

Contents

Preface	v
1	
<i>Introduction to Designed Experiments</i>	1
1.1 Strategy of Experimentation	1
1.2 Some Typical Applications of Experimental Design	8
1.3 Basic Principles	11
1.4 Guidelines for Designing Experiments	14
1.5 A Brief History of Statistical Design	21
1.6 Summary: Using Statistical Techniques in Experimentation	22
1.7 Problems	23
2	
<i>Basic Statistical Methods</i>	25
2.1 Introduction	25
2.2 Basic Statistical Concepts	27
2.3 Sampling and Sampling Distributions	30
2.4 Inferences About the Differences in Means, Randomized Designs	36
2.4.1 Hypothesis Testing	36
2.4.2 Confidence Intervals	43
2.4.3 Choice of Sample Size	44
2.4.4 The Case Where $\sigma_1^2 \neq \sigma_2^2$	48
2.4.5 The Case Where σ_1^2 and σ_2^2 Are Known	50
2.4.6 Comparing a Single Mean to a Specified Value	50
2.4.7 Summary	51
2.5 Inferences About the Differences in Means, Paired Comparison Designs	53
2.5.1 The Paired Comparison Problem	53
2.5.2 Advantages of the Paired Comparison Design	56
2.6 Inferences About the Variances of Normal Distributions	57
2.7 Problems	59
	xi

3		65
Analysis of Variance		
3.1	An Example	66
3.2	The Analysis of Variance	68
3.3	Analysis of the Fixed Effects Model	70
3.3.1	Decomposition of the Total Sum of Squares	71
3.3.2	Statistical Analysis	73
3.3.3	Estimation of the Model Parameters	78
3.3.4	Unbalanced Data	79
3.4	Model Adequacy Checking	80
3.4.1	The Normality Assumption	80
3.4.2	Plot of Residuals in Time Sequence	82
3.4.3	Plot of Residuals Versus Fitted Values	83
3.4.4	Plots of Residuals Versus Other Variables	88
3.5	Practical Interpretation of Results	89
3.5.1	A Regression Model	89
3.5.2	Comparisons Among Treatment Means	90
3.5.3	Graphical Comparisons of Means	91
3.5.4	Contrasts	92
3.5.5	Orthogonal Contrasts	94
3.5.6	Scheffé's Method for Comparing All Contrasts	96
3.5.7	Comparing Pairs of Treatment Means	97
3.5.8	Comparing Treatment Means with a Control	101
3.6	Sample Computer Output	102
3.7	Determining Sample Size	105
3.7.1	Operating Characteristic Curves	105
3.7.2	Specifying a Standard Deviation Increase	108
3.7.3	Confidence Interval Estimation Method	109
3.8	Other Examples of Single-Factor Experiments	110
3.8.1	Chocolate and Cardiovascular Health	110
3.8.2	A Real Economy Application of a Designed Experiment	110
3.8.3	Discovering Dispersion Effects	114
3.9	The Random Effects Model	116
3.9.1	A Single Random Factor	116
3.9.2	Analysis of Variance for the Random Model	117
3.9.3	Estimating the Model Parameters	118
3.10	The Regression Approach to the Analysis of Variance	125
3.10.1	Least Squares Estimation of the Model Parameters	125
3.10.2	The General Regression Significance Test	126
3.11	Nonparametric Methods in the Analysis of Variance	128
3.11.1	The Kruskal-Wallis Test	128
3.11.2	General Comments on the Rank Transformation	130
3.12	Problems	130
4		
Experiments with Blocking Factors		139
4.1	The Randomized Complete Block Design	139
4.1.1	Statistical Analysis of the RCBD	141
4.1.2	Model Adequacy Checking	149

4.1.3	Some Other Aspects of the Randomized Complete Block Design	150
4.1.4	Estimating Model Parameters and the General Regression Significance Test	155
4.2	The Latin Square Design	158
4.3	The Graeco-Latin Square Design	165
4.4	Balanced Incomplete Block Designs	168
4.4.1	Statistical Analysis of the BIBD	168
4.4.2	Least Squares Estimation of the Parameters	172
4.4.3	Recovery of Interblock Information in the BIBD	174
4.5	Problems	177

5

Factorial Experiments 183

5.1	Basic Definitions and Principles	183
5.2	The Advantage of Factorials	186
5.3	The Two-Factor Factorial Design	187
5.3.1	An Example	187
5.3.2	Statistical Analysis of the Fixed Effects Model	189
5.3.3	Model Adequacy Checking	198
5.3.4	Estimating the Model Parameters	198
5.3.5	Choice of Sample Size	201
5.3.6	The Assumption of No Interaction in a Two-Factor Model	202
5.3.7	One Observation per Cell	203
5.4	The General Factorial Design	206
5.5	Fitting Response Curves and Surfaces	211
5.6	Blocking in a Factorial Design	219
5.7	Problems	225

6

Two-Level Factorial Designs 233

6.1	Introduction	233
6.2	The 2^2 Design	234
6.3	The 2^3 Design	241
6.4	The General 2^k Design	253
6.5	A Single Replicate of the 2^k Design	255
6.6	Additional Examples of Unreplicated 2^k Design	268
6.7	2^k Designs are Optimal Designs	280
6.8	The Addition of Center Points to the 2^k Design	285
6.9	Why We Work with Coded Design Variables	290
6.10	Problems	292

7

Blocking and Confounding Systems for Two-Level Factorials 304

7.1	Introduction	304
7.2	Blocking a Replicated 2^k Factorial Design	305
7.3	Confounding in the 2^k Factorial Design	306

7.4	Confounding the 2^k Factorial Design in Two Blocks	306
7.5	Another Illustration of Why Blocking Is Important	312
7.6	Confounding the 2^k Factorial Design in Four Blocks	313
7.7	Confounding the 2^k Factorial Design in 2^p Blocks	315
7.8	Partial Confounding	316
7.9	Problems	319

8

Two-Level Fractional Factorial Designs

320

8.1	Introduction	320
8.2	The One-Half Fraction of the 2^k Design	321
8.2.1	Definitions and Basic Principles	321
8.2.2	Design Resolution	323
8.2.3	Construction and Analysis of the One-Half Fraction	324
8.3	The One-Quarter Fraction of the 2^k Design	333
8.4	The General 2^{k-p} Fractional Factorial Design	340
8.4.1	Choosing a Design	340
8.4.2	Analysis of 2^{k-p} Fractional Factorials	343
8.4.3	Blocking Fractional Factorials	344
8.5	Alias Structures in Fractional Factorials and other Designs	349
8.6	Resolution III Designs	351
8.6.1	Constructing Resolution III Designs	351
8.6.2	Fold Over of Resolution III Fractions to Separate Aliased Effects	353
8.6.3	Plackett-Burman Designs	357
8.7	Resolution IV and V Designs	366
8.7.1	Resolution IV Designs	366
8.7.2	Sequential Experimentation with Resolution IV Designs	367
8.7.3	Resolution V Designs	373
8.8	Supersaturated Designs	374
8.9	Summary	375
8.10	Problems	376

9

Other Topics on Factorial and Fractional Factorial Designs

394

9.1	The 3^k Factorial Design	395
9.1.1	Notation and Motivation for the 3^k Design	395
9.1.2	The 3^2 Design	396
9.1.3	The 3^3 Design	397
9.1.4	The General 3^k Design	402
9.2	Confounding in the 3^k Factorial Design	402
9.2.1	The 3^k Factorial Design in Three Blocks	403
9.2.2	The 3^k Factorial Design in Nine Blocks	406
9.2.3	The 3^k Factorial Design in 3^p Blocks	407
9.3	Fractional Replication of the 3^k Factorial Design	408
9.3.1	The One-Third Fraction of the 3^k Factorial Design	408
9.3.2	Other 3^{k-p} Fractional Factorial Designs	410

9.4	Factorials with Mixed Levels	412
9.4.1	Factors at Two and Three Levels	412
9.4.2	Factors at Two and Four Levels	414
9.5	Nonregular Fractional Factorial Designs	415
9.5.1	Nonregular Fractional Factorial Designs for 6, 7, and 8 Factors in 16 Runs	418
9.5.2	Nonregular Fractional Factorial Designs for 9 Through 14 Factors in 16 Runs	425
9.5.3	Analysis of Nonregular Fractional Factorial Designs	427
9.6	Constructing Factorial and Fractional Factorial Designs Using an Optimal Design Tool	431
9.6.1	Design Optimality Criteria	433
9.6.2	Examples of Optimal Designs	433
9.6.3	Extensions of the Optimal Design Approach	443
9.7	Problems	444

10

Regression Modeling **449**

10.1	Introduction	449
10.2	Linear Regression Models	450
10.3	Estimation of the Parameters in Linear Regression Models	451
10.4	Hypothesis Testing in Multiple Regression	462
10.4.1	Test for Significance of Regression	462
10.4.2	Tests on Individual Regression Coefficients and Groups of Coefficients	464
10.5	Confidence Intervals in Multiple Regression	467
10.5.1	Confidence Intervals on the Individual Regression Coefficients	467
10.5.2	Confidence Interval on the Mean Response	468
10.6	Prediction of New Response Observations	468
10.7	Regression Model Diagnostics	470
10.7.1	Scaled Residuals and PRESS	470
10.7.2	Influence Diagnostics	472
10.8	Testing for Lack of Fit	473
10.9	Problems	475

11

Response Surface Methodology **478**

11.1	Introduction to Response Surface Methodology	478
11.2	The Method of Steepest Ascent	480
11.3	Analysis of a Second-Order Response Surface	486
11.3.1	Location of the Stationary Point	486
11.3.2	Characterizing the Response Surface	488
11.3.3	Ridge Systems	495
11.3.4	Multiple Responses	496
11.4	Experimental Designs for Fitting Response Surfaces	500
11.4.1	Designs for Fitting the First-Order Model	501
11.4.2	Designs for Fitting the Second-Order Model	501
11.4.3	Blocking in Response Surface Designs	507
11.4.4	Optimal Designs for Response Surfaces	511
11.5	Experiments with Computer Models	523
11.6	Mixture Experiments	530
11.7	Evolutionary Operation	540
11.8	Problems	544

12		554
Robust Design		
12.1 Introduction		554
12.2 Crossed Array Designs		556
12.3 Analysis of the Crossed Array Design		558
12.4 Combined Array Designs and the Response		561
Model Approach		567
12.5 Choice of Designs		570
12.6 Problems		
13		573
Random Effects Models		
13.1 Random Effects Models		573
13.2 The Two-Factor Factorial with Random Factors		574
13.3 The Two-Factor Mixed Model		581
13.4 Sample Size Determination with Random Effects		587
13.5 Rules for Expected Mean Squares		588
13.6 Approximate F Tests		592
13.7 Some Additional Topics on Estimation of Variance Components		596
13.7.1 Approximate Confidence Intervals on Variance Components		597
13.7.2 The Modified Large-Sample Method		600
13.8 Problems		601
14		604
Experiments with Nested Factors and Hard-to-Change Factors		
14.1 The Two-Stage Nested Design		604
14.1.1 Statistical Analysis		605
14.1.2 Diagnostic Checking		609
14.1.3 Variance Components		611
14.1.4 Staggered Nested Designs		612
14.2 The General m -Stage Nested Design		614
14.3 Designs with Both Nested and Factorial Factors		616
14.4 The Split-Plot Design		621
14.5 Other Variations of the Split-Plot Design		627
14.5.1 Split-Plot Designs with More Than Two Factors		627
14.5.2 The Split-Split-Plot Design		632
14.5.3 The Strip-Split-Plot Design		636
14.6 Problems		637
15		642
Other Topics		
15.1 Nonnormal Responses and Transformations		643
15.1.1 Selecting a Transformation: The Box-Cox Method		643
15.1.2 The Generalized Linear Model		645

15.2	Unbalanced Data in a Factorial Design	652
15.2.1	Proportional Data: An Easy Case	652
15.2.2	Approximate Methods	654
15.2.3	The Exact Method	655
15.3	The Analysis of Covariance	655
15.3.1	Description of the Procedure	656
15.3.2	Computer Solution	664
15.3.3	Development by the General Regression Significance Test	665
15.3.4	Factorial Experiments with Covariates	667
15.4	Repeated Measures	677
15.5	Problems	679
	Appendix	683
Table I.	Cumulative Standard Normal Distribution	684
Table II.	Percentage Points of the t Distribution	686
Table III.	Percentage Points of the χ^2 Distribution	687
Table IV.	Percentage Points of the F Distribution	688
Table V.	Operating Characteristic Curves for the Fixed Effects Model Analysis of Variance	693
Table VI.	Operating Characteristic Curves for the Random Effects Model Analysis of Variance	697
Table VII.	Percentage Points of the Studentized Range Statistic	701
Table VIII.	Critical Values for Dunnett's Test for Comparing Treatments with a Control	703
Table IX.	Coefficients of Orthogonal Polynomials	705
Table X.	Alias Relationships for 2^{k-p} Fractional Factorial Designs with $k \leq 15$ and $n \leq 64$	706
	Bibliography	719
	Index	725