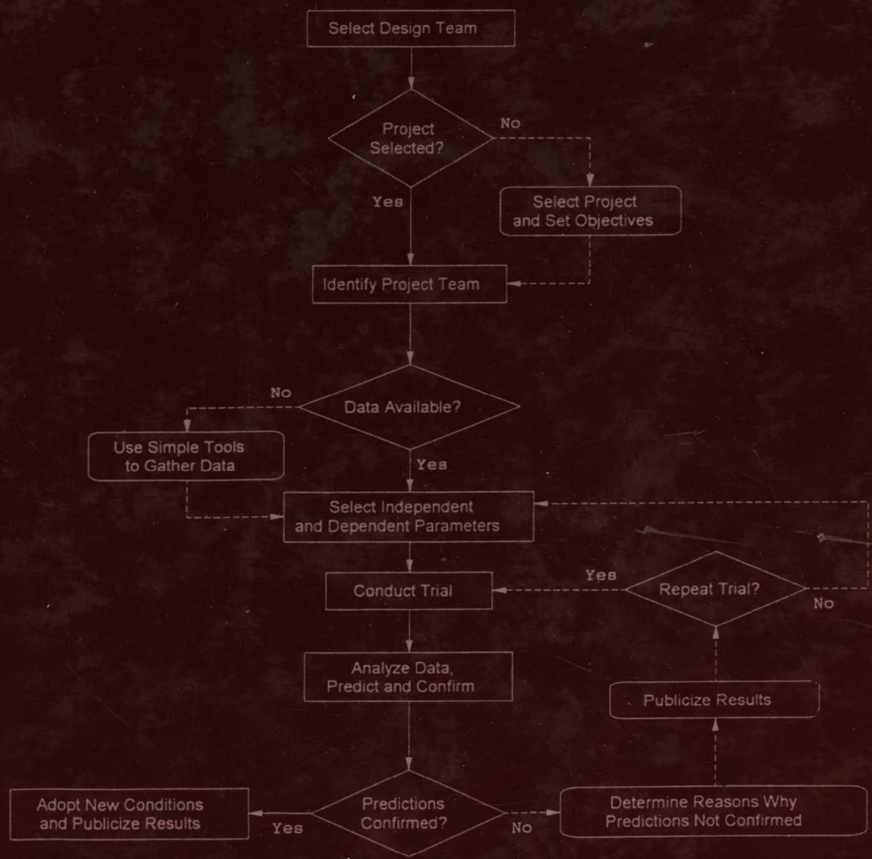
Successful Industrial Experimentation



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Preface

This text has been developed as an introductory guide to process and product improvement through the use of simple quality improvement techniques and experimental design methodology. The fundamentals of a sound experimental approach to problem solving that incorporates valid statistical analysis is stressed. The success of an experiment depends as much on the amount of planning and preparation that is done as it does on the theoretical background behind the statistics and designed experiments. Many experiments can be run and analyzed with a basic understanding of descriptive and inferential statistics, with the most successful being the ones that have had sufficient time devoted to up-front planning.

All techniques presented in this text have been applied in a variety of industrial situations by individuals with varying academic backgrounds. Key instruction sets have been clearly outlined to assist in the problem-solving process and a cookbook approach has been adopted for illustrating the various techniques available. This text is particularly beneficial to those individuals who are interested in performing experiments but have no inclination to become a statistician.

Users of this text are cautioned about the possibility of misapplication of these techniques. If there is any doubt about the design being contemplated for a given experimental setup, consultation with a qualified statistician is recommended. In fact, the text will be an ideal medium for introducing some of the basic terminology required for conversing with a statistician.

This text is divided into four main sections. The first section introduces some philosophy and then focuses the reader's attention on some of the simple quality tools recommended by quality experts to help an experimenter prepare for an experiment. Specific topics covered include (1) data collection, (2) flow diagrams, (3) Pareto analysis, and (4) cause and effect diagrams.

Following the introduction of the simple tools, a description of some of the fundamental statistical concepts such as central measures, variability, probability distributions, and analysis of variance (ANOVA) is provided. The calculation and interpretation of the mean, variance, and standard deviation are presented as part of this second section.

The concept of screening designs is discussed next. Orthogonal arrays will be used almost exclusively in this text for screening designs. Although these designs are being used, many other types of screening designs (e.g., Plackett–Burman, Greco-Latin Squares, and Hadamard) are available to the experimenter. However, to minimize the complexity of the text only orthogonal arrays will be discussed in any detail. Only one data analysis technique, the analysis of variance or ANOVA, will be discussed. Information on other designs and data analysis techniques can be obtained by consulting the reference texts mentioned in Appendix E.

Finally, the reader will be provided with tips on which arrays to use, how to deal with interactions, variable randomization, factor selection, use of noise factors, and how to choose good response variables.

It is expected that readers will obtain sufficient knowledge from this text to incorporate these techniques into their own job function and to be able to conduct and interpret a statistically designed experiment.

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August, 1995

Acknowledgments

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In addition, this text could not have been possible without the understanding of the author's wife and children during the preparation of this manuscript. Their patience during the many days (and nights) of writing is greatly appreciated. Thanks are also due to Ms. P. Kyle, Ms. L. Kane, Mr. S. Haynes, and Mr. A. Zahavich who unselfishly donated their time to proofread the manuscript and to evaluate its readability, grammatical accuracy, and statistical correctness.

Contents

CHAPTER 1

Introduction

"Here is Edward bear coming downstairs now, bump, bump, bump, on the back of his head, behind Christopher Robin. It is as far as he knows the only way of coming downstairs, but sometimes he feels that there is another way, if only he could stop bumping for a moment and think of it. And then he feels that perhaps there isn't. Anyhow here he is at the bottom."

A. A. Milne's, "Winnie the Pooh." Reprinted with permission.

"He uses statistics as a drunken man uses lamp posts—for support rather than illumination."

Andrew Lang, 1884–1912, Scottish author

1.1 Why Conduct Experiments?

Conducting experiments is an everyday occurrence in modern life. An experiment might be conducted to

- Determine the feasibility of a new idea or approach;
- Screen potential candidates for substitution into an existing product;
- Develop an entirely new product;
- Determine how production variables affect product and process quality;
- Optimize a product or process;
- Solve a problem;
- Reduce costs.

Where does one start to tackle some of these tasks? the dynamic and highly competitive nature of today's market demand that problems be solved effectively and efficiently. Generally speaking, financial and human resources are limited within an organization. Therefore, the strategy used to investigate an opportunity must be simple, easy to implement, understandable by all involved, and, of course, cost effective.

The foundations of an experimental program must be well understood and have the full commitment of almost everyone in the organization. This includes shop floor personnel as well as top level managers. If the top level managers are not committed to the program, the support needed by the operators and production engineers to successfully carry out the necessary experimentation will not be there.

Once employees are involved in the developmental process, knowledge of how the process operates and what it takes to get things done will increase. Key elements to this program would be trust and technical know-how. Attention will be focused on a particular opportunity rather than on individual bias. Decisions will begin to be made using data. Using data to gain commitment from co-workers for a particular point of view is always more productive. Being meticulous in the planning of each experiment will increase the probability of successfully completing a project. It is important to become familiar with all the techniques described in this text.

Consider the process of cooking a meal and the many alternative ways to do so. Familiarity with the recipe, availability of particular ingredients, cooking method, and even the type of pot used will all influence the final outcome. What if there was a taste difference each time the meal was prepared? What contributed to the inconsistency of the taste? Could it be the addition or substitution of an ingredient, too much or too little of one ingredient, or was the food overcooked. Could it possibly be something else that is not under the cook's control.

To determine what caused the change in taste, a series of trials, either statistically or randomly organized, could be conducted. Most commonly a random approach would be taken to this problem by initially changing one process factor at a time while all others factors are kept constant. This process would be repeated until the inconsistency in the taste was overcome to the satisfaction of the cook. The *change-one-factor-at-a-time* approach is shown graphically in Figure 1.1.

As an alternative, a statistically oriented technique could be used to find the cause of taste differences. This statistical approach is commonly referred to as designed experimentation, statistical experimental design, design of experiments, DoX, or DoE. This technique was developed in the 1920s by the renowned British statistician Sir R. A. Fisher. His motive was to improve the efficiency of the experiments he was conducting and to have a more precise method for interpreting his experimental data. A good guesser may beat a statistically designed approach occasionally, but in the long run the statistical approach will be better.

A classic example[1] of what designed experimentation can accomplish is illustrated in a 1953 experiment conducted by Ina Seito (now called INAX Corp.), a large

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[1] Taguchi, G., Wu, Y. "Introduction to Off-line Quality Control." Central Japan Quality Control Association, Meieki Nakamura-Ku Magaya, Japan, 1979.

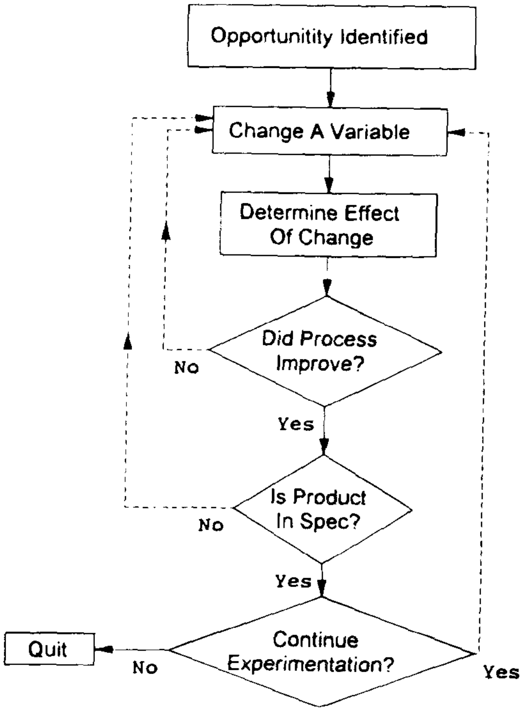

Figure 1.1. "Change-one-factor-at-a-time" problem-solving approach.

Japanese producer of ceramic tiles. The Ina Seito company had just purchased a multimillion dollar ceramic kiln. Although the kiln was new, production personnel found severe dimensional variation throughout each load of tiles coming out of the kiln. Dimensions of the tiles on the outside were found to have greater tile to tile size variation than inner dimensions. Production staff felt this variation in tile dimensions was primarily caused by an uneven temperature distribution in the kiln.

The obvious and traditional approach would have been to modify the kiln design to improve the temperature distribution. However, modification costs were estimated to be in the neighborhood of half a million dollars and an additional expenditure of this magnitude was unthinkable at the time. Since tremendous losses were being borne by the company the problem had to be solved quickly. Instead of succumbing to stereotyped problem-solving practices and modifying the design of the kiln, a nonconventional approach (at that time) was taken by the production staff and a designed experiment was conducted.

Representatives from throughout the company considered to be knowledgeable in the tile process were assembled into a team. They were allowed to brainstorm a list of variables that could potentially be contributing to the tile dimension problem. After compiling this list of variables, the ones considered the most likely to contribute to the variation in tile dimensions were then selected and finally incorporated into a designed experiment.

Appropriate statistical analysis of the experimental data identified both the significant contributors to tile variation and suggested appropriate settings for these variables. After setting up the process according to the results of this one experiment, the number of defective tiles decreased immediately to 1% from the initial 30%. In addition, an increase in the percentage of the cheapest raw material, from 1 to 5%, was found to improve product quality and decrease part-to-part variation.

In the end, superior quality tiles were produced by Ina Seito at a much cheaper price and with decreased tile-to-tile variation, all without having to modify the kiln design. This example illustrates how the application of statistical methods and simple quality tools results in a potent experimental strategy.

1.2 Stages of Experimentation

To achieve similar results to those of Ina Sieto an organization must develop a quality-oriented experimental strategy. The *stages of experimentation,* as discussed below, are one such strategy that can be used as a guideline to developing a system that works within the organizational structure of a company. An introduction to the stages of experimentation follows and they are summarized in the flow diagram illustrated in Figure 1.2.

Stage 1: Selection of a Design Team

Assuming a broad objective or a problem has been defined, the experimental process begins by selection of a design team. This team typically consists of a broad base of people with a variety of backgrounds and experiences from both inside and, if practical, outside the organization. Each organization is set up differently. Therefore, what may be acceptable to one company may not work well in another. The list provided below can be used as a guideline for selecting members for a design team.

Suggested Design Team Members

Production engineering
Management
Production foremen
Customers (where appropriate)
Research and development
Sales and marketing
Process operators (always!)
Industry consultants

A diverse design team should increase the probability of success. Each person affected by a problem or, more appropriately, an opportunity tends to have a different viewpoint of its exact nature and how it should be approached. Their ideas will be based on individual experience and training. Each one will bring one of the pieces

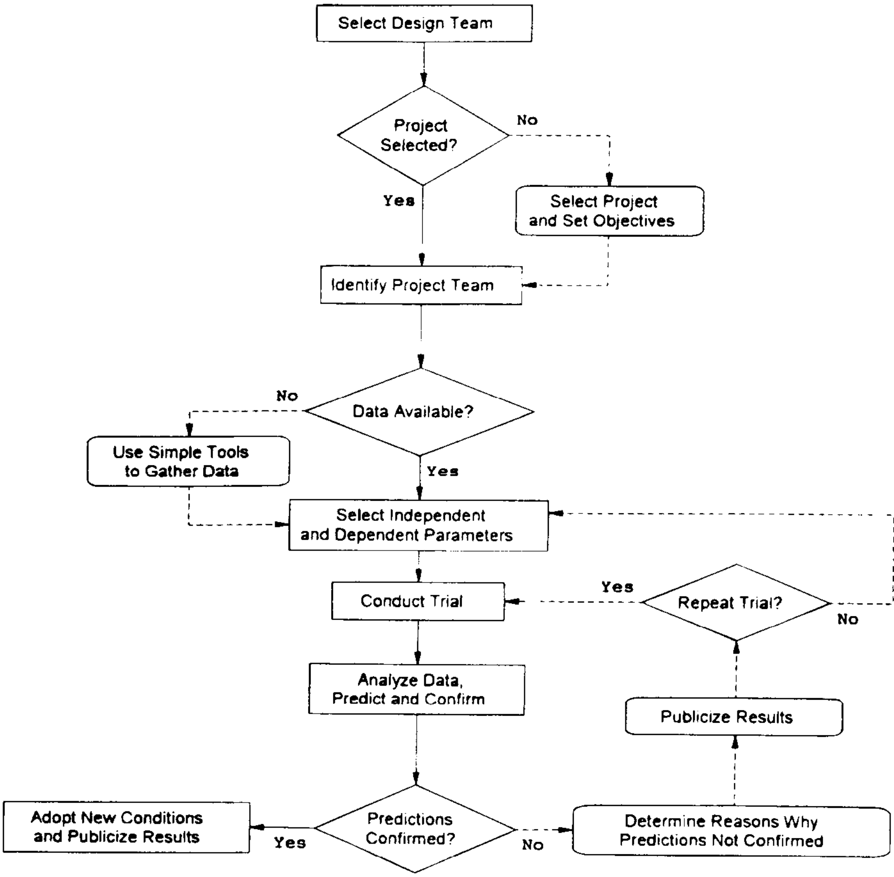

Figure 1.2. Stages of experimentation.

of the puzzle to the table. The synergy that results from getting a diverse group of people involved in a team will usually advance the problem-solving process.

Input should be encouraged from all the various line functions within an organization for another very important reason. Often it is necessary to have the support and the understanding of more than one function to be able to complete a project, in other words, each function affected by the project should buy into the program to maximize the likelihood of success. When one of the functions within an organization does not participate fully it could result in a misunderstanding of the program objectives or important factors being overlooked. This could result in an overall reduction of the effectiveness of the proposed solution.

Opportunity Identification

After deciding who will participate as members, the core design team is assembled and the various objectives of the program are defined. The key to having a successful outcome depends on determining precisely the internal and/or external needs of the customer. If there are insufficient data to determine this information or all members are not equally knowledgeable, background data must be collected and presented to the group. A number of simple tools can be employed to improve the knowledge base of the design team. The most commonly used tools are

Teams (brainstorming)
Control charts
Pareto charts
Experimental design
Data collection
Flow diagrams
Cause and effect diagrams

Each tool helps improve the understanding of how a process or product behaves. Variables important to product quality are effectively identified. For these tools to be effective, input is required from all functions, not just from one or two people. Therefore, a healthy working relationship begins to develop between the various functions in the organization. As each tool is mastered an increased sensitivity to quality will be formed and gains in productivity and quality will likely follow.

Stage 2: Preparation for Experiment

Making initial preparations for the experiment is the next responsibility of the design team. A decision on how to judge the success of the project is also required as well as choosing quality characteristics (i.e., dependent responses) and ways of measuring those parameters selected. The most probable variables that influence the project objectives or quality characteristic(s) are typically chosen from a cause and effect diagram. The team must then select an experimental design (e.g., screening design or 2 level factorial) suitable for the number of variables chosen and assign the variables to the design. Appropriate ranges for each variable must also be chosen and added to the design.

Table of Reasonableness

Next in this process is the construction of a *table of reasonableness*. This table establishes the practicality of the variables and ranges chosen for study and highlights unreasonable combinations of conditions before being carried out in the plant or laboratory. When unreasonable conditions (e.g., safety, cost, poor quality product, and time) are found, the design team must rethink its choices for variable and/or ranges for each variable. Settings are then adjusted accordingly; another table of reasonableness is constructed and the process is repeated. This is a key step in the design strategy and should not be avoided. Before proceeding with the trial the experimental plans should be published internally for review by other employees.

Pretrial Preparation

A pretrial preparation flow diagram, such as illustrated in Figure 1.3, can be used to ensure that all resources required are procured and commitment from all participants, such as material suppliers, analytical services, quality control, and production, are received so the trial will run smoothly.

Stage 3: Conduct Trial

Once the table of reasonableness has been approved and all necessary preparations have been made the experimental trials are conducted. The run order of the experiments is normally randomized to minimize the effect of experimental noise. Those experimental combinations considered to be the most difficult or the most likely to cause problems should be run first. This will verify the table of reasonableness and ensure that it is possible to run all other conditions. If these conditions can be run without great difficulty, the remaining trials in the experiment would be completed. Quality characteristics are then measured using a suitable measurement system.

Stage 4: Data Analysis

Test results are tabulated and analyzed using an appropriate technique and the results are made available to the design team. Using the results from the experiment, an

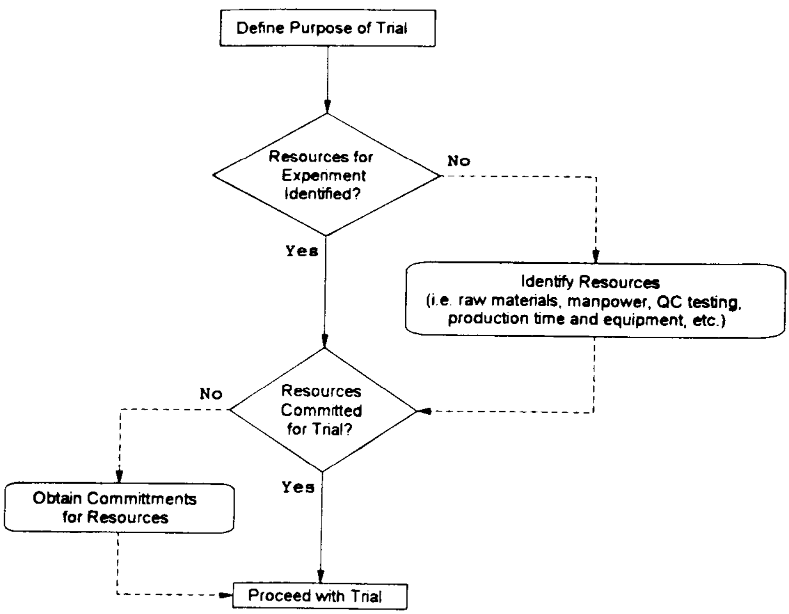

Figure 1.3. Flow diagram for pretrial preparation.