Finding Causes of Quality Variations

A Fundamental of Control Through Inspection

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IN this paper I shall consider only one fundamental inspection problem. It was Patrick Henry, I believe, who said, "I have no way of judging the future save by the past." The problem of finding the *best* way of judging the future in terms of the past is the fundamental problem which I wish to consider.

All of us know that experience counts; that it counts with one proviso, namely, that we know how to use it. I shall try to present some fundamental principles indicating the best way to analyze and interpret the past so as to forecast the future, i.e., to make the best use of the data of experience. Naturally the problem of how to make the best use of data does not belong to engineering inspection alone, because others than inspectors are supposed to make use of their experiences. Hence my remarks are based upon a survey of the results of efforts to solve this fundamental problem in many fields of human endeavor.

This paper forms the basis for answering the following important inspection problem: When do the observed differences between product for one period and product for another period indicate non-uniformity? When do quality differences of manufactured product, observed from one period to another, indicate fortuitous, chance or random variations produced by non-assignable causes which cannot reasonably be controlled without radically changing the manufacturing process; and when do observed quality differences indicate the possible existence of assignable causes which can be found and controlled?

For our present purpose we may classify all experience into two classes. One class contains those data, observations and perceptions which can be explained in terms of known laws of physics, chemistry, biology, economics and the other sciences. As an example, we can explain the occurrence of the eclipses of the sun, the motions of the planets, the operation of an induction coil and so on, indefinitely.

The other class contains the great mass of data or observed phenomena which cannot be explained satisfactorily in terms of known laws and which, therefore, are attributed to chance. Witness, for example, your state of health, the weather, the rise and fall of the stock market, the motion of molecules or electrons and practically all of our everyday experiences.

Naturally we desire to make use of both classes of experience.

By a very slow and laborious method of observation, hypothesis, deduction and experimental verification, we have been attempting throughout the ages to reduce our experiences to known laws. It has been natural for man to seek some law which would explain the future in terms of his past; to seek, as it were, something which would remain constant throughout all time. Obviously, in so far as man by scientific methods has been able to reduce his experiences to natural laws which persist throughout the future, he has been able to attain his object of judging the future in terms of the past. This human effort has been going on throughout the centuries with the result that we live in a scientific age—in an age when not only individuals and corporations but even nations plan their future in accordance with established laws of science.

Not everything in our experience, however, has been brought successfully under known laws; in fact as already noted, most of our experiences cannot be made use of in accord with established law. How then can we make use of such data which constitute the major portion of our experience? The real advance in the solution of this problem has come within the past 271 years, since the time when the chevalier de Mèré, the gambler, proposed to that famous mathematician, Pascal, the first problem in the theory of probability, which arose out of a game of chance being played by de Mèré. Within this period we have turned from the old unprofitable conception of chance to a new and profitable conception of [illegible]

In Fig. 1 I have tried to [illegible] central idea underlying the progress that has been made within the past two centuries dealing with [illegible] great body of our experience attributed to chance. Throughout the history of the ages we find again and again the recurring idea that chance results are those which do not happen according to any law. The history of the change in man's ideas of chance is largely associated with the history of his superstitions and his religion. If a thing happened at the hands of chance, it might be considered as the oracle of the gods or as a run of luck, either good or bad. Hence it was that probably no two individuals would interpret the bearing of the past experience upon the future in exactly the same way. How could they, for it was their belief that there was no particular universal law or laws behind such experience. The experiences of the future

were in the hands of the gods and were not necessarily foreshadowed by the experiences of the past.

This condition is represented by the left half of Fig. 1. The only useful experience under this view is that small portion reducible to law represented by the white area. Obviously it would be impossible to use the large fraction of experience represented by the dark area, upon the hypothesis that such experience foretells nothing about the future.

Within recent years, however, we have been coming more and more to the view that chance results represent the effects of a complex system of causes or natural laws.[1] We are coming more and more to the viewpoint of LaPlace that, if we knew at any instant all of the natural laws, we could foretell with precision all future events. We are coming more and more to the viewpoint of that great Danish actuary, Thiele, that everything that happens is the necessary consequence of a previous state of things. We are coming to see chance results, therefore, as the outward expression of numerous unknown laws of nature operating in such a manner that their resultant effects vary within limits which do not change with time.

It is useful therefore to view the resultant effects of this complex system of causes as happening in accord with a *law of chance*, which, when discovered through a study of chance data makes it possible for us to forecast future events *within certain limits;* whereas natural laws enable us to forecast future events with certainty. This change in viewpoint marks the beginning of the development of comprehensive methods for using chance data.

THEORY OF BEST AVAILABLE METHODS

I wish, now, to outline the high points in the theory underlying the best available methods for making use of chance data or experience. A list of references to the original memoirs of the past 271 years which have contributed to these methods would run over a thou- [illegible] among the list of authors we should find the [illegible] of four of our greatest physicists, Jeans, Gibbs, [illegible] Lord Kelvin; four of our greatest mathematicians, LaPlace, Poisson, [illegible] and Gauss; four of our greatest statisticians, Pearson, R. A. Fisher, Edgeworth and Yule; two of our greatest actuaries, [illegible] Gram and two of our greatest astronomers, [illegible] and Kapteyn. This list could be extended by citing leading representatives from the field of medicine, biology, agriculture, geology, psychology, education, sanitation, engineering and so on.

Naturally, therefore, all that I can hope to do is to bring a survey of the results of countless investigators living within the past 271 years who have undertaken to find the best way of judging the future in terms of chance data or chance experience by making use of *laws of chance*. With the aid of some of the most modern mathematical tools it is possible to lay a comparatively solid foundation for the method of attack which has been devolved.

[1] Incidentally, of course, we have come to believe that our so-called natural laws of physics, chemistry and the other experimental sciences are but approximations to the true laws of nature.

INSURANCE BUSINESS BUILT ON LAWS OF CHANCE

Although we cannot at this time enter upon the discussion of mathematical foundations underlying the method for using chance data in helping to judge the future, it may be well to recall some of the instances

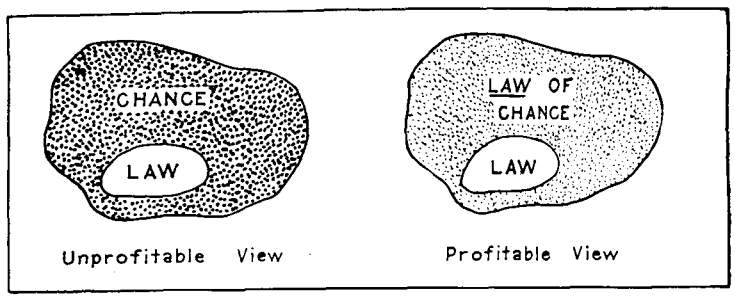

FIG. 1 WHY DO THINGS HAPPEN?

where the method has served a very useful purpose. Possibly one such illustration is sufficient. Perhaps the greatest monument to the practical utility of established laws of chance is the insurance business. Without much question the insurance business is one of the soundest in the world. For this business to grow from practically nothing in the short course of not much over two centuries, to a business which today is among the greatest is indeed a tribute to the economic

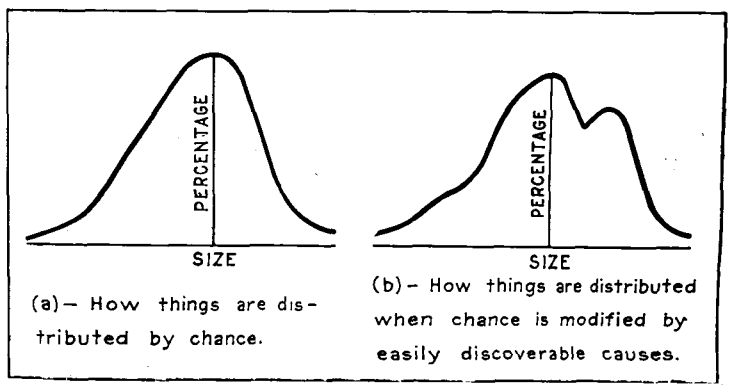

FIG. 2 SCHEMATIC REPRESENTATION OF METHOD FOR DETERMINING CAUSES OF VARIATIONS

usefulness of laws of chance in forecasting the future in terms of past experience.

The widespread growth of statistical departments in many of the leading corporations of the United States and other countries bears testimony to the accepted usefulness of some of the very elementary principles of the generalized method to be presented forthwith. Already a very widespread movement has started in Germany among the manufacturing organizations such as the Krupp's Works in which statistical methods are being used.

HOW THE NEED FOR A LAW OF CHANCE ARISES

All interested in engineering inspection realize that it is practically impossible to make two things which

are identical. All realize, when a manufacturing process is established to produce a product meeting certain specifications, that one unit of product will differ from another. We attribute this condition to the existence of uncontrolled factors such as possibly temperature, humidity, the physiological and psychological conditions of the personnel, wear and tear on the machinery and numerous other similar factors. Obviously it would not be practical to exert absolute control over all of these factors. In other words a better control of product would mean a better control of a large number of factors, and hence it would probably not be economical.

If, however, there are one or more major causes of variation in the product, it is reasonable to expect that appreciable improvement in quality of production may be effected by modifying these factors. But how is the manufacturer to know when the variations in product from one month to another are those which may be attributed to chance, that is, attributed to a complex system of causes which it would be exceedingly difficult to control, and when is he to know that the variations in the product are such as indicate that

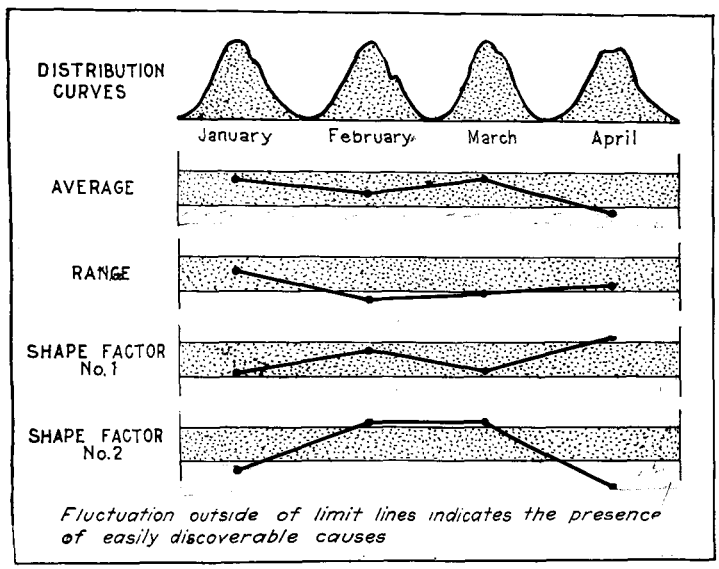

FIG. 3 SCHEMATIC FORM OF CONTROL CHART FOR VARIATIONS

there are one or more predominating causes of variation which it should be within his power to discover easily? In other words, how can the manufacturer use his past experience in respect to a given product in the best way to indicate the action that he should take in trying to modify this product?

HOW THE LAW OF CHANCE REVEALS ITSELF

Statistics comes to his aid and says, if the given kind of product is distributed as indicated in Fig. 2 (left) it is likely the differences between the units of product result from a complex system of causes whose effects would be difficult to separate. If, however, the product is distributed in the manner indicated by Fig. 2 (right), statistics says there are certain easily detectable primary causes of differences between the units of the product. These figures must, of course, be interpreted as a schematic representation of the fundamental idea underlying the method of detecting the existence of other than chance causes.

In other words events happening according to a law of chance, in the long run, distribute themselves in respect to size according to an approximately smooth distribution which persists unchanged throughout all time, whereas events happening according to a law of chance superposed upon a few primary causes distribute themselves in respect to size according to an irregular distribution which probably changes with time.

Perhaps we should call attention to the phrase "in the long run" used in the previous sentence. Its significance will be quite apparent upon second thought. We know from experience that the more observations we have the more likely we are to find that the observed distribution will apparently approach a smooth curve: in the long run, or when a very large number of observations are available, the distribution curve will be approximately smooth.

NUMBER OF OBSERVATIONS

But, you say, "We can't afford to take an infinite number of observations in order to discover if the observed distribution of data fit a smooth curve as shown in Fig. 2a." No, possibly we can't afford to take more observations than we do now, but possibly we take too many now, at least more than we need in some instances, if we use the latest methods for analyzing data referred to in the next paragraph. How then are we to discover whether or not an observed set of data are consistent with a law of chance? If they are, what is this law? I bring up these questions because they are customary stumbling blocks. Space does not permit the presentation of technical answers.

A survey of the really remarkable achievements made within the past three decades in [illegible] answers to these questions could not but prove interesting, but the following remark must suffice: The labors of a comparatively few great minds within recent years have provided us with methods for finding with a fair degree of certainty the law of chance behind a given set of data when that law exists. Probably I should not pass this point without the warning, however, that we cannot rely upon the eye to tell us that an observed distribution is smooth and of such a nature as to justify our assumption that the data are the sole results of a law of chance. Neither would the statistical methods of even the previous generation suffice in answering the questions propounded at the beginning of the preceding paragraph. Let me quote in this connection from a book by R. A. Fisher of the Rothamsted Experiment Station, England, who has made significant contributions to the answers to these questions. "Little experience is sufficient to show that the traditional machinery of statistical processes is wholly unsuited to the needs of practical

research.[2] Not only does it take a cannon to shoot a sparrow, but it misses the sparrow! The elaborate machinery built on the theory of infinitely large samples is not accurate enough for simple laboratory[2] data. Only by tackling small-sample problems[3] on their merits does it seem possible to apply accurate tests to practical data."

INTERPRETING THE FUTURE IN TERMS OF A LAW OF CHANCE

Let us next see how a law of chance can be used in forecasting future events: let us see how we can judge the future in terms of the past with the aid of a law of chance. As previously noted, a law of nature foretells how a thing will happen, a law of chance foretells within what range a thing will happen, or specifically a law of chance gives the probability that a thing will happen in a certain way. To enlarge upon this point:

Suppose a complex system of causes operates to produce things which differ in size according to a law of chance. Suppose that the things produced in a given period are examined for size and the observed distribution of sizes is plotted. Suppose that this is done for several consecutive periods and the results are compared. Naturally, the observed distributions will probably differ in one or more or even all of the following characteristics: average or central tendency, range or dispersion, and shape. So long as all of the sizes are controlled by the same law of chance, however, it is practically certain that, from one period to another, the differences in either average, range or shape will fall within certain easily determinable limits.

TELEPHONE TRANSMITTERS AS AN ILLUSTRATION

As an illustration, suppose we consider the production of telephone transmitters. Even when all precautions are taken, there is some variation in the efficiencies of various individual transmitters. We attribute this to many factors: we know, for example, that the efficiency depends upon the vibratory characteristics of the diaphragm; upon the properties of [illegible] assembly and similar factors. Here, we have a host of factors or causes which modify the efficiency. In turn each of these factors depends upon others in a manner not easily measurable and not thoroughly understood. So long as the effects of the interaction of this complex system of causes follow a law of chance we can expect the differences in either average, range or shape of observed distributions of efficiencies of transmitters from one period to another to fall within certain easily determinable limits.[4]

But what if one average, range or shape vary outside these established limits? The fact that one of these characteristics goes outside the limits indicates that the system of causes has probably changed; in other words that, superposed upon the random or chance system of causes, there are probably one or more major causes which can be discovered with comparable ease and possibly controlled. These limit lines are the engineer's fever thermometer. With their help he can tell when the product needs attention.

I have presented a schematic form of control chart in Fig. 3, illustrating the ideas just considered.

To summarize: The problem is, to find the best way to judge the future in terms of the past; the solution is, when possible, reduce the data to natural laws, when not possible, reduce the data to laws of chance. To make use of the greatest portion of our experience we must use the second method which is really not much older than we are, hence practically unknown. In closing, let us look at the industrial development based upon applied scientific laws, making use of only a small fraction of past experience, and then think of the industrial development of the future based upon applied laws and applied laws of chance thus making best use of all of our data.

[2] Or inspection, let me add.

[3] A paper on this subject by the present author will probably appear in the Bell Technical Journal for April, 1926.

[4] For an amplification of this concept of causation as a constant system of causes see my article in the Journal of the American Statistical Society, December, 1925.

Speculators or Machine Builders

THE letterheads of a certain machine shop proudly boast that it was established in 1848, and the general appearance inside and out bears out the claim. The original owner made money, sold out and died well off. His successor, who came up from the shop, had years of lean times, then made money, sold out and likewise died with a fortune. Some half a dozen men have taken substantial sums out of this old shop, and yet there is no modern equipment.

The word efficiency is never uttered inside the shop. Workmen come and go and do about as they please; someone orders castings from time to time, but usually the foundry makes what it seems likely the shop will use. The firm's credit is always good; overhead expenses are light. There may have been drawings once, but now they go by a book in the foreman's pocket.

The cycle of events is about like this: Mr. Blank made his pile and then sold the shop to the foreman. Mr. Foreman tells everyone business is dull and lays off most of the help. Gradually he hires them back at much lower wages. After a while he has the shop full, which means half the necessary men.

These men make machines, engine lathes, perhaps, in dozen lots and fill up the spare space in the shop. When the shop is full the old barn out back is used for a storehouse. When that is full there is a war, or export trade booms, or automobiles come into fashion, and storehouse and shop are emptied in no time at top prices. The present owner, Mr. Foreman, sells out to his foreman, and so on, all over again.

The question is, are these people machine tool builders or speculators in machinery? If they are speculators, why do not we all speculate?