# Contents

*Preface to Second Edition*  
*Preface to First Edition*  
*Abbreviations*  

## PART I  PRINCIPLES OF STATISTICAL THINKING AND ANALYSIS

1. **The Role of Statistical Methods in Modern Industry and Services**  
   1.1 The different functional areas in industry and services  
   1.2 The quality-productivity dilemma  
   1.3 Fire-fighting  
   1.4 Inspection of products  
   1.5 Process control  
   1.6 Quality by design  
   1.7 Information quality and practical statistical efficiency  
   1.8 Chapter highlights  
   1.9 Exercises

2. **Analyzing Variability: Descriptive Statistics**  
   2.1 Random phenomena and the structure of observations  
   2.2 Accuracy and precision of measurements  
   2.3 The population and the sample  
   2.4 Descriptive analysis of sample values  
      2.4.1 Frequency distributions of discrete random variables  
      2.4.2 Frequency distributions of continuous random variables  
      2.4.3 Statistics of the ordered sample  
      2.4.4 Statistics of location and dispersion  
   2.5 Prediction intervals  
   2.6 Additional techniques of exploratory data analysis  
      2.6.1 Box and whiskers plot  
      2.6.2 Quantile plots  
      2.6.3 Stem-and-leaf diagrams  
      2.6.4 Robust statistics for location and dispersion  
   2.7 Chapter highlights  
   2.8 Exercises

3. **Probability Models and Distribution Functions**  
   3.1 Basic probability  
      3.1.1 Events and sample spaces: Formal presentation of random measurements  
      3.1.2 Basic rules of operations with events: Unions, intersections  
      3.1.3 Probabilities of events
3.1.4 Probability functions for random sampling 46
3.1.5 Conditional probabilities and independence of events 47
3.1.6 Bayes formula and its application 49

3.2 Random variables and their distributions 51
3.2.1 Discrete and continuous distributions 51
3.2.2 Expected values and moments of distributions 55
3.2.3 The standard deviation, quantiles, measures of skewness and kurtosis 57
3.2.4 Moment generating functions 59

3.3 Families of discrete distribution 60
3.3.1 The binomial distribution 60
3.3.2 The hypergeometric distribution 62
3.3.3 The Poisson distribution 65
3.3.4 The geometric and negative binomial distributions 67

3.4 Continuous distributions 69
3.4.1 The uniform distribution on the interval \((a, b), a < b\) 69
3.4.2 The normal and log-normal distributions 70
3.4.3 The exponential distribution 75
3.4.4 The gamma and Weibull distributions 77
3.4.5 The Beta distributions 80

3.5 Joint, marginal and conditional distributions 82
3.5.1 Joint and marginal distributions 82
3.5.2 Covariance and correlation 84
3.5.3 Conditional distributions 86

3.6 Some multivariate distributions 88
3.6.1 The multinomial distribution 88
3.6.2 The multi-hypergeometric distribution 89
3.6.3 The bivariate normal distribution 90

3.7 Distribution of order statistics 92

3.8 Linear combinations of random variables 94

3.9 Large sample approximations 98
3.9.1 The law of large numbers 98
3.9.2 The Central Limit Theorem 99
3.9.3 Some normal approximations 99

3.10 Additional distributions of statistics of normal samples 101
3.10.1 Distribution of the sample variance 101
3.10.2 The “Student” \(t\)-statistic 102
3.10.3 Distribution of the variance ratio 102

3.11 Chapter highlights 104

3.12 Exercises 105

4 Statistical Inference and Bootstrapping 113
4.1 Sampling characteristics of estimators 113
4.2 Some methods of point estimation 114
4.2.1 Moment equation estimators 115
4.2.2 The method of least squares 116
4.2.3 Maximum likelihood estimators 118

4.3 Comparison of sample estimates 120
4.3.1 Basic concepts 120
4.3.2 Some common one-sample tests of hypotheses 122

4.4 Confidence intervals 128
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.4.1 Confidence intervals for $\mu$; $\sigma$ known</td>
<td>129</td>
</tr>
<tr>
<td>4.4.2 Confidence intervals for $\mu$; $\sigma$ unknown</td>
<td>130</td>
</tr>
<tr>
<td>4.4.3 Confidence intervals for $\sigma^2$</td>
<td>130</td>
</tr>
<tr>
<td>4.4.4 Confidence intervals for $p$</td>
<td>130</td>
</tr>
<tr>
<td>4.5 Tolerance intervals</td>
<td>132</td>
</tr>
<tr>
<td>4.5.1 Tolerance intervals for the normal distributions</td>
<td>132</td>
</tr>
<tr>
<td>4.6 Testing for normality with probability plots</td>
<td>134</td>
</tr>
<tr>
<td>4.7 Tests of goodness of fit</td>
<td>137</td>
</tr>
<tr>
<td>4.7.1 The chi-square test (large samples)</td>
<td>137</td>
</tr>
<tr>
<td>4.7.2 The Kolmogorov-Smirnov test</td>
<td>139</td>
</tr>
<tr>
<td>4.8 Bayesian decision procedures</td>
<td>140</td>
</tr>
<tr>
<td>4.8.1 Prior and posterior distributions</td>
<td>141</td>
</tr>
<tr>
<td>4.8.2 Bayesian testing and estimation</td>
<td>144</td>
</tr>
<tr>
<td>4.8.3 Credibility intervals for real parameters</td>
<td>147</td>
</tr>
<tr>
<td>4.9 Random sampling from reference distributions</td>
<td>148</td>
</tr>
<tr>
<td>4.10 Bootstrap sampling</td>
<td>150</td>
</tr>
<tr>
<td>4.10.1 The bootstrap method</td>
<td>150</td>
</tr>
<tr>
<td>4.10.2 Examining the bootstrap method</td>
<td>151</td>
</tr>
<tr>
<td>4.10.3 Harnessing the bootstrap method</td>
<td>152</td>
</tr>
<tr>
<td>4.11 Bootstrap testing of hypotheses</td>
<td>152</td>
</tr>
<tr>
<td>4.11.1 Bootstrap testing and confidence intervals for the mean</td>
<td>153</td>
</tr>
<tr>
<td>4.11.2 Studentized test for the mean</td>
<td>153</td>
</tr>
<tr>
<td>4.11.3 Studentized test for the difference of two means</td>
<td>155</td>
</tr>
<tr>
<td>4.11.4 Bootstrap tests and confidence intervals for the variance</td>
<td>157</td>
</tr>
<tr>
<td>4.11.5 Comparing statistics of several samples</td>
<td>158</td>
</tr>
<tr>
<td>4.12 Bootstrap tolerance intervals</td>
<td>161</td>
</tr>
<tr>
<td>4.12.1 Bootstrap tolerance intervals for Bernoulli samples</td>
<td>161</td>
</tr>
<tr>
<td>4.12.2 Tolerance interval for continuous variables</td>
<td>163</td>
</tr>
<tr>
<td>4.12.3 Distribution-free tolerance intervals</td>
<td>164</td>
</tr>
<tr>
<td>4.13 Non-parametric tests</td>
<td>165</td>
</tr>
<tr>
<td>4.13.1 The sign test</td>
<td>165</td>
</tr>
<tr>
<td>4.13.2 The randomization test</td>
<td>166</td>
</tr>
<tr>
<td>4.13.3 The Wilcoxon Signed Rank test</td>
<td>168</td>
</tr>
<tr>
<td>4.14 Description of MINITAB macros (available for download from Appendix VI of the book website)</td>
<td>170</td>
</tr>
<tr>
<td>4.15 Chapter highlights</td>
<td>170</td>
</tr>
<tr>
<td>4.16 Exercises</td>
<td>171</td>
</tr>
</tbody>
</table>

5 Variability in Several Dimensions and Regression Models

5.1 Graphical display and analysis                                      | 177  |
| 5.1.1 Scatterplots                                                     | 177  |
| 5.1.2 Multiple boxplots                                                | 179  |
| 5.2 Frequency distributions in several dimensions                     | 181  |
| 5.2.1 Bivariate joint frequency distributions                         | 182  |
| 5.2.2 Conditional distributions                                       | 185  |
| 5.3 Correlation and regression analysis                                | 185  |
| 5.3.1 Covariances and correlations                                    | 185  |
| 5.3.2 Fitting simple regression lines to data                         | 187  |
| 5.4 Multiple regression                                               | 192  |
| 5.4.1 Regression on two variables                                     | 194  |
| 5.5 Partial regression and correlation                                | 198  |
5.6 Multiple linear regression 200
5.7 Partial $F$-tests and the sequential SS 204
5.8 Model construction: Step-wise regression 206
5.9 Regression diagnostics 209
5.10 Quantal response analysis: Logistic regression 211
5.11 The analysis of variance: The comparison of means 213
5.11.1 The statistical model 213
5.11.2 The one-way analysis of variance (ANOVA) 214
5.12 Simultaneous confidence intervals: Multiple comparisons 216
5.13 Contingency tables 220
5.13.1 The structure of contingency tables 220
5.13.2 Indices of association for contingency tables 223
5.14 Categorical data analysis 227
5.14.1 Comparison of binomial experiments 227
5.15 Chapter highlights 229
5.16 Exercises 230

PART II ACCEPTANCE SAMPLING 235

6 Sampling for Estimation of Finite Population Quantities 237
6.1 Sampling and the estimation problem 237
6.1.1 Basic definitions 237
6.1.2 Drawing a random sample from a finite population 238
6.1.3 Sample estimates of population quantities and their sampling distribution 239
6.2 Estimation with simple random samples 241
6.2.1 Properties of $\bar{X}_n$ and $S^2_n$ under RSWR 242
6.2.2 Properties of $\bar{X}_n$ and $S^2_n$ under RSWOR 244
6.3 Estimating the mean with stratified RSWOR 248
6.4 Proportional and optimal allocation 249
6.5 Prediction models with known covariates 252
6.6 Chapter highlights 255
6.7 Exercises 256

7 Sampling Plans for Product Inspection 258
7.1 General discussion 258
7.2 Single-stage sampling plans for attributes 259
7.3 Approximate determination of the sampling plan 262
7.4 Double-sampling plans for attributes 264
7.5 Sequential sampling 267
7.6 Acceptance sampling plans for variables 270
7.7 Rectifying inspection of lots 272
7.8 National and international standards 274
7.9 Skip-lot sampling plans for attributes 276
7.9.1 The ISO 2859 skip-lot sampling procedures 276
7.10 The Deming inspection criterion 278
7.11 Published tables for acceptance sampling 279
7.12 Chapter highlights 280
7.13 Exercises 281
### PART III  STATISTICAL PROCESS CONTROL  283

#### 8 Basic Tools and Principles of Process Control  285

8.1 Basic concepts of statistical process control  285  
8.2 Driving a process with control charts  294  
8.3 Setting up a control chart: Process capability studies  298  
8.4 Process capability indices  300  
8.5 Seven tools for process control and process improvement  302  
8.6 Statistical analysis of Pareto charts  305  
8.7 The Shewhart control charts  308  
8.7.1 Control charts for attributes  309  
8.7.2 Control charts for variables  311  
8.8 Chapter highlights  316  
8.9 Exercises  316

#### 9 Advanced Methods of Statistical Process Control  319

9.1 Tests of randomness  319  
9.1.1 Testing the number of runs  319  
9.1.2 Runs above and below a specified level  321  
9.1.3 Runs up and down  323  
9.1.4 Testing the length of runs up and down  324  
9.2 Modified Shewhart control charts for $X$  325  
9.3 The size and frequency of sampling for Shewhart control charts  328  
9.3.1 The economic design for $X$-charts  328  
9.3.2 Increasing the sensitivity of $p$-charts  328  
9.4 Cumulative sum control charts  330  
9.4.1 Upper Page’s scheme  330  
9.4.2 Some theoretical background  333  
9.4.3 Lower and two-sided Page’s scheme  335  
9.4.4 Average run length, probability of false alarm and conditional expected delay  339  
9.5 Bayesian detection  342  
9.6 Process tracking  346  
9.6.1 The EWMA procedure  347  
9.6.2 The BECM procedure  348  
9.6.3 The Kalman filter  350  
9.6.4 Hoadley’s QMP  351  
9.7 Automatic process control  354  
9.8 Chapter highlights  356  
9.9 Exercises  357

#### 10 Multivariate Statistical Process Control  361

10.1 Introduction  361  
10.2 A review of multivariate data analysis  365  
10.3 Multivariate process capability indices  367  
10.4 Advanced applications of multivariate control charts  370  
10.4.1 Multivariate control charts scenarios  370  
10.4.2 Internally derived targets  370  
10.4.3 Using an external reference sample  371  
10.4.4Externally assigned targets  372
10.4.5 Measurement units considered as batches | 373
10.4.6 Variable decomposition and monitoring indices | 373
10.5 Multivariate tolerance specifications | 374
10.6 Chapter highlights | 376
10.7 Exercises | 377

PART IV DESIGN AND ANALYSIS OF EXPERIMENTS

11 Classical Design and Analysis of Experiments
11.1 Basic steps and guiding principles | 381
11.2 Blocking and randomization | 385
11.3 Additive and non-additive linear models | 385
11.4 The analysis of randomized complete block designs
   11.4.1 Several blocks, two treatments per block: Paired comparison | 387
   11.4.2 Several blocks, \( t \) treatments per block | 391
11.5 Balanced incomplete block designs | 394
11.6 Latin square design | 397
11.7 Full factorial experiments
   11.7.1 The structure of factorial experiments | 402
   11.7.2 The ANOVA for full factorial designs | 402
   11.7.3 Estimating main effects and interactions | 408
   11.7.4 \( 2^m \) factorial designs | 409
   11.7.5 \( 3^m \) factorial designs | 417
11.8 Blocking and fractional replications of \( 2^m \) factorial designs | 425
11.9 Exploration of response surfaces
   11.9.1 Second order designs | 430
   11.9.2 Some specific second order designs | 433
   11.9.3 Approaching the region of the optimal yield | 438
   11.9.4 Canonical representation | 440
11.10 Chapter highlights | 441
11.11 Exercises | 442

12 Quality by Design
12.1 Off-line quality control, parameter design and the Taguchi method
   12.1.1 Product and process optimization using loss functions | 447
   12.1.2 Major stages in product and process design | 448
   12.1.3 Design parameters and noise factors | 449
   12.1.4 Parameter design experiments | 450
   12.1.5 Performance statistics | 452
12.2 The effects of non-linearity | 452
12.3 Taguchi’s designs | 456
12.4 Quality by design in the pharmaceutical industry
   12.4.1 Introduction to quality by design | 458
   12.4.2 A quality by design case study – the full factorial design | 459
   12.4.3 A quality by design case study – the profiler and desirability function | 462
   12.4.4 A quality by design case study – the design space | 462
12.5 Tolerance designs | 462
12.6 More case studies
   12.6.1 The Quinlan experiment at Flex Products, Inc. | 467
   12.6.2 Computer response time optimization | 469
13 Computer Experiments 477
13.1 Introduction to computer experiments 477
13.2 Designing computer experiments 481
13.3 Analyzing computer experiments 483
13.4 Stochastic emulators 488
13.5 Integrating physical and computer experiments 491
13.6 Chapter highlights 492
13.7 Exercises 492

PART V RELIABILITY AND SURVIVAL ANALYSIS 495

14 Reliability Analysis 497
14.1 Basic notions 498
14.1.1 Time categories 498
14.1.2 Reliability and related functions 499
14.2 System reliability 500
14.3 Availability of repairable systems 503
14.4 Types of observations on TTF 509
14.5 Graphical analysis of life data 510
14.6 Non-parametric estimation of reliability 513
14.7 Estimation of life characteristics 514
14.7.1 Maximum likelihood estimators for exponential TTF distribution 514
14.7.2 Maximum likelihood estimation of the Weibull parameters 518
14.8 Reliability demonstration 520
14.8.1 Binomial testing 520
14.8.2 Exponential distributions 521
14.9 Accelerated life testing 528
14.9.1 The Arrhenius temperature model 528
14.9.2 Other models 529
14.10 Burn-in procedures 529
14.11 Chapter highlights 530
14.12 Exercises 531

15 Bayesian Reliability Estimation and Prediction 534
15.1 Prior and posterior distributions 534
15.2 Loss functions and Bayes estimators 537
15.2.1 Distribution-free Bayes estimator of reliability 538
15.2.2 Bayes estimator of reliability for exponential life distributions 538
15.3 Bayesian credibility and prediction intervals 539
15.3.1 Distribution-free reliability estimation 539
15.3.2 Exponential reliability estimation 540
15.3.3 Prediction intervals 540
15.4 Credibility intervals for the asymptotic availability of repairable systems: The exponential case 542
15.5 Empirical Bayes method 543
15.6 Chapter highlights 545
15.7 Exercises 545
List of R Packages 547
References and Further Reading 549
Author Index 555
Subject Index 557

Also available on book’s website: www.wiley.com/go/modern_industrial_statistics

Appendix I: An Introduction to R by Stefano Iacus
Appendix II: Basic MINITAB Commands and a Review of Matrix Algebra for Statistics
Appendix III: mistat Manual (mistat.pdf) and List of R Scripts, by Chapter (R_scripts.zip)
Appendix IV: Source Version of mistat Package (mistat_1.0.tar.gz), also available on the
Comprehensive R Archive Network (CRAN) Website.
Appendix V: Data Sets as csv Files
Appendix VI: MINITAB Macros
Appendix VII: JMP Scripts by Ian Cox
Appendix VIII: Solution Manual