PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Statistical Methodology: Prerequisites for Effective Implementation in Industry [and Discussion]

J. B. Whitney, J. C. Young and N. Logothetis

Phil. Trans. R. Soc. Lond. A 1989 **327**, 591-598
doi: 10.1098/rsta.1989.0014

Phil. Trans. R. Soc. Lond. A **327**, 591–598 (1989)
Printed in Great Britain

Statistical methodology: prerequisites for effective implementation in industry

By J. B. Whitney and J. C. Young

Department of Statistics and Actuarial Science and the Institute for Improvement in Quality and Productivity, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1

Our consulting and teaching experiences in industry have led us to conclude that if statistical methodology is to be effectively implemented in industry, the following prerequisites must be satisfied:

(i) statistical studies of processes must be perceived as carefully planned systematic investigations;

(ii) statistical techniques presented to industry must address their unique problems in a manner that is understandable to them;

(iii) training must be done by professional statisticians with extensive industrial experience.

This paper discusses our interpretations of these prerequisites and how we are assisting companies in meeting them through our work at the Institute for Improvement in Quality and Productivity at the University of Waterloo.

Introduction

Because of their potential for improving quality and thus productivity, there is greater interest in the use of statistical methods in industry than ever before. Unfortunately, professional statisticians are playing a relatively small role in the training and application of these methods. The non-professionals who are filling this gap often approach the subject in a very mechanical manner without paying adequate attention to the care required in data collection; as a result statistical methods are often naïvely or incorrectly applied. Unless professional statisticians pay greater attention to the special problems of industry, there will be few success stories and industry will quickly become disenchanted.

Industrial applications are complex and often expensive. Randomization is not always possible; one cannot always wait for statistical significance, and usually some assumptions must be made regarding the estimates of interactions. We must make informed compromises. The choices of the factors to be included in an experiment, and what levels to choose, are very difficult. Even more difficult is the problem of convincing management that statistical problem-solving tools are efficient and effective. Management has seen a lot of fads come and go and they are justifiably sceptical of what to them may be just another fad. Many expect a 'quick fix' both with respect to courses (they expect to learn statistical process control or experimental design in three days), and experiments (often answers are expected after a one-day study).

To avoid disenchantment and to have statistical methodology effectively implemented in industry, the following prerequisites must be met.

(i) Studies of processes must be perceived as being carefully planned, systematic, sequential scientific investigations that take random variation into account, and that recognize the need for factorial rather than one-at-a-time experimentation.

(ii) The statistical techniques used by industry must address their unique problems in a manner that is understandable to them.

(iii) Applied case studies relating the successful application of statistical methodology must be promptly communicated so that a body of statistical knowledge applicable to industry becomes available.

(iv) Training must be done by professional statisticians with extensive industrial experience.

This paper discusses our interpretation of these prerequisites and how we as statisticians can assist industry in meeting them.

Education

The problems to which statistical methodology is being applied in industry are often complex. The perception that statistical techniques will provide a 'quick fix' to these problems is one which will quickly discredit their usefulness. It is important that company personnel, especially upper and middle management, be convinced that statistical investigations require a strong commitment of time and resources. Education, through seminars and short courses, appears to be one of the most important methods of convincing industry to adopt this point of view. For these seminars to be effective it is important that

(i) the discussion of statistical techniques and the need for planning be done in the context of industry's problems with examples and case studies based on experience;

(ii) the seminar instructors have a thorough knowledge of statistics and industrial experience in its application;

(iii) when the purpose of the course is to develop some technical skills, the course enrolment should be limited to give ample time for course participants to work on case studies and to discuss problems with instructors;

(iv) the seminars stress that statistical investigations complement, enhance and depend on engineering know-how and ingenuity and are not a substitute for it.

At the Institute for Improvement in Quality and Productivity we are using one- to three-day management overview seminars on statistical process control and experimental design to reach upper and middle management. These seminars not only discuss the scope of the techniques available, but also heavily stress the dependence of successful implementation on

careful problem definition;
an intimate knowledge of the process being studied;
a knowledge of the crucial role of sample selection in any statistical analysis;
careful factor and level selection in an experimental design;
the team approach to problem solving;
a commitment of time and resources;
continuing management leadership and personal involvement as well as 'commitment'.

Even in the more technical courses, which are directed towards those who will be implementing the statistical techniques, there must be a heavy emphasis on planning in addition to the more detailed explanation of the relevant statistical techniques. However, in these more technical seminars we should observe the dictum of Tukey (1954) 'While techniques are important... knowing when to use them and why to use them is more important.'

This is particularly true when we consider that some of the techniques discussed, such as

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

experimental design, are very sophisticated and require not only a high level of statistical expertise, but also very careful management throughout. Often the solution to a serious problem is a simple data analysis, such as plotting a histogram for each of the separate streams of a process. We must avoid the temptation to train people who will go around looking for a place to apply specific techniques; rather we must train (and act as) general problem solvers.

In the two technical courses that we offer at the Institute (a 15-day statistical process control course and a 10-day design course) and the 3-day overview course, about half of the time is spent on tutorial sessions. These tutorials give hands-on experience with the techniques discussed and provide an understanding of how and why they work. In addition the tutorials are important in providing an opportunity for interaction between student and instructor. In these tutorial sessions, participants are also encouraged to discuss with the instructor the use of the course material in the context of the problems they have in their own plants, and, if appropriate, to give presentations to the group.

Another key to successful training is to provide it 'just in time', i.e. for immediate application. That is, the company sending participants to courses should be prepared to commit the time and resources to allow the participants to implement a good proportion of the material studied immediately on their return to the plant. There is no point in training people unless they plan to use the material immediately. To this end we encourage participants to bring problems to the course for discussion. For in-house 10-day design courses, we insist that every participant be involved in a project to which statistical design techniques can be applied. These projects are screened beforehand, and on-site follow-up consulting sessions are held with the participants to help and encourage their work on the project. These follow-up sessions tend to be very beneficial in that they

sustain the momentum of the project;
give an opportunity to reinforce points made in class in a production setting;
improve the statistician's image within industry.

The educational approaches discussed above will have an impact in the short term. However, for the long term, universities need to provide undergraduate engineers, some scientists and statisticians with in-depth training in the statistical techniques that are useful to industry. They should all be made aware that a statistical study takes time and careful planning. If we do not provide this undergraduate training, statistical process control and design of experiments will, as a result of improper use through poor training, become a passing fad in the industrial community.

Which concepts and techniques?

If statistical methodology is to be effectively implemented in industry, then we as statisticians must present statistical concepts and techniques which directly address the real problems. Below we discuss a few of the concepts and techniques that we have found to be important in this regard and which do not seem to be understood by many in industry.

The sources of variation that affect the quality characteristic under consideration dictate the method of data collection, the amount of data to be collected, the method(s) of analysis, and the interpretation that can be made. This principle is not well understood, even though it is basic to the implementation of statistical methods. Control charts, for instance, are a relatively

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

simple tool to use, but often the concepts of natural variability, statistical stability and the role of sample selection are not understood. As a result, control charts are often ineffective and thus doomed to be little more than wallpaper, viewed as an additional piece of bureaucracy. In experimental design, the use of blocking to control variation in unstable processes and the use of randomization to reduce the influence of possible systematic variation are not well understood, and in fact discouraged in many applications. Blocking and randomization are not always feasible in an industrial context; the costs are often prohibitive. We must, however, make clear that without blocking and randomization, many investigations may be misleading and/or uninformative; the result will be a mistrust of statistical methodology. The presentation of case studies that reflect failure due to lack of blocking or randomization often helps to make the point.

Statistically designed factorial and fractional factorial experiments provide the most efficient methodology for studying complex relations in modern manufacturing processes. The unique problem of trying to optimize process output and minimize process variability, in the presence of a very large number of potentially important factors, should cause us to rethink our approach to experimental design in such instances. Should we not, in such instances, be recommending a sequence of experiments? The first experiment should usually be a highly saturated design for the purpose of screening the factors that influence the process output. We denounce the one-at-a-time approach to experimentation for various reasons, one of which is that we have no way of judging the consistency of our findings on one factor over different levels of other factors 'held constant' (or ignored) during the experiment. Are the findings of an experiment on only three or four factors when there are twelve contenders much more reliable? Is it not better to try and screen as many factors as are of interest by including them all in a highly saturated design? Follow-up experiments can be done if necessary to sort out interactions. In many studies in which we have assisted, we found that if an interaction exists between two factors, it is most frequently 'synergistic' in that it does not alter conclusions regarding optimum conditions from those that would have been based on a main-effects design (see figure 1). Interactions which lead to different optimal factor levels than the main effects

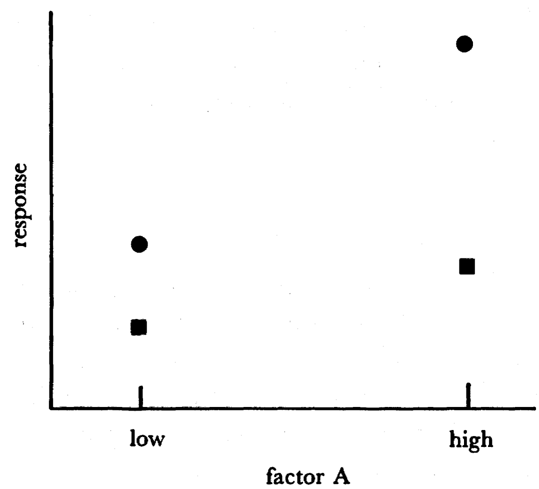

FIGURE 1. 'Synergistic' interaction plot of factors A and B. The symbol ● denotes the high level of factor B and ■ denotes its low level.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

are much less frequent. This may be why highly saturated designs have been so successful in screening the factors of a process.

When our main interest is centered on screening out the major factors and interactions, any reference made to t-tests, F-tests and confidence intervals only clouds the issue; economic considerations play a much more important role. The importance of normality, equality of variance and other model assumptions fade when compared to factor and level selection and data collection methods. A number of us involved with teaching and consulting at the Institute have found that Joiner's (1988) comment, 'We must learn to scrap a huge portion of what we worked so hard at to get those degrees in statistics', is much closer to the truth than we ever anticipated. It is, however, imperative that when we give overview seminars and more technical courses on experimental design we do our utmost to explain the efficiency of balanced fractional designs, interactions, confounding, blocking and randomization. If users understand these concepts and their importance, then they can judge the seriousness of ignoring or assuming them away in their particular applications.

In particular, we should point out the advantages of blocking. It is not well understood by industry that blocking can be used to protect an experiment against instability. In fact, it is often the view that processes need to be stable before an experiment can be carried out. Further, it is often not realized that the use of blocks that are representative of a wide range of production conditions will lead to more reliable conclusions. Blocking also provides a safety factor in that disaster during an experiment will usually only require restarting the current block of runs rather than the whole experiment. Finally, any study of a manufacturing process should be done under production conditions; blocking in runs of four often allows enough flexibility to do this without too much disruption.

Every effort should be made to keep the statistical procedures and analysis as simple as the problem will allow. Again this requires initial planning. Often considerable savings result from the use of Pareto diagrams or histograms plotted separately by process streams. We must encourage the investigator to think about what simple 'low tech' investigations would be fruitful before embarking on a complex 'high tech' statistical investigation such as an experimental design. In one instance, a fractional design of 11 factors seemed to indicate that none were significant. This led the investigator to compare the three streams in the process by using histograms; the streams were found to be dramatically different. A simple change resulted in direct cost savings of $250000 per year. Had this simple investigation been done first, the problem would have been solved much quicker by using only a fraction of the resources.

Documentation

Nothing inspires a company more than a well-documented, successful case study, especially when there is a significant pay-back and the area of application is very similar to the company's own processes. Such documented case studies are needed to keep up the momentum of statistical activity in industry. However, to create a pool of knowledge for the company to draw on, a detailed documentation of each study must be done, whether or not the study is viewed as being successful in improving the process or saving resources; we often learn more from mistakes than from successes.

A good deal of the documentation should be done before and during the study. Indeed to implement a systematic statistical study effectively, several crucial steps must be organized and followed before the study is done. These crucial steps and documentation for organizing the implementation of a factorial experiment are outlined below.

Project implementation steps

Define problem, set objective.
Establish project team.
Choose response quality characteristics.

Deliverable: written statement of objectives

Brainstorm potential factors.

Deliverable: cause-and-effect diagram

Ensure good measurement systems are in place.
Choose factor levels.
Develop experimental design.
Develop plan and schedule of experiment.

Deliverable: detailed written experimental plan

Perform representative trial runs.

Careful attention to these details will maximize the probability of success; ignoring one or more steps will do the reverse.

As well as providing a pool of knowledge within a company, information about the application of statistical methods to industrial problems should be published. Symposia, such as those conducted by the American Supplier Institute or General Motors of Canada Limited, are excellent for the presentation and discussion of case studies. However, it is usually the successful studies that are presented at such symposia. The valuable information that could be provided from some selected, less successful studies rarely appears.

Technical journals also provide an opportunity to present informative case studies. An excellent statistical process control case study discussing the moulding of a bumper is given in a paper by Werner & Berenter (1986). More publications of such studies would certainly aid in effective implementation of statistical process control through the information they provide directly to industrial personnel and through their use as teaching aids.

Summary

In this paper, we have discussed what we believe to be the main prerequisites for the effective implementation of statistical methodology. The most important prerequisite is painstaking up-front planning and the allowance of sufficient time and resources for careful implementation; in many instances, it appears that industry is too busy putting out fires to take this longer-term view. If we can convince industry to take the time to plan their studies on a sound statistical basis, we shall have made a large step towards the effective implementation of statistical methodology in industry, and thus to a dramatic improvement in quality and productivity.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

References

Joiner, B. 1988 *Quality Progress* Jan., 28–33.
Tukey, J. W. 1954 *J. Am. statist. Ass.* **49**, 706–731.
Werner, S. A. & Berenter, J. R. 1986 *Mod. Plast.* Feb., 68–74.

Discussion

N. Logothetis (*Technical Directorate, GEC Hirst Research Centre, Middlesex, U.K.*). Dr Whitney has made a strong point about 'blocking' in statistical experiments, with which I fully agree. However, blocking alone is not enough to deal with uncontrollable factors, which should always be considered together with the controllable factors in any 'brainstorming' stage between statisticians and engineers. Dr Whitney has only put emphasis on identifying and studying the controllable factors initially (to save experimental costs) and perhaps assess the uncontrollable factors during follow-up experiments. However, this approach can actually cost more in the long run! There are now techniques which allow the study of both types of factors in *one* experiment to find optimal settings of the controllable factors which will make the process robust against the effects of uncontrollable factors. Variation is the cause of bad quality and uncontrollable factors are the cause of variation. As statisticians we should emphasize these points to the engineers, and our techniques should concentrate on removing the effect of these uncontrollable factors.

Remove the effect, not the cause. Studying only controllable factors is not enough. Simulating the effects of the uncontrollable factors in an experiment requires additional effort, but this is always compensated for by future cost savings through robustness in the process and higher quality products.

J. B. Whitney. We agree with Dr Logothetis that controllable and uncontrollable factors should always be considered together in any brainstorming session between statisticians and engineers; one of the main objectives of an experimental design is to reduce variation in the quality characteristic under study. When we are involved in planning an experimental design, we encourage both the use of blocking and the incorporation of noise factors in some way. We interpret the reference to 'simulating the effects of the uncontrollable factors for the purpose of experimentation' to mean the systematic controlling of some noise factors during the runs of the experiment. This is an excellent idea if it can be accomplished.

In our paper the discussion on experimental design dealt mostly with the screening of factors. In these applications we feel that blocking takes precedence over simulating the effects of the uncontrollable factors for the following reasons.

1. Blocking can be used to remove systematic variation from day-to-day, shift-to-shift, batch-to-batch, etc., and thereby increase the precision of the experiment. Also with blocking, the experiment can be run under a wide range of operating conditions; the conclusions derived from such experiments are more reliable.

2. Blocking in runs of four or eight increases the possibility of doing the experiment under production conditions. This is highly desirable because recommendations based on the experimental results will be implemented under these conditions.

3. Some assessment of which factors and their settings make the process more robust against uncontrollable factors can be obtained by taking several observations for each treatment

combination in the proposed design. This assumes that several noise factors are varying across the testing period.

For all of the experimental design studies in which we have been involved, simulating the effects of uncontrollable factors (in our interpretation) would have been a time consuming and complicated effort, not a small additional effort. A fractional factorial design with blocking is already a very complex design to implement; much care and organization is needed for a flawless implementation. To include the simulation of the effects of uncontrolled factors in the design adds another level of complexity. The trade-off of adding this additional complexity must be carefully considered in terms of

(*a*) the purpose and objectives of the experiment;

(*b*) the experience of the implementation team in doing experimental designs;

(*c*) the wisdom of trying to meet all the objectives in one large experiment rather than in a sequence of experiments;

(*d*) time constraints on the team members.

Finally, if some noise factors can be controlled for the purposes of the experiment it might be worthwhile considering them as controllable factors and study their interaction with factors than can be controlled under production conditions.

[*Questioner not identified*]. We are considering the use of exponentially weighted moving average charts as an alternative to CUSUMS in various applications. Does Dr Whitney know of any recent study of their run-length properties?

J. B. WHITNEY. The only study we know of is that by T. J. Harris, Department of Chemical Engineering, Queen's University, Kingston, Ontario. Part of the study was presented at a seminar and a paper is in preparation. We suggest that the questioner contacts Professor Harris.

Editor's note. In connection with the last question, the following reference may prove useful: Crowder, V. S. 1987 A simple method for studying run-length distributions of exponentially weighted moving average charts. *Technometrics* **29**, 401–407.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES