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Foreword

MANAGEMENT, in the broad sense, is the judicious use of means to accomplish an end. In the business setting, management is the use of resources and skills in an economic environment for the purpose of making a profit.

As the means and the environment have grown in complexity, the methods of business management, over a long period of time, have advanced from the semi-intuitive to the near-scientific. The management process today is scientific in outlook and is becoming increasingly so in method.

Science is knowledge reduced to principle and embodied in a system. In the scientific method, observation and correlation of facts lead to the establishment of general principles, provable by quantitative measurement.

By this strict test, perhaps business management inherently cannot become wholly scientific. But the gap is narrowing as measurement replaces conjecture in ever-widening areas. As the art of navigation has developed from the science of astronomy, so in the continuing evolution will the precepts of business management become more closely coupled with the findings of science.

Complexity in the problems of management, although by no means new, has become intensified as a consequence of technological advances and economic changes in recent years. In this same period Operations Research, a comparatively new approach to these problems, has emerged as an aid to management. Operations Research in business is a method of evaluation in decision-making.

Although Operations Research has a wide range of usefulness in the study of business problems, its concepts and methods are not well understood in the business community today. The purpose of this pamphlet is to explain concisely, with minimum recourse to technical refinements, what Operations Research seeks to do and how it proceeds to accomplish its objectives.

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The Origin of Operations Research

The first applications of Operations Research on an appreciable scale were made by Great Britain and the United States in World War II. Operations Research methods helped to solve a broad range of military problems. Typical of these were the determination of size of convoys, fuse settings of depth charges dropped from aircraft against submarines, size of formations and techniques of bombing by aircraft, methods of sea mining, search patterns in hunting ships and submarines, and various radar detection problems. Typical also of the sphere of activity of Operations Research generally is that its contributions in all these wartime projects related primarily to the *uses* of the weapons and skills of the military organizations and only incidentally to the design of the weapons themselves.

Following the close of World War II, Operations Research almost immediately became firmly established in British trade and industry. In this country, it was not until 1952 that Operations Research began to attain comparable status. Since that time, interest in the method has steadily accelerated. By now, it is well established in the transportation industries, the chemical industries, and the aircraft industry. It has been used successfully by one or more representatives of many other types of industry or business, including banking, insurance, light and heavy metal manufacturing, food processing, and agriculture.

Basic Concepts

Operations Research is a composite activity in that it makes use of concepts and techniques from many fields of knowledge. For that reason, its meaning is not easily compressed and thus it is not surprising that a concise and meaningful definition of Operations Research has not so far appeared.

As the term implies, Operations Research is research on operations. Its purpose is to provide a basis for directing and controlling operations. To be directed and controlled, operations must be understood. The crux of Operations Research is its concept of the "understanding" of operations.

The approach to the understanding of operations is directed at their "structure" and "order". The physical scientists have found structure and order in the behavior of matter. The biologists, psychologists, and sociologists have found them in the behavior of living organisms, including man. The economists have found them in the market place. No less ambitiously, Operations Research seeks to find structure and order in the man-machine systems of business operations.

These, however, are rather broad abstractions. What is meant by "operations", "structure", and "order"?

An "operation" is any activity in which a responsible authority utilizes resources and skills to attain a specified objective. "Responsible authority" of course exists at various levels of a business organization. Accordingly, the Operations Research concept of "operation" is at once both flexible and inclusive. An operation is any form of activity, from lowest to highest magnitude, in which responsible authority has the power to make decisions.

"Structure" is concerned with the basic framework of the operation, and "order" relates to interaction among the elements of the structure. Structure is static; it is the resources, skills, and external factors entering into a business operation, as defined and in place. Order is the behavior of the various elements as action takes place within the structure.

Similarity in structure and order is found in many operations which are physically quite dissimilar. Typical examples of this are operations such as the processing of ships through a harbor, planes through an airport, and engines through a repair shop. In each case, individual items wait, advance through one stage in a total process, wait again, advance through another stage, and so on, maintaining their identities throughout. A common problem in controlling such operations is to minimize, at acceptable cost, the waiting time in passing from one stage to another.

In the same way, the structure and order of operations such as the manufacture of lumber, milk products, and petroleum products are also similar. In each instance, a few raw products are separated into a wider variety of finished or semi-finished products. A common problem in control is to obtain maximum utilization of varying grades of raw materials.

A third example of similarity is found in a wide variety of assembly operations. Here the finished products emerge by agglomeration, rather than separation. A common problem in control of agglomeration operations is to correlate and minimize the supply of components.

Analysis of these and other comparable operations has shown that, if a pattern of regularity can be found in observed behavior, it becomes possible in many cases to measure interactions within the operation and thus to predict the effects of changes in it. This, precisely, is what Operations Research strives to do: to find the pattern of behavior and to *predict* the effects of changes in the operation.

In substance, therefore, Operations Research looks at a business operation in terms of its structure and behavior patterns. The operation is viewed in its entirety, in the perspective of the intended objective.

Methods

Underlying its basic approach, Operations Research employs specific methods in the study of business problems. The key to the Operations Research method is the model. The model portrays, in mathematical terms, the structure and order of the operation. It is usually in the form of an equation in which the operation is described in relation to a selected measure of effectiveness.

The measure of effectiveness, in turn, is a quantitative statement of the desired objective. The objective may be maximum profit, minimum cost, minimum delay in meeting customer requirements, or any other result to be achieved.

In the conduct of Operations Research studies, a preliminary model usually is constructed after general observation of the operation. The preliminary model brings into focus the factors pertinent to the problem and also serves to define the data – from records of the operation or other sources – that will be needed in the subsequent investigation.

The operation is then studied intensively. Data are analyzed, further observations are made, and measurement of the factors of the problem is refined. Measurement may be conventional, in terms of such factors as elapsed time or units of production, or it may concentrate upon frequencies, dispersions, rates of change, or other variable elements of the operation. The results of these studies are fed into the model and adjustments made until a model is derived that represents the actual operation to a useful degree.

The research then enters the experimental stage. The model is successively manipulated by altering the factors, in various combinations, to the extent required to reach the desired objective. From this, the solutions to the problem emerge and are presented for decision of the management.

A single course of action may be indicated or there may be alternatives open to choice. On the other hand, it may be that the objective as stated involves unacceptable costs. For example, to achieve a desired minimum delay in meeting customer requirements may involve drastic speed-up of certain procedures or material increases in capital invested. If the associated costs are unacceptable, the model can produce further alternatives showing gradually increasing delays to the customer accompanied by diminishing costs. In this way, a decision can be reached as to the interval of delay that is economically acceptable.

Thus the model provides a basis for evaluation of alternatives in decision-making. Understandably, close precision in evaluation sometimes is unattainable. A mathematical model, especially one of a complex business operation, is seldom a perfect portrayal of reality. The model may be sensitive to assumptions built into it or there may be imponderables that do not cancel out.

To reduce the functioning of a business operation to mathematical terms obviously requires careful and thorough analysis of all of its phases. Contributions from various fields of knowledge may be needed to provide understanding of the operation as a whole. Thus the use of "mixed teams" of specialists is typical of Operations Research studies.

Operations Research is conducted today by many of the professions serving business and industry as well as by groups of specialists organized within individual companies. The usefulness of Operations Research is not dependent upon the size of the business enterprise: many operations are alike in principle even though differing greatly in volume of activity.

Mathematical Techniques

Various business problems, even though found in widely diverse settings, are mathematically similar. The sameness in principle is found both in the *mathematical structure* of the problem and in the *desired solution,* and hence the operation may be expressed in the same mathematical terms. The demonstration of this similarity is one of the most important contributions that Operations Research has made to the study of business problems.

Waiting Lines

Mention was made earlier of the similarity of operations such as the processing of ships through a harbor, planes through an airport, and engines through a repair shop. All such operations may be represented in mathematical models embodying queueing, or waiting line, theory.

More than 50 years ago, telephone engineers developed formulae to describe how long a user would have to wait, on the average, to obtain a response from central under varying assumptions as to available equipment and personnel and the average length of conversations. The formulae provided a basis for deciding upon the most economical basis of operation, that is, the minimum facilities and personnel required to provide acceptable service. These earlier studies have been modified and adapted to a broad range of operations similar in structure.

In all these operations, the core of the problem is waiting time. There may be waiting time in either the unit providing the service or the units to be serviced, or both; also, the length of the queue awaiting service may or may not be controllable and there may be a point beyond which any further lengthening of the queue will not be tolerated. The solution or decision required is the combination of facilities and personnel that will result in the lowest cost at an acceptable level of service.

Logistics

Another class of problem found in a wide variety of operations can best be described in military terms as the problem of logistics or supply. Here the problem is one of depletion and replenishment of a supply of commodities or services, and the decision required is when and how much, or how many, of the commodities or services to buy or produce from time to time.

As applied to the problem of product inventory, the mathematical model takes into account such factors as the pattern of demand, costs of replenishment of inventory, shelf-life or obsolescence, and costs of overages and shortages. The determination of these factors, in turn, usually requires special study. The model develops the indicated quantity and time of replenishment as well as an evaluation of alternatives so that, for example, a decision may be made whether to accept the risk and cost of a shortage or the cost of its avoidance.

The structure of many operations is similar in principle to that of the problem of product inventory. Mathematically, the scheduling and size of classes of training schools is basically a logistics problem. So, too, are certain problems involving the use and replacement of capital assets, such as freight cars, trucks, and machine tools.

Allocation

A third class of problem which also is present in widely diverse operations is that of allocation. In this problem, resources or skills are to be allocated to a set of objectives. There may be limitations or restrictions with respect to the resources or skills, or the objectives, or both. The problem is to find the best allocation consistent with the established objective – usually, lowest cost or highest profit.

Typical of the allocation problem are: determination of the locations and capacities of plants or warehouses, routings for the transportation of materials or products, assignments of personnel to a given set of tasks, and the application of materials to a mix of products. Here again, the determination of the various underlying factors usually requires special study.

In all such problems, the several factors are reduced to a cost per unit of resource or skill for each unit of objective. From these costs a series of equations is arrayed in matrix form and the solution of the matrix shows the best allocation for the desired objective. In all but the simplest allocation problems, the number of equations soon becomes formidable and a solution can be reached only by the techniques of mathematical programming.

Other Areas

To the present time, the contribution of Operations Research to decision-making has been made principally in these three problem areas – the problems of queues or waiting lines, logistics or supply, and allocation. Here the basic theories are generally well developed and thus the way has been opened to broad and fertile fields of application.

In the many other areas of decision-making, Operations Research may be said to be, itself, still at the research stage. Without minimizing the contributions that have been made, the field of application in these areas is as yet comparatively limited. Among problems which have been attacked successfully, although in limited contexts, are those of failure or survival of equipment, maintenance and replacement policy, sequencing of operations, and sales and profit forecasting.

As the methods and techniques for handling these several other areas of operations are developed, Operations Research is faced with larger and larger problems of synthesis – of describing the interactions *among* functional areas of business organizations to a useful degree. Organizations do not lend themselves to description by simple aggregation or combination of the models describing their separate areas. Techniques for handling multiple interactions are being developed and show considerable promise. Such techniques almost always require the use of electronic computers.

The Future of Operations Research

Operations Research is comparatively new and is therefore confronted with the difficulties normal to any growing activity. Perhaps its principal difficulty at the present stage is communication. Generally, the business public does not understand it.

A kindred difficulty is a tendency to expect more of Operations Research than it may reasonably be expected to deliver. After all, business enterprises in this country are generally well managed – in many cases superbly so. Moreover, capable managers are well aware of their problems and view them in appropriate perspective. Revolutionary effects from Operations Research therefore are not normally to be expected. Similarly, being scientific in approach, it follows implicitly that only rarely may Operations Research guarantee, in advance, an advantageous solution.

Notwithstanding this, Operations Research stands as a positive force of strong potential in the analysis of business problems. It provides better understanding, in itself a long range benefit, and frequently points the way to worthwhile immediate improvement. Operations Research is taking its place as a useful tool to aid management in decision-making. Extension of its acceptance in business must rest, as does the progress it has so far made, upon demonstrated worth.

Illustrative Cases

The following three illustrative cases are condensations of experiences in Operations Research as reported in published sources. The first case illustrates the application of a widely used mathematical model; the second case emphasizes breadth of analysis; and the last illustrative case indicates the degree of complexity of problems that may be involved in Operations Research studies.

A Waiting Line Problem

Tool-crib operations in a large aircraft plant were studied to determine the "best" number of clerks at tool-crib counters. Approximately 60 cribs were maintained at various locations in the plant.

The management desired to curtail overhead costs by reducing the number of clerks. On the other hand, the foremen wanted the existing level of service maintained so as to be sure that machinists would be served promptly at the tool cribs.

Waiting lines were involved but it was first necessary to make certain that queueing theory was applicable. Observation showed that: arrivals at the counters were random; the order of service, there being no priorities, also was random; and service times, that is, the times required to serve the machinists, were exponential, varying from service period to service period. These observations showed that a "standard" queueing equation of the following form could be used to determine the probability (P) that all clerks would be busy at any given time:

$$P = \frac{a^c}{(c-1)!\,(c-a)} \left[1 + \frac{a}{1!} + \frac{a^2}{2!} + \cdots \frac{a^{c-1}}{(c-1)!} + \frac{a^c}{(c-1)!\,(c-a)} \right]^{-1}$$

where c = the number of clerks

a = average number of arrivals per mean (average) serving time.

Proceeding from this basic equation, and others related to it, data on arrival times and service times and their distributions for different numbers of clerks were compiled. A simple recording device was used to facilitate the taking of these measurements. The results were then analyzed and plotted.

These steps yielded an understanding of the role of the components and of their interaction in the operation under study. In order to apply the understanding to the problem requiring decision, the cost of having a clerk wait for machinists and the cost of having a machinist wait for a clerk had to be determined. Reduction of the resulting cost equation to a basis where the cost of clerical waiting time was equal to the cost of machinist waiting time provided the desired solution.

The required number of clerks was found to be about 30 less than the existing clerical force.

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A Logistics Problem

Warehousing operations of a company engaged in the growing, processing, and distribution of foods were studied with the objective of minimizing warehousing costs.

The problem expressed itself in rising costs and increasing amounts of year-to-year inventory carryover as the supply of product overtook demand after World War II.

In this problem, the pattern and general level of production were determined by the ripening characteristics of the crop and the requirement for processing immediately after harvest. Storage facilities at the processing plants were limited, requiring the use of additional storage facilities at or near marketing centers. This requirement was reinforced by the necessity for having stocks quickly accessible at market centers to meet competition and the conditions of a buyer's market. Furthermore, in order to give customers the most favorable transportation costs by eliminating cross-hauling (prices being F.O.B. the factory), it was necessary to use warehouse facilities at a considerable number of market centers.

Some warehouses were rented on a space basis while others were rented on a case basis. In some warehouses, inventory was untaxed; in others, it was taxed on the basis of average annual level; and in still others, on the basis of level at the time the tax was levied.

Another condition affecting the problem was the shelf-life of the product, which required that it be moved out of the warehouses on a first-in, first-out basis and that stocks be so distributed among warehouses as to assure movement of any given pack within the shelf-life period.

To summarize, the system under study consisted of a source of product subject to important time limitations; relatively inexpensive local warehousing subject to the same time limitations; and expensive but highly flexible market-center warehousing subject to important market conditions. The decision required was the best utilization of the warehousing facilities.

The study was divided into three principal parts:

(1) Use of storage facilities at the plants.

(2) Stocks required in market-center warehouses to meet current sales requirements.

(3) Use of market-center warehouses for storage of temporary surplus stocks accumulated in the harvesting season.

The first step was to develop a pattern of best usage for factory warehouses. This pattern assured not only maximum use of these facilities but also that the shelf-life limitation would be taken into account and that the facilities would be freed to handle the next season's pack. The timing of stock movements thus evolved became a factor in the program for use of market-center warehouses.

In developing the stock levels required to meet current demands at the market-center warehouses, it was necessary of course to consider not only the day-to-day withdrawals to meet customers' orders but also the intervals between replenishments of stock, that is, the intervals between arrivals of shipments from the factory warehouses. The objective was to set the stock levels for each warehouse at a point such that, on the average, depletion of stock would be forestalled by shipment arrivals. If the safety margin were too large, however, the stock level would be excessively high. Accordingly, the margin was adjusted to a basis which guaranteed in each case that the warehouse would be out of stock not more than a maximum of 2.5 per cent of the time. This would occur in a situation where depletion was unusually rapid and the interval between arrivals unusually long. This limit was consistent with the company's experience and was considered acceptable. In this way, the stock levels in the respective market-center warehouses to meet sales requirements were established.

As a first step in connection with the problem of storage of temporary surplus stocks, the costs of storage at each market-center warehouse were analyzed on a month-to-month basis, taking into account the effect of inventory taxes and other factors. Then a program for stocking the respective warehouses was developed by assuming one-case-at-a-time shipments. The lowest cost warehouse was used until the cost of storing the next case equaled the cost at a second warehouse. Then both were used in a proportion that kept the cost per case equal between them until that cost equaled the cost at a third warehouse. The procedure was repeated until all of the warehouses theoretically were filled. However, no warehouse was given an allocation that exceeded the shelf-life limitation. The effect of the procedure was to develop a pattern showing the order in which shipments could most economically be stored at the respective warehouses, assuming all warehouses to be empty at the outset.

However, the decision required from time to time was to select the warehouses to which shipments of surplus stocks should be made and of course not all – more likely, none – of the warehouses would in fact be empty at such a time. This being the case, the pattern developed as described in the preceding paragraph was used as a basic cost table and applied on a trial-and-error basis to reach the required decision. A given storage cost was selected and the surplus stock was distributed proportionally among the warehouses with the same or a lower cost. If the available storage at these levels of storage costs were more than required to accommodate the surplus stock, a lower storage cost was selected as the starting point and the procedure repeated. On the other hand, if the storage available at the cost levels first selected were less than required, a higher cost was substituted as the starting point and the procedure similarly repeated. In this way, the most economical apportionment of storage of surplus stocks at market-center warehouses was determined.

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An Allocation Problem

A French electric utility company had the problem of planning an investment program for a five-year period. In essence, the problem was to provide a 40 per cent increase in generating capacity subject to a maximum limitation upon funds available for investment.

Five types of plants could be built: steam, hydroelectric with no reservoir, daily reservoir, or seasonal reservoir, and tidal. The decision required was: what is the best allocation, singly or among the various types of plant, of the required capacity within the limit of the funds available?

Obviously, in a problem of this scope, a formidable number of factors are involved. The interactions among so large a number of variables and constants can be manipulated simultaneously only by mathematical programming. Applications of this technique to business problems were virtually unknown until a few years ago. The method makes practicable the timely determination of not one but several alternatives for evaluation in reaching the best decision. Because of the many intricacies involved, the instant case is looked upon as a significant illustration of the capabilities of Operations Research techniques.

Approximately 60 possible solutions were tested and their effects determined, taking into account such factors as the capacity required (in terms of guaranteed, annual, and peak output), fluctuations in demand, the five types of plant, capital and operating costs, and surplus output.

The best solution, given the limitation on capital, was to provide all the required increase in capacity by building steam plants only. But the solution also showed that this was the most expensive program over-all because of the high operating costs of thermal plants.

A valuable by-product of the study was the knowledge gained concerning the effects of changes in conditions. For example, if more funds had been available, the building of tidal plants would have become preferable at a certain level. Also, with no limitation upon available funds, the study showed the point at which any further investment would be uneconomical.

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