## Contents

Pre	face Statistical Adequacy Constant of Means 1 Adequate Market Means 1 Adequate Means 1 Adeq	V
1		
inti	roduction to Designed Experiments	1
1.1 1.2 1.3 1.4 1.5 1.6	Strategy of Experimentation Some Typical Applications of Experimental Design Basic Principles Guidelines for Designing Experiments A Brief History of Statistical Design Summary: Using Statistical Techniques in Experimentation Problems	1 8 11 14 21 22 23
2 Bas	sic Statistical Methods	25
2.1 2.2 2.3 2.4 2.5	Introduction Basic Statistical Concepts Sampling and Sampling Distributions Inferences About the Differences in Means, Randomized Designs 2.4.1 Hypothesis Testing 2.4.2 Confidence Intervals 2.4.3 Choice of Sample Size 2.4.4 The Case Where $\sigma_1^2 \neq \sigma_2^2$ 2.4.5 The Case Where $\sigma_1^2$ and $\sigma_2^2$ Are Known 2.4.6 Comparing a Single Mean to a Specified Value 2.4.7 Summary Inferences About the Differences in Means, Paired Comparison Designs 2.5.1 The Paired Comparison Problem 2.5.2 Advantages of the Paired Comparison Design Inferences About the Variances of Normal Distributions	25 27 30 36 36 43 44 48 50 50 51 53 56 57
2.7	Problems my in the 2 Francisch Drysman Alabom 2.1.4	xi

*	3 Ana	alysis of Variance	65
	3.1	An Example	66
		The Analysis of Variance	68
3	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	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	3.5	Practical Interpretation of Results	89
		3.5.1 A Regression Model	89
		3.5.2 Comparisons Among Treatment Means	90
		3.5.4 Contracts	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	3.6	Sample Computer Output	102
3	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	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
2	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
1	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 And Andrews A	130
	1		
a i	-	2.5 Interences About the Effort reside 11.05 Paired Compa	100
	Exp	periments with Blocking Factors	139
4	4.1	The Randomized Complete Block Design	139
		4.1.1 Statistical Analysis of the RCBD Mod A Associated and S	14
		4.1.2 Model Adequacy Checking	149

		Contents	xiii
	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		168 172
	4.4.2 Least Squares Estimation of the Parameters		174
15	4.4.3 Recovery of Interblock Information in the BIBD Problems		177
4.5	Problems		1//
_			
5			
Eas	torial Evacuiments call to not age that and ad I = C		183
rac	torial Experiments		103
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 and ball knows and seed and self 1.8.		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		201 202
	5.3.6 The Assumption of No Interaction in a Two-Factor Model		202
<i>5 1</i>	5.3.7 One Observation per Cell		206
5.4	The General Factorial Design		211
5.5	Fitting Response Curves and Surfaces		219
5.6	Blocking in a Factorial Design		225
5.7	Tiodellis		223
6			
_			233
IWC	o-Level Factorial Designs		233
6.1	Introduction		233
6.2	The 2 <sup>2</sup> Design		234
6.3	The 2 <sup>3</sup> Design		241
6.4	The General 2 <sup>k</sup> Design		253
6.5	A Single Replicate of the $2^k$ Design		255
6.6	Additional Examples of Unreplicated 2 <sup>k</sup> Design		268
6.7	2 <sup>k</sup> 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			292
114	Experimental Designs for Fitting Respirate Sugar Sugar State		
_			
Blo	cking and Confounding Systems for Two-Level Fact	torials	304
7.1	Introduction		304
7.2	Blocking a Replicated 2 <sup>k</sup> Factorial Design		305
73	Confounding in the 2 <sup>k</sup> Factorial Design		306

7.4	Confounding the 2 <sup>k</sup> Factorial Design in Two Blocks		306
	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 <sup>k</sup> Factorial Design in 2 <sup>p</sup> Blocks		315
			316
7.8	Partial Confounding		
7.9	Problems		319
8			
_	A Company Day E		220
IW	o-Level Fractional Factorial Designs		320
8.1	Introduction		320
8.2	The One-Half Fraction of the 2 <sup>k</sup> Design		321
0.2	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
0.2	The One-Quarter Fraction of the $2^k$ Design		333
8.3			
8.4	The General $2^{k-p}$ Fractional Factorial Design		340
	8.4.1 Choosing a Design of the branch from the least the second of the least		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			374
8.9			375
	Summary make Kandom Canada and Bodoubound		
8.10			376
0			
-	3.10.2 The Grand Changain at St. St. and and bull languists A	0,0,	20
Ot	her Topics on Factorial and Fractional Facto	orial Designs	394
9.1	The 3 <sup>k</sup> Factorial Design		395
7.1	9.1.1 Notation and Motivation for the 3 <sup>k</sup> Design		395
			396
	9.1.2 The 3 Design		397
			402
0.0			
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 <sup>k</sup> Factorial Design		408
	9.3.1 The One-Third Fraction of the 3 <sup>k</sup> Factorial Design		408
	9.3.2 Other $3^{k-p}$ Fractional Factorial Designs		410

	Factorials with Mixed Levels	412
	9.4.1 Factors at Two and Three Levels	412
	9.4.2 Factors at Two and Four Levels applied saudo?	414
	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
	Constructing Factorial and Fractional Factorial Designs Using	101
	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
40		
10	A Treening Ponts dispositions and mounts/	
Rea	ression Modeling	449
10.1	Introduction Telpow beam notice lower entry a Fig.	449
10.2	Linear Regression Models	450
	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 ugizad bakad bandawi Tadi 1.11	475
11	14.1.2 Diagnostic Checking	
" "		
Res	ponse Surface Methodology	478
11.1	Introduction to Response Surface Methodology	478
	The Method of Steepest Ascent	480
		486
11.5	Analysis of a Second-Order Response Surface	486
	11.3.1 Location of the Stationary Point	488
	11.3.2 Characterizing the Response Surface	495
	11.3.3 Ridge Systems 11.3.4 Multiple Responses	496
11 /	Experimental Designs for Fitting Response Surfaces	500
11.4	11.4.1 Designs for Fitting the First-Order Model	501
	11.4.2 Designs for Fitting the First-Order Model  11.4.2 Designs for Fitting the Second-Order Model	501
		507
	11.4.3 Blocking in Response Surface Designs 11.4.4 Optimal Designs for Response Surfaces	511
11.5	Experiments with Computer Models mages Hammong A. L. A.	523
	Mixture Experiments I mount of the man and	530
11.0	Evolutionary Operation Manual Box 18 page 2017 5.1.51	540
		544
11.0	Problems	244

12	
Robust Design	554
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	556
Model Approach	561
12.5 Choice of Designs	567
	570
12.6 Problems	370
Problems	
13	
Random Effects Models	573
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	
13.5 Rules for Expected Mean Squares	588
13.6 Approximate F Tests	
13.7 Some Additional Topics on Estimation of Variance Compor	
13.7.1 Approximate Confidence Intervals on Variance Component	
13.7.2 The Modified Large-Sample Method	600
13.8 Problems	601
10.5.2. Confidence Interval on the Albain Response.	
14	
Experiments with Nested Factors	
and Hard-to-Change Factors	604
and mard-to-change ractors	101
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 <i>m</i> -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	627 632
14.5.2 The Split-Plot Design 14.5.3 The Strip-Split-Plot Design	636
14.6 Problems	637
Experimental Designs for Fluing Response Supposed Linear Pro-	377
11.4.1 Designs for Fitting the Frost Order Model. 11.4.2 Designs for Fitting the Second Order Model. 11.4.2	
The transfer of the state of th	642
Other Topics	042
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

	Contents	XVII
15.2.1 Pr	ed Data in a Factorial Design oportional Data: An Easy Case oproximate Methods	652 652 654
	e Exact Method	655
	ysis of Covariance escription of the Procedure	655
	omputer Solution	656 664
	evelopment by the General Regression Significance Test	665
	ctorial Experiments with Covariates	667
15.4 Repeated	Measures	677
15.5 Problems		679
<b>Appendix</b>		683
Table I.	Cumulative Standard Normal Distribution	684
Table II.	Percentage Points of the t Distribution	686
Table III.	Percentage Points of the $\chi^2$ Distribution	687
Table IV.	Percentage Points of the F Distribution	688
Table V.	Operating Characteristic Curves for the Fixed Effects Model	n no.
CONSIGNING EXT	Analysis of Variance	693
Table VI.	Operating Characteristic Curves for the Random Effects Model	<0 <b>=</b>
Table XIII	Analysis of Variance	697
Table VII. Table VIII.	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 $k \le 15$	105
y of Experi	and $n \le 64$	706
Bibliograph	ny	719
Index	do between part of and art and are all hart against him and a	725
maex		725