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light for that gaging point informs him which is the erring dimension. Theoretically, at least, the capacity of the instrument is unlimited, pinions 1/8 in. in length and 0.010 in. in diameter being checked as easily as large-caliber shells and large automotive parts. Nor is there any limit to the number of gaging points, for interior or exterior dimensions, that may be used at one time.

Women Inspectors

Although women have been employed to a limited extent on peacetime production inspection, the shortage of qualified men for this work during the current national emergency has greatly stimulated the training of women inspectors. In such training courses they are given the same instruction as the men. The subjects include review of mathematics, drawing and blueprint reading, materials testing, metallography, manufacturing methods, machine-shop work, jigs, fixtures, gages and inspection methods, and actual inspection practice with the use of a wide variety of precision-measurement instruments.

The magnitude of the present war production has prompted tremendous improvements in inspection instruments and technique so that we may look forward to the ultimate resumption of peacetime activities on a far more advanced level than prior to the war, necessity being still the mother of invention and progress.

Statistical Control in Applied Science

By W. A. SHEWHART,[7] NEW YORK, N. Y.

Foreword

Statistical quality control was born eighteen years ago. It was Dr. Alford, at that time editor of *Manufacturing Industries*, who two years later announced the birth, as it were, by the publication of a short article in that journal.[8] Thereafter he watched with an active, critical interest the development of statistical-control techniques and when, in 1932, he wrote his report, "Ten Years' Progress in Management, 1923–1932," he called attention to statistical control as a tool of far-reaching significance to management. It is therefore particularly gratifying to be able to present here a brief survey of developments in statistical control that are of interest from the viewpoint of management in the hope that the comparatively rapid development of the theory and application of statistical control both here and abroad during the past ten years will bear additional testimony to Dr. Alford's ability to sense the importance of new developments in scientific method to the solution of everyday problems of management.

THIRTEEN years ago The American Society of Mechanical Engineers, in co-operation with the American Society of Testing Materials, called a round-table conference on the application of statistics in engineering and manufacturing, out of which came the organization of a committee which is now sponsored jointly by five societies.[9] Progress in the application of statistical quality control during the past ten years is largely attributable to this co-operative attempt on the part of representatives from several engineering and scientific organiza[tions to] get people from different groups to merge their common [knowl]edge of statistical techniques and to discuss their prob[lems in] order to get a broader view of the usefulness of sta[tistics]. Co-operation of this character did not stop in Americ[a], through the efforts of the Joint Committee and its [sub]groups, engineering societies in other countries, parti[cularly] in Great Britain, were asked to join in surveying the p[ossible] contributions of statistics.

Increase in Applications of Statistical Contro[l]

A report of the Joint Committee describing these early [activi]ties was published in MECHANICAL ENGINEERING for Nov[ember] 1932, and should be consulted for a brief review of the ear[ly steps] in organizing this co-operative effort to further the appli[cation] of statistics in engineering. Since then, members of th[e Com]mittee and its sponsor organizations have taken an activ[e part] in the development of the application of statistics. .. share of the credit for progress in this direction should go [to The] American Society of Mechanical Engineers which, thro[ugh its] journal and its sectional and annual meetings, has done m[uch to] promote the work of the Joint Committee.

The few applications of statistical quality control in in[dustry] in 1932 have grown to many in 1942; too many to list he[re. It] may be interesting, however, to review some events, bo[th here] and abroad, which, viewed from their aftereffects, seem [to have] been most influential in helping to spread the knowledge [and] value of statistical methods.

Through the co-operation of the American Standards A[ssocia]tion and the engineering societies represented on the com[mittee] in 1932, the British Standards Institution became interest[ed and] appointed a committee to look into the subject with the [result] that an excellent monograph[10] by Prof. E. S. Pears[on was] published by them in 1935. Next in line chronologically [was the] awakening of the interest of the United States War Depa[rtment] in the value of statistical methods in the production of ordn[ance] which finally resulted in the request of the War Departm[ent to] the American Standards Association to standardize the [quality-]control-chart techniques to make possible their more gene[ral use] throughout the country. In accord with this reque[st, the] American Standards Association has recently issued [three] standards on this subject.[12]

At the present time, the Office of the Chief of Ordnan[ce has] undertaken a program of training conferences on the pri[nciples] of the quality-control technique in the various ordnanc[e dis]tricts throughout the country. The American War Sta[ndards] prepared by the American Standards Association were [adopted] by the British Standards Institution in England. Last [year a] joint meeting of the Institutions of Civil, Mechanic[al, and] Electrical Engineers was held in London, which, accor[ding to] reports in several scientific journals,[13] showed by the

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[7] Bell Telephone Laboratories. Chairman of the Joint Committee for the Development of Statistical Applications in Engineering and Manufacturing.

[8] "Finding Causes of Quality Variations," by W. A. Shewhart, *Manufacturing Industries*, vol. 11, no. 2, February, 1926, pp. 125–128.

[9] Joint Committee for the Development of Statistical Applications in Engineering and Manufacturing sponsored by THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS, the American Society for Testing Materials, The American Mathematical Society, the American Statistical Association, and the Institute of Mathematical Statistics.

[10] "The Application of Statistical Methods to Industrial Stan[dardi]zation and Quality Control." In 1942, the part of this de[aling with] quality-control charts was reissued in a revised edition prepar[ed by] B. P. Dudding and W. J. Jennett, BS 600R: 1942. Prior [to this] the A.S.T.M. had issued an important monograph "Manual [on Pres]entation of Data," 1932; supplement, 1935.

[11] See "An Engineer's Manual of Statistical Methods," by C[. . .] Simon, John Wiley and Sons, 1941, and "Quality Control [in] War," by the same author, *Electrical Engineering*, September, [. . .]

[12] Z1.1, Guide for Quality Control; Z1.2, Control Chart Meth[od of] Analyzing Data; Z1.3, Control Chart Method of Controlling [Quality] During Production.

[13] See, for example, "The Statistical Method in Quality C[ontrol]: A Review of Progress in a New Industrial Technique," by H. [. . .] *BEAMA Journal*, May, 1942, pp. 130–133.

number (over 800) in attendance the interest already aroused at the same time did much to promote new applications.

Contributions to Mass Production

Statistical control in mass production may be thought of as an attempt to maximize the advantages to be attained through interchangeability, a commonplace of production today but revolutionary when Eli Whitney made his muskets in 1798. Four specific ways in which statistical control makes this contribution may be mentioned:

1 *Minimizes cost of inspection.* At each stage in the process of attaining a state of statistical control of a production operation, the application of statistical theory makes possible the establishment of sampling plans,[14] that will screen at minimum cost the output of such an operation so as to meet previously specified tolerance requirements and previously specified producer and consumer risks.

2 *Minimizes number of rejections.* By helping the engineer detect the presence of assignable causes of variation so that these causes may be discovered and removed, statistical control techniques help to reduce variability of quality and hence the number of rejections.

3 *Maximizes 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 per cent inspection because of the destructive nature of a test.

4 *Minimizes tolerance range.* The operation of statistical control provides an experimental technique for minimizing tolerance ranges. 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. Preliminary studies indicate that the operation of statistical control also provides a useful technique for eliminating assignable causes of variability in certain kinds of human effort as, for example, typing and other forms of transcription. Both strategically and commercially, industrial groups and even nations often need every increment of efficiency in the use of limited quantities of raw materials and human effort that can be provided through the application of the operation of statistical control. Likewise, they often need maximum refinement in quality through elimination of assignable causes, not only in pursuit of the arts of peace but also in time of war. As one example, the attainment of maximum homogeneity and hence minimum tolerance ranges in the properties of raw and fabricated materials may extend the potential carrying capacities of ships both in the air and on the sea.

Need for an Adequate Science of Control

Out of the successful effort to apply statistical techniques in the control of quality has grown a general theory and technique of statistical control in applied science that is applicable in the whole field of the science of management defined[15] by the Management Division of the A.S.M.E. as follows:

> "Management is the art and science of preparing, organizing and directing human effort applied *to control* the forces and to utilize the materials of nature for the benefit of man."

Management of today is interested not only in a science of control helpful in "preparing, organizing, and directing human effort" to win this war but also in one helpful in utilizing to a maximum "the materials of nature for the benefit of man" when peace comes, because transition to peacetime production will present again many of the problems encountered in going from peace to war production. But that is not all. After the war, there may come proposals from many quarters, industrial, social,[16] political, and the like, about the art and science of organizing and directing human effort in producing goods to satisfy in the most adequate, dependable, and economic manner the wants of all. As pointed out in a recent editorial on "Science and Politics" in one of the journals of the American Institute of Physics: ". . . it behooves scientists to give their serious consideration to the *role of science*[17] in a state which is becoming increasingly centralized. . . . Important problems exist between these fields[18] which can be solved to the great benefit of each if, firstly, the will to co-operate exists, secondly, the problems are fairly and properly formulated, and, thirdly, their solutions are determinedly sought under wise and resolute leadership."[19]

One example of a field of universal interest wherein exist many important technical problems that overlap the fields of natural and social sciences is that of price-quality control. Perhaps *there are few fields where there is greater need that the problems* be fairly and properly formulated. To do this, means that we must discard many popular methods of control based upon the concept of an exact or deterministic science and replace them by scientific methods that take into account, as does the theory of statistical control, the fact that the quality of goods cannot be specified with exactness and that even though they could be specified with exactness, they could not be inspected with certainty because of the inherent variability between measurements.[20] Then there are those many instances where the qualities cannot be measured at all without destroying that which is measured, as in the case of many quality characteristics of foods, drugs, clothes, ammunition, and so on indefinitely. Hence it is that the science of control cannot be exact but only probable. *In order that we may judge wisely in these days to come, we shall likely need as never before to distinguish clearly* what is, from what is not, *an adequate science of control.*

Requirements of an Adequate Science of Control

To make clear what I have in mind, let us first consider a field familiar to mechanical engineers, namely, that of mechanics. Many observed phenomena can be described satisfactorily by the laws of Newtonian mechanics. These are *deterministic* in the sense that they assume that if such *and* such an *operation* is performed, such and such measurable events will surely happen. However, some mechanical phenomena, such as those treated in statistical mechanics, cannot be explained *in terms of* deterministic laws: instead *statistical* laws must be introduced. Moreover, there is not *one* statistical theory of mechanics but several.

[14] For tables to assist in establishing sampling plans see "Single Sampling and Double Sampling Inspection Tables," by H. F. Dodge and H. G. Romig, *Bell System Technical Journal*, vol. 44, January, 1941, pp. 1–61.

[15] Trans. A.S.M.E., vol. 35, 1913, p. 1272.

[16] While writing this paragraph, an announcement of a book, "Readings in the Social Control of Industry," to be published by the Blakiston Company, Philadelphia, came to my desk. In addition to carrying fifteen signed articles, it is to give an indexed bibliography of more than 250 journal articles published mainly in the last twenty years.

[17] Italics author's.

[18] Science and politics.

[19] "The Review of Scientific Instruments," vol. 13, August, 1942, p. 313.

[20] For example, Dean-Emeritus Roscoe Pound of the Harvard Law School has discussed "The Relation of Statistical Quality Standards to Law and Legislation," in the volume, "Fluid Mechanics and Statistical Methods in Engineering," published by the University of Pennsylvania Press, 1941, page 137–146. As a background for this he makes use of the article, "Some Aspects of Quality ..." published in *Mechanical Engineering*, Dec... [illegible]

The theories differ fundamentally in the physical assumptions made the basis of the assumed statistical laws. The choice between them as an interpretation of physical phenomena must be based upon their comparative abilities to fit observed facts.

The fact that observable phenomena are not explainable in terms of deterministic laws does not necessarily mean that they are explainable in terms of statistical laws. In general, as has been shown elsewhere, there are what have been called *assignable causes* that must be found and either eliminated or taken into account before valid scientific predictions can be made in terms of the tolerance limits on observable values. An adequate science of control must provide practical techniques for discovering such causes. *Such a theory is provided by the theory of statistical control.*

Statistical Control Not Mere Application of Statistics

Most of us have a certain curiosity to know something about what we are getting into before we begin to learn a new discipline. Unless we have some ideas about it and its relation to things otherwise familiar, we may not wish to study it at all. In the remaining paragraphs, I shall go a little way toward satisfying this curiosity, by showing how a statistical theory of control differs from simply the application of statistics to certain problems in control.

Common to any statistical theory either of mechanics or of statistical control is the use of mathematical probability or distribution theory. But the theories differ in the underlying physical postulates. In this sense, there may be more than one statistical theory of control in much the same sense that there may be, and is, more than one statistical theory of matter, and any such theory is more than classical distribution theory of mathematical statistics.

Four of the specific ways that statistical control theory *in the* present sense differs from classical statistics are:

1 Classical statistics start with the assumption that a statistical universe exists, whereas control theory starts with the assumption that a statistical universe does *not* exist.

Even in the statistical theory of mechanics and of radiation phenomena, it is assumed that if a deterministic theory is not adequate, then a theory based upon the assumption of the existence of laws of chance will be adequate. In the field of quality control, as already noted, it is now generally accepted, however, that measurable phenomena do not obey laws of chance until what is known as assignable causes have been discovered and taken into account.[21]

2 Statistical control theory assumes that assignable causes can be found and either eliminated or taken into account in making valid predictions.

Statistical quality control has developed and provided a proving ground for two techniques for discovering such causes. These are: (1) the control chart *technique for control* of quality in production, now standardized by the American Standards Association and the British Standards Institution, and (2) the statistical run *chart technique for finding* assignable causes of variation in research and development.

3 Classical statistics ignores completely the ultimate goal of an applied scientist to make valid predictions in terms of tolerance limits as contrasted with the confidence limits of classical statistics.

Control engineers pointed out this fact in 1928 but it was not until 1941 that an academic statistician took note of the pro[illegible] of making valid predictions in terms of tolerance limits.[22] [illegible]cidentally, knowledge of the theory of tolerance-range type [illegible]diction gives promise of contributing much to the theor[illegible] estimation and the theory of testing hypotheses of clas[illegible] statistics in much the same manner that consumer and prod[illegible] risks introduced into statistical quality-control theory in [illegible] were the forerunner of the very important developments [illegible] J. Neyman and E. S. Pearson, in the theory of errors of the [illegible] and second kinds in modern mathematical statistics. That [illegible] say, control theory has had to consider some problems r[illegible] belonging in the realm of classical statistics before they [illegible] recognized there.

4 Classical theory is based upon the concept of inferen[illegible] from a single sample from a statistical universe, t[illegible] ordering within the sample being ignored, while *cont[illegible]* theory must be based upon evidence provided by a su[illegible]cession of samples, ordering within the sample, and oth[illegible] *pertinent information.*

Hence the three scientific steps, hypothesis, design of ex[illegible]ment, and test of hypothesis in approaching a state of statis[illegible] control differ from those discussed in classical statistics.[23] M[illegible]over, the problems, before a state of statistical control has [illegible] reached, as viewed by the control statistician are essent[illegible] different. For example, at *the round-table conference thir[illegible]* years ago, statistical science was implicitly defined by the c[illegible]man, Colonel Rorty, as: (1) The assembly of broad mass[illegible] data, (2) the reduction of such data graphically or mathem[illegible]cally to a more compact and useful form, and (3) the ana[illegible] of such data to determine useful conclusions and general laws.

But the control statistician is not concerned with assemb[illegible] and reducing data in this sense until he has data worth as[illegible]bling and reducing. Likewise his experience in the fiel[illegible] quality control has shown the uselessness of inferring "statis[illegible] laws" until the effects of assignable causes have been taken [illegible] account, or, in other words, until such laws exist to be infe[illegible]. Moreover, the help of the control statistician is usually ne[illegible] in designing the experiment that will give the data necessar[illegible] tracking down assignable causes; in fact his greatest cont[illegible]tion is most likely that of helping to design such experim[illegible] rather than in analyzing the data.

After a state of statistical control has been attained, [illegible] principles of statistical inference provided by modern ma[illegible]matical statistics may be taken over and applied directly fo[illegible] purpose of *inference in terms of* confidence limits and tes[illegible] statistical hypotheses. However, even under these condit[illegible] the control statistician needs to go beyond the mathema[illegible] theory discussed in texts on *mathematical* statistics as n[illegible] previously, if he is to be able to make valid predictions in t[illegible] of tolerance ranges as is desirable in applied science.

The Future Problem

An adequate science of control for management should [illegible] into account the fact that measurements of phenomena in [illegible] social and natural science for the most part obey neither d[illegible]ministic nor statistical laws, *until* assignable causes of variab[illegible] have been found and removed. Statistical control prov[illegible] practical control-chart and run-chart techniques for discove[illegible] such causes *so that they can be removed, or taken into* acco[illegible] and it provides statistical hypotheses, experiments, and tes[illegible]

[21] For a fuller explanation of this see Chapter 1 of "*Statistical* Method from the Viewpoint of Quality Control," by W. A. Shewhart, published by the Graduate School of the Department of Agriculture, 1939.

[22] "Determination of Sample Sizes for Setting Tolerance Lim[illegible]" by S. S. Wilks, "Annals of Mathematical Statistics," vol. 12, n[illegible] March, 1941, pp. 91–96. This is a very important paper from [illegible] viewpoint of control.

[23] For a specific illustration of how these differ, see Shewhart *[illegible] cit.*, pp. 39 and 40.

theses for discovering and using statistical laws resulting the assignable causes have been removed.
e steps involved in attaining and making the most efficient f a given degree of control often involve the co-ordinated of literally thousands of employees, including physicists, ists, engineers, sales agents, purchasing agents, lawyers, and omists. Very few of these people have ever had training in classical statistics and probability and yet many of them be sold on the use of statistical control techniques if the rol statistician is to have an opportunity of making his full ribution to management in the solution of its problems. situation constitutes a problem, not only for those now in stry, but also for those responsible for training the industrial ers of tomorrow so that they will have sufficient knowledge to them recognize the potential contributions of statistical rol theory and technique.
the future, the control statistician must do more than ly study, and measure the effects of, existing cause systems; must help his colleagues devise means for modifying these e systems in the best way to satisfy human wants. The rol statistician must not be satisfied with simply measuring demand for goods; he must help change that demand by ving, among other things, how to improve the quality of e goods to the consumer. He must not be content with suring production costs; he must help decrease them.
he future contribution of the statistical control statistician not so much in analyzing data put to him as in helping to get in which assignable causes have been segregated so that lysis will lead to valid conclusions not otherwise possible. only may each industry expect to profit by having on its sulting staff a highly trained control statistician with a ad background of training in the physical and social sciences with a flair for co-operation with his colleagues, but there lso great need for creating, through college training,[24] a istically minded new generation of those natural and social ntists who will have charge of preparing, organizing, and cting the effort of those who are "to control the forces and to ze the materials of nature for the benefit of man."