RISK ASSESSMENT AND DECISION ANALYSIS WITH BAYESIAN NETWORKS

NORMAN FENTON
MARTIN NEIL
Contents

Foreword xi
Preface xiii
Acknowledgments xvii
Authors xix

Chapter 1 There Is More to Assessing Risk Than Statistics 1
1.1 Introduction 1
1.2 Predicting Economic Growth: The Normal Distribution and Its Limitations 3
1.3 Patterns and Randomness: From School League Tables to Siegfried and Roy 7
1.4 Dubious Relationships: Why You Should Be Very Wary ofCorrelations and Their Significance Values 10
1.5 Spurious Correlations: How You Can Always Find a Silly ‘Cause’ of Exam Success 14
1.6 The Danger of Regression: Looking Back When You Need to Look Forward 16
1.7 The Danger of Averages 18
1.7.1 What Type of Average? 19
1.7.2 When Averages Alone Will Never Be Sufficient for Decision Making 20
1.8 When Simpson’s Paradox Becomes More Worrisome 21
1.9 Uncertain Information and Incomplete Information: Do Not Assume They Are Different 23
1.10 Do Not Trust Anybody (Even Experts) to Properly Reason about Probabilities 26
1.11 Chapter Summary 29
Further Reading 29

Chapter 2 The Need for Causal, Explanatory Models in Risk Assessment 31
2.1 Introduction 31
2.2 Are You More Likely to Die in an Automobile Crash When the Weather Is Good Compared to Bad? 31
2.3 When Ideology and Causation Collide 35
2.4 The Limitations of Common Approaches to Risk Assessment 37
2.4.1 Measuring Armageddon and Other Risks 37
2.4.2 Risks and Opportunities 39
2.4.3 Risk Registers and Heat Maps 40
2.5 Thinking about Risk Using Causal Analysis 42
2.6 Applying the Causal Framework to Armageddon 46
2.7 Summary 49
Further Reading 49

Chapter 3 Measuring Uncertainty: The Inevitability of Subjectivity 51
3.1 Introduction 51
3.2 Experiments, Outcomes, and Events 52
3.2.1 Multiple Experiments 56
3.2.2 Joint Experiments 57
Chapter 4  The Basics of Probability ..................................................69
4.1 Introduction .............................................................................69
4.2 Some Observations Leading to Axioms and Theorems of Probability ...........................................................................69
4.3 Probability Distributions ........................................................81
  4.3.1 Probability Distributions with Infinite Outcomes .................83
  4.3.2 Joint Probability Distributions and Probability of Marginalized Events ..........................................................85
  4.3.3 Dealing with More than Two Variables ...............................88
4.4 Independent Events and Conditional Probability ......................89
4.5 Binomial Distribution ...............................................................96
4.6 Using Simple Probability Theory to Solve Earlier Problems and Explain Widespread Misunderstandings .........................101
  4.6.1 The Birthday Problem ......................................................101
  4.6.2 The Monty Hall Problem ..................................................103
  4.6.3 When Incredible Events Are Really Mundane ....................105
  4.6.4 When Mundane Events Really Are Quite Incredible ............109
4.7 Summary ................................................................................110
Further Reading ...........................................................................111

Chapter 5  Bayes’ Theorem and Conditional Probability ..................113
5.1 Introduction ............................................................................113
5.2 All Probabilities Are Conditional ............................................113
5.3 Bayes’ Theorem ......................................................................116
5.4 Using Bayes’ Theorem to Debunk Some Probability Fallacies .....121
  5.4.1 Traditional Statistical Hypothesis Testing ...........................122
  5.4.2 The Prosecutor Fallacy Revisited .......................................124
  5.4.3 The Defendant’s Fallacy ....................................................124
  5.4.4 Odds Form of Bayes and the Likelihood Ratio ....................125
5.5 Second-Order Probability ........................................................127
5.6 Summary ................................................................................129
Further Reading ...........................................................................129

Chapter 6  From Bayes’ Theorem to Bayesian Networks ..................131
6.1 Introduction ............................................................................131
6.2 A Very Simple Risk Assessment Problem ...............................132
6.3 Accounting for Multiple Causes (and Effects) .........................134
6.4 Using Propagation to Make Special Types of Reasoning Possible ..............................................................................137
6.5 The Crucial Independence Assumptions ..................................139
6.6 Structural Properties of BNs ...................................................144
  6.6.1 Serial Connection: Causal and Evidential Trails ................144
  6.6.2 Diverging Connection: Common Cause ..............................147
  6.6.3 Converging Connection: Common Effect .........................149
  6.6.4 Determining Whether Any Two Nodes in a BN Are Dependent 151
### Chapter 6: Propagation in Bayesian Networks
6.7 Propagation in Bayesian Networks .......................................................... 153
6.8 Using BNs to Explain Apparent Paradoxes ............................................. 156
6.8.1 Revisiting the Monty Hall Problem ..................................................... 156
6.8.1.1 Simple Solution ............................................................................. 156
6.8.1.2 Complex Solution ........................................................................ 157
6.8.2 Revisiting Simpson’s Paradox ............................................................... 161
6.9 Steps in Building and Running a BN Model ............................................ 162
6.9.1 Building a BN Model ............................................................................ 162
6.9.2 Running a BN Model ............................................................................. 166
6.9.3 Inconsistent Evidence .......................................................................... 168
6.10 Summary .................................................................................................. 169

### Further Reading
- Theoretical Underpinnings ....................................................................... 169
- BN Applications ......................................................................................... 169
- Nature and Theory of Causality ................................................................. 170
- Uncertain Evidence (Soft and Virtual) ....................................................... 170

### Chapter 7: Defining the Structure of Bayesian Networks
7.1 Introduction ............................................................................................ 171
7.2 Causal Inference and Choosing the Correct Edge Direction .................. 172
7.3 The Idioms ............................................................................................... 174
7.3.1 The Cause–Consequence Idiom .......................................................... 175
7.3.2 Measurement Idiom ............................................................................. 177
7.3.3 Definitional/Synthesis Idiom ................................................................. 184
7.3.3.1 Case 1: Definitional Relationship between Variables .................. 184
7.3.3.2 Case 2: Hierarchical Definitions .................................................. 184
7.3.3.3 Case 3: Combining Different Nodes Together to Reduce Effects of Combinatorial Explosion (“Divorcing”) .............................. 185
7.3.4 Induction Idiom ................................................................................... 188
7.4 The Problems of Asymmetry and How to Tackle Them ....................... 190
7.4.1 Impossible Paths ................................................................................ 190
7.4.2 Mutually Exclusive Paths ................................................................... 192
7.4.3 Distinct Causal Pathways ................................................................... 194
7.4.4 Taxonomic Classification .................................................................. 196
7.5 Multiobject Bayesian Network Models .................................................. 202
7.6 The Missing Variable Fallacy .................................................................. 207
7.7 Conclusions ............................................................................................ 212

### Further Reading
.......................................................... 213

### Chapter 8: Building and Eliciting Node Probability Tables
8.1 Introduction ............................................................................................. 215
8.2 Factorial Growth in the Size of Probability Tables ............................... 215
8.3 Labeled Nodes and Comparative Expressions ....................................... 217
8.4 Boolean Nodes and Functions ................................................................. 221
8.4.1 The Asia Model ................................................................................ 222
8.4.2 The OR Function for Boolean Nodes ................................................. 227
8.4.3 The AND Function for Boolean Nodes .............................................. 234
8.4.4 $M$ from $N$ Operator ........................................................................ 235
10.2.4 Model Comparison: Choosing the Best Predictive Model
10.2.5 Accommodating Expert Judgments about Hypotheses
10.2.6 Distribution Fitting as Hypothesis Testing
10.2.7 Bayesian Model Comparison and Complex Causal Hypotheses
10.3 Confidence Intervals
10.3.1 The Fallacy of Frequentist Confidence Intervals
10.3.2 The Bayesian Alternative to Confidence Intervals
10.4 Summary
Further Reading

Chapter 11 Modeling Operational Risk
11.1 Introduction
11.2 The Swiss Cheese Model for Rare Catastrophic Events
11.3 Bow Ties and Hazards
11.4 Fault Tree Analysis (FTA)
11.5 Event Tree Analysis (ETA)
11.6 Soft Systems, Causal Models, and Risk Arguments
11.7 KUUUB Factors
11.8 Operational Risk in Finance
11.8.1 Modeling the Operational Loss Generation Process
11.8.2 Scenarios and Stress Testing
11.9 Summary
Further Reading

Chapter 12 Systems Reliability Modeling
12.1 Introduction
12.2 Probability of Failure on Demand for Discrete Use Systems
12.3 Time to Failure for Continuous Use Systems
12.4 System Failure Diagnosis and Dynamic Bayesian Networks
12.5 Dynamic Fault Trees (DFTs)
12.6 Software Defect Prediction
12.7 Summary
Further Reading

Chapter 13 Bayes and the Law
13.1 Introduction
13.2 The Case for Bayesian Reasoning about Legal Evidence
13.3 Building Legal Arguments Using Idioms
13.3.1 The Evidence Idiom
13.3.2 The Evidence Accuracy Idiom
13.3.3 Idioms to Deal with the Key Notions of “Motive” and “Opportunity”
13.3.4 Idiom for Modeling Dependency between Different Pieces of Evidence
13.3.5 Alibi Evidence Idiom
13.3.6 Explaining away Idiom
13.4 Putting it All Together: Vole Example
13.5 Using BNs to Expose Further Fallacies of Legal Reasoning
<table>
<thead>
<tr>
<th>Contents</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>13.5.1 The Jury Observation Fallacy</td>
<td>433</td>
</tr>
<tr>
<td>13.5.2 The “Crimewatch UK” Fallacy</td>
<td>435</td>
</tr>
<tr>
<td>13.6 Summary</td>
<td>438</td>
</tr>
<tr>
<td>Further Reading</td>
<td>438</td>
</tr>
<tr>
<td>Appendix A: The Basics of Counting</td>
<td>441</td>
</tr>
<tr>
<td>Appendix B: The Algebra of Node Probability Tables</td>
<td>449</td>
</tr>
<tr>
<td>Appendix C: Junction Tree Algorithm</td>
<td>455</td>
</tr>
<tr>
<td>Appendix D: Dynamic Discretization</td>
<td>465</td>
</tr>
<tr>
<td>Appendix E: Statistical Distributions</td>
<td>483</td>
</tr>
<tr>
<td>Index</td>
<td>495</td>
</tr>
</tbody>
</table>