Improving Quality Through Planned Experimentation

Ronald D. Moen
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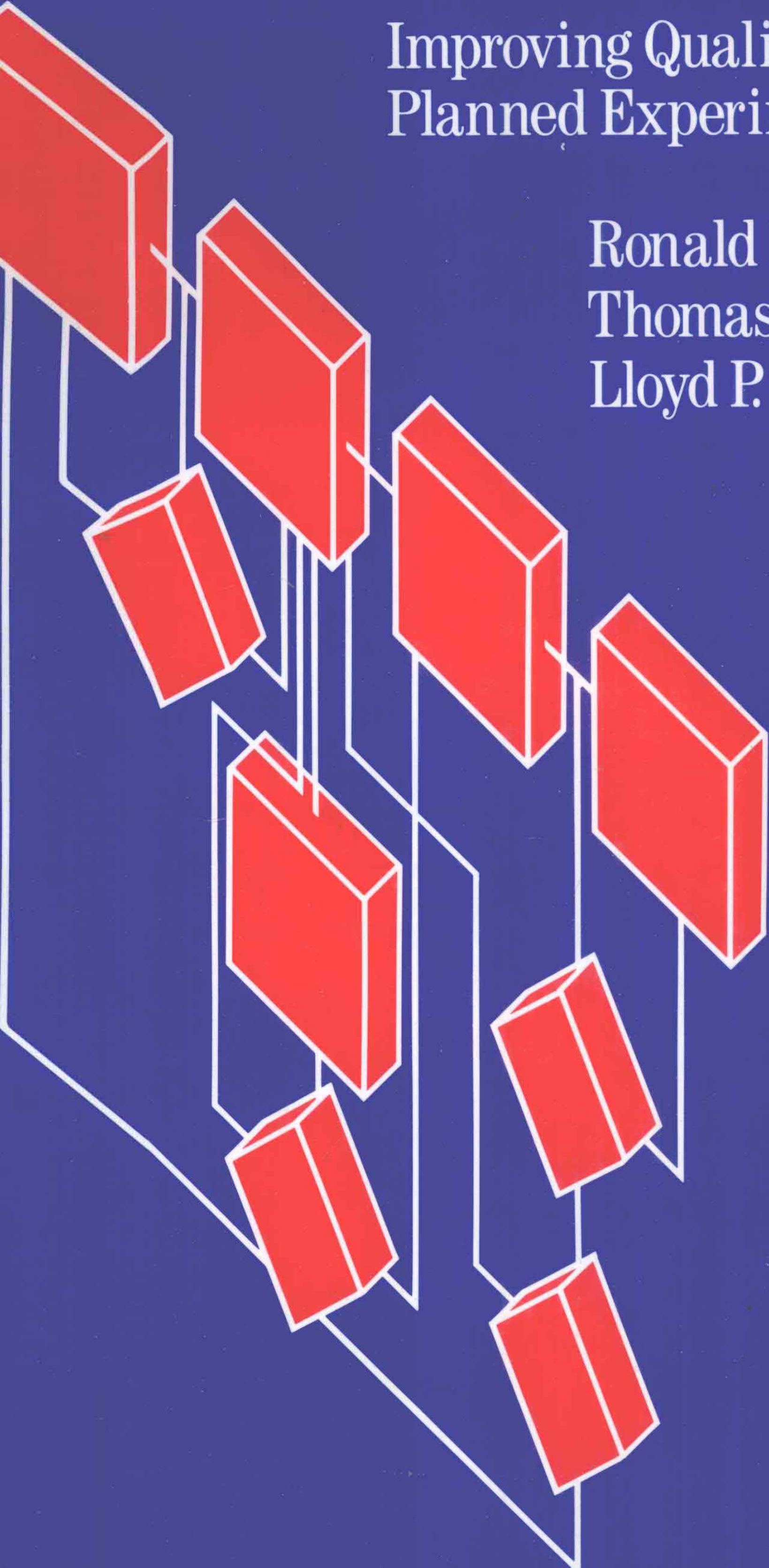

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ABOUT THE AUTHORS

Ronald D. Moen, **Thomas W. Nolan**, and **Lloyd P. Provost** have worked as a team for almost 20 years. They first met in the early 1970s, when they worked at the U.S. Department of Agriculture. It was there that their interest in planned experimentation began. This was their first opportunity to work with scientists and managers to design experiments.

Their understanding of the needs of experimenters expanded in the early 1980s as they worked with managers, scientists, and engineers engaged in improving the quality of their products and services. This work included providing assistance in the planning of experiments for product design, process design, improvements in manufacturing, start-up of new plants, and research.

In 1984 they founded Associates in Process Improvement, a consulting group that assists organizations to make quality a key business strategy.

Ronald Moen has an M.S. in statistics from the University of Missouri. Thomas Nolan has a Ph.D. in statistics from George Washington University. Lloyd Provost has an M.S. in statistics from the University of Florida.

THIS BOOK IS DEDICATED TO THE MANY STUDENTS AND CLIENTS OVER THE LAST SEVERAL YEARS WHO HAD TO ENDURE VARIOUS STAGES IN THE EVOLUTION OF THIS PRODUCT. UNDER CONTINUAL IMPROVEMENT, A BOOK IS NEVER FINISHED. YOUR FEEDBACK GAVE US THE UPDATED CURRENT KNOWLEDGE NECESSARY FOR IMPROVEMENT.

THANK YOU.

FOREWORD

This book by Messrs. Ronald D. Moen, Thomas W. Nolan, and Lloyd P. Provost breaks new ground into the problem of prediction based on data from comparisons of two or more methods or treatments, tests of materials, and experiments.

Why does anyone make a comparison of two methods, two treatments, two processes, two materials? Why does anyone carry out a test or an experiment? The answer is to predict; to predict whether one of the methods or materials tested will in the future, under a specified range of conditions, perform better than the other one.

Prediction is the problem, whether we are talking about applied science, research and development, engineering, or management in industry, education, or government.

The question is, what do the data tell us? How do they help us to predict?

Unfortunately, the statistical methods in textbooks and in the classroom do not tell the student that the problem in use of data is prediction. What the student learns is how to calculate a variety of tests (t-test, F-test, chi-square, goodness of fit, etc.) in order to announce that the difference between the two methods or treatments is either significant or not significant. Unfortunately, such calculations are a mere formality. Significance or the lack of it provides no degree of belief— high, moderate, or low— about prediction of performance in the future, which is the only reason to carry out the comparison, test, or experiment in the first place.

Any symmetric function of a set of numbers almost always throws away a large portion of the information in the data. Thus, interchange of any two numbers in the calculation of the mean of a set of numbers, their variance, or their fourth moment does not change the mean, variance, or fourth moment. A statistical test is a symmetric function of the data.

In contrast, interchange of two points in a plot of points may make a big difference in the message that the data are trying to convey for prediction.

The plot of points conserves the information derived from the comparison or experiment. It is for this reason that the methods taught in this book are a major contribution to statistical methods as an aid to engineers, as well as to anyone in industry, education, or government who is trying to understand the meaning of figures derived from comparisons or experiments. The authors are to be commended for their contributions to statistical methods.

W. Edwards Deming
Washington
14 July 1990

PREFACE

This book is about planned experimentation to improve quality. We believe that statistical methods of planned experimentation are powerful aids to managers, engineers and scientists, and technicians. But these methods have been applied in only a small fraction of the circumstances in which they would have been useful. The aim of this book is to provide a system of planned experimentation in such a way that there will be a substantial increase in the number of people who will use these methods.

Our approach to accomplish this aim contained several components. We continually strove to increase our understanding of the needs of managers, engineers, and others with regard to methods of experimentation. We studied and integrated theory and methods of others with our own ideas and experiences. We were especially influenced by studying the works of W. Edwards Deming, George Box, Stuart Hunter, William Hunter, and Genichi Taguchi. Finally we developed a system of experimentation that met the essential needs of experimenters but required a lower level of mathematical and statistical sophistication than was previously necessary.

We learned a great deal from Deming's papers on analytic studies (studies to improve a product or process in the future), including

- Prediction as the aim of an analytic study
- The importance of conducting analytic studies over a wide range of conditions
- The limitations of commonly used statistical methods such as analysis of variance to address the important sources of uncertainty in analytic studies
- The importance of certain graphical methods

Chapters on factorial and fractional factorial designs in *Statistics for Experimenters* by Box, Hunter, and Hunter (John Wiley and Sons, 1978) provided the foundations for our chapters on these subjects. Especially useful to us was their description of factorial designs at two levels as a link of paired comparisons and their system of fractional factorial designs.

Taguchi's contributions to the application of planned experimentation to the design of product and processes have been integrated throughout the book, but especially in Chapter 10. We are in agreement with Taguchi that most experimenters are in need of a small number of design matrices (called orthogonal arrays by Taguchi) that cover most of their applications with only minor adaptations. Our approach to fractional factorial designs blends that approach with the important concepts of confounding included in the book by Box, Hunter, and Hunter.

The spirit of our approach to analysis of data from experiments owes much to Dr. Tukey's methods of exploratory data analysis. We have blended these ideas with Deming's counsel that confirmation of the results of exploratory analysis comes primarily from prediction rather than from the use of formal statistical methods such as confidence intervals. Satisfactory prediction of the results of future studies conducted over a wide range of conditions is the means to increase the degree of belief that the results provide a basis for action.

In 1984 we were asked by Dr. Deming to write a book on planned experimentation from the viewpoint of analytic studies described in several of his papers and books. As notes on earlier drafts became available, they were used in almost a hundred seminars and were improved based on observation of their usefulness to the participants both during and after the seminars.

There are several aspects of this book that, when combined, make it different from others currently available. The book is written to be compatible with Deming's viewpoint of analytic studies. Also, we have presented planned experimentation as a system in the context of a model for improving quality. This system includes the integration of methods of statistical design of experiments with statistical process control. As part of the system we have emphasized the sequential use of experiments and provided guidance on how to build the sequence.

We have included guidance on many of the practical aspects of planning experiments and have provided a form so that these aspects are addressed during the planning phase. Most of the examples in the book are based on our experiences. We have included examples that contain some of the problems often encountered in actual experimentation in a manufacturing plant or research facility. We offer suggestions on what to do in those situations. Another distinctive attribute of the book is the almost exclusive use of graphical methods for analysis of data from experiments.

Since we are aiming at a relatively broad audience, we have sometimes substituted methods that could be learned and used by this broad audience in place of the more traditional methods. Our feedback from experimenters convinced us of the importance of the use of original engineering units in interpreting data from experiments. We have not included designs that would require development of a mathematical model for analysis. That is why designs for mixtures or formulations and central composite designs are only briefly discussed. These are extremely useful designs, but the model-based approach necessary for their analysis would not have been compatible with approaches used throughout the rest of the book. In the case of central composite designs, we have substituted factorial or fractional factorial designs.

We have not included fairly common statistical methods such as standard errors, confidence intervals, and analysis of variance. We recognize that experimenters need to distinguish between variation that is a result of planned changes in the factors and variation that results from other sources, e.g., measurement. Based on the principles of analytic studies in Chapter 3 and the concept of common and special causes in Chapter 2, we have chosen to use graphical methods to help experimenters ascertain how much the planned changes in the factors are contributing to the variation in the data.

ACKNOWLEDGMENTS

We wish to thank Dr. W. Edwards Deming for his continuing encouragement and his work on the distinction between enumerative and analytic studies. We appreciate the comments and suggestions of our associates, Jerry Langley and Kevin Nolan. Most importantly, we wish to thank the experimenters that we had the opportunity to work with and learn from. We appreciate their patience with us as we used earlier, sometimes very rough, drafts of this book.

Ronald D. Moen
Thomas W. Nolan
Lloyd P. Provost

CONTENTS

CHAPTER 1

IMPROVEMENT OF QUALITY

1.1 INTRODUCTION

Global competitive pressures are causing organizations to find ways to better meet the needs of their customers, to reduce costs, and to increase productivity. Improvement of quality has developed as a focal point in meeting these objectives. Continuous improvement of quality has become a necessary and integral part of the business strategy of organizations.

Improvement of quality is predicated on change. Imai (1986) describes two kinds of change: gradual and abrupt. Gradual change results from small improvements to the status quo through continuous efforts that involve everyone. Abrupt change comes from innovation—a drastic improvement in the status quo.

The requirements for improvement of quality are a common purpose and knowledge of concepts and methods so that change results in improvement. The overriding goal is continuous improvement in every activity. Getting better and better is more important than whether the current results are good or bad.

Purpose of This Book

The purpose of this book is to provide the philosophy, principles, and methodologies to plan and conduct experiments that lead to improvement of quality. Quality will be improved through understanding current and future needs of the customer, designing the product to meet those needs, and designing the process that results in the product. The better the knowledge of these processes, the more likely planned changes are to result in improvement.

The methods of *planned experimentation* will help people to learn about the many factors that impact the quality of the product or process and to use this knowledge to improve quality and make changes to prevent problems and reduce variation. This planned approach replaces the old philosophy of finding something that works and maximizes learning relative to the resources expended.

The primary reason to carry out an experiment is to provide a basis for action on the product, service, or process to improve its performance in the *future*. Interpreting the results of an experiment is prediction —that a change in a product or process will lead to improvement in the future.

The formulation of a scientific basis for prediction has its beginnings with W. A. Shewhart (1931), who said, "A phenomenon will be said to be controlled when, through the use of past experience, we can predict, at least within limits, how the phenomenon may be expected to vary in the future."

Deming (1950) expands on the idea of improving performance of a product or service in the future by differentiating enumerative and analytic studies. Deming states that most problems in industry are analytic. In the spirit of Shewhart and Deming, this book is concerned with the design of analytic studies to improve quality and with the analysis of data from these studies.

The methodologies presented in this book are integrated into a model for improving quality. This model is designed to increase knowledge of the process, knowledge that in turn leads to improvement of the product or service. The model is fundamental to the improvement of quality and is used throughout the book.

The concepts behind improvement of quality and the model for improving quality are developed in the next two sections of this chapter. Chapter 2 features Shewhart's concept of sources of improvement and control charting. Chapter 3 develops the concepts behind the design and interpretation of analytic studies. Chapter 4 lists the tools and properties of a good experiment.

With these foundations for experimentation in place, subsequent chapters present the methods of planned experimentation. Chapter 10 is devoted to the application of methods to improve the design of a product (new or existing) and the processes to manufacture that product. Chapter 11 shows through two case studies how the model and the methods work together as a system of experimentation.

1.2 IMPROVEMENT OF QUALITY

An organization is composed of people—not only machines, policies, activities, or organization charts. Improvement of quality involves the (external) customers and suppliers as part of the organization of people. How should this expanded organization be viewed?

The Organization as a System

A starting point for improvement is adopting a new view of the organization. Deming (1986) views the organization as a system that includes the goal of improvement of quality in every stage from receipt of incoming materials to the consumer, as well as redesign of products and services for the future. All functions and activities are directed at a *common purpose*. Deming illustrated production as a system by means