

# Contents

<b>List of Tables</b>	<b>xiii</b>
<b>List of Figures</b>	<b>xiv</b>
<b>Preface</b>	<b>xix</b>
<b>About the Companion Website</b>	<b>xxiii</b>
<b>I Linear Time Series Methods</b>	<b>1</b>
<b>R and Time Series Analysis</b>	<b>3</b>
Overview	3
Some Useful R Functions for Time Series Analysis	4
<b>1 Introduction to Linear Time Series Models</b>	<b>7</b>
1.1 Overview	7
1.2 Time Series Data	8
1.3 Patterns in Time Series	9
1.4 Stationary versus Non-Stationary Series	9
1.5 Examples of Univariate Random Processes	12
1.5.1 White Noise Processes	12
1.5.2 Random Walk Processes	13
1.6 Characterizing Time Series	14
1.6.1 The Autocorrelation Function	14
1.6.2 The Sample Autocorrelation Function	16
1.6.3 Non-Stationarity and Differencing	16
1.7 Tests for White Noise Processes	18
1.7.1 Individual Test for $H_0: \rho_k = 0$ —Bartlett’s Test	18
1.7.2 Joint Test for $H_0: \rho_1 = 0 \cap \rho_2 = 0 \cap \dots \cap \rho_k = 0$ — Ljung & Box’s Test	19
1.7.3 A Simulated Illustration—Testing for a White Noise Process	19
1.7.4 A Simulated Illustration—White Noise Tests when the Series is a Random Walk Process	21

<b>2</b>	<b>Random Walks, Unit Roots, and Spurious Relationships</b>	<b>23</b>
2.1	Overview	23
2.2	Properties of a Random Walk	24
2.3	The Autocorrelation Function for a Random Walk	25
2.4	Classical Least Squares Estimators and Random Walks	25
2.5	Classical Least Squares Inference and Random Walks	26
2.5.1	Cross-Section (I.I.D. Data) Monte Carlo	26
2.5.2	Time Series (Random Walk) Monte Carlo	27
2.5.3	Time Series (Random Walk with Drift) Monte Carlo	29
2.6	Unit Root Tests	30
2.6.1	Testing for a Unit Root in Spot Exchange Rates	32
2.7	Random Walks and Spurious Regression	33
<b>3</b>	<b>Univariate Linear Time Series Models</b>	<b>37</b>
3.1	Overview	37
3.2	Moving Average Models ( $MA(q)$ )	38
3.2.1	Structure of $MA(q)$ Processes	38
3.2.2	Example—Residential Electricity Sales	38
3.2.3	Properties of $MA(q)$ Processes	39
3.2.4	Stationarity of $MA(q)$ Processes	40
3.2.5	The Autocorrelation Function and Identification of $MA(q)$ Processes	40
3.2.6	Forecasting $MA(q)$ Processes	41
3.2.7	Forecasting $MA(q)$ Processes Assuming the $\epsilon_{T-i}$ and the $\theta_i$ are Known	41
3.2.8	Forecasting $MA(q)$ Processes when the $\epsilon_{T-i}$ and the $\theta_i$ are Estimated	42
3.2.9	Forecasting $MA(q)$ Processes in the Presence of a Trend	43
3.3	Autoregressive Models ( $AR(p)$ )	44
3.3.1	Structure of $AR(p)$ Processes	44
3.3.2	Example—Residential Electricity Sales	45
3.3.3	Properties of $AR(p)$ Processes	46
3.3.4	Stationarity of $AR(p)$ Processes	48
3.3.5	Invertibility of Stationary $AR(p)$ Processes	50
3.3.6	Identification of $AR(p)$ Processes—The Partial Autocorrelation Function	50
3.3.7	Forecasting $AR(p)$ Processes	51
3.3.8	Forecasting $AR(p)$ Processes when the Parameters $\phi_i$ are Unknown	53
3.3.9	Forecasting $AR(p)$ Processes in the Presence of a Trend	54
3.4	Non-Seasonal Autoregressive Moving Average Models ( $ARMA(p, q)$ )	55

3.4.1	Structure	55
3.5	Non-Seasonal Autoregressive Integrated Moving Average Models (ARIMA( $p, d, q$ ))	55
3.5.1	Structure	55
3.5.2	Stationarity of ARIMA( $p, d, q$ ) Models	56
3.5.3	Identification of ARIMA( $p, d, q$ ) Processes	57
3.5.4	Estimation of ARIMA( $p, d, q$ ) Processes	57
3.5.5	Forecasting ARIMA( $p, d, q$ ) Processes	58
3.5.6	Trends, Constants, and ARIMA( $p, d, q$ ) Models	59
3.5.7	Model Selection Criteria, Trends, and Stationarity	62
3.5.8	Model Selection via <code>auto.arima()</code>	65
3.5.9	Diagnostics for ARIMA( $p, d, q$ ) Models	67
3.6	Seasonal Autoregressive Integrated Moving Average Models (ARIMA( $p, d, q$ )( $P, D, Q$ ) $_m$ )	67
3.6.1	Example—Modelling and Forecasting European Quarterly Retail Trade	71
3.6.2	Example—Modelling Monthly Cortecosteroid Drug Sales	72
3.7	ARIMA( $p, d, q$ )( $P, D, Q$ ) $_m$ Models with External Predictors	74
3.8	Assessing Model Accuracy on Hold-Out Data	77
	<b>Problem Set</b>	<b>81</b>
	<b>II Robust Parametric Inference</b>	<b>85</b>
	<b>R, The Bootstrap and the Jackknife</b>	<b>87</b>
	Overview	87
	Some Useful R Functions for Data-Driven Inference	87
	<b>4 Robust Parametric Inference</b>	<b>89</b>
4.1	Overview	89
4.2	Analytical Versus Numerical, i.e., Data-Driven, Procedures	90
4.2.1	Drawbacks of the Analytical Approach	91
4.2.2	An Illustrative Example—Testing for a Unit Root	91
4.3	Alternatives to Analytical Approaches	92
4.3.1	Motivating Example—Compute the Standard Error of $\bar{X}$	92
4.4	An Introduction to Efron's Bootstrap	93
4.4.1	Bootstrapping a Standard Error for the Sample Mean	93
4.4.2	Bootstrap Implementations in R	94
4.5	Jackknifing—Background and Motivating Example	95
4.6	Jackknife and Bootstrap Estimates of Bias	97
4.7	To Bootstrap or Jackknife?	99

4.8	Data-Driven Covariance Matrices	99
4.8.1	Bootstrap Heteroskedasticity Consistent Covariance Matrix Estimation	100
4.9	The Wild Bootstrap	102
4.10	Bootstrapping Dependent Processes	104
4.11	Bootstrap Confidence Intervals	105
4.11.1	Example—Nonparametric Confidence Intervals for the Population Mean	106
4.12	Bootstrap Inference	108
4.12.1	How Many Bootstrap Replications?	109
4.12.2	Generating $\hat{\theta}^*$ Under the Null	110
4.12.3	Example—The Two-Sample Problem	111
4.12.4	Example—Regression-Based Bootstrap Inference	112
4.12.5	Example—Unit Root Testing	114
	<b>Problem Set</b>	<b>117</b>
	<b>III Robust Parametric Estimation</b>	<b>119</b>
	<b>R and Robust Parametric Estimation</b>	<b>121</b>
	Overview	121
	Some Useful R Functions for Robust Parametric Estimation	121
<b>5</b>	<b>Robust Parametric Estimation</b>	<b>123</b>
5.1	Overview	123
5.2	Robust Estimation Basics	124
5.2.1	Outlier	124
5.2.2	Breakdown Point	125
5.2.3	Sensitivity Curve	125
5.2.4	Contamination Neighborhoods	126
5.2.5	Influence Function	128
5.3	Unmasking Univariate Outliers	129
5.3.1	$L_1$ and $L_2$ -norm Estimators of Central Tendency	130
5.3.2	Robustness versus Efficiency	132
5.3.3	$M$ -Estimator Methods	133
5.3.4	Optimal Robustness	135
5.3.5	Huber's $M$ -Estimator of Location—A More Efficient Robust Location Estimator than the Median	135
5.3.6	Rousseeuw and Croux's $Q_n$ Estimator of Scale—A More Efficient Robust Scale Estimator than $MAD_n$	137
5.3.7	$M$ -Estimators of Scale	139
5.3.8	Unmasking Univariate Outliers—The <i>three-sigma edit</i> rule	142

5.4	Unmasking Multivariate Outliers	142
5.5	Unmasking Regression Outliers	148
5.5.1	Outliers in the $Y$ Direction	148
5.5.2	Outliers in the $X$ Direction	150
5.5.3	Leverage Points	150
5.5.4	Dealing with Outlying Observations and Leverage Points	152
5.6	Robust Regression	160
5.6.1	Robust Residuals and High Breakdown Diagnostics	164
5.7	Some Useful Points to Remember	165
	<b>Problem Set</b>	<b>167</b>
	<b>IV Model Uncertainty</b>	<b>171</b>
	<b>R and Model Uncertainty</b>	<b>173</b>
	Overview	173
	Some Useful R Functions for Model Uncertainty	173
	<b>6 Model Uncertainty</b>	<b>175</b>
6.1	Overview	175
6.1.1	Model Selection References	176
6.1.2	Model Averaging References	176
6.1.3	Resources	177
6.2	A Reflection on Models and Data Generating Processes	177
6.2.1	Model Selection and Averaging--A Simulation	181
6.2.2	Discussion	183
6.3	Kullback-Leibler Distance and Maximum Likelihood Estimation	184
6.4	Model Selection Methods	186
6.4.1	AIC, BIC, $C_p$ and Cross-Validated Model Selection Criteria	186
6.5	Model Averaging Methods	189
6.5.1	Solving for the Optimal Model Average Weights	190
6.5.2	Selecting Candidate Models	191
6.5.3	Pitfalls of Model Selection and Model Averaging	196
6.5.4	An Experimental Robust Regression M-Estimator Model Averaging Procedure	196
	<b>Problem Set</b>	<b>201</b>

<b>V</b>	<b>Advanced Topics</b>	<b>207</b>
	<b>R and Advanced Topics</b>	<b>209</b>
	Overview	209
	Some Useful R Functions for Advanced Topics	209
<b>7</b>	<b>Advanced Topics</b>	<b>211</b>
	7.1 Overview	211
	7.2 Classification Analysis and Support Vector Machines	211
	7.2.1 <i>The Confusion Matrix</i>	212
	7.2.2 Support Vector Machines	213
	7.3 Nonparametric Kernel Regression	220
	<b>Problem Set</b>	<b>225</b>
<b>VI</b>	<b>Appendix</b>	<b>227</b>
<b>A</b>	<b>R, RStudio, TeX, and Git</b>	<b>229</b>
	A.1 Installation of R and RStudio Desktop	229
	A.2 What is R?	229
	A.2.1 R in the News	230
	A.2.2 <i>Introduction to R</i>	230
	A.2.3 Econometrics in R	230
	A.3 What is RStudio Desktop?	231
	A.3.1 Introduction to RStudio	231
	A.4 Installation of TeX	231
	A.5 <i>Installation of Git</i>	231
<b>B</b>	<b>R Markdown for Assignments</b>	<b>233</b>
	B.1 Source Code (R Markdown) for this Document	233
	B.2 R, RStudio, TeX and git	233
	B.3 What is R Markdown?	233
	B.4 Creating a New R Markdown Document in RStudio	234
	B.5 Including R Results in your R Markdown Document	234
	B.6 Reading Data from a URL	234
	B.7 Including Plots	235
	B.8 Including Bulleted and Numbered lists	236
	B.9 Including Tables	237
	B.10 Including Verbatim, i.e., Freeform, Text	237
	B.11 Typesetting Mathematics	237
	B.12 Flexible Document Creation	238
	B.13 Knitting your R Markdown Document	238
	B.14 Printing Your Assignment for Submitting in Class	238
	B.15 Troubleshooting and Tips	239

<b>C</b>	<b>Maximum Likelihood Estimation and Inference</b>	<b>243</b>
C.1	Maximum Likelihood Estimation	243
C.2	Properties of the Maximum Likelihood Estimators	244
C.3	Maximum Likelihood Estimation in Practice	246
C.4	A Simple Example Using Discrete Data	246
C.4.1	Example—	247
C.4.2	Example—	248
C.5	Maximum Likelihood Estimation of the Normal Linear Multivariate Regression Model	249
C.6	Information and the Normal Linear Multivariate Model	252
C.6.1	Example—	253
C.7	Restricted Maximum Likelihood Estimates	254
C.8	Hypothesis Testing in a Maximum Likelihood Framework	254
C.8.1	Example—	255
C.8.2	Example—	256
<b>D</b>	<b>Solving a Quadratic Program Using R</b>	<b>259</b>
D.1	Example	260
<b>E</b>	<b>A Primer on Regression Splines</b>	<b>263</b>
E.1	Overview	263
E.2	Bézier curves	264
E.2.1	Example—A quadratic Bézier curve	264
E.2.2	The Bézier curve defined	265
E.2.3	Example—A quadratic Bézier curve as a linear interpolation between two linear Bézier curves	265
E.2.4	Example—The quadratic Bézier curve basis functions	266
E.3	Derivatives of spline functions	267
E.4	B-splines	267
E.4.1	B-spline knots	267
E.4.2	The B-spline basis function	268
E.4.3	Example—A fourth-order B-spline basis function with three interior knots and its first derivative function	269
E.5	The B-spline function	269
E.6	Multivariate B-spline regression	269
E.6.1	Multivariate knots, intervals, and spline bases	271
E.7	Spline regression	272
	<b>Bibliography</b>	<b>273</b>
	<b>Author Index</b>	<b>281</b>