
Preface

Two-level factorial designs fascinated me when, as a senior at Georgia Tech, I was introduced to their clever structure and utility. Courses in design of experiments and response surface methodology persuaded me to pursue a career in Statistics. One year later, the eminently successful book *Statistics for Experimenters* by Box, Hunter, and Hunter (BHH) (1978) was published. That book, more than any other, has enabled scientists and engineers to employ these useful designs. I recall loaning my copy of BHH to an engineering graduate student years ago, to introduce him to fractional factorial designs. To my surprise, it was the simpler 2^k full factorial designs that captured this student's interest. I had incorrectly assumed that he and other engineers would already be familiar with full factorial experiments. But that was not the case; the notion of experimenting with many factors simultaneously was completely new. Indeed, such an idea was truly novel in the 1920s, when Sir Ronald A. Fisher, the father of experimental design, wrote:

No aphorism is more frequently repeated in connection with field trials, than that we must ask Nature few questions, or, ideally, one question, at a time. The writer is convinced that this view is wholly mistaken. Nature, he suggests, will best respond to a logical and carefully thought out questionnaire; indeed, if we ask her a single question, she will often refuse to answer until some other topic has been discussed. (Fisher, 1926)

Two-level factorial and fractional factorial designs, Plackett–Burman designs, and two-level orthogonal arrays are now widely used. A search on Web of Science[®] in December 2008 yielded over 7000 articles mentioning factorial designs and nearly 500 more mentioning Plackett–Burman designs. While many of these factorial design applications involve factors with more than two levels, two-level factorial designs are the most common and are the easiest to understand and analyze. Thus, while this book will be an introduction to 2^k full factorial designs for some, its primary objectives go beyond an introduction. First, the purpose of this book is to help practitioners design and

analyze two-level factorial designs correctly. As I reviewed published examples, I routinely found mistakes and misunderstandings, especially in the analysis. This book will help nonstatisticians plan and analyze factorial experiments correctly. The following chapters contain 50 analyses of actual data from two-level designs. By carefully studying these examples, how to properly analyze one's own data will become clear. In the past, I thought intelligent software could automatically analyze the data. While it is true that statistical software packages such as JMP[®], Design-Expert[®], and Minitab[®] have made incredible strides in the last 10 years to facilitate the analysis of these designs, there are many details that distinguish one application from the next and necessitate subtle changes to the analysis. Nothing will replace the requirement for an experienced user. The numerous analyses documented in this book are intended to help build the needed expertise.

Beyond exposure to factorial designs and the knowledge to perform an analysis correctly, this book has the further objective of making new developments accessible to practitioners. Over the last 30 years, the statistical literature regarding two-level factorial designs has exploded. General design of experiment books cannot cover such growth in the literature. My goal in writing this more focused book has been to sift through the hundreds of recent articles with new theory and methods, to decide what is most useful, and then to summarize and illustrate that useful material.

This book's comprehensiveness is unique. As a reference book, it will benefit both practitioners and statisticians. To aid the reader, the book is divided into three parts. For those with little or no exposure to factorial experimentation, Part I: Full Factorial Designs is the most relevant material. Chapter 1 introduces the reader to the advantages of factorial experiments, presents the basic regression models that become the foundation for the analysis, and concludes with a four-step strategy for planning these experiments. Chapter 2 serves as a manual for data analysis. Chapter 3 concerns further design details, to improve either the precision or convenience of the experiment. Part I concludes with Chapter 4's extended analysis of three examples. In total, 15 full factorial experiments are analyzed in Part I.

Part II is intended for readers who are familiar with factorial designs and encounter applications with a large number of factors—although Chapter 2's analysis tips and Chapter 3's explanation of blocking structures should not be skipped. The seven chapters of Part II all deal with fractional factorial designs. The simplest of these, regular fractional factorial designs, are introduced in Chapter 5. Following this introduction, Chapters 6–8 present both regular fractional factorial designs and the orthogonal array designs based on Hadamard matrices. Chapter 6 presents the most frugal designs in terms of run size, including designs popularized by Plackett and Burman (1946), where the number of factors is nearly as large as the number of runs. Section 6.5 even contemplates attempts to use designs with more factors than runs. Chapter 7 presents fractional factorial designs that are somewhat less risky in their assumptions, where the number of runs is at least twice the number

of factors. Chapter 8 discusses designs that are large enough to estimate the two-factor interaction model [defined by (1.3) in Section 1.2]. Since the fractional factorial designs of Part II require assumptions to interpret the data, Chapter 9 details how one may follow these designs with additional runs either to confirm or to clarify the results. Akin to the last two chapters of Part I, Chapter 10 describes how to run and analyze fractional factorial experiments with blocking restrictions, and Chapter 11 presents detailed analysis for four more examples.

As comprehensive as Parts I and II are for full factorial and fractional factorial designs, some details were deferred, as they were judged to be either tangential to the main thrust or because their need is more specialized. Part III contains this deferred material. It begins with Chapter 12's brief introduction to designs for fitting second-order models, complete with quadratic terms for each factor. Two-level designs do not support estimation of such models, but two-level designs can easily be augmented to do so. Such topics are the domain of a field called *response surface methodology*; for a thorough treatment, the reader is directed to other books. Finally, Chapter 13 covers specialized topics related to the design choice, and Chapter 14 discusses matters of analysis. Practical questions not covered earlier are addressed here, such as how wide to space the levels of a quantitative factor and how to sample within runs to study variation. The book concludes with numerous tables needed for design construction and analysis.

The book's final section is Section 14.7: Four Analysis Blunders to Avoid. But more common and more serious than mistakes in the analysis is the failing to experiment at all, or failing to plan experiments well. Discussing Coleman and Montgomery's (1993) "A Systematic Approach to Planning for a Designed Industrial Experiment," Bert Gunter (1993) writes:

(R)ational experimental planning leads inevitably to the recognition that ALL experiments are designed experiments; the only question is whether well or poorly. The choice is therefore not whether or not statistical methods are used but whether or not sensible planning is done. Sensible planning will almost always result in the application of statistical design. Failure to do such planning will almost always lead to wasted expenditures and poor results... (T)he absence of statistical design in industry is the consequence of sloppy or absent experimental planning, not just ignorance of the methods.

Successful experimentation is hard work. This book will not remove any of the hard work. But I hope that this record of others' successes and missteps will encourage many readers to take up the challenge. May your efforts be well rewarded.

As mentioned earlier, thoroughly understanding proper statistical analysis of data requires practice. To that end, all data for examples presented in this book are available online at <http://soms.utk.edu/mee>. Repeating or extending the analyses offered here is a certain means of developing your expertise

in gaining insight through data. If, as you work through the examples, you have questions or wish to point out a suspected error, please send e-mail to rmee@utk.edu. Tips on using JMP and R software will be added to the website in response to readers' questions. As errors or ambiguities in the book are found, clarifications and corrections will also be posted.

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<http://www.springer.com/978-0-387-89102-6>

A Comprehensive Guide to Factorial Two-Level
Experimentation

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2009, XXIII, 545 p., Hardcover

ISBN: 978-0-387-89102-6