The Role of Operations Research in a University Hospital

*A Review and Bibliography**

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Introduction

Traditionally, the universities have led business and industry in research methods. Since the end of World War II, however, the business world has effected increased efficiency in its many activities by the application of a variety of techniques commonly known as Operations Research (O.R.). More important, however, is the change of attitude that this indicates. It is now felt that the scientific approach (with several major restrictions) can be used to study the organization of groups, with the objective of optimizing the work of the group. Such groups may be composed of cells in a tissue culture, doctors in a hospital, instructors in a school, operators in a factory, or members of a business firm. The approach used is not magical but rather a combination of various new and old techniques from different fields. It is natural to express the logic of the system and the relationships between components of the system in the form of mathematical equations. While such aridity may dissuade some from the adoption of these techniques, the reduction of a particular O.R. problem to its mathematics may reveal its similarity to a problem already considered in the literature. Any specific problem, however, usually requires the collaboration of persons from different areas, and the strength of O.R. techniques may lie in this interdisciplinarian approach. This includes higher management, for there is little point in a solution which is not used.

The purpose of this paper is to briefly describe some of the methods used in O.R. and to indicate where these can be applied in patient care. (See Levy and Cammarn [1968] for a review of the applications of information systems and computers to medical care.) Hospital administrators are increasingly concerned with the rising costs of hospitalization. Directors of hospitals, as well as those individuals training in hospital administration, should seek to familiarize themselves with O.R. techniques as possible tools in the search for increased efficiency and reduced costs. Likewise, doctors and medical students should find it useful to be acquainted with the methods and philosophy of O.R. Thus, they will better appreciate the actions of the administrator seeking to increase the efficiency of the hospital, and they may, themselves, initiate some O.R. studies within their clinic, practice, or laboratory. The shortage of nurses and other health personnel demands their effective use when on duty. This situation emphasizes the importance not only of selection and training, but of the provision of adequate facilities and an encouraging environment for work. Conditions leading to a high personnel turnover must be discovered and eradicated, wherever possible. Finally, in attempting to provide better patient care, we must at all times consider the patient and seek advice from him. A system which is efficient for the staff is suboptimal if the patient is severely inconvenienced. Patients talk among themselves of uncomfortable dental chairs, long waits in drafty corridors, nurses who do not answer a buzzer, and dehumanizing treatment at the hands of doctors. This information (even though critical and, at times, uncalled for) should not go unused.

The objective of this paper is to encourage those engaged in medical care and hospital administration to regard the system they are part of, or are responsible for, as a suitable and acceptable area of research. Such research does not require a detailed knowledge of O.R. but does require an intimate knowledge of the system studied and of the objectives of the group or person responsible for its creation and functioning.

In the remainder of this paper various aspects of O.R. methods are described. However, O.R. is best typified by a willingness to examine and to change the system of interest in a systematic way. O.R. is implicitly economic, because it is concerned with optimization procedures. In the business world the objectives are to maximize profits and to minimize costs, and it is easy to quantify these ideas. In medical applications of O.R. we are faced with the need

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to quantify such objectives as giving the patient superior health care. Perhaps our research efforts should be concentrated in the area of definition and quantification of patient care. If this proves impossible, we then need to devise methods other than those described here which can be applied to hospitals, clinics, and general practice to reduce costs and to make our treatment and handling of the patient more effective.

Mathematical Programming

Definition: Here we wish to find the conditions which will maximize or minimize a function of a set of variables subject to a set of constraints.

If the function to be optimized and the constraints are linear equations, then the procedure is called *Linear Programming.* (A weighted sum of a number of variables is said to be linear.)

If the variables are restricted to take only integer values or whole numbers, then the procedure is called *Integer Programming.*

When some of the constraints are defined in terms of random variables (a random variable has a given probability of taking a given value), the procedure is called *Stochastic Programming.* Multistage decision processes are studied by the methods of *Dynamic Programming.*

Comments: Note that mathematical programming is unrelated to computer programming. Confusion between the two has arisen because explicit solutions of realistic problems in mathematical programming are rare, and empirical solutions are sought either by using a variety of computer algorithms or by using the computer to simulate the system to find a heuristic solution.

Examples: The development of hospital diets (Balintfy, 1966) is the classical biomedical example of linear programming. Here one wishes to minimize the cost to the dietary department subject to the diet containing adequate daily amounts of carbohydrates, fats, proteins, vitamins and other trace elements and subject to the palatability of the recommended diet. The treatment of the patient is a multistage decision process (Rustagi, 1968). Consider the maintenance of anesthesia, for example.

References: Gass (1958) and Chapter 9 of Morse and Bacon (1967) are useful introductory texts to mathematical programming. Riley and Gass (1958) list an extensive bibliography in linear programming, and Praeger (1956) shows how linear programming may be applied to the composition of diets. Ledley (1965) gives examples of the application of linear programming (p452) and dynamic programming (p459) to the treatment of patients. Bellman (1968) gives an excellent nontechnical introduction to the role of dynamic programming in control theory.

Allocation

Definition: Under this heading are listed assignment and transportation problems. In assignment we wish to choose the best way of allocating n facilities to n tasks in order to maximize some criterion such as effectiveness or cost. It is assumed that the effectiveness or cost of each facility to do each task is given. In the transportation situation we wish to find the cheapest way of transporting material from m sources to n destinations. We are given the costs of transportation for each source to each destination, the amount of the commodity at each source and the amount required at each destination.

Comment: Assignment and transportation are extensions of mathematical programming and are often covered under that heading rather than under the separate heading of allocation.

Biomedical Applications: The scheduling of medical personnel, e.g., interns and student nurses, to various services may be considered a problem in allocation. Scheduling of classrooms and conference rooms at a college, however, would be a problem in transportation in that we would wish to minimize the distance travelled by attendees as well as the number of seats unfilled or the number of people unseated.

References: Chapter 12 of Churchman, Ackoff and Arnoff (1957) and Goddard (1963) give good introductions to allocation problems.

Inventory Control

Definition: Under this heading comes the problem of finding the best reordering policy to minimize inventory costs. The costs are generally made up of the costs of purchases, storage, and the cost of being out of stock. A solution to an inventory control problem will be given as a strategy telling how to decide when to reorder and how much of a given item to reorder.

Production control is clearly a variation of inventory control, and the two may be combined into a study of production and inventory control. Here we are concerned with the ordering and storage of raw material as well as the storage and sale or disposition of the finished product.

Comment: Although inventory control is one of the most widely used techniques of O.R., no general theory has as yet emerged. Individual problems in inventory control are tackled independently, though recourse can be had to other studies with similar characteristics. Note that, while the costs of purchasing and storing are generally available or can be evaluated, the cost of an item in demand but out of stock may be difficult to assess or quantify in the medical field.

Biomedical Applications: Published studies have described straightforward applications in a hospital. Reports #4 and #8 of the Oxford

Regional Hospital Board have given optimum purchasing policy for hospital stores and have published tables for use in implementing the policy. The optimum purchasing policy is validated by reference to the Central Stores of the Churchill Hospital. The reports also show how the choice of purchase by a regional center versus purchase by the hospital will depend upon such factors as demand, lead time, and cost of storage.

Inventory control has been applied to the administration of a blood bank (Rockwell, Barnum and Griffin, 1962; Elston and Pickrell, 1963, 1965). The object here is twofold—to minimize the chance that the bank is depleted and to minimize the volume of blood which becomes unusuable because of ageing.

References: Chapter 8 of Churchman, Ackoff and Arnoff (1957); Arrow (1958); Magee (1958); Chapter 12 of Flagle, Huggins and Roy (1960); and Moran (1960) are basic texts in the theory and application of inventory control.

Queuing Theory

Definition: A study of the "arrival" times and the "waiting" times of "customers" wanting "service" and of the "server" times and the "idle" times of the server.

Queuing situations are typified by:

(a) the distribution of arrival times of customers;
(b) the distribution of server times;
(c) the queue discipline, i.e., whether first come, first served or other arrangement to determine the next waiting customer to be served;
(d) the number of servers.

Generally one is interested in the average number of customers at any time or the mean queue length when the situation reaches a stationary state, if it ever does. Of interest also are the average waiting time of customers in the queue and the frequency with which the server will be idle. The object of queuing theory is to see whether, by means of small technological or organizational changes, one can drastically improve the queuing situation in terms of the above statistics—mean queue length, mean customer waiting time, frequency of idle server.

The concept of queuing may be expanded to include the situation where there are a number of servers maintaining a number of "machines" which require service intermittently. Here one is interested in the frequency with which a given number of the servers will be idle. Clearly this situation is related to the assignment problem.

Comments: It is obvious that in a queuing situation there is a tradeoff between the length of the queue (and, hence, of the mean waiting time) and how busy the server is kept. As the utilization rate of the server increases above 80%, the mean queue length will (in general) increase extremely quickly. At this level, minor perturbations in the system (such as the server taking a coffee break) will have an untoward effect out of all proportion to its size.

Biomedical Applications: All aspects of queuing theory are directly applicable to the organization of patient care. Appointment systems for outpatients have been studied as a queuing process by White and Pike (1964), among others. The Oxford Unit of Biometry is studying the application of queuing theory at St. Thomas' Hospital in order to determine a policy of non-emergency hospital admissions and thereby increase bed utilization.

The description (Chapter 25 of Flagle, Huggins and Roy, 1960) of a study of inpatient care at the Johns Hopkins Hospital is essentially an example of the queuing and assignment problem described above. Instead of machines breaking down or requiring adjustment intermittently from one of a number of servers, we have bedridden patients in a service requiring the attention of one of the nurses on that service. Flagle recommends that, in the context of his study, more efficient use of nurses' time could be achieved by:

(a) Removing unnecessary chores from the nursing staff. This led him to advocate the use of prepackaged and disposable items stocked and distributed by a Central Supply department.
(b) Reduction of other unscheduled duties either by their elimination (e.g., in spite of (a), keeping a small inventory of emergency drugs maintained at the ward to remove the need for a nurse going to the Pharmacy) or by pooling services (e.g., having a centralized messenger and escort service).
(c) A flexible policy of staffing (e.g., by switching nurses as needed from one ward to the next or by meeting anticipated peaks in demand through scheduling of additional nurses for duty).
(d) Better selection, training and guidance of new members of the health care team.

Flagle found that direct bedside nursing care varied from 15 to 37 hours in his study ward. This variability is extremely large, and perhaps the most direct way to increase nurse utilization is to seek ways to reduce this variation. By the law of averages, if the size of the ward is increased, the relative variation will decrease; hence, the conclusion that (in general) small self-contained wards are necessarily inefficient.

The other revealing finding in this study which led to (d) is that, of the 359 new employees followed up, only about *25%* were employed after six months. It is suggested that the fluctuation in workload—from underemployment to overemployment—may have been a factor in this personnel turnover.

References: Cox and Smith (1961) and Khintchine (1960) give a mathematical treatment to queuing theory. Doig (1957) may be consulted for other references to the theory of queuing. Lee (1966) is a readable introduction to queuing theory with examples from aviation. For applications to the hospital, see Connor (1964), Thompson, Avant and Spiker (1960) and Katz (1969).

Decision Theory

Definition: Decision theory is concerned with making the best choice from a number of potential alternative decisions (including the decision to do nothing) or constructing the best strategy in making a series of decisions.

Decision theory seeks to maximize the expected utility or to minimize the expected loss. The expected utility may be defined as:

Gain × P(decision correct)
− Loss × P(decision wrong)
where P denotes probability

The other criterion frequently used in decision theory is the minimax loss principle. This is very conservative, since the decision chosen under this criterion is the one which minimizes the maximum loss in all circumstances. The minimax loss principle is illustrated in Table 1.

Decision theory leads naturally to a theory of games. In game theory the objective is to pick the best strategy of operation in repeated competitive situations.

Comments: Since the theory of games is concerned with competitive situations, such as war or business, decision theory may be considered a special case of game theory in which the competitor is nature and, therefore, is neutral. A special case of statistical decision theory is differential medical diagnosis (or at least its idealized equivalent). In differential diagnosis the emphasis is on the recognition of the underlying disease process rather than on economics or other utilities. However, treatment may be started under varying degrees of knowledge about the condition (Lusted, 1968).

Biomedical Applications: Consider the use of the minimax principle in medical decision making. Assume a hypothetical case of treating a patient who may have one and only one of the possible diseases—A, B, C, D. Further, assume that there are four possible treatments—I, II, III, IV. (There is no reason why the number of treatments [decisions] should correspond to the number of diseases [states of nature].) Furthermore, assume that the result of using any treatment with any condition is measured in terms of the likely number of days the patient will remain hospitalized. Arrange this information in a payoff table as shown in Table 1.

The minimax decision is given by listing the maximum duration of hospitalization for each treatment or row

I	13
II	36
III	8
IV	15

and then choosing that treatment which gives the smallest figure. In the table this is Treatment III. A patient who may have one of the four conditions, A, B, C, or D, and who is treated by III will be discharged no more than eight days after hospitalization. It may be argued that this is obvious, since III is the best treatment for three of the four conditions. However, at this point we should try to bring into the decision process our knowledge of the relative frequency of the four diseases. This can be done by multiplying the days in bed given in each column of the table by the relative frequency of occurrence of the disease heading that column. If we have no knowledge of those frequencies, we could say that they are equally likely and multiply each column by one-fourth. This, of course, will lead to the same minimax decision to use Treatment III, since the numbers in the payoff table are unchanged relative to each other. Let us now assume, however, either from our experience with other patients or from the symptoms and signs of the current patient, that the probability of the patient's having Condition B is twice that of the other conditions. From this, the probabilities are P(A) = P(C) = P(D) = 0.2 and P(B) = 0.4.

Multiplying the second column by 0.4 and the others by 0.2 gives the results shown in Table 2.

TABLE 1

	Disease			
Treatment	A	B	C	D
I	12	3	13	12
II	4	5	36	3
III	1	8	5	0
IV	15	10	12	10

TABLE 2

	Disease			
Treatment	A	B	C	D
I	2.4	1.2	2.6	2.4
II	0.8	2.0	7.2	0.6
III	0.2	3.2	1.0	0.0
IV	3.0	4.0	2.4	2.0

For each treatment row the maximum is selected

I	2.6
II	7.2
III	3.2
IV	4.0

and the smallest of these occurs with Treatment I which is now the minimax decision. In other words, we have here combined our knowledge of the relative likelihood of the four diseases with the effectiveness of their treatments to give in some sense a "best" decision as to which treatment is to be used. Although this is extremely artificial, the references cited below indicate the progress being made in medical decision theory at other centers.
References: Basic introductions to the theory of decision making are to be found in Wald (1950), Good (1952), and Luce and Raiffa (1957). Morse and Bacon (1967), Chapter 6-2, and Ledley (1965), Chapter 12-6, describe some examples of medical decision making. Others are Katz (1967) and Reale et al. (1968).

Network Analysis

Definition: This procedure seeks to minimize the time and/or the cost of completing a project with a given set of resources. The project typically is broken up into its components, and these are arranged in a logical sequence. The time necessary to complete each component is estimated, and a schedule is arranged. A study of the schedule reveals the "critical path," i.e., the sequence of components in which a delay will delay the completion of the project. The money or resources available may then be reallocated to ensure the earliest completion of the project. Alternatively, the original sequencing of the components may be reordered (where possible) to produce a cheaper or faster method of achieving the project goals. A simple example of network analysis is the cooking of a meal in the shortest time.

A variety of names and abbreviations is used to describe different approaches to network analysis. The most common of these are the Program Evaluation and Review Technique (PERT) and the Critical Path Method (CPM). A glossary of these names and abbreviations is available in Frambes (1964).
Comment: Network analysis is at present unrelated to the study of neural networks, since the latter depends entirely on the pattern of interconnection between neurons (Chuang, Bell and Stacy, 1967). Network analysis is different from the scheduling aspects of mathematical programming. However, these distinctions are likely to become blurred by future research application.

The origins of network analysis may be traced back to the Special Projects Office of the United States Navy, which first used PERT in the development of the Polaris missile, and to du Pont, which developed CPM for the commercial production of consumables. Since that time extensive use has been made of these techniques both in government and in industry. It is likely that the recent successes of NASA with their Apollo program are due to the coordination of research and production via network analysis.
Biomedical Applications: Network analysis could be used in the construction of a new or special health care facility, in the renovation of existing facilities, in the development of new medical schools and medical curricula and in the organization of medical care. Reduction of the time taken in surgical procedures or other complex health care procedures may also be achieved by network analysis.
References: Miller (1962) and Rawle (1964) give good nonmathematical introductions to PERT. Battersby (1964) may be used as an introductory text for network analysis. A recent application of PERT to the organization of a medical research project is given by Woolf, Cass and McElroy (1968).

Other Procedures

There is no firm agreement as to an exhaustive listing of O.R. techniques. Other topics which might have been considered are Cybernetics (Wiener, 1948; Ashby, 1956); Information Theory (Raisbeck, 1963); Evolutionary Operation, or EVOP, (Box, 1957; Hunter and Kittrell, 1966); Computer Simulation (Meyer, 1956; Fetter and Thompson, 1965; Evans, Wallace and Sutherland, 1967); and Operational Gaming (Greene and Sisson, 1959).

Search Theory is concerned with the ability to discriminate among different types. It may be considered as an application of statistical decision theory but is given prominence here because of the importance of medical screening. The objective of search theory is to decide on the optimal allocation of resources to detect an object, e.g., the best way to scan cells in a biopsy to detect abnormalities. These considerations lead, however, to the relationship between the frequency of false positives and false negatives and to the definition of clinical norms (Morse and Bacon, 1967, pp146-155).

Operational Gaming uses a computer to simulate complex systems requiring human intervention. These programs generally are of competitive situations, e.g., military combat and business management, and are used to train military officers and business executives by predicting the response of the system to their decisions. Operational Gaming promises to be a potent method of training medical students in clinical decision making (Feurzeig et al., 1964). A hypothetical patient is described, and the student at the computer console is required to ask questions, call for hypothetical lab tests and prescribe treatment as he proceeds to form a diagnosis.

Discussion

Figure 1 shows the relationship between the basic academic fields and the biosciences, indicating that all of these contribute to the study and improvement of health care via the O.R. team. An important member of the Health Care research team is the doctor or other specialist delivering the care. Only with his cooperation can the efforts of the team be relevant and, hence, ultimately successful.

It may be of use to state here the basic premises of the O.R. approach and to outline the type of problems that it can tackle. O.R. workers tacitly assume that:

- The system under interest is not wholly indeterminate;
- It is possible to experiment or to adjust the system at will and to study its responses (in engineering terms, it is possible to control the system and to gather feedback information);
- It is possible to construct a mathematical or other type of model of the system.

It is then possible to study the model and the effects of perturbations on it without interfering with the smooth working of the system.

An alternative way of saying the above is to describe a system suitable for an O.R. study. It is assumed that:

- There is an opportunity for decision among different courses of action;
- Quantitive study and measurement is possible;
- Past data are available on the performance of the system or that such data can be collected prospectively;
- Ready evaluation of the results of the study should be possible.

The problem should not be so large and complex as to be beyond definition and modeling. However, while the choice of a discrete area to study is advocated, the relationship of this area to the whole should also be considered. Ignoring this relationship will sometimes lead to suboptimization rather than to optimization. Suboptimization occurs when the solution is correct for the subsystem studied but wrong for the total system which is relevant. A given radiation dose may kill a tumor, but if it also kills the patient or produces severe side effects, it is a suboptimal dose.

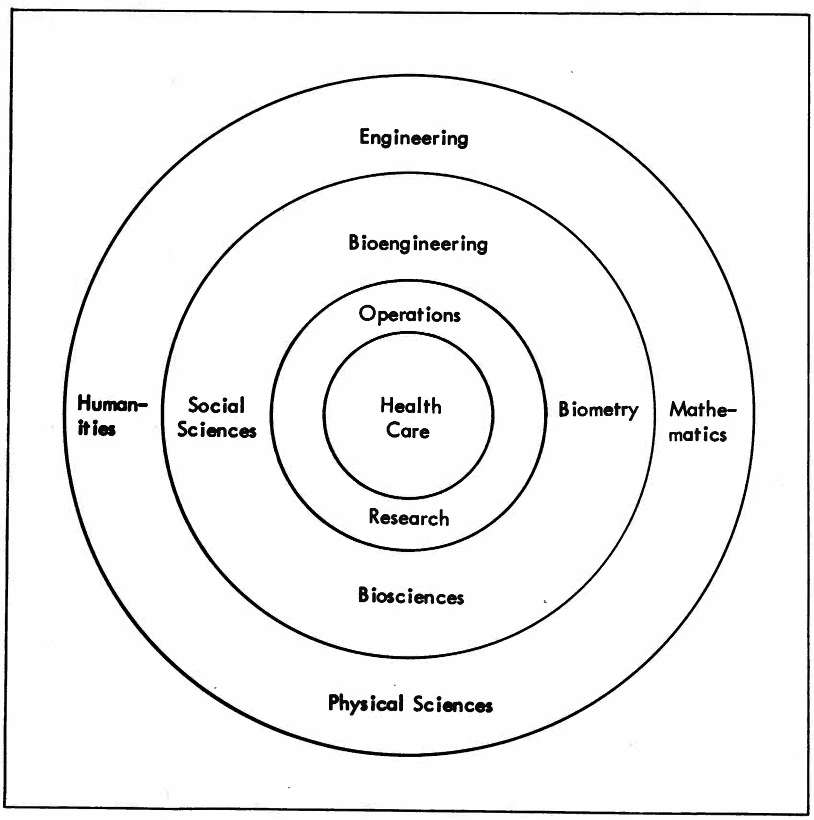

Fig. 1—Focus of various academic disciplines on health care research.

Excellent introductions to O.R. procedures are given by Churchman, Ackoff and Arnoff (1957) and Flagle, Huggins and Roy (1960.) Perhaps the best paperback introducing O.R. to the busy executive was written by Duckworth (1965). It needs to be read, however, in conjunction with the present article since it gives no medical applications. Apart from isolated chapters in the texts mentioned above, the only other sources for information on hospital applications of O.R. are the annual listing of Hospital Studies of the National Health Service and the summary of NIH grants.

The Wayne Commission Report, in discussing the obligations and goals of the urban university, states: "The urban university accepts the responsibility to participate fully in the urban problem-solving process. Hence, the various colleges and their faculties accept as one primary objective the development of new ways to meet the unsolved needs of the urban area" (Virginia, 1967, pp33-34). The tools to be used in the solution of these urban problems will include those outlined by this paper. Morse and Bacon (1967) describe some applications of the O.R. approach to problems of the city. Some references to various uses of O.R. in education are: Koenig et al. (1966), McKee and Ripley (1966), and Johnson and Wolfenden (1968).

Conclusion

In the 1968 Annual Report of the Medical College of Virginia (*Bulletin,* 1968, pp8,18) the shortage of trained medical personnel is stressed as a serious problem in the care of the sick. As a result of this personnel shortage, approximately 100 beds have recently been closed in the University Hospital. This underlies the need for large medical centers to use O.R. techniques in developing more efficient use of existing medical personnel and in seeking cost reductions while increasing the quality and coverage of medical care. When the medical center is a component of an urban university, both urban and medical problems amenable to the O.R. approach are best tackled by an academic department of the university.

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