SAS° FOR LINEAR MODELS

Fourth Edition

Ramon C. Littell Walter W. Stroup Rudolf J. Freund

Contents

Acknowledgments xi

Chapter 1 Introduction

- 1.1 About This Book 1
- 1.2 Statistical Topics and SAS Procedures 1

Chapter 2 Regression

2.1 Introduction 3

2.2 The REG Procedure 4

- 2.2.1 Using the REG Procedure to Fit a Model with One Independent Variable 5
- 2.2.2 The P, CLM, and CLI Options: Predicted Values and Confidence Limits 10
- 2.2.3 A Model with Several Independent Variables 12
- 2.2.4 The SS1 and SS2 Options: Two Types of Sums of Squares 14
- 2.2.5 Tests of Subsets and Linear Combinations of Coefficients 17
- 2.2.6 Fitting Restricted Models: The RESTRICT Statement and NOINT Option 18
- 2.2.7 Exact Linear Dependency 21

2.3 The GLM Procedure 22

- 2.3.1 Using the GLM Procedure to Fit a Linear Regression Model 22
- 2.3.2 Using the CONTRAST Statement to Test Hypotheses about Regression Parameters 24
- 2.3.3 Using the ESTIMATE Statement to Estimate Linear Combinations of Parameters 26

2.4 Statistical Background 27

- 2.4.1 Terminology and Notation 27
- 2.4.2 Partitioning the Sums of Squares 28
- 2.4.3 Hypothesis Tests and Confidence Intervals 29
- 2.4.4 Using the Generalized Inverse 31

Chapter 3 Analysis of Variance for Balanced Data

3.1 Introduction 33

3.2 One- and Two-Sample Tests and Statistics 34

- 3.2.1 One-Sample Statistics 34
- 3.2.2 Two Related Samples 37
- 3.2.3 Two Independent Samples 39

3.3 The Comparison of Several Means: Analysis of Variance 42

- 3.3.1 Terminology and Notation 42
 - 3.3.1.1 Crossed Classification and Interaction Sum of Squares 44
 - 3.3.1.2 Nested Effects and Nested Sum of Squares 45
- 3.3.2 Using the ANOVA and GLM Procedures 40
- 3.3.3 Multiple Comparisons and Preplanned Comparisons 48

3.4 The Analysis of One-Way Classification of Data 49

- 3.4.1 Computing the ANOVA Table 52
- 3.4.2 Computing Means, Multiple Comparisons of Means, and Confidence Intervals 55
- 3.4.3 Planned Comparisons for One-Way Classification: The CONTRAST Statement 56
- 3.4.4 Linear Combinations of Model Parameters 59
- 3.4.5 Testing Several Contrasts Simultaneously 59
- 3.4.6 Orthogonal Contrasts 60
- 3.4.7 Estimating Linear Combinations of Parameters: The ESTIMATE Statement 60

3.5 Randomized-Blocks Designs 62

- 3.5.1 Analysis of Variance for Randomized-Blocks Design 64
- 3.5.2 Additional Multiple Comparison Methods 65
- 3.5.3 Dunnett's Test to Compare Each Treatment to a Control 70

3.6 A Latin Square Design with Two Response Variables 72

3.7 A Two-Way Factorial Experiment 74

- 3.7.1 ANOVA for a Two-Way Factorial Experiment 75
- 3.7.2 Multiple Comparisons for a Factorial Experiment 78
- 3.7.3 Multiple Comparisons of METHOD Means by VARIETY 80
- 3.7.4 Planned Comparisons in a Two-Way Factorial Experiment 82
- 3.7.5 Simple Effect Comparisons 84
- 3.7.6 Main Effect Comparisons 85
- 3.7.7 Simultaneous Contrasts in Two-Way Classifications 86
- 3.7.8 Comparing Levels of One Factor within Subgroups of Levels of Another Factor 87
- 3.7.9 An Easier Way to Set Up CONTRAST and ESTIMATE Statements 89

Chapter 4 Analyzing Data with Random Effects

4.1 Introduction 91

4.2 Nested Classifications 93

- 4.2.1 Analysis of Variance for Nested Classifications 96
- 4.2.2 Computing Variances of Means from Nested Classifications and Deriving Optimum Sampling Plans 99
- 4.2.3 Analysis of Variance for Nested Classifications: Using Expected Mean Squares to Obtain Valid Tests of Hypotheses 99
- 4.2.4 Variance Component Estimation for Nested Classifications: Analysis Using PROC MIXED 101
- 4.2.5 Additional Analysis of Nested Classifications Using PROC MIXED: Overall Mean and Best Linear Unbiased Prediction 104

4.3 Blocked Designs with Random Blocks 106

- 4.3.1 Random-Blocks Analysis Using PROC MIXED 107
- 4.3.2 Differences between GLM and MIXED Randomized-Complete-Blocks Analysis: Fixed versus Random Blocks 110
 - 4.3.2.1 Treatment Means 111
 - 4.3.2.2 Treatment Differences 112

4.4 The Two-Way Mixed Model 113

- 4.4.1 Analysis of Variance for the Two-Way Mixed Model: Working with Expected Mean Squares to Obtain Valid Tests 114
- 4.4.2 Standard Errors for the Two-Way Mixed Model: GLM versus MIXED 117
- 4.4.3 More on Expected Mean Squares: Determining Quadratic Forms and Null Hypotheses for Fixed Effects 120

4.5 A Classification with Both Crossed and Nested Effects 122

- 4.5.1 Analysis of Variance for Crossed-Nested Classification 124
- 4.5.2 Using Expected Mean Squares to Set Up Several Tests of Hypotheses for Crossed-Nested Classification 124
- 4.5.3 Satterthwaite's Formula for Approximate Degrees of Freedom 129
- 4.5.4 PROC MIXED Analysis of Crossed-Nested Classification 131

4.6 Split-Plot Experiments 135

4.6.1 A Standard Split-Plot Experiment 136 4.6.1.1 Analysis of Variance Using PROC GLM 137 4.6.1.2 Analysis with PROC MIXED 139

Chapter 5 Unbalanced Data Analysis: Basic Methods

5.1 Introduction 141

5.2 Applied Concepts of Analyzing Unbalanced Data 142

- 5.2.1 ANOVA for Unbalanced Data 144
- 5.2.2 Using the CONTRAST and ESTIMATE Statements with Unbalanced Data 146
- 5.2.3 The LSMEANS Statement 147
- 5.2.4 More on Comparing Means: Other Hypotheses and Types of Sums of Squares 147

5.3 Issues Associated with Empty Cells 148

- 5.3.1 The Effect of Empty Cells on Types of Sums of Squares 149
- 5.3.2 The Effect of Empty Cells on CONTRAST, ESTIMATE, and LSMEANS Results 150
- 5.4 Some Problems with Unbalanced Mixed-Model Data 151

5.5 Using the GLM Procedure to Analyze Unbalanced Mixed-Model Data 152

- 5.5.1 Approximate F-Statistics from ANOVA Mean Squares with Unbalanced Mixed-Model Data 152
- 5.5.2 Using the CONTRAST, ESTIMATE, and LSMEANS Statements in GLM with Unbalanced Mixed-Model Data 155

- 5.6 Using the MIXED Procedure to Analyze Unbalanced Mixed-Model Data 156
- 5.7 Using the GLM and MIXED Procedures to Analyze Mixed-Model Data with Empty Cells 158
- 5.8 Summary and Conclusions about Using the GLM and MIXED Procedures to Analyze Unbalanced Mixed-Model Data 161

Chapter 6 Understanding Linear Models Concepts

6.1 Introduction 163

6.2 The Dummy-Variable Model 164

- 6.2.1 The Simplest Case: A One-Way Classification 164
- 6.2.2 Parameter Estimates for a One-Way Classification 167
- 6.2.3 Using PROC GLM for Analysis of Variance 170
- 6.2.4 Estimable Functions in a One-Way Classification 175

6.3 Two-Way Classification: Unbalanced Data 179

- 6.3.1 General Considerations 179
- 6.3.2 Sums of Squares Computed by PROC GLM 182
- 6.3.3 Interpreting Sums of Squares in Reduction Notation 183
- 6.3.4 Interpreting Sums of Squares in µ-Model Notation 185
- 6.3.5 An Example of Unbalanced Two-Way Classification 188
- 6.3.6 The MEANS, LSMEANS, CONTRAST, and ESTIMATE Statements in a Two-Way Layout 191
- 6.3.7 Estimable Functions for a Two-Way Classification 194
 - 6.3.7.1 The General Form of Estimable Functions 194
 - 6.3.7.2 Interpreting Sums of Squares Using Estimable Functions 196
 - 6.3.7.3 Estimating Estimable Functions 201
 - 6.3.7.4 Interpreting LSMEANS, CONTRAST, and ESTIMATE Results Using Estimable Functions 201
- 6.3.8 Empty Cells 203

6.4 Mixed-Model Issues 214

- 6.4.1 Proper Error Terms 214
- 6.4.2 More on Expected Mean Squares 216
- 6.4.3 An Issue of Model Formulation Related to Expected Mean Squares 221

6.5 ANOVA Issues for Unbalanced Mixed Models 222

6.5.1 Using Expected Mean Squares to Construct Approximate F-Tests for Fixed Effects 222

6.6 GLS and Likelihood Methodology Mixed Model 225

- 6.6.1 An Overview of Generalized Least Squares Methodology 225
- 6.6.2 Some Practical Issues about Generalized Least Squares Methodology 227

Chapter 7 Analysis of Covariance

7.1 Introduction 229

7.2 A One-Way Structure 230

- 7.2.1 Covariance Model 230
- 7.2.2 Means and Least-Squares Means 234
- 7.2.3 Contrasts 237
- 7.2.4 Multiple Covariates 238

7.3 Unequal Slopes 239

- 7.3.1 Testing the Heterogeneity of Slopes 240
- 7.3.2 Estimating Different Slopes 241
- 7.3.3 Testing Treatment Differences with Unequal Slopes 244
- 7.4 A Two-Way Structure without Interaction 247
- 7.5 A Two-Way Structure with Interaction 249

7.6 Orthogonal Polynomials and Covariance Methods 256

- 7.6.1 A 2×3 Example 256
- 7.6.2 Use of the IML ORPOL Function to Obtain Orthogonal Polynomial Contrast Coefficients 259
- 7.6.3 Use of Analysis of Covariance to Compute ANOVA and Fit Regression 261

Chapter 8 Repeated-Measures Analysis

8.1 Introduction 265

8.2 The Univariate ANOVA Method for Analyzing Repeated Measures 269

- 8.2.1 Using GLM to Perform Univariate ANOVA of Repeated-Measures Data 270
- 8.2.2 The CONTRAST, ESTIMATE, and LSMEANS Statements in Univariate ANOVA of Repeated-Measures Data 272

8.3 Multivariate and Univariate Methods Based on Contrasts of the Repeated Measures 274

- 8.3.1 Univariate ANOVA of Repeated Measures at Each Time 274
- 8.3.2 Using the REPEATED Statement in PROC GLM to Perform Multivariate Analysis of Repeated-Measures Data 275
- 8.3.3 Univariate ANOVA of Contrasts of Repeated Measures 279

8.4 Mixed-Model Analysis of Repeated Measures 280

- 8.4.1 The Fixed-Effects Model and Related Considerations 281
- 8.4.2 Selecting an Appropriate Covariance Model 284
- 8.4.3 Reassessing the Covariance Structure with a Means Model Accounting for Baseline Measurement 291
- 8.4.4 Information Criteria to Compare Covariance Models 292
- 8.4.5 PROC MIXED Analysis of FEV1 Data 296
- 8.4.6 Inference on the Treatment and Time Effects of FEV1 Data Using PROC MIXED 298 8.4.6.1 Comparisons of DRUG*HOUR Means 299
 - 8.4.6.2 Comparisons Using Regression 301

Chapter 9 Multivariate Linear Models

- 9.1 Introduction 305
- 9.2 A One-Way Multivariate Analysis of Variance 306
- 9.3 Hotelling's T² Test 309
- 9.4 A Two-Factor Factorial 312
- 9.5 Multivariate Analysis of Covariance 317
- 9.6 Contrasts in Multivariate Analyses 320
- 9.7 Statistical Background 321

Chapter 10 Generalized Linear Models

10.1 Introduction 325

10.2 The Logistic and Probit Regression Models 328

- 10.2.1 Logistic Regression: The Challenger Shuttle O-Ring Data Example 328
- 10.2.2 Using the Inverse Link to Get the Predicted Probability 331
- 10.2.3 Alternative Logistic Regression Analysis Using 0-1 Data 334
- 10.2.4 An Alternative Link: Probit Regression 336

10.3 Binomial Models for Analysis of Variance and Analysis of Covariance 339

- 10.3.1 Logistic ANOVA 339
- 10.3.2 The Analysis-of-Variance Model with a Probit Link 344
- 10.3.3 Logistic Analysis of Covariance 347

10.4 Count Data and Overdispersion 353

- 10.4.1 An Insect Count Example 353
- 10.4.2 Model Checking 357
- 10.4.3 Correction for Overdispersion 362
- 10.4.4 Fitting a Negative Binomial Model 366
- 10.4.5 Using PROC GENMOD to Fit the Negative Binomial with a Log Link 367
- 10.4.6 Fitting the Negative Binomial with a Canonical Link 369
- 10.4.7 Advanced Application: A User-Supplied Program to Fit the Negative Binomial with a Canonical Link 372

10.5 Generalized Linear Models with Repeated Measures—Generalized Estimating Equations 377

10.5.1 A Poisson Repeated-Measures Example37710.5.2 Using PROC GENMOD to Compute a GEE Analysis of Repeated Measures379

10.6 Background Theory 384

- 10.6.1 The Generalized Linear Model Defined 385
- 10.6.2 How the GzLM's Parameters Are Estimated 386
- 10.6.3 Standard Errors and Test Statistics 386
- 10.6.4 Quasi-Likelihood 387
- 10.6.5 Repeated Measures and Generalized Estimating Equations 388

Chapter 11 Examples of Special Applications

11.1 Introduction 389

- **11.2** Confounding in a Factorial Experiment38911.2.1Confounding with Blocks39011.2.2A Fractional Factorial Example394
- 11.3 A Balanced Incomplete-Blocks Design 398
- 11.4 A Crossover Design with Residual Effects 402
- 11.5 Models for Experiments with Qualitative and Quantitative Variables 409
- 11.6 A Lack-of-Fit Analysis 413
- 11.7 An Unbalanced Nested Structure 416

11.8 An Analysis of Multi-Location Data 420

- 11.8.1 An Analysis Assuming No Location×Treatment Interaction 421
- 11.8.2 A Fixed-Location Analysis with an Interaction 423
- 11.8.3 A Random-Location Analysis 425
- 11.8.4 Further Analysis of a Location×Treatment Interaction Using a Location Index 428
- 11.9 Absorbing Nesting Effects 431

References 441

Index 447