STATISTICAL CONTROL

in the

CONSERVATION AND UTILIZATION OF RESOURCES

by

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ABSTRACT

The basic contribution of statistics to the science of control is an improved scientific method in which each of the three steps, hypothesis, experiment, and test of hypothesis, is modified to take account of the fact that valid inference can never be more than probable. The use of this method in analyzing the way men and equipment act together in an organization to determine what changes, if any, need to be made in order that the organization may come closer to attaining its objective, has already proved an effective means in many industries for conserving natural resources and human effort in the mass production of goods of standard quality.

The urge to control our environment to suit ourselves is as old as the human race. In fact, this urge largely differentiates man from other animals. However, the act or method of control has shown a marked development down through the ages - first instinctively guided by trial and error, later supplemented by appeal to the supernatural, then gradually modified in accord with the developing climate of scientific ideas. Our object here is to trace in bold outline some of the modifications brought about in the act of control through the introduction and use of statistical concepts.

GROWING NEED FOR STATISTICAL CONTROL

A basic problem in control is that of devising an operation of using raw materials at our disposal that, *if* carried out, will give a thing that is useful in satisfying some human want. It is desirable to differentiate between two kinds of factors that must be taken into account. Over one man has little or no control, as, for example, the weather; he must be content with trying to make valid predictions. Likewise no industrial organization has much control over a large number of factors such as fluctuations and trends in human wants, available supplies of raw materials, economic and business conditions, labor supply, the laws and mores of the people, the growth of population, and international relations. In fact, it is alleged in some quarters that human affairs of this character are essentially unpredictable and beyond the reach of research and experimentation, thus falling outside the scope of scientific inquiry. In marked contrast are those factors in the field of the natural sciences where it is possible to make reproducible experiments; where it is assumed that phenomena obey laws that can be discovered through scientific inquiry; and where it is assumed that valid prediction is possible.

A man of practical affairs must take into account both types of factors. The fact that he has learned through sad experience that it is not yet possible to forecast with certainty the future trend of social and economic phenomena has not deterred him from trying to make such forecasts. Experience has taught him that his short-term forecasts based upon social, economic, and business data are better than no forecasts at all. The subject of statistics had its origin in the attempt to satisfy this need of the man of practical affairs for factual information upon which to base such forecasts.

For example, when the Royal Statistical Society of London was founded a little over a century ago, its stated objective was "to collect, arrange, digest, and publish facts illustrating the condition and prosperity of society in its material, social, and moral relations". Even today in many quarters the statistician is thought of as one engaged in the collection, tabulation, and reduction of data, particularly of a financial and economic character. Gradually there grew up a statistical methodology "adapted to the elucidation of quantitative data affected by a multiplicity of causes". It grew up as something apart from scientific method - in fact, it grew up to serve the need of the practical man in fields which many scientists would claim are beyond the pale of scientific inquiry.

Turning our attention to fields in which scientific inquiry is admittedly possible, we find that the scientist has not only accepted the fact that the only kind of observable constancy is statistical but he has also found it necessary to go further and develop statistical theories to account for the many conceptual properties of the particles of modern physics. Although the basis of the scientific process is often taken as the reproducible experiment, it has long been realized that the outcome of the repetition of such an experiment can only be predicted within limits upon the basis of probability theory. Measurement itself is a fundamental operation of this character and the theory of errors was developed by Gauss more than a century ago to take account of the statistical nature of repetitive measurements.

Even so, however, the pure scientists in these fields have paid little attention to the methods of the statistician as such. True enough, natural scientists have long computed probable errors but by and large these errors have been used only in a perfunctory manner. For example, a great physicist, the late Lord Rayleigh, once said that error theory was something to read up on and then forget. Within the past quarter century, however, the applied scientist at least has begun to take cognizance of the statistician and his ways. Why, you may ask, has this change come about? The answer is not hard to find. The applied scientist has run head on into certain types of problems in his attempt to control the variability in the results of repetitive operations and to disentangle and measure the effects of different causes of variation upon some variable that he wishes to control.

Obviously the manufacturing process may be thought of as a repetitive operation analogous in many ways to the repetitive experiment and measurement in science. We may conceive of the manufacturing process as an operation that may be repeated again and again, and thus capable of producing an indefinitely long sequence of physical objects. Such processes are often refined to the state that the repetitions are made under presumably the same essential conditions. Even so, we find that the qualities of the objects thus produced vary from piece to piece in much the same way that a sequence of repetitive measurements of the pure scientist may vary.

For example, consider the production of a protective fuse designed to blow within a given interval of time when subjected to a specified load. Obviously all fuses cannot be tested because the test itself is destructive; yet one or more persons may lose their lives or at least there may be large property damage if a fuse fails to blow within the specified limits. Here it becomes vitally important to be able to make valid probability predictions within specified limits. Whereas in the field of error theory the scientist usually <u>assumes</u> that a sequence of observed values made under essentially the same conditions will approximately obey the normal law of error, the production man early found that such assumptions were not valid in his field. The operation of statistical control was introduced about a quarter of a century ago to help the practical man detect the presence of assignable causes of variability in his production process that had to be taken into account before valid prediction was possible.

Even where the inspection test is not destructive, it is often found that a small percent of product made under presumably the same essential conditions will fall outside of the tolerance limits and usually must either be scrapped or reconditioned. This adds to the cost of production. Here again it often becomes of great importance to study the causes of variability in the process with a view to reducing the percentage of product falling outside of tolerance limits. Oftentimes, it is also important to close up on the tolerance limits in order to effect certain economies, on the one hand, and to attain a more desirable product on the other.

For these reasons, if no others, it is important from the viewpoint of conservation and utilization of raw materials in manufacture to detect the presence of assignable causes of variation in the repetitive act of manufacturing. Another reason stems from the work of R. A. Fisher on the design of experiment as introduced in the field of agricultural experimentation. The classical ideal of experimentation is to keep all of the independent variables constant except one. Fisher was the first to point out the advantages to be gained by including in the same experiment as many as possible of the factors whose effects are to be determined. Not only does this provide greater efficiency and provide measures of the variability attributable to each of the different factors; it also provides a means of determining the extent to which the factors themselves <u>interact</u>.

To illustrate, let us consider once again a manufacturing operation. In the development of a complicated manufacturing process of modern industry many operational steps are involved and these are sources of causes of variation in the final product. In the industrial research underlying the development of such a process, it is often highly desirable to be able to determine the contribution of each of these steps to the over-all variability. Moreover, in any such process it is almost certain that the interaction between the effects of some of the factors will be of great importance. Fisher's theory of the design of experiment sets forth the principles for efficient experimentation in such instances. This is particularly true in the development of processes of production of such items as thermionic devices, varistors, thermistors, and transistors, to mention only a few coming out of recent advances in modern physics and chemistry.

STATISTICAL CONTROL

The theory of statistical control is concerned with the development of a scientific method of making the most efficient use of raw materials in the production of things to satisfy human wants; a scientific method that takes into account the fact that inferences can only be probable; a method that will help us to obtain maximum validity in the field of prediction and that will provide a rational routine for minimizing variability in the repetitive act of production through the detection and removal of assignable causes of variation. The theory of control as here conceived must take into account all steps in the act of control including the determination of human wants, the selection of raw materials, and the more formalized steps of industrial research, development, design, specification, production, and inspection.

For our present purpose we may think of scientific method as involving three important steps:

1. The adoption of an hypothesis and the development of a formal theory for making valid predictions provided the hypothesis is true.

2. Experimentation to provide the data with which to test the hypothesis.

3. Development of ways and means of using the data in testing the hypothesis.

The fundamental role of statistics is that of modifying each of these three steps. The method of statistical control is one in which we start with statistical hypotheses, make use of statistically designed experiments, and apply statistical tests of the hypotheses. Such a view no longer conceives of statistical method as something apart from scientific method but rather as an improved scientific method.

Turning our attention to the production of manufactured goods, it is customary to consider three fundamental steps in the act of control, namely, 1) the specification of the physical and chemical properties of the thing wanted, 2) production, and 3) inspection. From the viewpoint of statistical control theory, these three steps are analogous to the three steps in scientific method. Based upon industrial research and development, the engineer or applied scientist comes out with the design of something that is presumably wanted. In order for the parts of such a design to function, it is necessary that they be controlled within specified tolerance limits. Such limits, however, cannot be drawn out of the air but must conform to the limitations imposed by lack of homogeneity of raw materials and chance causes of variation in the production process.

As a preliminary step in arriving at such specifications, it has long been the practice in industry to build and try out tool-made models. In many instances, it has been found necessary to go even further and to make use of what is customarily known as a pilot plant production. From the viewpoint of statistical control, it is highly desirable in these stages to make use of statistical control theory and techniques, first in weeding out assignable causes of variability and then in making estimates or tolerance limits based upon the rational use of probability theory. It is particularly desirable at this stage to make use of available criteria for statistical control and also the statistical design of experiment in determining the effects of different factors and their interactions.

This use of statistical control procedures becomes a very important tool in setting up specifications that may reasonably be expected to be satisfactory from the viewpoint of mass production. Even so, it is usually found that when such specifications are used under the necessary conditions of mass production, additional assignable causes of variation come into play. Fundamentally, therefore, the specification is of the nature of the best possible hypothesis to be tried out in the second step, production. The third step, inspection, was originally conceived as a screening. From the viewpoint of statistical control, however, it is much more than this: it can really be made a crucial step in testing the hypothesis implied in a specification.

CONTRIBUTIONS OF STATISTICAL CONTROL

In a recent article in the Wall Street Journal, it is estimated that the potential annual savings to American industry through the contribution of statistical control within the fields of production and inspection alone is of the order of magnitude of two or three billion dollars. There are several corporations that have reported actual annual savings running above a million dollars. However, so far as I know, no corporation has as yet explored the full possibilities of effecting savings at all steps in the over-all problem of control as set forth in this paper. There are six ways in which the advantages to date have been most felt.

1. Reduce the amount of inspection - At each stage in the process of attaining a state of statistical control of a production operation from the sampling of raw materials to the production of the finished piecepart, statistical theory has made possible the establishment of efficient sampling plans that screen at minimum cost the output of each operation so as to meet previously specified tolerance requirements and previously specified consumer and producer risks.

2. Minimize the number of rejections and hence the quantity of scrap - By helping the engineer to detect the presence of assignable causes of variation so that these may be discovered and removed, statistical control techniques help to reduce variability of quality and hence the number of rejections. This is not only important from the viewpoint of reducing costs but also nationally and internationally important from the viewpoint of conserving available quantities of scarce materials.

3. Maximize quality assurance - As assignable causes of variation are detected and removed, the quality of a given product approaches a state of statistical control for which the assurance that the quality of a piece of product will meet its tolerance requirements is a maximum. This fact is of particular importance for goods that cannot be given 100% inspection because of the destructive nature of the inspection test.

4. Increase output of goods of standard quality - This advantage is of particular importance in times of both war and peace when production falls below the levels required within a given nation or group of nations. At such times, savings in dollars alone does not adequately measure the importance of the contribution of increased production.

5. Increase employee satisfaction - Through the application of statistical control techniques, it becomes feasible to detect whether or not excessive variability in the quality of output has been occasioned by some physical factor or by some human factor. In many instances, the operator of a machine has taken

great interest in the results of applying such techniques because it assures him that he will not be penalized for low production when the cause is either in materials or machines. Statistical control techniques are also useful in detecting and helping to eliminate assignable causes of variability in many kinds of human effort thus helping the operator to maximize his efficiency.

6. Minimize tolerance range - The operation of statistical control provides an experimental technique for minimizing tolerance limits. Such an operation makes possible the most efficient use of limited quantities of raw materials and provides the maximum degree of refinement attainable by any production process. Both strategically and commercially, industrial groups and even nations often need the maximum assurance of quality and the minimum tolerance ranges that can be obtained from the elimination of assignable causes, not only in pursuit of the arts of peace but also in time of war. For example, the attainment of maximum control may extend the potential carrying capacities of ships both in the air and on the sea.

THE FUTURE OF STATISTICAL CONTROL

The primary concern of this conference is stated to be the "practical application of science to resource management and human use". Management in this sense may be defined as the art and science of organizing and directing human effort in the control of our environment for the benefit of man. The broad function of the theory and practice of statistical control is to provide management with an adequate scientific statistical method for collecting the best possible quantitative information and drawing valid probable inferences therefrom in regard to the operations under its control.

Even assuming that a perfect methodology for effecting control were at hand, there would still remain the really stupendous problem of organizing human effort in the use of this methodology. Consider, for example, a large industrial organization such as the Bell System. More than 100,000 different kinds of piece-parts are required in the physical system to make it possible for one subscriber to talk to any other in the System. Many of these parts have an annual production running into the millions. The human effort required in the production of these parts is provided by thousands of employees. No one group of employers is solely responsible for control - instead each employee plays a part. The maximum advantages of statistical control come about only when every employee is in possession of the "know-how" adequate for his job. For this reason many corporations have provided in-company "short-courses" attended in some instances by all employees concerned from the vice-presidents down. The know-how gotten across in this way may be adequate training for the majority of the employees but far more advanced training is essential for others responsible for the more complicated control operations. The customary organizational set-up for developing and using company standards of quality as a guide in production and inspection became a logical means of developing and coordinating the statistical control efforts of those engaged within a company in production and inspection.

There remains, however, the problem of controlling the quality of incoming raw and fabricated materials. Some idea of the magnitude of this problem in any large industry can be gleaned from the fact that in a typical post war year something like 90,000 tons of steel, more than 100,000 tons of copper, more than 100,000 tons of lead, 7,000 tons of cable paper, 6,500 tons of wood pulp for cable insulation, 7,000,000 lbs. of cotton yarn, and 2,000,000 lbs. of acetate rayon yarn were purchased by the Bell System. These are just a few of the thousands of items purchased from thousands of suppliers. Such supplies come from every state in the Union and from many foreign countries - literally from the four corners of the earth. The practice of buying in accord with specified standards of quality subject to rigid inspection makes possible a thorough job of screening to insure maintenance of standards of quality. However, to the extent that outside suppliers adopt statistical control procedures, there accrues a reduction in the amount of inspection required and in the amount of material rejected as sub-standard, both of which are reflected in savings. Moreover, the use of such procedures gives maximum assurance that quality standards are being maintained even in those instances where 100% inspection could not be carried out because of the destructive nature of the test.

Industrial groups in many countries have long appreciated the mutual advantage of common standards of quality to all engaged in trade one with another. For this reason, national standardizing bodies have been established in many countries since the turn of the century and an international standardizing organization has been set up since World War II. Some of these organizations were among the first to appreciate the mutual desirability of extending the use of statistical control procedures throughout industry. In fact, the American Standards Association at the request of the war department, developed certain standards of quality control by statistical techniques that were used extensively here and in England, Canada and Australia to attain the advantages of statistical control in war production. More recently, the Indian Standards Institution has republished these as tentative standards to be used in the development of her industries. By and large, statistical quality control has gained a toe-hold in industry within several nations largely through existing organizations devoted to standardization. To date we have only begun to reap the benefits of the movement started in this way.

However, before any appreciable percent of the potential contribution of statistical control in industry can be reached, it is necessary that applied scientists, engineers, and others engaged in research, development, design, and specification avail themselves of the latest developments in the theory and practice of the science of control. Ground has already been broken by way of organizing effort to explore the possibilities in this direction. In several large scientific and engineering societies, committees have been organized to develop the application of statistical control procedures in their specialized fields.

An American Society for Quality Control has also recently been organized and now has a membership of more than 2500 members. Such groups can be relied upon to extend the fields of application.

It is, however, to the universities and colleges that industry must look for leadership in the development of new and improved statistical hypotheses or models, improved methods of applying statistics in the design of complicated experimentation, and new and more powerful statistical tests of statistical hypotheses, all of which constitute the basic foundation of statistical control theory. We must also rely upon engineering schools to develop the art, as well as the science of statistical control which goes beyond statistical theory per se as I have tried to imply in what has gone before.

Any prognostication about the future of statistical control would not be complete without a comment on that toughest of all problems, the establishment of the goal of control in terms of that which will give the greatest satisfaction of human wants, to the ultimate user. This implies, among other things, the need to make valid prediction of trends in the non-controllable natural and social factors and of how these will tend to modify and shape his future wants. This involves, among other things, the study of individual and group patterns of motivation and preference and then an attempt to determine how to make valid predictions about future trends in a user's behaviour in terms of available knowledge of his present preferences in relation to prevailing economic and social conditions.

One ray of hope from the viewpoint of this aspect of control has shown above the horizon - I refer to the development in the past few years of a theory of prediction based upon the introduction of new statistical models of so-called stochastic processes. To date the psychologist, economist, and social scientist has not been prone to base much hope on the use of probability theory. This tendency is partly attributable to the fact that their concept of probability was limited to that of a random repetitive process in which the successive observations are independent. It is obviously possible, however, to develop statistical models for which the successive observations are not independent. Such models have proved their usefulness in such diverse fields as the study of stellar phenomena, cosmic rays, and the theory of communication. Attempts have been and are being made in several quarters to develop similar models applicable in the field of economics. How the continuing theoretical developments in this direction will affect the control theory of the future no one knows - that they will modify our present views of control theory is, however, almost a certainty.

Finally a word about the ultimate user whose wants are to be satisfied. In the last analysis, a nation can be great in science only to the extent that the population has an inkling of the objectives, methods, and limitations of scientific work. Unfavorable reaction is sooner or later bound to result from any disposition to regard science as a form of magic. In some quarters there has been a tendency to emphasize the "fact" that applied science has reached a stage where it was possible to buy and sell in accord with exact engineering specifications of quality. In fact, I recently read the following advice in a publication distributed widely among the consuming public: "Buy as your Uncle Sam does, in accord with exact specifications of quality". The implication is that at least in some instances specifications can be written that specify unequivocally an object of trade. This is like advertising the magic of science. It is not possible to specify the quality of the simplest thing in an absolute manner. But even if it were, it would not be possible to determine with <u>certainty</u> that the object had the specified quality. In the last analysis, scientific method can only lead to a probable inference. The public should not be led to expect the impossible from scientific control. Its full support, requisite for achieving the greatest success in the scientific control of our environment, can only come when it is acquainted with the limitations of science imposed by the fact that valid inference can never be more than probable.

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