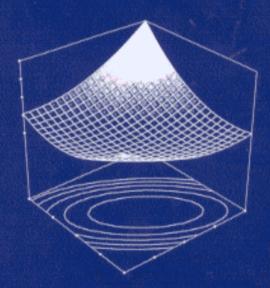


Response Surface Methodology

Process and Product Optimization Using Designed Experiments

SECOND EDITION



Raymond H. Myers

Douglas C. Montgomery

WILEY SERIES IN PROBABILITY AND STATISTICS

Contents

Pref	face		xiii	
1.	1. Introduction			
	1.1	Response Surface Methodology, 1 1.1.1 Approximating Response Functions, 3 1.1.2 The Sequential Nature of RSM, 10 1.1.3 Objectives and Typical Applications of RSM, 12 1.1.4 RSM and the Philosophy of Quality Improvement, 13		
	1.2	Product Design and Formulation (Mixture Problems), 14		
	1.3	Robust Design and Process Robustness Studies, 15		
	1.4	Useful References on RSM, 16		
2	Build	ing Empirical Models	17	
	2.1	Linear Regression Models, 17		
	2.2	Estimation of the Parameters in Linear Regression Models, 18		
	2.3	Properties of the Least Squares Estimators and Estimation of σ^2 , 25		
	2.4	Hypothesis Testing in Multiple Regression, 29 2.4.1 Test for Significance of Regression, 29 2.4.2 Tests on Individual Regression Coefficients and Groups of Coefficients, 33		
	2.5	 Confidence Intervals in Multiple Regression, 37 2.5.1 Confidence Intervals on the Individual Regression Coefficients β, 38 		

vi CONTENTS

		2.5.2 A Joint Confidence Region on the Regression Coefficients β, 38	
		2.5.3 Confidence Interval on the Mean Response, 39	
	2.6	Prediction of New Response Observations, 41	
	2.7	Model Adequacy Checking, 43	
		2.7.1 Residual Analysis, 43	
		2.7.2 Scaling Residuals, 44	
		2.7.3 Influence Diagnostics, 502.7.4 Testing for Lack of Fit, 51	
	2,8		
	2.9	_	
		Transformation of the Response Variable, 68	
		rcises, 74	
	LAC	10000, 71	
3	Two-	Level Factorial Designs	85
	3.1	Introduction, 85	
	3.2	The 2 ² Design, 85	
	3.3	The 2 ³ Design, 100	
	3.4	The General 2^k Design, 111	
	3.5		
	3.6	S ,	
	3.7	5	
		 3.7.1 Blocking in the Replicated Design, 134 3.7.2 Confounding in the 2^k Design, 136 	
	Exe	rcises, 143	
4	Two-l	Level Fractional Factorial Designs	155
	4.1	Introduction, 155	
	4.2	The One-Half Fraction of the 2^k Design, 156	
	4.3	The One-Quarter Fraction of the 2 ^k Design, 170	
	4.4	The General 2 ^{k-p} Fractional Factorial Design, 178	
	4.5	Resolution III Designs, 183	
	4.6	Resolution IV and V Designs, 192	
	4.7	Summary, 194	
	Exe	rcises, 195	
5	Proc	ess Improvement with Steepest Ascent	203
	5.1	Determining the Path of Steepest Ascent, 205	
		5.1.1 Development of the Procedure, 205	

CONTENTS vii

	5.1.2	Practical Application of the Method of Steepest Ascent, 207			
5.2	2 Consideration of Interaction and Curvature, 213				
		What About a Second Phase?, 216			
	5.2.2	What Happens Following Steepest			
		Ascent?, 216			
5.3	Effect	of Scale (Choosing Range of Factors), 218			
5.4	Confid	dence Region for Direction of Steepest Ascent, 220			
5.5	Steepe	est Ascent Subject to a Linear Constraint, 224			
Exe	rcises,	229			
The A	Analysis	s of Second-Order Response Surfaces	235		
6.1	Secon	d-Order Response Surface, 235			
6.2	Secon	d-Order Approximating Function, 235			
	6.2.1	The Nature of the Second-Order Function			
		and Second-Order Surface, 236			
	6.2.2	Illustration of Second-Order Response Surfaces, 237			
6.3	.3 A Formal Analytical Approach to the Second-Order				
	Model, 241				
		Location of the Stationary Point, 242			
	6.3.2	Nature of the Stationary Point			
	(22	(Canonical Analysis), 242			
		Ridge Systems, 247 Role of Contour Plots, 251			
6.4		·			
0.4	_	Analysis of the Response Surface, 254			
	6.4.2	What Is the Value of Ridge Analysis?, 255 Mathematical Development of Ridge			
	0.7.2	Analysis, 255			
6.5	Sampl	ling Properties of Response Surface Results, 262			
-	6.5.1	-			
		Confidence Region on the Location of the			
		Stationary Point, 264			
	6.5.3	Use and Computation of the Confidence Region			
		on the Location of the Stationary Point, 266			
	6.5.4	\mathcal{L}			
		Analysis, 271			
6.6	-	ple Response Optimization, 273			
6.7		er Comments Concerning Response Surface sis, 286			
Exe	rcises.	287			

6

Ехре	rimenta	al Designs for Fitting Response Surfaces—I	303
7.1	Desira	able Properties of Response Surface Designs, 303	
7.2		ibility Region, Region of Interest, and Model quacy, 304	
7.3	Design	n of Experiments for First-Order Models, 307	
	7.3.1	The First-Order Orthogonal Design, 308	
	7.3.2	Orthogonal Designs for Models Containing Interaction, 310	
	7.3.3	Other First-Order Orthogonal Designs— The Simplex Design, 314	
	7.3.4	Another Variance Property—Prediction Variance, 318	
7.4	Desig	ns for Fitting Second-Order Models, 321	
	7.4.1	The Class of Central Composite Designs, 321	
	7.4.2		
	7.4.3	Rotatability and the CCD, 331	
	7.4.4	The Cuboidal Region and the Face-Centered Cube, 335	
	7.4.5	Q U 1	
		Summary Statements Regarding CCD, 342	
		The Box-Behnken Design, 343	
	7.4.8	Other Spherical RSM Designs; Equiradial Designs, 351	
	7.4.9	Orthogonal Blocking in Second-Order Designs, 353	
Exe	ercises,	366	
Exp	eriment	al Designs for Fitting Response Surfaces—II	377
8.1	Desig	ns That Require a Relatively Small Run Size, 378	
	8.1.1	The Small Composite Design, 378	
		Koshal Design, 384	
		Hybrid Designs, 386	
	8.1.4	Designs, 390	
8.2		ral Criteria for Constructing, Evaluating, Comparing Experimental Designs, 390	
	8.2.1	Practical Design Optimality, 393	
	8.2.2	Use of Design Efficiencies for Comparison of Standard Second-Order Designs, 399	
	8.2.3	Graphical Procedure for Evaluating the Prediction Capability of an RSM Design, 402	

CONTENTS ix

	8.3	Computer-Generated Designs in RSM, 413	
		8.3.1 Important Relationship Between Prediction Variance and Design Augmentation for <i>D</i> -Optimality, 414	
		8.3.2 Illustrations Involving Computer-Generated Design, 416	
	8.4	Some Final Comments Concerning Design Optimality and Computer-Generated Design, 428	
	Exe	rcises, 429	
9.	Adva	nced Response Surface Topics—I	437
	9.1	Effects of Model Bias on the Fitted Model and Design, 437	
	9.2	A Design Criterion Involving Bias and Variance, 441	
		9.2.1 The Case of a First-Order Fitted Model and Cuboidal Region, 444	
		9.2.2 Minimum Bias Designs for a Spherical Region of Interest, 451	
		9.2.3 Simultaneous Consideration of Bias and Variance, 453	
		9.2.4 How Important Is Bias?, 454	
	9.3	RSM in the Presence of Qualitative Variables, 456	
		9.3.1 Models That Are First-Order in the Quantitative Design Variables (Two-Level Design), 457	
		9.3.2 First-Order Models with More Than Two Levels of the Qualitative Factors, 459	
		9.3.3 Models with Interaction Among Qualitative and Quantitative Variables, 460	
		9.3.4 Design Considerations: First-Order Models With and Without Interaction, 461	
		9.3.5 Design Considerations: Models That Are Second-Order in the Quantitative Variables, 465	
		9.3.6 Use of Computer-Generated Designs, 468	
		9.3.7 Further Comments about Qualitative Variables, 478	
	9.4	Errors in Control of Design Levels, 478	
	9.5	Experiments with Computer Models, 481	
	9.6	Minimum Bias Estimation of Response Surface Models, 485	
	9.7	Neural Networks, 489	
	Exe	ercises, 492	

10.	Adva	nced Re	sponse Surface Topics—II	500
	10.1	RSM for Nonnormal Responses—Generalized Linear Models, 501		
			Model Framework: The Link Function, 502	
			The Canonical Link Function, 502	
			Basis For Estimation of Model Coefficients, 503 Properties of Model Coefficients, 505	
			Model Deviance, 506	
			Overdispersion, 507	
			Examples, 509	
		10.1.8	Diagnostic Plots and Other Aspects of the	
		v	GLM, 516	
	10.2	Restric	ctions in Randomization in RSM, 521	
		10.2.1	The Dilemma of Difficult-to-Change	
			Factors, 522	
		10.2.2	•	
		10.2.3	3 ··· r	
		10.2.4	Structure, 526	
		10.2.4	Mixed Model Approach, 528 Use of Generalized Estimating Equations, 529	
	Ever			
	EXCI	cises, 53	12	
11	Robu	st Parai	meter Design and Process Robustness Studies	536
	11.1	Introdu	uction, 536	
	11.2	What I	Is Parameter Design?, 536	
		11.2.1	Examples of Noise Variables, 537	
		11.2.2	An Example of Robust Product Design, 538	
	11.3	The Ta	aguchi Approach, 539	
			Crossed Array Designs and Signal-to-Noise	
			Ratios, 539	
		11.3.2	Analysis Methods, 543	
		11.3.3	Further Comments, 550	
	11.4	The R	esponse Surface Approach, 552	
		11.4.1	The Role of the Control \times Noise Interaction, 552	
		11.4.2	A Model Containing Both Control and Noise Variables, 557	
		11.4.3	Generalization of Mean and Variance Modeling, 561	
		11.4.4	Analysis Procedures Associated with the Two Response Surfaces, 565	
		11.4.5	•	

12

13

		Direct Variance Modeling, 579 Lice of Generalized Linear Models, 582			
11.5	11.4.7 Use of Generalized Linear Models, 5825 Experimental Designs for RPD and Process Robustness				
11.5	Studies				
		Combined Array Designs, 587			
		Second-Order Designs, 589			
	11.5.3	· · · · · · · · · · · · · · · · · · ·			
11.6	•	sion Effects in Highly Fractionated Designs, 591			
		The Use of Residuals, 592			
	11.6.2	Further Diagnostic Information from Residuals, 593			
	11.6.3	Further Comments Concerning Variance Modeling, 601			
Exerc	cises, 60	_			
		: *	614		
Expe	riments	with Mixtures	014		
12.1	Introdu	ection, 614			
12.2	Simple	x Designs and Canonical Mixture Polynomials,			
	618				
		Simplex Lattice Designs, 618			
	12.2.2	The Simplex-Centroid Design and Its Associated			
		Polynomial, 628			
	12.2.3	Augmentation of Simplex Designs with Axial Runs, 630			
12.3	Respon	nse Trace Plots, 638			
12.4					
Exer	Exercises, 643				
		re Design and Analysis Techniques	652		
13.1	Constr	raints on the Component Proportions, 652			
		Lower-Bound Constraints on the Component			
		Proportions, 653			
	13.1.2	Upper-Bound Constraints on the Component Proportions, 665			
	13.1.3				
	13.1.4	Multicomponent Constraints, 684			
13.2	Mixtu	re Experiments Using Ratios of Components, 685			
13.3		ss Variables in Mixture Experiments, 690			
13.4		ning Mixture Components, 701			
	cises, 7	2			
	•				

14	Conti	nuo	us Process Improvement with Evolutionary Operation	715
	14.1	Int	roduction, 715	
	14.2	An	Example of EVOP, 716	
	14.3	EV	OP Using Software, 721	
	14.4	Sin	nplex EVOP, 725	
	14.5	Sor	me Practical Advice About Using EVOP, 727	
	Exerc	ises	, 728	
Refe	erences			731
Ap	pendix	1.	Variable Selection and Model Building in Regression	742
Ap	pendix	2.	Multicollinearity and Biased Estimation in Regression	759
Ap	pendix	3.	Robust Regression	770
Ap	pendix	4.	Some Mathematical Insights into Ridge Analysis	778
Ap	pendix	5.	Moment Matrix of a Rotatable Design	779
Ap	pendix	6.	Rotatability of a Second-Order Equiradial Design	784
Ap	pendix	7.	Relationship Between D -Optimality and the Volume of a Joint Confidence Ellipsoid on β	787
Ap	pendix	8.	Relationship Between the Maximum Prediction Variance in a Region and the Number of Parameters	789
Ap	pendix	9.	The Development of Equation (8.21)	790
App	endix 1	10.	Determination of Data Augmentation Result (Choice of x_{r+1} for the Sequential Development of a D -Optimal Design)	791
ر Inde	×			793