears to be relatively insensitive to variations in objective function coefficients. For example, profit contribution for color sets ( $x_4$ ) may vary from \$66.67 to \$133.33 per set without affecting the optimal schedule. For standard ( $x_1$ ) and deluxe ( $x_2$ ) sets the lower coefficient limit is represented by  $-\infty$ . This is so since the presence of ten units of each style in the optimal schedule is conditioned solely by contractual agreements for this amount reflected in the model as constraints, i.e.  $x_1 \geq 10$  and  $x_2 \geq 10$ . From a managerial standpoint the lower limit of the objective function coefficient would presumably have to be greater than zero since acceptance of contracts for less not only would incur opportunity losses, but would decrease profits in the absolute sense as well.

Next, what would be the optimum schedule and profit if the supplier should increase the price of color cathode-ray picture tubes by \$35 per unit?

From the preceding analysis we have observed that the lower limit for the objective function coefficient for color sets ( $x_4$ ) is \$66.67. The possible \$35 increase in cost would reduce the unit profit contribution for color sets from \$100 to \$65. Since the resulting profit contribution is outside the indifference range the manager may well be interested in an alternate optimum schedule. A comparison between the original and adjusted optimal schedule and contribution profit follows:

| Variable                    | Style    | Optimal schedule (units) |          |            |
|-----------------------------|----------|--------------------------|----------|------------|
|                             |          | Original                 | Adjusted | Difference |
| $x_1$                       | Standard | 10                       | 10       |            |
| $x_2$                       | Deluxe   | 10                       | 10       |            |
| $x_3$                       | Super    | 49                       | 196      | +147       |
| $x_4$                       | Color    | 99                       | 11       | - 88       |
| Maximum contribution profit |          | \$12,410                 | \$9,105  | -\$3,305   |

reworking the problem. I would like to express grateful acknowledgement to my colleague, Professor Joseph L. Balintfy, who developed the 'Fortran Program for Simplex Linear Programming' (SIMUPF) used to solve the linear programming problems in this paper. For most of the examples to follow, sensitivity is studied on a *ceteris paribus* basis, i.e. that one parameter value is varied while all others are held constant. This is done in the interest of keeping the illustrations relatively simple. The analyst may vary any number of parameter values to study relevant sensitivity patterns.

There are significant changes in the new schedule for super ( $x_3$ ) and color ( $x_4$ ) sets. This is a particularly interesting result since the lower limit of the objective function coefficient was breached by only \$1.67, i.e. lower limit of \$66.67 less adjusted profit contribution for color ( $x_4$ ) sets of \$65. It should be noted that the manager may find it appropriate to add an upper-bounded constraint for super ( $x_3$ ) sets if demand is projected to be less than 196 units.

How sensitive is the optimal schedule and contribution profit to alternative pricing patterns for the four set styles? Where the first two questions in this section involve variations in parameter values which, by and large, are not subject to control by the decision maker, this question involves variations in a decision variable since management is presumably in a position to establish prices.

A new manufacturer of color cathode-ray picture tubes has offered to meet one-half of the company's requirements at \$5.00 per unit less than the price charged by the current supplier.

This question serves to illustrate the difference between optimal schedule sensitivity and optimal profit sensitivity. We determined earlier that the \$100 profit contribution for color sets ( $x_4$ ) may vary from \$66.67 to \$133.33 without affecting the optimal schedule. Consequently, in this situation the profit contribution would increase from \$100 to \$105 and no change in the optimal schedule results. There is, however, an increase of \$250 in the optimal profit contribution. This increase results from obtaining a \$5 per unit cost reduction for one-half of the ninety-nine color sets scheduled under the optimal plan. The benefit of a \$250 increase in profit must now be weighed against the uncertainties and possibly unfavorable consequences of dealing with a new and untested supplier.

### *Variations in technological coefficients*

1. The technological coefficients are based upon values taken from the company's standard cost system. Due to personnel problems in the Sub-assembly Department and possibly to a relatively high rate of turnover, an average unfavorable labor efficiency variance of 10 per cent is a distinct possibility. Does this affect the optimal schedule and profit? A labor efficiency variance

also affects the objective function coefficients. For example, at a \$3.00 per hour labor rate in the department a 10 per cent increase in labor time would increase cost by \$3.60 per unit for the standard ( $x_1$ ) sets, i.e. 1.2 increased hours at \$3.00 per hour. The model with adjusted coefficients is now expressed as:

$$\begin{aligned}
 \text{Maximize: } Z &= 21.4x_1 + 25.5x_2 + 36.5x_3 + 92.5x_4 \\
 \text{subject to: } &13.2x_1 + 16.5x_2 + 16.5x_3 + 27.5x_4 \leq 3500 \\
 &10x_1 + 12x_2 + 13x_3 + 20x_4 \leq 3000 \\
 &0.5x_1 + 0.6x_2 + 0.6x_3 + 2x_4 \leq 240 \\
 &x_1 \geq 10 \\
 &x_2 \geq 10 \\
 &x_3, x_4 \geq 0
 \end{aligned}$$

The solution to this revised problem indicates that the optimal schedule and profits are sensitive to labor inefficiencies in the Sub-assembly Department. This result is not altogether surprising since sub-assembly as well as testing capacities are fully utilized in the original optimal schedule while there are 147 man-hours of slack in the Assembly Department. A comparison between the original and adjusted optimal schedule and contribution profit follows:

| Variable                    | Style    | Optimal schedule (units) |          |            |
|-----------------------------|----------|--------------------------|----------|------------|
|                             |          | Original                 | Adjusted | Difference |
| $x_1$                       | Standard | 10                       | 10       |            |
| $x_2$                       | Deluxe   | 10                       | 10       |            |
| $x_3$                       | Super    | 49                       | 6        | -43        |
| $x_4$                       | Color    | 99                       | 112      | +13        |
| Maximum contribution profit |          | \$12,410                 | \$11,118 | -\$1,292   |

2. From the original optimal schedule management noted that sub-assembly and testing represented the limiting resources. In view of this and the low rework rate, active consideration is being given to reducing the testing time on color sets from an average of two hours to  $1\frac{1}{2}$  hours per unit. While this policy change would increase maximum profit from \$12,410 to a new optimal of \$13,450, super ( $x_3$ ) sets would be eliminated from the schedule. This development will be examined more fully in connexion with discussion involving addition of constraints.

### *Variations in requirements vector coefficients*

1. The requirements vector coefficients are 3500, 3000, and 240 daily man-hours in the sub-assembly, assembly, and testing departments, respectively. How far can available labor capacity for each of the three departments vary before a change is generated in the optimal solution?

The average or best-estimate of labor hour capacity for the Sub-assembly and Testing Departments must be exact for the optimal solution to be stable. Profits would decrease if actual capacities were less than estimated capacities since estimated capacities were fully utilized in the solution. The dual evaluators or shadow prices for sub-assembly and testing capacity are \$1.33 and \$33.33, respectively. These shadow prices represent the decrease in profit associated with making one less hour of these resources available. Conversely, these shadow prices also represent the incremental profit from increasing these two resources by one hour, respectively.

As indicated earlier, there are 147 man-hours of unused or slack time in the Assembly Department. Thus, the 3000 estimated man-hours may actually be as little as 2853 hours (3000 less 147) and the solution would remain unchanged. Similarly, additional assembly capacity would not benefit profit since the resources of the other two departments remain the limiting resources.

2. Since sub-assembly as well as testing facilities are fully utilized in the original optimal schedule, management has reasoned that with a minimum of plant rearrangement about one-hundred hours of man-hour capacity can be transferred beneficially from the Assembly Department to the Sub-assembly Department. They wish to know the optimal schedule and profit if such a transfer is accomplished, and testing time for color ( $x_4$ ) sets is two hours?  $1\frac{1}{2}$  hours?

If testing time for color ( $x_4$ ) sets is reduced to  $1\frac{1}{2}$  hours then once again super ( $x_3$ ) sets are excluded from the optimal solution, an unacceptable condition to management. If testing time were to remain at two hours per color set, then the rearrangement of sub-assembly and assembly capacities would increase maximum daily profit contribution from \$12,410 to \$12,450. This benefit must then be weighed against the cost associated with plant rearrangement.

*Addition of new constraints*

Because of the brisk demand for color sets, the company's supplier may well limit shipments of color cathode-ray picture tubes to ninety per day. How costly would this be and what is the new optimum schedule?

With the addition of this constraint maximum profit contribution is reduced from \$12,410 to \$12,150, a reduction of \$260. The optimum schedule again calls for the production of ten units each of standard ( $x_1$ ) and deluxe ( $x_2$ ) styles. Sixty-five super ( $x_3$ ) sets are now to be produced daily, while the upper limit of ninety color ( $x_4$ ) sets is called for under the new optimum schedule.

Before the recent popularity of color ( $x_4$ ) sets, the super ( $x_3$ ) set was the company's most popular and profitable style. Indeed, the company's growing reputation for quality has been developed largely through the marketing of the super set. In light of this, management believes that despite active consumer demand for the more profitable color sets, demand for super sets should continue to be met to a reasonable extent. The original optimal schedule calls for a daily production rate of forty-nine super sets. Management estimates current demand to be approximately one hundred sets per day. Management wishes to know the costs of deviating from the previously established optimal solution for satisfying various percentages of demand for super sets. For example, if we wish to test the effect of meeting 75 per cent of the demand, the following constraint would be added to the original model:

$$x_3 \geq 75$$

*Addition or deletion of variables*

The company's sales volume for the two lower-priced sets, the standard ( $x_1$ ) and the deluxe ( $x_2$ ), has been disappointing despite concentrated marketing effort. In order to be able to offer a 'full line' the company must market a lower priced set. Management believes that either the standard or the deluxe style can be gradually discontinued without seriously jeopardizing the 'full line' image. What impact would each of these two possible changes have upon the optimum schedule and profit?

The foregoing questions represent but a limited sample of

potentially relevant inquiries once initial model results have been established. The important point is that a wealth of information can be gleaned from sensitivity studies and that the basis for decision making can be significantly improved with the use of this technique.

### Sensitivity Analysis for Information Decisions

Sensitivity analysis can provide systematic guidelines for allocating organizational resources to data collection and refinement activities.<sup>6</sup> Management science techniques are not only applicable to operating decisions, but offer guidance for decisions concerning the information system as well. After the analyst has constructed a model and tested it with initial parameters, he is faced with a decision problem. He may choose to collect additional data, refine initial parameters, alter the model, or use the model results as a basis for recommending action to management. On the significance of this decision, William T. Morris comments:

The nature of management science is such that sooner or later it has to recommend some action other than making more observations. Usually this comes sooner rather than later. Eventually it will suggest that action be taken consistent with either acceptance or rejection of the hypothesis. It will recommend management 'act as if' the hypothesis were true or 'as if' it were false. *Indeed, the fundamental question in management science may well be when to stop collecting data and developing the model, and when to produce a recommendation for action.* (Morris, 1963, p. 113.)

A theory of the cost and value of information for 'information decisions' is critically needed. In an increasingly technological society, information costs are ascending to previously unimagined

6. 'The term "data" is used here to represent messages that can be available to the individual but which have not as yet been evaluated for their worth in a specific situation. All communications in a firm may be considered as some form of data processing. "Information" is used here as the label for *evaluated data* in a specific situation. When the individual singles out one of his problems and finds among his data materials that help him solve the problem, he is converting or isolating information from data. Note that a given message may remain constant in content and yet, under this approach change from data to information when it is put to use in making a decision.' (McDonough, 1963, pp. 71-2.) Given the foregoing definitions, we see that data collection and refinement activities can be evaluated solely in terms of the resulting information. This explains the choice of the term 'information economics' rather than 'data economics'.



heights. Further, impressive advances in electronic data processing signal an even more staggering amount of information potential. In the past, the emphasis has been on whether information required for decision making could be developed. With our growing capacity to generate data, the emphasis now appears to be shifting to the question of to what extent this capacity can be utilized beneficially. This question is the fundamental concern of those interested in information economics.

A sound economic theory of information requires an understanding of the determinants of both cost and value of alternative information configurations. Accuracy, reliability, and timeliness represent principal factors affecting both cost and value of information. The cost of increased accuracy, reliability, and timeliness can be approximated at various stages of processing. Value, on the other hand, must ultimately be related to benefits resulting from management action. Consequently, the analyst is faced with the recognition that while the collection and refinement of incremental data are costly, they may serve to improve recommendations for action. In perhaps most cases, the analyst has little basis for projecting whether the additional information is worth its cost. There will be numerous instances in which the additional information will not be worth the incremental costs. Indeed, in some cases it may not even be worthwhile to obtain initial information to determine whether developing the main information is economically sound. The gross decision rule which suggests that data collection and refinement be continued until marginal costs exceed marginal benefits to the decision maker furnishes little practical guidance.

The limited help offered by the deterministic marginal cost and revenue decision rule is attributable to the fact that oftentimes little is known about the characteristics of the information not yet developed. Statistical decision theory, a methodology for choosing a reasonable course of action under uncertainty, appears to offer more promising results in the area of information decisions. The basic inputs required for a statistical decision theory model for information decisions are neatly summarized by Morris (1964, p. 483):

To apply this principle quantitatively it is necessary to be able to enumerate the possible outcomes of future data collection efforts, and

further, to compute the probabilities of these outcomes. In addition, it must be possible to indicate just how the information will quantitatively change the decision maker's view of his choice.<sup>7</sup>

These requirements are not easily dismissed. They are essential to the information decision model, but unfortunately often difficult to realize. An illustration will serve to demonstrate the importance of being able to enumerate possible outcomes of data collection efforts and to assign probabilities with a reasonable degree of confidence.

Grayson, in a particularly lucid exposition, demonstrates the application of decision theory to drilling decisions by oil and gas operators and also to the decision problem of whether to purchase additional information before making a final drilling decision.<sup>8</sup> Let us briefly outline the procedure.

The decision maker is confronted with the necessity of choosing between two acts: 'drill' or 'don't drill'. The decision rule is to choose the act with the highest expected monetary value (EMV).<sup>9</sup> The EMV of an act is calculated by multiplying the monetary consequences of possible outcomes by the probability of occurrence associated with each outcome and then adding the resulting values for each outcome. For example, the EMV of \$34,000 for the act 'drill' is calculated as follows:

| <i>Possible<br/>outcomes</i> | <i>Profit<br/>or (loss)</i> | <i>Probability</i> | <i>EMV</i> |
|------------------------------|-----------------------------|--------------------|------------|
| Dry hole                     | (\$50,000)                  | 0.7                | (\$35,000) |
| 200,000 barrels              | 130,000                     | 0.2                | 26,000     |
| 500,000 barrels              | 430,000                     | 0.1                | 43,000     |
| Expected<br>monetary value   |                             |                    | \$34,000   |

The above probabilities are the geologists' personal or subjective estimates based upon presently available information. If a decision were to be made now, the act 'drill' with an EMV of \$34,000 would be favored over the act 'don't drill' which has an EMV of \$0. But the decision maker has the choice of either

7. See also Bedford and Onsi, (1966).

8. The discussion to follow is based upon the illustrations presented in Grayson, 1960, ch. 11.

9. EMV decision rule is used by Grayson as a substitute for expected utility value solely to simplify the illustration.

making the final decision with available information or obtaining additional information before making it. The decision maker must, of course, recognize that additional information is neither free nor perfectly predictable as to outcomes. In sum, the information decision is of much the same nature as the 'drill - don't drill' operating decision.

Assume that the additional information under consideration is seismic and will cost \$10,000. Seismograph information will lead to one of six interpretations. Using past frequencies as a guide, the decision maker is willing to stipulate the probability of each outcome (dry hole, 200,000 barrels, 500,000 barrels), conditional on obtaining a particular seismic result. An illustrative table from Grayson (1960, p. 330) follows:<sup>10</sup>

*Table 1* Conditional Probabilities Given Seismic Results

|                             | <i>Dry<br/>hole</i> | <i>200,000<br/>barrels</i> | <i>500,000<br/>barrels</i> | <i>Total</i> |
|-----------------------------|---------------------|----------------------------|----------------------------|--------------|
| <i>Seismic result: good</i> |                     |                            |                            |              |
| Structure closed            | 0.30                | 0.50                       | 0.20                       | 1.0          |
| Structure not closed        | 0.75                | 0.15                       | 0.10                       | 1.0          |
| No structure                | 0.86                | 0.07                       | 0.07                       | 1.0          |
| <i>Seismic result: fair</i> |                     |                            |                            |              |
| Structure closed            | 0.30                | 0.60                       | 0.10                       | 1.0          |
| Structure not closed        | 0.90                | 0.10                       | 0                          | 1.0          |
| No structure                | 0.80                | 0.20                       | 0                          | 1.0          |

All of the above outcome probabilities are *conditional* upon given seismic results. Next, consideration must be given to the unconditional probability of obtaining each of the six possible seismic results. Once again, historical data is used as a basis for projecting these probabilities. At this point, all data required to make the decision of whether to purchase seismic information are available.

Earlier we stated that the EMV of the act 'drill' without obtaining additional information is \$34,000. Consequently, the net EMV (after deducting the \$10,000 cost of seismic information) of the act 'buy seismic' must be greater than \$34,000 for it

10. See Charnes and Cooper, 1961, vol. 11, ch. XIX, for relationship of game theory to linear programming.

to be considered favorably. The net EMV of the act 'buy seismic' is calculated as follows:

1. Calculate the EMV for each of the six possible seismic results. This is done by multiplying the monetary consequences of each outcome (dry hole, 200,000 barrels, 500,000 barrels) by the probabilities conditional on obtaining each particular seismic result, and adding the resulting values for each outcome.
2. Multiply each of the six EMV's (from Step 1) by the unconditional probability of obtaining each of the six seismic results. Add the resulting six EMV's for seismic results to obtain the EMV of the act 'buy seismic'.
3. Subtract the \$10,000 cost of seismic information from EMV of the act 'buy seismic' to obtain the net EMV.

In the Grayson illustration the net EMV of the act 'buy seismic' is \$46,400. Thus, following the predetermined decision rule, the decision maker would presumably buy seismic information. Thereafter, a drilling decision can be made on the basis of the EMV of the resulting seismic interpretation.

Let us now consider the conditions under which a statistical decision theory approach, as described above, can be employed for making information decisions. The Grayson model requires the following inputs:

(a) To obtain EMV of the decision 'don't buy seismic':

1. Monetary consequences of possible outcomes.
2. Probabilities associated with each outcome.

(b) To obtain net EMV of the decision 'buy seismic':

1. Cost of additional information.
2. Possible results of further data collection efforts.
3. Probabilities associated with each data result.
4. Monetary consequences of possible outcomes.
5. Conditional probabilities of outcomes given each possible result of data collection.

Let us postulate that inputs (a)-1 and (a)-2 above can be developed, although with varying degrees of confidence. Let us further assume that input (b)-1 can be reasonably approximated. For many important business decisions, there is serious question regarding the capacity of analysts and decision makers to develop reason-

able parameters for inputs (b)-2 through (b)-5. This again is the nagging problem of situations in which the analyst has little basis for projecting the value of incremental information. Unfortunately, in too many situations 'seismic-type information' is not easily developed. By 'seismic-type information' is meant information characterized by two principal data-gathering attributes.

1. There are a finite number of data-gathering results. They can be enumerated in advance of actual data gathering.
2. The probability of obtaining each data-gathering result can be specified with a reasonable degree of confidence, and further, can be related quantitatively to the expected value of the decision. The foregoing analysis of the decision theory approach to information economics suggests that it appears to offer an invaluable guide when 'seismic-type information' is available. In the absence of 'seismic-type information' other strategies for making information decisions should be explored.

Simon offers the following view of sensitivity analysis:

Because management scientists became keenly aware of the imperfections of the data with which they worked, they early developed an interest in 'sensitivity analysis'. Sensitivity analysis is aimed at estimating the costs of making decisions with bad data and, correlatively, at estimating the value of procedures to improve the data (Simon, 1961).

Simon emphasizes the 'risk analysis' and 'information economics' applications of sensitivity analysis. This is not surprising since these two applications of sensitivity analysis can be performed simultaneously. We will use the linear programming model presented earlier to illustrate the validity of the foregoing proposition. Also, we wish to show how decision theory and sensitivity analysis are each relevant to information decisions.

Let us first compare the basic questions asked in the decision theory and sensitivity analysis approaches to information decisions.

*Decision theory:* Will the expected value (utility) of additional information be worth the cost (effort) of obtaining it?

*Sensitivity analysis:* How sensitive is the value of the decision to possible parameter variations?

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Under the sensitivity analysis approach if the value of the decision is insensitive to estimated parameter variations, then the decision to purchase no additional information can be made without introducing a statistical decision model. If the decision is sensitive, then some judgement must still be made regarding the wisdom of initiating further data collection and refinement. It is at this point that a statistical decision model may be applied beneficially, as shall be illustrated later. To summarize, there are two important advantages for the sensitivity analysis approach to information decisions:

1. A sensitivity analysis underlying an information decision can be performed simultaneously with the sensitivity analysis for the evaluation of risk.
2. A sensitivity analysis which discloses decision insensitivity to estimated parameter variations precludes the necessity of introducing more costly, time-consuming statistical decision models into the analysis.

### *Case study of an information decision*

Let us now return to the linear-programming model used to solve the television product-mix problem. We shall now attempt to illustrate how sensitivity analysis and statistical decision can be used jointly for information decisions. In our earlier analysis, we noted that the lower limit for the objective function coefficient for color sets ( $x_4$ ) is \$66.67. Management is concerned over a possible \$35 increase in the price of color cathode-ray picture tubes. Such an increase would decrease the profit coefficient for color sets from \$100 to \$65. Since \$65 is outside the indifference range we resolved the problem and obtained the following comparative results:

| Variable                    | Style    | Optimal schedule (units) |         |            |
|-----------------------------|----------|--------------------------|---------|------------|
|                             |          | Original                 | Revised | Difference |
| $x_1$                       | Standard | 10                       | 10      |            |
| $x_2$                       | Deluxe   | 10                       | 10      |            |
| $x_3$                       | Super    | 49                       | 196     | +147       |
| $x_4$                       | Color    | 99                       | 11      | - 88       |
| Maximum contribution profit |          | \$12,410                 | \$9105  | -\$3305    |

Management is quite concerned over the significant changes in profits and production schedules under the revised optimal solution. Management believes that radical and numerous changes in production mix can be expensive both in terms of average employee productivity and set up costs. For this reason, management would prefer to maintain either the original or the revised production schedule for the forthcoming month. Management cannot expect to know the supplier's pricing decision until it becomes effective on the first day of next month. Customers require promised shipping dates. The production planning department requires advance notice of any major changes in production mix. Consequently, the production decision for next month must be made before the first of the month.

Management thus has two choices, to follow the original or the revised optimal schedule in the face of two possible outcomes, no price increase or a \$35 price increase. The value of daily outcomes for each possible act or decision can be presented in a payoff table as follows:

|       | $O_1$  | $O_2$ |
|-------|--------|-------|
| $A_1$ | 12,410 | 8945  |
| $A_2$ | 9490   | 9105  |

where,

$A_1$  = the act 'implement original optimal schedule'

$A_2$  = the act 'implement revised optimal schedule'

$O_1$  = the outcome 'no price increase'

$O_2$  = the outcome '\$35 price increase'

The payoffs for  $A_1O_1$  and  $A_2O_2$  represent the initial and revised maximum profit contributions, respectively. The opportunity loss of using the revised schedule in the event of no price increase is \$2920, i.e. \$12,410-\$9490. The opportunity loss associated with

## Algorithmic Models

implementing the original schedule in the event the \$35 price increase materializes is \$160, i.e. \$9105–\$8945.

To convert the daily payoff table to a payoff table for the forthcoming month, all values are multiplied by twenty-five, the number of planned production days:

|       | $O_1$   | $O_2$   |
|-------|---------|---------|
| $A_1$ | 310,250 | 223,625 |
| $A_2$ | 237,250 | 227,625 |

Based on presently available information management assigns probabilities of 0.60 and 0.40 to  $O_1$  and  $O_2$ , respectively. If management were willing to invest approximately \$1000 for researching this problem, it is believed that the odds are 9 to 1 that they will correctly predict the actual outcome. Should management invest in the research necessary to develop the additional information?

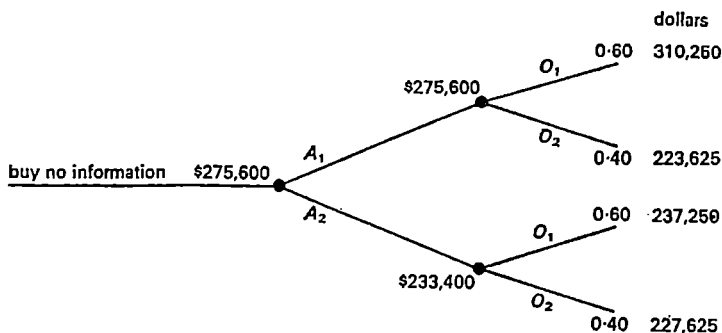


Figure 1 Decision tree diagram illustrating EMV of best decision with presently available information



First we will calculate the  $EMV^{11}$  of the best decision with presently available information. This is done using the decision tree format in Figure 1 and yields an answer of \$275,600.

We now calculate the EMV of the best decision, assuming that management decides to invest \$1000 to obtain additional information. As stated earlier, management believes that the additional research will lead to a correct prediction of an outcome 90 per cent of the time. The matrix presented below summarizes the relevant joint and marginal probabilities.

|       | $O_1$ | $O_2$ | Total |
|-------|-------|-------|-------|
| Say 1 | 0.54  | 0.04  | 0.58  |
| Say 2 | 0.06  | 0.36  | 0.42  |
| Total | 0.60  | 0.40  | 1.00  |

where

Say 1 = the prediction 'no price increase'

Say 2 = the prediction '\$35 price increase'

$O_1$  = the outcome 'no price increase'

$O_2$  = the outcome '\$35 price increase'

We know that the prior expectations for  $O_1$  and  $O_2$  are 0.60 and 0.40, respectively. These figures are reflected as the column totals of the matrix. If  $O_1$  can be expected with 0.60 probability and predictions are correct with 0.90 probability, then the joint probability of both events occurring simultaneously is 0.54, i.e.  $0.60 \times 0.90$ . This condition is reflected in element Say 1- $O_1$  of the matrix. Conversely, the joint probability of  $O_1$  and an incorrect prediction of Say 2 is 0.06, i.e.,  $0.60 \times 0.10$ . This is naturally reflected in element Say 2- $O_1$  of the matrix. A like procedure is followed to obtain the joint probabilities for the  $O_2$  column. The now totals of the matrix reflect the marginal probabilities associated with Say 1 and Say 2. That is, Say 1 and Say 2 will occur with probabilities 0.58 and 0.42, respectively.

11. Just as in the Grayson model, the EMV decision rule is used instead of expected utility value solely to keep the illustration simple. When utility is not linear, the EMV decision rule must be used with discretion.

From the data in the matrix the posterior probabilities for outcomes can easily be calculated. For example, given that Say 1 is predicted, what is the probability ( $P$ ) that  $O_1$  will occur? By reference to the matrix we know that Say 1 will be predicted with probability 0.58 and that the joint probability of Say 1- $O_1$  is 0.54. Thus, we see that:

$$P(O_1 \mid \text{Say 1}) = \frac{0.54}{0.58} = 0.931$$

We can further state that:

$$P(O_2 \mid \text{Say 1}) = \frac{0.04}{0.58} = 0.069$$

$$P(O_1 \mid \text{Say 2}) = \frac{0.06}{0.42} = 0.143$$

$$P(O_2 \mid \text{Say 2}) = \frac{0.36}{0.42} = 0.857$$

We will again revert to the decision tree format to illustrate the calculation of the EMV of the best decision with additional information available. In Figure 2, working from right to left, we find the dollar payoffs or consequences for the various action-outcome combinations. These values are taken directly from the monthly payoff matrix presented on page 336. These payoffs are

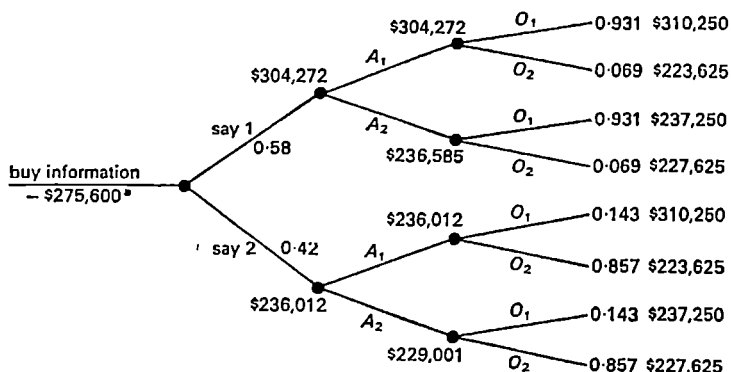


Figure 2 Decision tree diagram illustrating EMV of best decision with additional information

multiplied by the posterior probabilities to obtain EMVs for the outcomes. These EMVs, \$304,272, \$236,585, \$236,012 and \$229,001, can be found at the series of nodes one step back from the right endpoints. At this point a choice between  $A_1$  and  $A_2$  is made using the 'maximize EMV decision rule'. In each case,  $A_1$  is chosen and the associated EMV recorded at the next node. The EMV of the best decision with the additional information is then calculated by: (i) multiplying the EMV of  $A_1$  given Say 1 (\$304,272) by the probability that Say 1 will occur (0.58); (ii) multiplying the EMV of  $A_1$  given Say 2 (\$236,012) by the probability that Say 2 will occur (0.42); and (iii) adding the results of the first two steps.

We note that the value of the decision with the additional information is \$275,600 and also that this is equal to the EMV of the decision without additional information. Why is this so? It is because the best act given Say 1 is  $A_1$ , and the best act given Say 2 is  $A_1$ . Consequently the information that management receives, whether it be Say 1 or Say 2, will not affect its choice. If this is the case, common sense dictates that the information is valueless. In sum, we have employed a statistical decision model and determined that the value of the decision in this problem is insensitive to incremental information which can correctly predict the actual outcome 90 per cent of the time.

### Summary

1. In its applied organizational setting, sensitivity analysis may be broadly defined as a study to determine the responsiveness of the conclusions of an analysis to changes or errors in parameter values used in the analysis.
2. Sensitivity analysis tests the responsiveness of model results to possible changes in parameter values, and thereby offers valuable information for appraising the relative risk among alternative courses of action.
3. Sensitivity analysis can provide systematic guidelines for allocating scarce organizational resources to data collection and data refinement activities.
4. Under the sensitivity analysis approach, if the value of a decision is insensitive to estimated parameter variations, the

decision to purchase no additional information can be made without introducing a statistical decision model.

5. If the value of a decision is sensitive to estimated parameter variations and the information decision is not obvious, a statistical decision model may be developed to guide the information decision.

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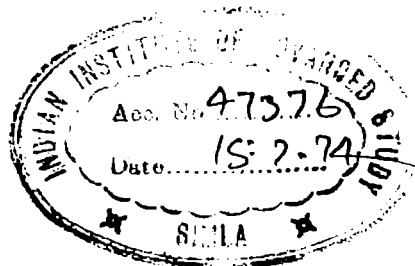


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Decision making is not a simple process. There are many approaches to an explanation of the activity, but Professor Cyert and Dr. Welsch have started from the famous work of the Carnegie 'school'. This regards decision making by the manager as embracing the whole of his behaviour. It begins with his finding the opportunities for decision making, the identification, analysis and choice among the possible alternatives, and leads to the implementation of his decision.

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