Operations Research: Decision Aid for Management

George W. Morgenthaler

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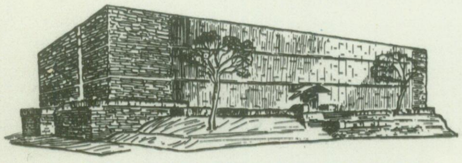

THE CHARLES STEWART MOTT BUILDING

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CONTENTS

OR: What It Is and What It Aims to Do

Section One

This booklet and the next one in this series are a brief introduction to Operations Research, often called OR. The present booklet is concerned with the what of OR and with its accomplishments, the why. The how of OR--its general approach to management problems--is also described, and particular mathematical methods found useful in OR are briefly discussed.

The next booklet (A View of the Methods of Operations Research) provides an explanation of those techniques which have enabled Operations Research analysts to contribute to the solution of important industrial, business, and military problems.

The language and point of view of each booklet are non-technical. It is assumed that the reader does not expect to become a practitioner of OR but that he is an executive who might use OR services. As such, he is now getting acquainted with OR and its potentialities so that he may be a more intelligent consumer.

NEW PROBLEMS IN THE NEW AGE

Every age has its unique problems, and those which beset management today require new medicine. One has only to ponder the rapid strides and innovations made by technology, the accelerating rate of change in the social and economic realities of modern life, the decreased decision time, and the fact that businesses and even whole industries are interdependent in ever more complicated ways, to realize the problems which challenge today's executive. He is steering us through the evolutionary stages of a new industrial revolution. Gone is the day when a simple economy and patterned way of life made it sufficient to hire an "experienced man" as chief executive.

Today's executive must often make decisions about phenomena of which he has no previous experience. Should the production line of a motor car company install computer-operated milling machines? In this decision, installation costs must be balanced against greater productivity, improved product quality, and labor requirements. There is no past experience with such machines. But a decision must be made.

Sometimes the more intense competition of modern business necessitates a change in operations. Shipping costs may have to be pared if competitive prices are to be maintained. The shipping department is now sending the product from five warehouses to thirty cities, each city getting its supply from certain warehouses. Is the present routing optimum?

Let's look at the shipping facilities themselves. Should the proposed new truck docking facilities have four docks, each capable of serving five trucks, or the cheaper alternative of three docks, each servicing six trucks? Will the service rate be adversely affected in the latter case?

Similar management decisions on automation, handling atomic energy, inventory levels, building and locating new plants, etc. involve large expenditures of capital with considerable uncertainty of outcome. Management needs an objective, quantitative evaluation of the consequences associated with alternative courses of action and needs guidance in the improvement of operations.

Management might guess at the most likely numerical level for each variable involved in a decision and, computing on this basis, determine how to act. However, if there were ten variables and each could be correctly estimated 75 times out of 100, the chance that all ten had been correctly estimated would be less than six out of 100. These are not good odds for gambling with millions!

Many management problems involve finding the optimum combination of many variables. Some companies have been trying for years to "hunt and peck" or "trial and error" their way to a solution. The chances of success are slim indeed. Lindsay (3) has estimated that for the classical travelling salesman problem in which the salesman wants to plan a trip to the 48 state capitals (now 50) in such a way as to minimize the total distance travelled, there are about 10^{50} possible routes. A million employes working a million years, each doing a million trials per second, couldn't accomplish one per cent of these trials for management! Obviously more direct techniques for minimizing are needed.

These and other management problems have been attacked and solved by OR. Whether required to provide quantitative guidance on new problems, or to find more efficient ways of dealing with old problems, OR has brought a fresh look; has insisted on a dispassionate, objective appreciation of facts; has challenged old ways of doing things; and, as someone has said, has prevented hardening of the business arteries.

OPTIMIZING THE OVER-ALL GOAL

Morse and Kimball (6) have stated, "Operations Research is a scientific method of providing executive departments with a quantitative basis for decision regarding the operations under their control."

Many definitions of OR have been proposed. Most of them share the view that OR is research on operations to gain understanding for the purpose of control and improvement. As might be expected, experts sometimes disagree on OR's exact meaning or emphasis. However, the lack of agreement is not necessarily catastrophic. Although electronic scientists do not really understand what an electron is, we still enjoy television every day.

The operations researcher tries to understand the over-all goal of the operation. He studies it, notes all the important variables, collects the pertinent data, tries to find a measure of operational effectiveness, creates and checks out a mathematical model (that is, a set of equations describing the operation). Then he asks, "What happens to the efficiency of the operation if you increase or decrease the value of the variables? Which values of the variables give the best results?" Answers are obtained by computing and predicting, using the mathematical model.

It may seem strange to the executive to have to spell out exactly the relationships among variables which enter his business decisions. However, it is precisely this insistence on understanding the factors which up to now have been obscured under the heading "business judgment" that makes OR so valuable. OR insists on measuring and quantifying so that it may evaluate the merit of alternative courses of action.

The analyst must be careful that it is the over-all goal of the operation which is being optimized. In designing motor vehicles, for example, the suspension engineer may wish to build in the smoothest possible ride, the carburetion expert may wish to build in the most efficient carburetor, the interior stylist may select the finest fabrics, etc. Despite such aims (in fact, because of them), the vehicle may be a poor design. Sometimes a sub-optimization or optimization with respect to secondary objectives can actually detract from over-all effectiveness. The maximum is not always the optimum when constraints of total cost, total weight, production time, etc. are considered.

So it is with large-scale, complex management decisions. The emphasis is away from component or departmental optimization towards system optimization, optimizing with respect to the over-all military, business, or economic goals. Industry and technology have become so complex that we have become a generation of specialists. OR attempts to integrate. As Goland and Konigsberg have said, "Operations Research is a sort of super-control that directs the other controls, coordinates the other applied sciences."

A side observation underscores the fact that OR is really a new frame of mind more than a basically new scientific discipline: several of the problems to which OR has been successfully applied have been solved with age-old mathematical methods. Some of the simpler inventory problems, for example, require nothing more than algebra and calculus for their solution. They could have been solved long ago, except that the peculiar viewpoint of OR had not been applied.

RELATION TO OTHER MANAGEMENT TOOLS

Perhaps we can get some further understanding of the nature of OR by saying what OR is not, and by noting how it differs from other management tools.

OR is not mathematics. The mathematician is interested in establishing the validity of propositions about mathematical objects (lines, numbers, distances, etc.) independently of whether his theorems have application in the real world. The operations analyst (aside from his personal interest in culture as such) is interested in mathematics to the extent that it can assist him in making a model of the operation. The analyst is the go-between in putting the latest mathematical results to work on industry's problems.

OR is a heavy user of statistics and probability, but it is neither statistics nor probability. These theories are interested in the methodology of drawing inferences from numerical data. OR is interested in what these disciplines can contribute to understanding an operation. The analyst, for example, in studying the problem of optimum allocation of money between several forms of advertising, might utilize the statistician to develop a special data questionnaire, a sampling procedure, and an experimental design. The statistician helps the analyst get the data he needs as inputs into the mathematical model of the advertising process.

Basic concepts of physics and electronics are used to relate variables in a model. The theory of air-borne search with radar was developed by OR personnel during World War II. The theory certainly utilized knowledge of radar principles. However, OR is not concerned with the development of new radar equipment nor with uncovering basic electronics knowledge; it is not physics.

Principles of design, quality control techniques, time and motion studies, and other industrial engineering methods are often important parts of a thorough OR study. However, problems of optimum development and production of new products which management has already decided to build are not the everyday fare of OR personnel. Others are very likely more skilled at these tasks. OR is more concerned with the decision of what to produce, considering over-all company objectives. OR is not engineering, per se.

The principal task of market research is to quantitatively measure the market demand by various sampling techniques and to report these data in a form useful to management. OR is also interested in these data, but less as an end in themselves and more as a device for arriving at an understanding of the selling operations of the company. The next level of abstraction is the inclusion of this new understanding in a model of the marketing operation. It is this last step which distinguishes OR.

Costing, accounting, and data-reduction techniques supply management with timely data on the state of health of the business. Data are also used for decisions and control of the operation. OR, however, generally utilizes these data as inputs into models which are then used to predict the optimum operating levels. It strives to build new techniques for wringing additional decisionary information out of the data, and is more encompassing in scope and less strongly influenced by traditional methods of handling the raw data. OR is not wholly any one of these accounting-type services.

Management consulting is an older service which today includes many OR practitioners. Many of these advisors have themselves had management experience and are using their broad experiences to participate in the making of the client's decisions. OR relies more on the quantitative, mathematical model approach and remains in a definitely staff role--it leaves the decision to the executive.

APPLICATIONS

OR is a tool, and as such it can be applied to broad classes of problems in all types of industry. Some of the successful military applications of OR are discussed later in this booklet. The following are areas of recent and possible future applications of OR to management problems.

Agriculture

As far back as 1947, OR was applied to bottleneck problems in the harvesting and processing of peas at Seabrook Farms. Observing that plants grew at different rates at different times of the growing season, Dr. Thornthwaite developed a climatic calendar which expressed the number of growth units to be expected at any time of the year. With the aid of this calendar, peas were planted in such a way that a certain portion were ready for harvest each day. Harvesting labor and equipment costs were reduced and spoilage was cut (17, Feb., 1953, and Oct., 1958).

Educational Planning

Many writers have suggested that we overhaul our programs at the various levels of our educational system. Rather than have each level act to sub-optimize the educational experience of that level, we might apply the OR total-mission concept. This might produce a better, more integrated, and more efficient solution to the whole problem. Improved university registration techniques are an oft wished for development. At the May, 1959 meeting of the Operations Research Society of America, it was reported that digital computers had been programmed at two universities to perform individual course scheduling. OR applications to the pressing problem of library storage have also been reported, and simulation studies of campus layout have been made.

Hospitals and Institutions

Improved allocation of hospital resources has been studied at the Johns Hopkins Hospital. Studies on reduction of in-patient waiting time have been made. Purchasing and inventory of supplies and maintenance are other potential application areas. OR applications to the nation's postal system have begun, and prison administration is also a potential area of OR application.

Inspection Procedures

Professor Mitten of Ohio State University reported an extremely interesting OR study of considerable ingenuity and scope. It was undertaken to improve the visual inspection procedures of a large manufacturing company which had an annual volume of over two billion small parts. Research included studies of eye movements, worker attitudes, inspection techniques, inspector training, illumination, and motivation. It involved the scientific method and the team approach. An interesting conclusion was that the team felt that OR work on defect-prevention would have been even more profitable than research on defect-locating (1).

Inventory Control

In inventory problems one must balance fixed order costs and variable production or carrying costs against a demand for the product. Usually the demand is fluctuating, but it may be accounted for in a statistical way. Mathematics can then be used to derive optimum inventory policies (1).

Logistics and Spare Parts Stocks

Determining the optimum mixture and quantity of spare parts is a complicated problem. A related problem deals with large, high-cost, one-shot equipment purchases. For example, suppose large generators are ordered for a new hydroelectric dam. Rotors will eventually wear out, and it may be far less expensive to include a request for spares directly in the contract. How many and which component spares should be requested? The Rand Corporation has devoted a large effort to the spare parts problem in the aircraft industry, and considerable progress has been made.

Maintenance and Replacement Policies

Every automobile owner must sooner or later decide whether to invest in repair or to use the same money for replacement. On a much larger scale, firms that use much plant machinery, many delivery vehicles, etc. ought to carefully integrate equipment costs, operating rates, depreciation allowances, and labor costs, in a mathematical model which can be used to arrive at optimum replacement and maintenance policies (1).

Purchasing Policies

The theory of games and linear programming hold promise for laying down specific guides to buyers operating in an open market.

Railroad Traffic Control

The Westinghouse Airbrake Company has simulated the operation of railroads. The study guided its research and development staffs in the design of new equipment systems for the control of railroad traffic. Classification yard capacity, train size, and line operating policies were important factors which were varied in the study. Permanent characteristics of particular equipment were arrived at as requirements for improved operation of the rail system.

Warehousing and Food Distribution

General Foods has performed a study of where to warehouse and how to distribute the production of four plants which pack a frozen vegetable. The packing is done during one month of the year, but the product is consumed during the whole year. Its consumption rate is seasonal and is affected by availability of fresh vegetables. The purpose of the study was to develop a schedule which had minimum warehousing, handling, and distribution cost. The transportation problem method of linear programming was used to obtain a solution.

We could cite many other OR accomplishments: scheduling of barge lines, development of ore reserves in mining, applications to retailing, applications to the Federal Aviation Agency's Air Safety Program, evaluation of urban facilities, optimum assignment of personnel to jobs, optimum usage of cranes in a steel yard, investigation of strategy in foreign affairs, and even assistance in the planning of Disneyland (17, Feb., 1955). We shall go no further, however, for the reader will no doubt already see potential OR applications in his own field.

SOME LIMITATIONS

So we have here, then, a lamp and a genie which can be called forth to solve our every problem? Not so. There are many management decision problems for which, at present, OR can supply no concrete solution.

Sometimes the data on really important variables in the operation are insufficient or are lacking entirely. The vulnerability of military vehicles which at the time exist only on the drawing board, for example, can only be "guesstimated." Obviously no firing test results are available.

Another roadblock to the use of OR occurs with factors which cannot be quantified. In planning for production of women's clothing, for example, there may be no way of arriving at a numerical probability that Paris dress designers will design above or below the knees three years hence. Moral and ethical factors or prestige are also difficult to include. In the military realm, it is obvious that an enemy could make effective use of sabotage in destroying our ICBM forces. We can even imagine the various forms the sabotage may take, but it is virtually impossible to assign numerical probabilities to the occurrence of these sabotage forms. We cannot read the enemy's mind.

In some cases the objective and criterion of goodness by which to measure results is in question. To make money sounds like the obvious indisputable business goal. But how much should "profit" take the form of long-term good will, public relations, plant improvement, employee morale, and so on, rather than immediate money in the coffers? Some enlightened corporations now publicly espouse anti-inflation or other national goals as part of their business credo.

Sometimes an OR problem is clear-cut: the principal variables immediately suggest themselves, an index of effectiveness is chosen, relationships are evident, and a model is directly forthcoming. Alas, not all mathematics is equivalent in difficulty to 2 + 2 = 4. There are cases in which difficulties of a highly technical and mathematical sort prevent us from attaining a solution, even after the equations have been found. Perhaps adequate methodology has not been developed as yet. Or the problem might be too large for solution by existing computers.

Other technical roadblocks are complexity and time. Some systems have too many variables for the present level of OR experience to create a valid model. More research is needed. Research takes time, and perhaps lack of decision time alone prevents the business man from using OR services. Then too, with long-term projects, expenses mount. Perhaps the potential gain cannot justify the costs of a long-term OR effort.

The above difficulties are mentioned only to convey the notion that OR cannot solve all problems. However, even in these frustrating cases OR can help. It can suggest which data should be collected and in what manner. When non-quantitative factors are present, it can often indicate a series of "if - then" statements. If sabotage method A is employed, then the outcome will be so and so. If method B is used, then such and such will happen. And so on. Such statements provide useful information to the decision-maker, even if they are not as helpful as direct recommendations on alternative courses of action.

In the case of lack of adequate technique, the critic must exercise forbearance and realize that OR is a young field. Only as technical roadblocks appear will the attention of mathematicians be focused toward a break-through in methodology. Some of these difficulties will disappear in time.

CAN WE FIRE THE EXECUTIVE?

If OR can quantify the alternatives in decisions, can we not dispense with the executive? The temptation is to envision the absent-minded, humorless scientist, coldly pushing buttons on an electric computer as he sits at the ex-manager's desk. The answer to the question, however, is a resounding no.

Most major decisions must deal with a mixture of physical, mathematical, and statistical facts, and also with moral, political, psychological, timing, and morale factors. Elements of personnel appraisal and just plain business judgment are also present. The role of OR is to remove the guessing, in so far as this is possible, from all measurable aspects and thus leave more time for the skilled executive to deal with the intangibles. He ultimately integrates all factors into the decision.

To be sure, clean-cut problems which are almost entirely quantitative appear occasionally. In these cases OR can remove drudgery from the executive by supplying a numerical indication of the best decision. However, adeptness in decision-making will continue to be the touchstone of executive success.

It is conceivable that an experienced analyst may be invited to assume executive responsibilities. This has happened in the insurance business, where actuaries have assumed important executive positions. While such a situation may work out well because of the all-around excellence and broad experience of the man involved, the individual becomes an executive, with executive duties. It will be hard for him to find the time and frame of mind to perform the same methodical, dispassionate analyses which he did as an OR worker. The background, motivation, and methods of procedure of the OR scientist and the executive are opposites and hence complementary.

The executive has probably had business training and a liberal education, with perhaps a smattering of law. His on-the-job training has fitted him for command, with increases in responsibility as time went on. He is often compelled to arrive at decisions without all the facts and a thorough analysis. He is judged by his percentage of right decisions.

The scientist has received advanced training in a narrow field and knows painstaking research from personal experience. His answers have not been required by a specific time or date. He is trained to check and recheck all his conclusions. He has no personal attachment to the answers. He just wants the facts.

IN SUMMARY

OR has broadened the approach to operating problems and has introduced new techniques to the world of affairs. With its total-mission approach OR can:

1. Save time for the executive by summarizing and exploring solutions
2. Identify and relate important operating factors
3. Reduce costs, improve production, increase profits
4. "Brainstorm" and investigate new products, new markets, and new uses for plant and facilities
5. More clearly define company objectives
6. Organize existing data and develop means of rapidly and inexpensively processing data when problems require this
7. Quantitatively relate the operations of various divisions, departments, individuals, and jobs to the over-all company objectives
8. Test sensitivity of suggested solutions to possible changes in the operating circumstances
9. Furnish a vehicle (the model) useful for combining the opinions of the company's subject-area experts
10. Fill the gap between "know-how" in technical fields and ways of conducting operations in the company

The OR Approach to Management Decision Problems

Section Two

Not all problems which management feels it has are true problems for OR application. Then again, the problem which the executive poses may not be the problem which should be solved.

SELECTING PROBLEMS

A problem reported by Ackoff was originally phrased as how to determine the relative production effort that should be devoted to two product lines. But the problem turned out to be one of increasing the efficiency of producing one of the product lines. A problem of how much to increase a warehouse's capacity may really be one of altering the inventory or ordering procedures. It will require close study of operations and close contact with company personnel to correctly formulate the OR problem.

In some instances, the proposed problem is not worthy of the talent and effort which will be expended on a solution. In essence, a cannon is being used to kill a fly. The potential return in terms of money saved must be weighed against the study costs. Moreover, the problem must be sufficiently complicated by important relations to require professional OR leadership in finding its solution.

Finally, the problem should be sufficiently pressing and important to top management so that the proper support in information-gathering will be obtained, and final conclusions assimilated and acted upon.

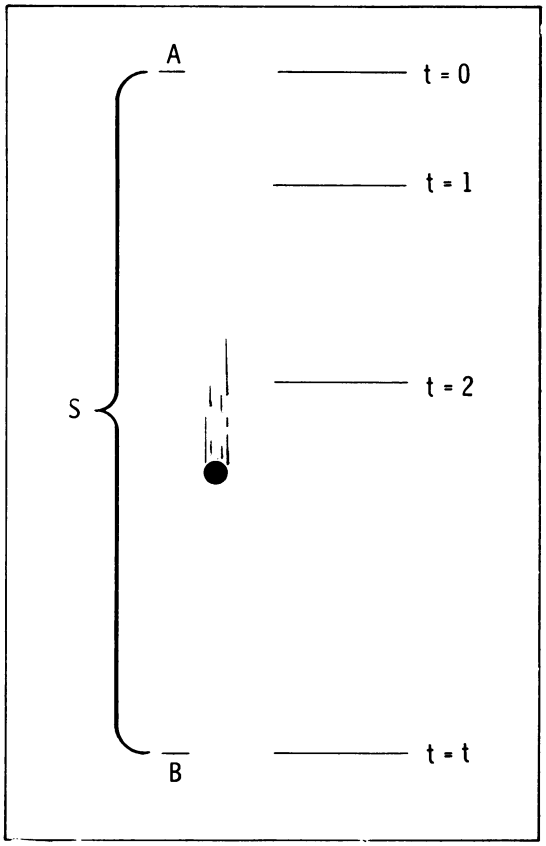
The analyst and management should have a preliminary meeting of the minds on the general nature of the problem, its importance, the chances of success, and the available solution time. This orientation is valuable to management in deciding whether to proceed with the study and also in understanding what to expect as the product. Such a preliminary survey is valuable to the analyst in determining a study timetable, in selecting suitable approaches, and most important, in formulating the basic mission of the operation as it is conceived by top management. He is now ready to apply the scientific method.

THE SCIENTIFIC METHOD

The basic tool of western civilization which has led to its technological ascendancy over past civilizations is the scientific method. In essence, the scientific method is a belief in the consistency of physical phenomena. It believes that if we can but capture in quantitative form the physical laws of our environment, the effects of certain actions can be predicted by computation and deduction.

The basic steps of the method are:

1. Observation of a given physical phenomenon
2. Inductive reasoning leading to a generalization or "law" of nature about the phenomenon
3. Construction of a theory to explain the phenomenon
4. Use of the theory deductively to make predictions which can be verified by experiment
5. Comparison of theoretical prediction with experimental data
6. Acceptance or rejection of the theory



Distance vs. Time

In the case of rejection, the scientist will repeat the cycle. He will gather fresh and more exacting observations and will theorize again and again, until a scientifically acceptable explanation has been obtained.

A simple but recognizable example from elementary physics may serve to clarify these steps. Consider a ball released from rest and allowed to fall to earth. From repeated observations with various objects and heights, certain facts are noted. First, objects always fall downward, toward earth. The longer they fall, the faster they go, but their acceleration is constant. Heavy weights fall at the same speed as lighter weights (Galileo's famous experiment of dropping unequal weights from the leaning tower at Pisa), and so on.

The scientist can now write formulas relating the time of fall of an object to the distance it has travelled. Let t be the lapsed time from a position of rest at A to arrival at B, a distance S feet below A. The object has a constant acceleration, g feet per second per second. At the end of the first second, it is traveling at a velocity of g feet per second. At the end of the second second, 2g feet per second. At the end of the third second, 3g feet per second, and at the end of the t^{th} second, gt feet per second. Since it started its fall at zero velocity, the average velocity under constant acceleration is $(0+gt)/2 = gt/2$ feet per second for the first t seconds. If it has taken t seconds to go S feet and the average velocity is $gt/2$ feet per second, it follows that $S = (gt \cdot t)/2 = (gt^2)/2$.

The next step is prediction. This model can now be used to predict the time it will take a ball to fall from a 100 foot tower to the earth. It is known that g = 32 feet per second per second at the surface of the earth. Thus:

$$\frac{32}{2} t^2 = 100$$

$$t^2 = \frac{2(100)}{32} = 6.25$$

$$t = \sqrt{6.25} = 2.5 \text{ seconds.}$$

If you have a ball, a tower, and a stopwatch, you can perform an experiment to determine whether the model gives correct predictions. As the reader may recall from his brush with high school physics, this model has been found satisfactory for this type of problem.

The scientist knows, however, that his most elaborate models are only approximations to nature. At some level of application the model ceases to be accurate enough for investigating the problem at hand. For example, in the foregoing model the mass of the object being dropped was assumed to be constant. Einstein's theories of relativity startled the scientific world by suggesting that at sufficiently high velocities the mass will change.

Curious time-shortening effects are also predicted by his theory at these high velocities. In fact, one of the experiments which is currently planned for satellites (which move at velocities of about 2 to 4 miles per second) is to carry a precision atomic clock to check this time change of relativity against an earth-bound duplicate clock. Note again the constant theorizing and experimentation to ever better understand nature's laws.

THE SCIENTIFIC METHOD IN ACTION

Suppose we are to investigate the desirability of adding certain alternate circuits to a complex teletype system. Delays in message sending have become too long and costly. Trial and error is out of the question because the cost of acquisition of right-of-way and the cost of poles, wires, transmitters, and receivers would make such experimentation prohibitive. How can the scientific method help in this problem? (The problem described was recently studied by Caywood-Schiller, Associates.)

The first step in applying the scientific method is to obtain a detailed understanding of the system. Certain data are noted. How many receivers and transmitters are used? What is the distribution of message lengths? At what times of the day is the system most used, and when is it at rest? What is the method of identifying messages? What is the message transmission rate? What is the distribution of present waiting times in message sending?

Next, a measure of effectiveness for the system must be established so that one can measure and compare alternative system improvements. One measure of system performance is the probability of waiting more than a given number of minutes to send a message. Another measure of effectiveness is the probability that upon the arrival of a message at the teletype desk, there are a given number of other messages waiting to be sent.

The next step is to generalize from the available data to an inductive law about the behavior of the system. The time between arrival of messages fluctuates. Sometimes a wait of several minutes between messages is experienced, and at other times several messages arrive in rapid succession. Also, the messages are of varying lengths, so that the so-called message "service time" also fluctuates in a chance manner. The assumption is made that these two fluctuating times obey a statistical law known as the Poisson distribution law.

Having hypothesized a law of behavior, we can then manipulate mathematically to arrive at an equation whose solution gives the probability, P_n, that at any instant of time there are n messages waiting to be sent. This is a model of how the system behaves.

A model is thus a representation of reality. At first the model may be crude and contain only major factors. As understanding grows, it may be made more complicated and better able to reflect reality.

Since it was possible to observe the operation of the teletype system, model-predicted probabilities could be checked against the number of messages actually waiting. The values obtained checked sufficiently well with the model. The model could thus be used with confidence to predict how much waiting would be reduced if the proposed circuit additions to the teletype system were made.

As in this teletype example, the scientific method in OR will usually include the following major steps: gathering facts and reaching an understanding of the operation, determining the operational objective, selecting a measure of effectiveness, creating a model, checking the model with experiments, applying the model to the alternatives, and making recommendations for action.

The presence of the measure of effectiveness, or as it is sometimes called "index of goodness," is a distinguishing feature of OR. It is extremely important that early in the problem a consistent, management-accepted statement of the fundamental goals be arrived at. Some measure--a cost function, probability of success, tons per unit cost, average damage, profit per dollar of invested capital--must be set up as the quantity to be maximized or minimized by varying the alternatives.

THE IMPORTANCE OF TIMING

While OR has a scientific research aspect, it is also a profession, and there is a client or customer. It is part of the analyst's professional task to appraise the job to be done and reach agreement with the client on the useful technical level and time of delivery of the end-product. It would do little good if OR finally and completely solved the problem of the optimum calibre aircraft gun in 1970. By then military aircraft may be obsolete or armed entirely with guided missiles. The optimal solution today to the inventory problem for horse collars would be just about as exciting. No, a solution, whether it is merely better understanding, data description, or qualitative recommendation, is due the customer on time.

If the analyst senses that a technical breakthrough in new methods will be required to adequately solve the problem, he should so inform the customer. A decision can then be made as to whether time and money will permit the gamble on the ability of mathematicians to arrive at a method.

The customer, on the other hand, must realize that all research is a gamble. Some problems in mathematics and physics have defied solution down through the ages, the efforts of the greatest minds notwithstanding. Fermat's last theorem is still an unproved conjecture in mathematics. Your problem, too, may be really hard.

THE TEAM APPROACH

Much has been said about the team approach in OR. Historically, many of the groups which worked on military OR problems during the war represented a mixture of disciplines. Some feel that this was by design. Others suggest that the mixed teams were probably due as nuch as anything to shortages of scientific manpower. Many men of

Highest Degree Attained	Academic Field											
	Math.	Mech.Eng.	Chem.	Aero.Eng.	Ind. Eng.	Elec. Eng.	Bus. Adm.	Econ.	Statistics	Physics	Chem.Eng.	Other
BS (61.2% of total)	19%	15%	12%	11%	9%	7%	7%	4%				16%
MS (28.2% of total)	26%	8%		12%	4%	6%	8%	4%	8%	4%	10%	10%
PhD (10.6% of total)	35%	6%				6%	2%	4%	10%	8%		19%

TABLE 1 Background of Industrial OR Staffs

certain scientific backgrounds which were most needed for OR work were also needed on other wartime scientific projects. Others were thus called into OR and adapted.

A 1958 survey (17, Dec. 1958) of U.S. companies revealed the educational backgrounds of their OR staffs. Table 1 shows the results of the survey.

Whatever the reason for such diversity, several statements can be made with some assurance. OR problems are frequently so broad that they require knowledge at various levels in the several scientific fields. It is almost necessary that specialists in these fields pool their talents if a valid and realistic solution is to be obtained.

In almost all instances, and particularly when the OR talent is from an outside consulting firm, it is desirable that one member of the team be a knowledgable, communicative, and objective company man. He is indispensable in helping others to understand the operation, in formulating the objectives, in creating interest within the company, in judging the validity of working hypotheses, and in avoiding an OR answer which might be considered "ivory tower."

The team approach was experienced by the author as a member of a University of Chicago project which made an analysis of the desirability of various weapons and aids designed to assist the Strategic Air Command in penetrating enemy heartland. A large simulation of a full-scale strategic air war was chosen as the appropriate model. Some of the penetration aids were electronic devices designed to confuse information systems; others were deceptive in nature; and still others were actual destructive weapons. In this case the group contained engineers, physicists, mathematicians, computer specialists, statisticians, and for a while, a psychologist, economist, and zoologist. The "company man" was extremely important in this case. He was not one man, but several officers from the SAC staff. These men very effectively assisted in placing the problem in context so that resulting answers and recommendations could be readily utilized by SAC planners.

MATHEMATICAL TECHNIQUES

The actual model building in OR often utilizes ingenious and specialized techniques. The second booklet in this series will explain these techniques in a more complete manner than we can here. Here it will suffice to briefly identify, define, and exemplify some of them.

Probability Theory

Crudely speaking, the probability of event A occurring is the ratio of the number of times A occurs in a long series of trials to the total number of trials. It is a quantitative expression of how likely it is that A will occur on any given future trial. For example, an unbalanced coin is tossed 1,000 times and 609 heads appear. The probability of a head with this coin is approximately .61, not .50. On any toss of this coin, the odds are about 6 to 4 in favor of a head appearing.

Suppose that past advertising experience has indicated that a certain promotional circular influences 1 out of 10 readers to place an order for $3.00 book-ends. 100,000 circulars are to be mailed. What is the probability that about 10,000 orders will be received? It can be shown that the probability of between 9,800 and 10,200 orders is approximately .97. Probability explicitly takes into account the inherent randomness of human reaction.

Monte Carlo Methods

Monte Carlo is a clever technique for by-passing the solution of extremely difficult mathematical equations. The method consists of replacing the equation with a probability game, which on the surface may seem to have nothing to do with the equation. The mathematician designs the game in such a way that the data gathered from playing the game provide the solution to the equation. Ordinarily a digital computer or table of random numbers is used.

The celebrated Buffon needle trick for estimating the value of π is one of the best light-hearted examples of the Monte Carlo method. π is the ratio of the circumference of a circle to its radius, and this value is about 3.14. In high school gemometry, laborious formulas are given for calculating π to any prescribed number of decimal places. The needle trick shows how to calculate π merely by playing a game.

Draw a set of parallel lines separated by the exact length of a needle. Now simply toss the needle at random, over and over, and observe whether it falls on a line or not. Count the number of times you toss it and the number of times it falls on a line. Twice the number of tosses, divided by the number of times it falls on a line is the estimate of π. For example, if, in 500 tosses, a line was straddled 315 times, π is approximately 1000/315, or 3.17. More trials give greater accuracy.

Monte Carlo is one form of a broader technique called simulation. At Massachusetts Institute of Technology, inventory problems have been studied by Monte Carlo simulation on the Whirlwind Computer. Operational gaming is another form of simulation in which human beings perform some of the decision functions.

Statistics

In business, in the military, and in OR, information is drawn from collected data. Since data is fraught with human variability and observational error, there is no way to draw conclusions from the data without some risk of being in error. Statistics seeks to extract the greatest possible information from the data with the least risk of being wrong.

A company plans to produce a large quantity of medium-priced men's suits, and it wishes to know how many to produce of each of several suit sizes. Statistical theory gives guidance in setting up the proper sampling procedure: the form of the questionnaire, the sample size, whether to sample special age and racial groups, etc.

Queuing Theory

A processing facility has a limited capacity. The facility may be an automobile wash station, a toll gate, a telegraph office, an elevator in an office building. Units--whether people, cars, messages--arrive at the facility at an uncontrollable, fluctuating rate. Moreover, the facility may necessarily spend more processing time with some units than with others. A queue or waiting line forms.

Many business problems will require that management reduce the length of queues. Queuing theory is the mathematical tool for handling uncertainty in processing times and arrivals. It enables quantitative assessment of the improvement offered by a change in the facility.

Linear Programming

This technique uses the simplest type of mathematical model, a "linear" model, for describing the interrelation of system components. It is perhaps best described by an example. Peas cost 15¢ per can, beets 10¢ per can, and spinach 18¢ per can. The per can vitamin content for these vegetables is 4 units, 2 units, and 5 units, respectively. You are purchasing vegetables for a summer camp of hungry boys and are limited to a budget of $100. Also, a minimum vitamin content of 2400 units must be purchased. Disregarding taste, you desire to return with the greatest number of cans of food for the hungry camp. What quantities of each do you buy?

If you buy p cans of peas, b cans of beets, and s cans of spinach, the total number of cans will be $C = p+b+s$. C must be maximized by choice of p, b, s. However, the choice is restricted by the cost condition:

$$\$.15p + \$.10b + \$.18s \text{ cannot exceed } \$100;$$

and the vitamin constraint:

$$4p + 2b + 5s \quad \text{must not be less than 2400 units.}$$

Problems which maximize or minimize a "linear" expression such as that for C, subject to "linear" conditions, are called linear programming problems. Danzig mentions a saving of $54,000 per quarter when the Argus Camera Company applied linear programming in its screw machine department (15, Jan., 1957).

Game Theory

Game theory considers situations in which there are two or more opposing individuals or opposing coalitions. Competition between two refineries sharing a market with relatively fixed demand has been studied as a two-person, zero-sum game by Symonds (Econometrica, Oct., 1954). Military applications, competitive bidding, and determination of optimum advertising strategies have also been studied. The greatest contribution of game theory thus far has not been in furnishing direct answers to simplified problems, but in providing a framework for viewing more complex competitive situations.

Information Theory

This method applies to problems of storing and transmitting information. The information content of various message forms and signals may be quantitatively measured. Mathematical procedures enable conclusions to be drawn concerning alternative signal forms which yield valuable design assistance. The theory has been important in the design of electronic computers, telephone networks, and systems of record keeping.

Other techniques of importance in OR are search theory, decision theory, inventory control theory, quality control, dynamic programming, and symbolic logic.

IMPLEMENTATION OF RESULTS

It is not enough to solve a problem and plunk the final report on the executive's desk. Assuming that management adopts the OR results in some form, the services of the analyst may be required to overcome unforseen operating difficulties, to instruct nontechnical employees in details of the new system, or to assist in designing the mechanical aids which may be required, such as new inventory or requisition forms, new data sheets, new line layout, etc. Often employees must be "sold" on making changes in operations, and here too the detailed acquaintance of the analyst with the new system may be most helpful.

The Development of OR

Section Three

OR has always had to remain close to those particular problems and interests which required its services and could support it. In our times this has meant the military. OR was ripe for development at the beginning of World War II, and it was used extensively during the war. All the while, however, OR has been experimenting with solving problems of business and industry.

The obvious analogy between the ability of OR to be useful to military commanders and its ability to aid peace-time management seems now to have caught on. Firms large and small have turned OR personnel loose on their problems. If the growth of OR has not been completely planned and orderly, it has been surprisingly swift and sound.

This section will do no more than sketch the highlights of OR history. For a more extensive historical account, see McCloskey and Trefethen (4).

BIRTH AND EARLY YOUTH

Some of the work of Leonardo daVinci and Malthus as well as the Civil War work on Gatling guns might today be called Operations Research. At about the time of World War I, Erlang, the Danish mathematician, began his work on telephone waiting-line problems. This work was to set the stage for the development of queuing theory. Contemporary with this was the classical work of the aeronautical pioneer, F. W. Lanchester. His "Aircraft in Warfare," published in 1916, formulated a quantitative theory of combat.

Thomas Edison in World War I, working on problems of avoiding German submarines, utilized a "tactical game board," a device surprisingly close to present simulation models. He studied the effectiveness of zig-zagging and other evasive maneuvers.

OR as a distinct activity began to emerge in the '30's. Working for L. Bamberger and Company, H. C. Levinson did studies on buying habits, mail order acceptance, advertising, and desirability of night store hours. By the close of the 1930's, the term Operations Research had been mentioned numerous times, and all that was needed to bring the new science into being was pressing problems and proper support. World War II provided this stimulus.

WORLD WAR II AND THE KOREAN WAR

The British defensive organizations used OR almost from the start of the war. Early work concerned itself with how surveillance early-warning radars could be utilized in conjunction with visual observations from the ground. Other applications were to anti-aircraft gunnery, bombing accuracy, communications systems, and prediction of bomb damage. A truly significant application of OR was to problems of aerial anti-submarine warfare. It was discovered in the course of systematic analysis of data that the charges being dropped on the just submerging submarines were set to go off at 100-foot depths or greater. Lessening of the setting on the depth of explosion resulted in an increase of several hundred percent in submarine destructions.

American World War II OR originated because of pressing problems of integrating radar warning equipment with existing defenses. Military leaders observed the British successes with OR and wished to avail themselves of similar technical advice. The pattern of growth was similar to that of British units, with a central unit near military headquarters in Washington and outlying field units serving the operating commands. Army, Navy, and Air Force developed OR units to advise them. Research on aerial mining of Japanese shipping waters, optimum methods of search for enemy submarines, and techniques for minimizing enemy suicide aerial attacks on shipping--all resulted in very successful improvement of operational capability.

Discussions with captured German scientists after the war indicated that the Germans analyzed some combat gunnery film for aim wander data and fighter tactics. They also performed analytical studies of armament.

Following the war, the Armed Forces continued their OR groups. Investigations now left the realm of day-to-day operations and involved predictions of the efficacy of as yet untried weapons. Studies of tactical uses of nuclear weapons began. Here the guidance of technically refined imagination and judgment was of great value because of the complete lack of other aids to decision-makers. Special agencies for long-range analytic study of strategy and weapons were formed.

When the Korean conflict began, analysts were sent to the field to observe problems first hand and to suggest immediate solutions. The Institute for Air Weapons Research at The University of Chicago set up a facility for the statistical analysis and interpretation of Korean combat gunnery film. Valuable suggestions for the improvement of guns, ammunition, and air-to-air and air-to-ground combat tactics emerged from these studies.

Toward the end of the Korean conflict, it became evident to the Administration, to the military, to scientists, and to the national defense industries that a long-range research and development program for weapons would be an intrinsic part of the Cold War. Also it was apparent that decisions on the use of these future weapons were largely unrelated to past tactics. OR would be needed.

EVOLUTION OF NON-MILITARY WORK

Following the war, the British nationalized many industries. Under such a framework, it was relatively easy and natural that the concept of the OR staff supporting executive decision, as in the war years, should carry over. In fact, the serious economic straits which confronted the British economy after the war demanded that the greatest possible efficiency in production and management be attained.

In the United States, the development has been principally along two channels. The larger, more progressive companies have created OR groups within the house. Some of the largest rubber companies, steel firms, railroads, oil companies, and chemical firms have such groups, and the list is growing.

A second force in the spread of OR applications to business and industry has been the OR consultant firm. OR consultant groups have been formed by various individuals or teams of analysts who themselves had participated widely in the applications of OR in the defense effort. These people had confidence in what OR could offer and believed that the value of the service offered would soon become apparent to industry.

THE FUTURE

Few professional fields can point to a record of growth equal to that established by OR in the last 20 years. This growth and OR's acceptance are all the more remarkable when one considers that many of the most important OR case histories have been kept from the attention of the business world, either because of military secrecy or because industrial case histories have been considered proprietary.

The real factor which has promoted growth has probably been the need. Most experts feel that this need will continue and will even increase. Automation will increase the technological content of business decisions. A science of management will gradually be developed. While decision-making will always be necessary, it will be done at higher levels of planning and at the fringes of the existing techniques. For more mundane decisions and controls, techniques will have been perfected and computers will be on hand for use when needed.

Danzig (15, Jan., 1957) has suggested the following pattern of development of automation:

1. Mechanization: Machines replace human energy tasks.
2. Automation: Machines replace simpler human control tasks.
3. Super-Automation: Machines replace complex human control tasks.

The third step is undoubtedly still a good way off. OR must assist in constructing the mathematical and scientific models which will form the theory of automated management science. One cannot stress too much the need for continued development of new OR methodology.

The obstacles and pitfalls which threaten this encouraging future for OR have been pointed out by several leaders. In his address as retiring President of the Operations Research Society of America, Rinehart listed five problems (17, Aug., 1954):

1. OR has done a poor job of communicating to business and industry.
2. OR has given too many different definitions of its activity.
3. OR must establish and maintain professional standards.
4. OR must develop and practice a code of professional ethics.
5. OR must not be oversold in a burst of enthusiasm.

These problems must be solved, and the sooner the better. On the other hand, management should permit publication of new OR methodology developed in studies, so long as the proprietary data and decisions involved are not disclosed. Moreover, the business world should endeavor to give a more sustained long-range support to research in the OR field. This will increase the ability of OR to make its valuable contribution.

Obtaining OR Services

Section Four

Those companies which can afford it may wish to maintain their own OR group. OR services may also be purchased from reputable consulting organizations.

For small and middle-sized companies, consultants are the answer. They bring a broad base of experience, specialists, and on-demand services which could not conceivably be duplicated by the company on its own. Spending money for occasional top OR consulting is generally better than assigning a junior member of the firm to chop away full-time at problems which are beyond his level. For the larger firms, consultants have been used to help set up in-house OR staffs, to be an objective third party to sensitive decisions, to provide new ideas, and to buttress in-house staffs at times of "crash programs."

Who should practice OR? The operations analyst is frequently confronted with problems about which little formal knowledge exists. He must therefore be original, enterprising, willing to learn, and imaginative, as well as competent scientifically. He usually has a broad knowledge, extending into several scientific fields, mathematical training, and possibly also some business contacts in his background. (See p. 21.) He is able to work well with a team, and has a strong compulsion to get a valid answer and to get it on time. The most common mistake is for the firm to assign "available" staff who do not fit well elsewhere to do the OR function.

It is impossible to obtain needed cooperation from line personnel unless the OR man has an engaging personality and an abundance of tact. Moreover, he must be able to present results orally and in writing in a way which interests management and which the executive can understand. In short, he must be able to <u>sell</u>. With all these sterling qualities demanded, it is not surprising that good OR men are scarce.

Hertz (12) has indicated a range in the average size of company OR groups from 3 persons in the food industry to about 20 in the aircraft industry. The larger groups often form smaller task forces which are assigned to problems as they arise.

Where does the OR group fit into the company structure, and from whom does it receive its problems? It is essential that the OR group be able to present its findings to top management. Being a staff organization, it frequently happens that the OR group reports directly to the president or executive vice-president. Some successful structures have placed the OR group farther down the company ladder, but with full access to information at all levels and freedom to report to the top level. These last two freedoms are essentials, not desirables. Without them the wrong problems are solved for lack of information, or the solutions to the right problems do not reach the ears of those who can bring action.

To give a statistical picture, of 365 companies queried by Hertz, 65 reported that their OR group reported to the president or top management; 144 to a vice-president; 40 to a chief engineer or equivalent; and the remainder to important individuals, e.g., the treasurer, director of research, etc.

The first problems of the new OR unit are critical to its future. They should be a modest bite of the main stream of the company operation. This will offer a quick return on investment to management and will help immerse the new men in company policies. A written record should probably be kept, an agreed upon cut-off point for the problem established, and a few intermediate, informal progress reports should be given. These latter will help to keep the OR group oriented toward the true problem, and will keep management more patient during the tedious adjustment period.

Problems should come from top management, middle management, and operating units. In this way the OR group becomes further oriented to all the company personnel and to the full operation. Some problems should be self-generated. They should be done merely because the OR staff believes they will contribute to understanding and add to the ability of the group to solve future problems.

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