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## *Letters to the Editor*

### OPERATIONAL RESEARCH AND THE DESIGN OF EXPERIMENTS

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THERE is no general agreement on the definition of operational or operations research and indeed it has been referred to as a new science, a new branch of science, a new branch of engineering, and a new level of research. It has also been emphasized that operational research is not experimental and that all that it requires is the data of the experimental work to arrive at a conclusion<sup>1</sup>. However the importance of direct experiments<sup>2</sup> and the experimental point of view<sup>3</sup> has also been mentioned and it has been suggested<sup>4</sup> that to four approaches (descriptive, variational, statistical, theoretical) commonly used in operational research the experimental method should be added. There is accordingly difference of opinion regarding the relation between operational research and experimentation.

Irrespective of differences in the various definitions of operational research the common denominator of them all is the emphasis on the application of scientific method to problems in government, industry, or war. The essential features of the scientific method may be set forth as follows: (a) *an examination of what is already known about the phenomenon of interest*, (b) *the formulation of an hypothesis that may account for the phenomenon*, (c) *the design of an experiment to test the hypothesis*, (d) *the collection of observations or data representing the results of the experiment*, (e) *acceptance or rejection of the hypothesis*.

Statistics contributes to each of the last three phases, which are sometimes grouped together and called 'testing the hypothesis,' and, although there may be agreement on the important role of statistics in operational research, the contribution of the design of experiments is sometimes overlooked or not fully appreciated. However if the above phases of scientific method be granted (and on these there is general agreement), the design of experiments appears as an integral and vital part of the whole scientific process. Consequently, since operational research is based on scientific method, the design of experiments must be recognized as an integral part of this type of research.

#### EXPERIMENTATION AND MILITARY OPERATIONAL RESEARCH

IT HAS BEEN STATED that all wars are experiments, and from this point of view the association of experimentation and military operational research has been a very close one. However the association is more than in name only. On the military side three types of 'experiments' may be recognized: uncontrolled, partially controlled, and controlled.\* In actual war operations only uncontrolled experiments occur and difficulties arise in their study because the data are generally not fully or properly recorded. On maneuvers or exercises partial control may obtain, while in some peacetime cases it may be possible for operational research to have

\* Control refers to control by the operational-research workers.

full control. The validity of even carefully collected data obtained from non-battle or non-operational experiments is another matter, but in some cases the effectiveness of the man-weapon performance can be satisfactorily estimated on realistic military maneuvers.

Information on organization, communications, clothing, and equipment obtained from partially controlled experiments such as training exercises may be useful in determining logistics methods, methods of control, and the size of basic units, and also in testing types of clothing and equipment for operations. It is also possible to derive basic data on weapons effects and characteristics on such maneuvers although controlled experiments are much better for these purposes. Obviously when new weapons or weapons systems and new clothing and equipment are being studied, only the experimental method can provide satisfactory measures of operational performance, although objective analysis and theoretical estimates of the likely performance of new items or systems are always helpful. In military operational research the experimental approach has had and will continue to have an important part to play.

#### EXPERIMENTAL DESIGN IN OPERATIONAL RESEARCH

THE LACK of emphasis on experimental design in operational research in general may be due in part to a misunderstanding of what is meant by the design of an experiment. If by the term observation we mean any sort of numerical recording of information then we may define the design of an experiment as the pattern of observations to be collected. According to this definition every operational-research project involves the design of an experiment. But observations collected in one way may be completely useless for purposes of drawing sound conclusions from their analyses or of testing the hypothesis of interest, while those obtained in another way can serve these ends. Many well-known examples of this fact could be cited, but it obviously is essential to ensure that the observations obtained will enable valid conclusions or inferences to be drawn and will provide a valid test of the hypothesis. This is not always easy to do and in operational research, in particular, where controlled experiments are not often feasible, great care should be exercised in designing trials and collecting data. Some general remarks concerning the design of experiments and operational-research trials are made below but a full treatment of these topics cannot be attempted here.

#### GENERAL COMMENTS ON THE DESIGN OF EXPERIMENTS

IF IN experimentation we define the term treatments to mean the different procedures whose effects are to be measured or compared, then we note that the results of experiments are affected not only by the treatments but also by extraneous variations that tend to mask the treatment effects. The term 'experimental errors' is often applied to these variations and it is usual to distinguish between two main sources of experimental errors. The first is the inherent variability of the experimental treatment and the second is the failure or inability to standardize the experimental technique. The analyst is primarily concerned with the former but he cannot overlook the latter. He must design the experiment so as to eliminate errors of the second type, if possible, or to minimize their effects. At the same time the experiment must provide a valid estimate of the first kind of error by which the significance of the experimental results must be judged. The design may be nothing more than the application of common sense, but it may also be a highly elaborate pattern based on the mathematical theory of finite geometries. The basic principles of the design of experiments (e.g., randomization, replication,

block control, etc ) have been available for some years so that anyone engaged in any form of scientific research involving experimentation can have access to them or can consult with a statistician acquainted with them

Since the conclusions and inferences that can be made as a result of the analysis depend on the way in which the observations were collected, it is important to realize that the time to think about the design of the experiment is during the planning of the project before the data are collected. Failure to comply with this obvious requirement is almost always disastrous

An important consideration in the design of an experiment is the number of observations to be taken or the size of the sample. The advantages resulting from methods whereby valid conclusions can be drawn from a minimum number of essential observations are very important. They can represent enormous savings of time and expense but unfortunately the advantages of such techniques have not always been well appreciated or, if they have, the techniques themselves have not been known. The techniques vary with the problem, but all cases of the technique are concerned with the mathematics of probability. Before the minimum number of essential observations can be determined some knowledge of the variability of the data or observations concerned is essential. No one can determine how large a sample should be or how many observations are necessary in order to permit valid conclusions, unless he knows or can satisfactorily estimate the variance of the population concerned. This estimate may be based on a preliminary sample or on past experience

It is not necessary that a sample be limited in size to the minimum number of observations necessary for valid conclusions, and, if time and costs permit, larger samples may be advisable. In operational trials unforeseen events adversely affecting the conduct of the trials or the collection of the data often occur so that it is usually unwise to design such trials in such a way that every planned observation is essential, unless the trials can be rigidly controlled. Generally speaking, operational designs should be such that satisfactory conclusions may be reached despite unforeseen changes or breakdowns in the original plan. The corresponding requirements will vary with the objects of the experiments as well as with other pertinent factors and are beyond the scope of the present paper, but in general they would include simplicity rather than complexity of design, sample sizes larger than the minimum number of essential observations estimated for the original plan, and the application of the basic principles of the design of experiments

Wherever, as a result of the quantitative analysis of the data, it is desired to make statistical inferences it is necessary that some element of randomness be introduced into the collection of the observations. Statistical inference is impossible from non-random observations or non-randomized experiments. Realization of this fact prevents unwarranted conclusions and sweeping generalizations. Even though the operational research worker may not be working with a complicated design, he must collect observations and the inferences or conclusions that he can draw from their analysis depend upon whether or not the observations have been collected at random. Further, there is no method of measuring the reliability of his estimates unless he has provided for doing so in the design of his experiment or in the manner of selecting his data

#### THE IMPORTANCE OF THE PROPER EXPERIMENTAL DESIGN

IT HAS BEEN pointed out that operational research has sometimes achieved great success with only limited data, and in such cases there can be little opportunity to select the pattern of observations since all the relevant observations available are

used. But in cases where data are plentiful, the choice of the pattern of observations to be collected (that is the proper design of the experiment) is extremely important and may be difficult to achieve. If not properly collected the observations may be completely worthless and it may then be impossible or prohibitively costly to select another set. Unfortunately worthless observations are not always recognized as such, and the unwary scientist may draw unwarranted conclusions or be led to accept an hypothesis when it should have been rejected or vice versa.

In spite of the fact that controlled experiments are usually very costly and are not often available to the operational-research analyst he will find it advantageous to use them wherever possible. On the military side they are widely used in 'engineering' and 'user' trials, and the proper design of these trials is receiving much attention. The design of the pattern of observations to be collected is always of prime importance in any field of operational research, because the analyst can draw valid conclusions only if he knows or has determined the design of the experiment whose results he proposes to analyze.

While the operational-research worker has done and can do much with even limited data and may, in some cases, be able to make a purse out of a sow's ear, correct use of the principles of experimental design may often enable him to make a silk purse out of a sow's ear.

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### SOME QUALITIES TO BE DESIRED IN OPERATIONS-RESEARCH PERSONNEL\*

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THE PURPOSE of this paper is to provide a conceptual framework within which the problem of personnel selection for operations research can be practically discussed. A complete solution of that problem will not be attempted here.

Before deciding what qualities may be desirable in OR personnel, it is necessary to have some agreement as to what we mean by operations research. Many definitions of operations research are already available, it is not proposed to add to this collection. The approach, rather, is to single out one characteristic that is common to most activities called operations research, and from which several useful implications may be drawn.

Let us introduce a spectrum of intellectual activity defined by classifying problems according to the number of independent variables necessary to characterize

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