

## Contents

1	SCIENCE AND STATISTICS			
	1.1 1.2 1.3 1.4 1.5	The Learning Process The Role of Experimental Design Difficulties Mitigated by Statistical Methods A Typical Investigation How to Use Statistical Techniques	1 4 7 9 14	
P <b>A</b> i	RT I	COMPARING TWO TREATMENTS		
2	USE MEA	OF EXTERNAL REFERENCE DISTRIBUTION TO COMPARE TWO NS	21	
	2.1	Relevant Reference Sets and Distributions	21	
	2.2	Theory: Probability Distributions, Parameters, and Statistics	24	
	2.3	The Industrial Experiment: External Reference Distribu- tion	31	
	2.4	Theory: Normal and t Distributions	38	
	2.5	The Industrial Experiment: An External Reference Distribution Based on the t Distribution	51	
	App	vendix 2A Calculation of the Sample Average, Sample Variance, and Sample Standard Deviation by Coding Data	53	
		Counig Data		
3	RANI	DOM SAMPLING AND THE DECLARATION OF INDEPENDENCE	57	
	3.1	Theory: Statistical Dependence and Independence and the Random Sampling Model	57	
			хi	

xii CONTENTS

	3.2	3.2 The Industrial Experiment: Reference Distribution Based on Random Sampling Model, External Value for $\sigma$							
	3.3	The Industrial Experiment: Reference Distribution Based	74						
	5.5	on Random Sampling Model, Internal Estimate of $\sigma$	76						
	3.4	Summary: What Have We Learned from the Industrial	, 0						
	J. 1	Experiment Example?	82						
	Ann	endix 3A Mean and Variance of a Linear Combination of							
	App	Observations	87						
	<b>A</b>		89						
		endix 3B Robustness of Some Statistical Procedures							
	App	endix 3C Fisher's Concept of Sufficiency	91						
4	RAN	DOMIZATION AND BLOCKING WITH PAIRED COMPARISONS	93						
	4.1	Randomization to the Rescue: Tomato Plant Example	93						
	4.2	Randomized Paired Comparison Design: Boys' Shoes							
		Example							
	4.3	Example 9 Blocking and Randomization 10							
	4.4	Noise Structure, Models, and Randomization 10							
	4.5								
		Blocking in Simple Comparative Experiments	105						
5		IIFICANCE TESTS AND CONFIDENCE INTERVALS FOR MEANS, IANCES, PROPORTIONS, AND FREQUENCIES	107						
	5.1	A More Detailed Discussion of Significance Tests	107						
	5.2	Confidence Intervals for a Difference in Means: Paired							
		Comparison Design	110						
	5.3	•							
		Design	115						
	5.4	Inferences about Variances of Normally Distributed Data	117						
	5.5	Inferences about Proportions: The Binomial Distribu-	/						
		tion	123						
	5.6	Inferences about Frequencies: The Poisson Distribu-							
		tion	137						
	5.7	Contingency Tables and Tests of Association	145						
			0						

PROBLEMS FOR PART I

152

## PART II COMPARING MORE THAN TWO TREATMENTS

5	EXP	EXPERIMENTS TO COMPARE $k$ TREATMENT MEANS					
	6.1	Blood Coagulation Times with Four Different Diets	165				
	6.2	Estimating the Amount of Variation Within and Between					
		Treatments	167				
	6.3	The Arithmetic and Geometry of the Analysis of Variance					
	0.0	Table	170				
	6.4	Decomposition of the Observations Implied by the Analysis	175				
	6.5	Diagnostic Checking of the Basic Model	182				
	6.6						
	6.7	the second of th	187 190				
	6.8	Summary	193				
		endix 6A Shortcut Method for Constructing the Analysis	.,,				
	App	of Variance Table	194				
	Apr	endix 6B Vectors and Geometry Associated with the					
	-1.1	Analysis of a Sample	197				
	Apr	endix 6C Multiple Comparisons	203				
7	RAN	DOMIZED BLOCKS AND TWO-WAY FACTORIAL DESIGNS	208				
	7.1	Example: Comparison of Four Variants of a Penicillin					
		Production Process	209				
	7.2	A Model with Corresponding Decomposition of Observa-					
		tions	210				
	7.3	Implications of the Additive Model	218				
	7.4	Diagnostic Checking of the Model	220				
	7.5	Use of the Analysis of Variance Table	223				
	7.6	The Use of Reference Distributions To Compare Individual					
		Means	226				
	7.7	A Two-Way (Factorial) Design	228				
	7.8	Simplification and Increased Sensitivity from Transfor-					
		mation	231				
	7.9	Likelihood Estimation of the Transformation	239				
	7.10	Summary	241				
		endix 7A Calculations for Constructing Analysis of Vari-					
	· • PF	ance Table for Randomized Block Design	241				

	Appendix 7B Algebraic Demonstration of the Additivity of the Sums of Squares in a Randomized Block	243			
8	DESIGNS WITH MORE THAN ONE BLOCKING VARIABLE				
	<ul> <li>8.1 Latin Square Designs: Automobile Emissions and Synthetic Yarn Examples</li> <li>8.2 Graeco- and Hyper-Graeco-Latin Squares: First Wear Testing Example</li> <li>8.3 Balanced Incomplete Block Designs: Second Wear Testing Example</li> </ul>				
	Appendix 8A Some Useful Latin Squares and How to Use Them to Construct Graeco-Latin and Hyper- Graeco-Latin Square Design	261			
	Appendix 8B Analysis of Variance for $k \times k$ Latin Square Designs with $r$ Replicates	263			
	Appendix 8C Some Useful Balanced Incomplete Block Designs	269			
	Appendix 8D Analysis of Variance and Computation of Adjusted Treatment Averages for Balanced				
	Incomplete Block Designs	275			
PRO	BLEMS FOR PART II	281			
PA	RT III MEASURING THE EFFECTS OF VARIABLES				
9	EMPIRICAL MODELING	291			
	<ul><li>9.1 Mathematical Models</li><li>9.2 Geometric Representation of Empirical Relationships</li></ul>	291 296			
	<ul><li>9.3 The Problem of Experimental Design</li><li>9.4 Comprehensive Versus Sequential Approach to Experi-</li></ul>	298			
	9.4 Comprehensive Versus Sequential Approach to Experimental Investigations	303			
10	FACTORIAL DESIGNS AT TWO LEVELS	306			
	<ul> <li>10.1 General Factorial Designs and Designs at Two Levels</li> <li>10.2 An Example of a 2<sup>3</sup> Factorial Design: Pilot Plant Investi-</li> </ul>	306			
	gation	307			

CON	TENTS		ΧV			
	10.3	Calculation of Main Effects	309			
	10.4	Interaction Effects	313			
	Interpretation of Results	317				
	10.6 Calculation of Standard Errors for Effects Using Repli-					
cated Runs						
	10.7	Quicker Methods for Calculating Effects	322 324			
10.8 A 24 Factorial Design: Process Development Study						
	10.9	•	329			
		Transformation of Data from Factorial Designs	334			
		Blocking	336			
	10.12	Summary	342			
	Appe	ndix 10A Yates's Algorithm	342			
	Appe	ndix 10B More on Blocking Factorial Designs	344			
11	MORE	APPLICATIONS OF FACTORIAL DESIGNS	352			
	11.1	Example 1: The Effects of Three Variables on Clarity of Film	352			
	11.2					
		Properties of a Polymer Solution	353			
	11.3					
		Water Overflows	354			
	11.4	Example 4: Simple Factorials Used Sequentially in Evolu-				
		tionary Operation—Petrochemical Plant	362			
	11.5					
		Evolutionary Operation—Polymer Unit	365			
	11.6	Summary	368			
	Appe	endix 11A A Suggested Exercise	368			
12	FRACTIONAL FACTORIAL DESIGNS AT TWO LEVELS					
	12.1	Dadundanay	374			
	12.1	Redundancy A Half-Fraction of a 2 <sup>5</sup> Design: Reactor Example	376			
	12.2		310			
	14.3	Example	381			
	12.4	• • • • • • • • • • • • • • • • • • •	385			
	12.5	Resolution III Designs: Bicycle Example	390			
	12.5	Resolution IV Designs: Injection Molding Example	398			
	12.7	Elimination of Block Effects in Fractional Designs	404			
		Timination of Picar Tilano III y 1840 offer Pacific	101			

xvi			CO	NTENTS
	12.8	Designs of	of Resolution V and Higher	407
	12.9	Summary	_	409
	Appe	ndix 12A	Structure of the Fractional Designs	409
	Appe	ndix 12B		
	11		guities from Fractional Factorials	413
13	MORE	APPLICATION	ONS OF FRACTIONAL FACTORIAL DESIGNS	419
	13.1	Example	1: Effects of Five Variables on Some Properties	
		of Cast F		419
	13.2		2: Stability of New Product	422
	13.3	Industrial	<u> </u>	424
	13.4	-	4: Sensitivity Analysis of a Simulation Model—	429
	13.5		r-Aircraft System	432
		FOR PART  BUILD	DING MODELS AND USING THEM	434
14	SIMPL	E MODELIN	G WITH LEAST SQUARES (REGRESSION ANALYSIS)	453
	14.1	One-Para Aerosol l	ameter Model (Straight Line through the Origin):	453
	14.2		ameter Model: Impurity Example	462
	14.3		Line Model: Welding Example	473
	14.4	General (	Case for Models Linear in the Parameters	479
	14.5	-	ial Model: Growth Rate Example	480
	14.6 14.7		or Model: Biochemical Oxygen Demand Example of Fitting Regression Equations to Happenstance	
		Data		487
	Appe	endix 14A	Why Do the Normal Equations Yield Least Squares Estimates?	498
	Anne	endix 14B	Matrix Version of the Normal Equations	501

CO	NTENTS	3	xvii	
	Appendix 14C Analysis of Factorials, Botched and Otherwise Appendix 14D Unweighted and Weighted Least Squares			
15	RESPO	ONSE SURFACE METHODS	510	
	15.1	Weakness of Classical One-Variable-at-a-Time Strategy:		
		Chemical Example	510	
	15.2	Illustration of Response Surface Methodology: Chemical Example	513	
	15.3	A Specification Problem	526	
	15.4	Maxima, Ridges, and Canonical Analysis	526	
	15.5	Applications of Response Surface Methods	534	
	15.6	Summary	535	
16	месн	ANISTIC MODEL BUILDING	540	
	16.1	Empirical and Mechanistic Models	540	
	16.2	Possible Advantages of Mechanistic Models	544	
	16.3	Techniques for Mechanistic Modeling	546	
	16.4	The Model-Building Process	548	
	16.5	Model Testing with Diagnostic Parameters	550	
	16.6	Importance of Plotting Data in the Age of Computers	552	
	16.7	Summary	552	
17	STUD	Y OF VARIATION	556	
	17.1	Graphs and Control Charts: Impurity Determination		
		Example	556	
		Transmission of Error	563	
		Variance Components: Pigment Paste Example	571	
	Appe	ndix 17A Calculating Variance Components from an		
		Analysis of Variance Table	581	
18	MODE	LING DEPENDENCE: TIME SERIES	584	
	18.1	The Industrial Data of Chapter 2 Reconsidered as a Time Series	585	
	18.2	Statistical Modeling Revisited	588	

xviii	CON	ITENTS
18.3	Forecasting: Refrigerator Sales Example	591
18.4	Feedback Control: Dye Level Example	598
18.5	Intervention Analysis: Los Angeles Air Pollution Example	602
Appe	endix 18A Derivation of Equation 18.4	604
PROBLEMS	FOR PART IV	606
APPENDIX	: TABLES	629
INDEX		645