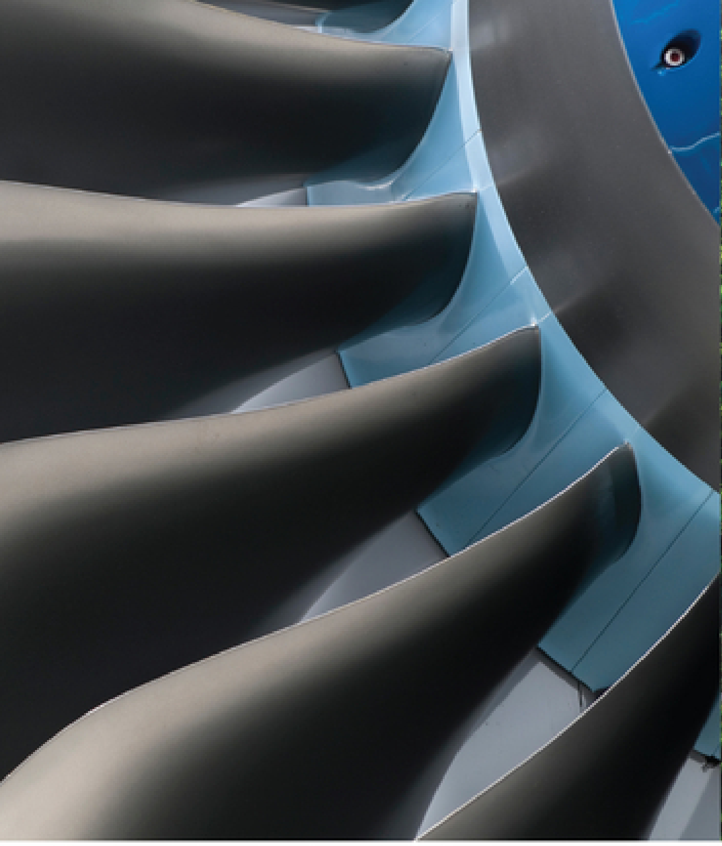


INTERMITTENT DEMAND FORECASTING

CONTEXT, METHODS AND APPLICATIONS

JOHN E. BOYLAN
ARIS A. SYNTETOS

with website

WILEY

Intermittent Demand Forecasting

Intermittent Demand Forecasting

Context, Methods and Applications

John E. Boylan
Lancaster University
Lancaster, UK

Aris A. Syntetos
Cardiff University
Cardiff, UK

WILEY

This edition first published 2021

Registered Offices
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Office
9600 Garsington Road, Oxford, OX4 2DQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Library of Congress Cataloging-in-Publication Data applied for

ISBN 978-1-119-97608-0 (hardback); LCCN - 2021011006

Cover Design: Wiley
Cover Image: Mata Atlantica - Atlantic Forest in Brazil © FG Trade/Getty Images, Turbine © Brasil2/Getty Images

Set in 9.5/12.5pt STIXTwoText by SPi Global, Chennai, India

10 9 8 7 6 5 4 3 2 1

For Jan and Rachel

Contents

Preface *xix*
Glossary *xxi*
About the Companion Website *xxiii*

1 Economic and Environmental Context *1*
1.1 Introduction *1*
1.2 Economic and Environmental Benefits *3*
1.2.1 After-sales Industry *3*
1.2.2 Defence Sector *4*
1.2.3 Economic Benefits *5*
1.2.4 Environmental Benefits *5*
1.2.5 Summary *6*
1.3 Intermittent Demand Forecasting Software *6*
1.3.1 Early Forecasting Software *6*
1.3.2 Developments in Forecasting Software *6*
1.3.3 Open Source Software *7*
1.3.4 Summary *7*
1.4 About this Book *7*
1.4.1 Optimality and Robustness *7*
1.4.2 Business Context *8*
1.4.3 Structure of the Book *9*
1.4.4 Current and Future Applications *10*
1.4.5 Summary *10*
1.5 Chapter Summary *11*
Technical Note *11*

2 Inventory Management and Forecasting *13*
2.1 Introduction *13*
2.2 Scheduling and Forecasting *13*
2.2.1 Material Requirements Planning (MRP) *13*
2.2.2 Dependent and Independent Demand Items *14*
2.2.3 Make to Stock *15*
2.2.4 Summary *15*

2.3 Should an Item Be Stocked at All? *15*
2.3.1 Stock/Non-Stock Decision Rules *16*
2.3.2 Historical or Forecasted Demand? *18*
2.3.3 Summary *18*
2.4 Inventory Control Requirements *19*
2.4.1 How Should Stock Records be Maintained? *19*
2.4.2 When are Forecasts Required for Stocking Decisions? *22*
2.4.3 Summary *24*
2.5 Overview of Stock Rules *25*
2.5.1 Continuous Review Systems *25*
2.5.2 Periodic Review Systems *26*
2.5.3 Periodic Review Policies *28*
2.5.4 Variations of the (R, S) Periodic Policy *29*
2.5.5 Summary *30*
2.6 Chapter Summary *30*
Technical Notes *31*

3 Service Level Measures *33*
3.1 Introduction *33*
3.2 Judgemental Ordering *34*
3.2.1 Rules of Thumb for the Order-Up-To Level *34*
3.2.2 Judgemental Adjustment of Orders *34*
3.2.3 Summary *35*
3.3 Aggregate Financial and Service Targets *35*
3.3.1 Aggregate Financial Targets *36*
3.3.2 Service Level Measures *36*
3.3.3 Relationships Between Service Level Measures *38*
3.3.4 Summary *39*
3.4 Service Measures at SKU Level *39*
3.4.1 Cost Factors *39*
3.4.2 Understanding of Service Level Measures *40*
3.4.3 Potential Service Level Measures *40*
3.4.4 Choice of Service Level Measure *41*
3.4.5 Summary *42*
3.5 Calculating Cycle Service Levels *42*
3.5.1 Distribution of Demand Over One Time Period *43*
3.5.2 Cycle Service Levels Based on All Cycles *44*
3.5.3 Cycle Service Levels Based on Cycles with Demand *45*
3.5.4 Summary *47*
3.6 Calculating Fill Rates *48*
3.6.1 Unit Fill Rates *48*
3.6.2 Fill Rates: Standard Formula *49*
3.6.3 Fill Rates: Sobel's Formula *51*
3.6.4 Summary *53*

3.7 Setting Service Level Targets *53*
3.7.1 Responsibility for Target Setting *53*
3.7.2 Trade-off Between Service and Cost *54*
3.7.3 Setting SKU Level Service Targets *55*
3.7.4 Summary *56*
3.8 Chapter Summary *56*
Technical Note *57*

4 Demand Distributions *59*
4.1 Introduction *59*
4.2 Estimation of Demand Distributions *60*
4.2.1 Empirical Demand Distributions *60*
4.2.2 Fitted Demand Distributions *62*
4.2.3 Summary *64*
4.3 Criteria for Demand Distributions *64*
4.3.1 Empirical Evidence for Goodness of Fit *64*
4.3.2 Further Criteria *64*
4.3.3 Summary *65*
4.4 Poisson Distribution *65*
4.4.1 Shape of the Poisson Distribution *66*
4.4.2 Summary *67*
4.5 Poisson Demand Distribution *67*
4.5.1 Poisson: A Priori Grounds *67*
4.5.2 Poisson: Ease of Calculation *67*
4.5.3 Poisson: Flexibility *68*
4.5.4 Poisson: Goodness of Fit *69*
4.5.5 Testing for Goodness of Fit *70*
4.5.6 Summary *72*
4.6 Incidence and Occurrence *72*
4.6.1 Demand Incidence *72*
4.6.2 Demand Occurrence *73*
4.6.3 Summary *74*
4.7 Poisson Demand Incidence Distribution *75*
4.7.1 A Priori Grounds *75*
4.7.2 Ease of Calculation *75*
4.7.3 Flexibility *76*
4.7.4 Goodness of Fit *76*
4.7.5 Summary *79*
4.8 Bernoulli Demand Occurrence Distribution *79*
4.8.1 Bernoulli Distribution: A Priori Grounds *79*
4.8.2 Bernoulli Distribution: Ease of Calculation *80*
4.8.3 Bernoulli Distribution: Flexibility *81*
4.8.4 Bernoulli Distribution: Goodness of Fit *81*
4.8.5 Summary *82*
4.9 Chapter Summary *82*
Technical Notes *83*

5 Compound Demand Distributions *87*
5.1 Introduction *87*
5.2 Compound Poisson Distributions *88*
5.2.1 Compound Poisson: A Priori Grounds *89*
5.2.2 Compound Poisson: Flexibility *89*
5.2.3 Summary *89*
5.3 Stuttering Poisson Distribution *90*
5.3.1 Stuttering Poisson: A Priori Grounds *91*
5.3.2 Stuttering Poisson: Ease of Calculation *91*
5.3.3 Stuttering Poisson: Flexibility *93*
5.3.4 Stuttering Poisson: Goodness of Fit for Demand Sizes *93*
5.3.5 Summary *95*
5.4 Negative Binomial Distribution *96*
5.4.1 Negative Binomial: A Priori Grounds *96*
5.4.2 Negative Binomial: Ease of Calculation *96*
5.4.3 Negative Binomial: Flexibility *97*
5.4.4 Negative Binomial: Goodness of Fit *98*
5.4.5 Summary *99*
5.5 Compound Bernoulli Distributions *100*
5.5.1 Compound Bernoulli: A Priori Grounds *100*
5.5.2 Compound Bernoulli: Ease of Calculation *100*
5.5.3 Compound Bernoulli: Flexibility *100*
5.5.4 Compound Bernoulli: Goodness of Fit *101*
5.5.5 Summary *101*
5.6 Compound Erlang Distributions *101*
5.6.1 Compound Erlang Distributions: A Priori Grounds *103*
5.6.2 Compound Erlang Distributions: Ease of Calculation *104*
5.6.3 Compound Erlang-2: Flexibility *104*
5.6.4 Compound Erlang-2: Goodness of Fit *104*
5.6.5 Summary *105*
5.7 Differing Time Units *105*
5.7.1 Poisson Distribution *106*
5.7.2 Compound Poisson Distribution *106*
5.7.3 Compound Bernoulli and Compound Erlang Distributions *107*
5.7.4 Normal Distribution *108*
5.7.5 Summary *110*
5.8 Chapter Summary *110*
Technical Notes *111*

6 Forecasting Mean Demand *117*
6.1 Introduction *117*
6.2 Demand Assumptions *118*
6.2.1 Elements of Intermittent Demand *119*
6.2.2 Demand Models *119*
6.2.3 An Intermittent Demand Model *120*
6.2.4 Summary *121*

6.3 Single Exponential Smoothing (SES) *121*
6.3.1 SES as an Error-correction Mechanism *122*
6.3.2 SES as a Weighted Average of Previous Observations *122*
6.3.3 Practical Considerations *125*
6.3.4 Summary *126*
6.4 Croston's Critique of SES *126*
6.4.1 Bias After Demand Occurring Periods *126*
6.4.2 Magnitude of Bias After Demand Occurring Periods *128*
6.4.3 Bias After Review Intervals with Demands *128*
6.4.4 Summary *129*
6.5 Croston's Method *129*
6.5.1 Method Specification *129*
6.5.2 Method Application *130*
6.5.3 Summary *131*
6.6 Critique of Croston's Method *132*
6.6.1 Bias of Size-interval Approaches *132*
6.6.2 Inversion Bias *132*
6.6.3 Quantification of Bias *133*
6.6.4 Summary *134*
6.7 Syntetos–Boylan Approximation *134*
6.7.1 Practical Application *134*
6.7.2 Framework for Correction Factors *135*
6.7.3 Initialisation and Optimisation *135*
6.7.4 Summary *138*
6.8 Aggregation for Intermittent Demand *138*
6.8.1 Temporal Aggregation *138*
6.8.2 Cross-sectional Aggregation *141*
6.8.3 Summary *142*
6.9 Empirical Studies *143*
6.9.1 Single Series, Single Period Approaches *143*
6.9.2 Single Series, Multiple Period Approaches *144*
6.9.3 Summary *145*
6.10 Chapter Summary *145*
Technical Notes *146*

7 Forecasting the Variance of Demand and Forecast Error *151*
7.1 Introduction *151*
7.2 Mean Known, Variance Unknown *151*
7.2.1 Mean Demand Unchanging Through Time *152*
7.2.2 Relating Variance Over One Period to Variance Over the Protection Interval *152*
7.2.3 Summary *153*
7.3 Mean Unknown, Variance Unknown *153*
7.3.1 Mean and Variance Unchanging Through Time *154*
7.3.2 Mean or Variance Changing Through Time *155*

7.3.3 Relating Variance Over One Period to Variance Over the Protection Interval *156*
7.3.4 Direct Approach to Estimating Variance of Forecast Error Over the Protection Interval *158*
7.3.5 Implementing the Direct Approach to Estimating Variance Over the Protection Interval *160*
7.3.6 Summary *160*
7.4 Lead Time Variability *161*
7.4.1 Consequences of Recognising Lead Time Variance *161*
7.4.2 Variance of Demand Over a Variable Lead Time (Known Mean Demand) *162*
7.4.3 Variance of Demand Over a Variable Lead Time (Unknown Mean Demand) *163*
7.4.4 Distribution of Demand Over a Variable Lead Time *164*
7.4.5 Summary *165*
7.5 Chapter Summary *165*
Technical Notes *166*

8 Inventory Settings *169*
8.1 Introduction *169*
8.2 Normal Demand *170*
8.2.1 Order-up-to Levels for Four Scenarios *170*
8.2.2 Scenario 1: Mean and Standard Deviation Known *170*
8.2.3 Scenario 2: Mean Demand Unknown Standard Deviation Known *172*
8.2.4 Scenario 3: Mean Demand Known Standard Deviation Unknown *175*
8.2.5 Scenario 4: Mean and Standard Deviation Unknown *176*
8.2.6 Summary *177*
8.3 Poisson Demand *177*
8.3.1 Cycle Service Level System when the Mean Demand is Known *177*
8.3.2 Fill Rate System when the Mean Demand is Known *178*
8.3.3 Poisson OUT Level when the Mean Demand is Unknown *179*
8.3.4 Summary *181*
8.4 Compound Poisson Demand *181*
8.4.1 Stuttering Poisson OUT Level when the Parameters are Known *181*
8.4.2 Negative Binomial OUT Levels when the Parameters are Known *183*
8.4.3 Stuttering Poisson and Negative Binomial OUT Levels when the Parameters are Unknown *183*
8.4.4 Summary *184*
8.5 Variable Lead Times *184*
8.5.1 Empirical Lead Time Distributions *184*
8.5.2 Summary *185*
8.6 Chapter Summary *185*
Technical Notes *186*

9 Accuracy and Its Implications *193*
9.1 Introduction *193*
9.2 Forecast Evaluation *194*
9.2.1 Only One Step Ahead? *194*
9.2.2 All Points in Time? *194*
9.2.3 Summary *195*
9.3 Error Measures in Common Usage *195*
9.3.1 Popular Forecast Error Measures *195*
9.3.2 Calculation of Forecast Errors *197*
9.3.3 Mean Error *197*
9.3.4 Mean Square Error *198*
9.3.5 Mean Absolute Error *198*
9.3.6 Mean Absolute Percentage Error (MAPE) *198*
9.3.7 100% Minus MAPE *199*
9.3.8 Forecast Value Added *199*
9.3.9 Summary *200*
9.4 Criteria for Error Measures *200*
9.4.1 General Criteria *200*
9.4.2 Additional Criteria for Intermittence *201*
9.4.3 Summary *201*
9.5 Mean Absolute Percentage Error and its Variants *201*
9.5.1 Problems with the Mean Absolute Percentage Error *202*
9.5.2 Mean Absolute Percentage Error from Forecast *202*
9.5.3 Symmetric Mean Absolute Percentage Error *203*
9.5.4 MAPEFF and sMAPE for Intermittent Demand *204*
9.5.5 Summary *205*
9.6 Measures Based on the Mean Absolute Error *205*
9.6.1 MAE: Mean Ratio *205*
9.6.2 Mean Absolute Scaled Error *206*
9.6.3 Measures Based on Absolute Errors *207*
9.6.4 Summary *208*
9.7 Measures Based on the Mean Error *208*
9.7.1 Desirability of Unbiased Forecasts *209*
9.7.2 Mean Error *209*
9.7.3 Mean Percentage Error *210*
9.7.4 Scaled Bias Measures *210*
9.7.5 Summary *211*
9.8 Measures Based on the Mean Square Error *211*
9.8.1 Scaled Mean Square Error *212*
9.8.2 Relative Root Mean Square Error *212*
9.8.3 Percentage Best *213*
9.8.4 Summary *213*

9.9 Accuracy of Predictive Distributions *214*
9.9.1 Measuring Predictive Distribution Accuracy *214*
9.9.2 Probability Integral Transform for Continuous Data *215*
9.9.3 Probability Integral Transform for Discrete Data *215*
9.9.4 Summary *217*
9.10 Accuracy Implication Measures *218*
9.10.1 Simulation Outline *218*
9.10.2 Forecasting Details *218*
9.10.3 Simulation Details *219*
9.10.4 Comparison of Simulation Results *220*
9.10.5 Summary *221*
9.11 Chapter Summary *221*
Technical Notes *221*

10 Judgement, Bias, and Mean Square Error *225*
10.1 Introduction *225*
10.2 Judgemental Forecasting *225*
10.2.1 Evidence on Prevalence of Judgemental Forecasting *226*
10.2.2 Judgemental Biases *226*
10.2.3 Effectiveness of Judgemental Forecasts: Evidence for Non-intermittent Items *229*
10.2.4 Effectiveness of Judgemental Forecasts: Evidence for Intermittent Items *230*
10.2.5 Summary *231*
10.3 Forecast Bias *232*
10.3.1 Monitoring and Detection of Bias *232*
10.3.2 Bias as an Expectation of a Random Variable *234*
10.3.3 Response to Different Causes of Bias *235*
10.3.4 Summary *236*
10.4 The Components of Mean Square Error *236*
10.4.1 Calculation of Mean Square Error *236*
10.4.2 Decomposition of Expected Squared Errors *236*
10.4.3 Decomposition of Expected Squared Errors for Independent Demand *238*
10.4.4 Summary *239*
10.5 Chapter Summary *240*
Technical Notes *240*

11 Classification Methods *243*
11.1 Introduction *243*
11.2 Classification Schemes *244*
11.2.1 The Purpose of Classification *244*
11.2.2 Classification Criteria *245*
11.2.3 Summary *245*
11.3 ABC Classification *246*
11.3.1 Pareto Principle *246*

11.3.2 Service Criticality *246*
11.3.3 ABC Classification and Forecasting *247*
11.3.4 Summary *248*
11.4 Extensions to the ABC Classification *248*
11.4.1 Composite Criterion Approach *249*
11.4.2 Multi-criteria Approaches *250*
11.4.3 Classification for Spare Parts *250*
11.4.4 Summary *251*
11.5 Conceptual Clarifications *251*
11.5.1 Definition of Non-normal Demand Patterns *251*
11.5.2 Conceptual Framework *252*
11.5.3 Summary *253*
11.6 Classification Based on Demand Sources *254*
11.6.1 Demand Generation *254*
11.6.2 A Qualitative Classification Approach *254*
11.6.3 Summary *255*
11.7 Forecasting-based Classifications *255*
11.7.1 Forecasting and Generalisation *256*
11.7.2 Classification Solutions *257*
11.7.3 Summary *258*
11.8 Chapter Summary *259*
Technical Notes *260*

12 Maintenance and Obsolescence *263*
12.1 Introduction *263*
12.2 Maintenance Contexts *264*
12.2.1 Summary *265*
12.3 Causal Forecasting *265*
12.3.1 Causal Forecasting for Maintenance Management *266*
12.3.2 Summary *268*
12.4 Time Series Methods *268*
12.4.1 Forecasting in the Presence of Obsolescence *269*
12.4.2 Forecasting with Granular Maintenance Information *272*
12.4.3 Summary *273*
12.5 Forecasting in Context *273*
12.6 Chapter Summary *275*
Technical Notes *276*

13 Non-parametric Methods *279*
13.1 Introduction *279*
13.2 Empirical Distribution Functions *280*
13.2.1 Assumptions *281*
13.2.2 Length of History *281*
13.2.3 Summary *282*
13.3 Non-overlapping and Overlapping Blocks *282*

13.3.1 Differences Between the Two Methods *282*
13.3.2 Methods and Assumptions *284*
13.3.3 Practical Considerations *284*
13.3.4 Performance of Non-overlapping Blocks Method *285*
13.3.5 Performance of Overlapping Blocks Method *285*
13.3.6 Summary *286*
13.4 Comparison of Approaches *286*
13.4.1 Time Series Characteristics Favouring Overlapping Blocks *286*
13.4.2 Empirical Evidence on Overlapping Blocks *287*
13.4.3 Summary *289*
13.5 Resampling Methods *289*
13.5.1 Simple Bootstrapping *289*
13.5.2 Bootstrapping Demand Sizes and Intervals *290*
13.5.3 VZ Bootstrap and the Syntetos–Boylan Approximation *292*
13.5.4 Extension of Methods to Variable Lead Times *293*
13.5.5 Resampling Immediately After Demand Occurrence *293*
13.5.6 Summary *294*
13.6 Limitations of Simple Bootstrapping *294*
13.6.1 Autocorrelated Demand *294*
13.6.2 Previously Unobserved Demand Values *295*
13.6.3 Summary *296*
13.7 Extensions to Simple Bootstrapping *296*
13.7.1 Discrete-time Markov Chains *296*
13.7.2 Extension to Simple Bootstrapping Using Markov Chains *297*
13.7.3 Jittering *299*
13.7.4 Limitations of Jittering *300*
13.7.5 Further Developments *300*
13.7.6 Empirical Evidence on Bootstrapping Methods *300*
13.7.7 Summary *302*
13.8 Chapter Summary *302*
Technical Notes *303*

14 Model-based Methods *305*
14.1 Introduction *305*
14.2 Models and Methods *305*
14.2.1 A Simple Model for Single Exponential Smoothing *306*
14.2.2 Critique of Weighted Least Squares *307*
14.2.3 ARIMA Models *307*
14.2.4 The ARIMA(0,1,1) Model and SES *308*
14.2.5 Summary *309*
14.3 Integer Autoregressive Moving Average (INARMA) Models *309*
14.3.1 Integer Autoregressive Model of Order One, INAR(1) *310*
14.3.2 Integer Moving Average Model of Order One, INMA(1) *312*
14.3.3 Mixed Integer Autoregressive Moving Average Models *312*
14.3.4 Summary *313*

14.4 INARMA Parameter Estimation *313*
14.4.1 Parameter Estimation for INAR(1) Models *313*
14.4.2 Parameter Estimation for INMA(1) Models *314*
14.4.3 Parameter Estimation for INARMA(1,1) Models *314*
14.4.4 Summary *315*
14.5 Identification of INARMA Models *315*
14.5.1 Identification Using Akaike's Information Criterion *315*
14.5.2 General Models and Model Identification *316*
14.5.3 Summary *317*
14.6 Forecasting Using INARMA Models *317*
14.6.1 Forecasting INAR(1) Mean Demand *318*
14.6.2 Forecasting INMA(1) Mean Demand *318*
14.6.3 Forecasting INARMA(1,1) Mean Demand *319*
14.6.4 Forecasting Using Temporal Aggregation *319*
14.6.5 Summary *319*
14.7 Predicting the Whole Demand Distribution *319*
14.7.1 Protection Interval of One Period *320*
14.7.2 Protection Interval of More Than One Period *320*
14.7.3 Summary *322*
14.8 State Space Models for Intermittence *322*
14.8.1 Croston's Demand Model *323*
14.8.2 Proposed State Space Models *324*
14.8.3 Summary *325*
14.9 Chapter Summary *325*
Technical Notes *325*

15 Software for Intermittent Demand *329*
15.1 Introduction *329*
15.2 Taxonomy of Software *330*
15.2.1 Proprietary Software *330*
15.2.2 Open Source Software *332*
15.2.3 Hybrid Solutions *333*
15.2.4 Summary *333*
15.3 Framework for Software Evaluation *333*
15.3.1 Key Aspects of Software Evaluation *334*
15.3.2 Additional Criteria *335*
15.3.3 Summary *336*
15.4 Software Features and Their Availability *336*
15.4.1 Software Features for Intermittent Demand *336*
15.4.2 Availability of Software Features *337*
15.4.3 Summary *338*
15.5 Training *339*
15.5.1 Summary *340*
15.6 Forecast Support Systems *340*
15.6.1 Summary *341*

15.7 Alternative Perspectives *341*
15.7.1 Bayesian Methods *342*
15.7.2 Neural Networks *342*
15.7.3 Summary *343*
15.8 Way Forward *343*
15.9 Chapter Summary *345*
Technical Note *345*

References *347*
Author Index *365*
Subject Index *367*

Preface

The images on the front of this book highlight a crucial tension for all advanced economies. There is a desire to travel more and consume more, but also a growing awareness of the detrimental effects that this is having on the environment. There is a belated realisation that those of us living in countries with developed economies need to consume less and waste less.

Waste can occur at all stages of the supply chain. Consumers may buy food they never eat or clothes they never wear. Retailers and wholesalers may order goods from manufacturers that never sell. These wastages can be significantly reduced by better demand forecasting and inventory management. Some items conform to regular demand patterns and are relatively easy to forecast. Other items, with irregular and intermittent demand patterns, are much harder.

Wastage can be addressed by changes in production, moving away from built-in obsolescence and towards products that can be maintained and repaired economically. For this to be an attractive proposition, spare parts need to be readily available. Unfortunately, these items are often the most difficult to forecast because many of them are subject to the sporadic nature of intermittent demand. Although there have been significant advances in intermittent demand forecasting over recent decades, these are not all available in commercial software. In the final chapter of this book, we highlight the progress that has been made, including methods that are freely available in open source software.

The reasons for the slow adoption of new forecasting methods and approaches in commercial software are varied. We believe that one of the reasons is a lack of appreciation of the benefits that may accrue. Because intermittent demand items are so difficult to forecast, it may be thought that *highly accurate* forecasting methods can never be found. This may be true. However, it is possible to find *more accurate* methods, which can contribute towards significant improvements in inventory management.

There is also a need for greater awareness of the methods that have been developed in recent years. Information on them is scattered amongst a variety of academic journals, and some of the articles are highly technical. Therefore, we have set ourselves the challenge of synthesizing this body of knowledge. We have endeavoured to bring together the main strands of research into a coherent whole, and assuming no prior knowledge of the subject.

There are various perspectives from which demand forecasting can be addressed. One option would be to take an operations management view, with a focus on forecasting and planning processes. Another would be to take a more statistical perspective, starting with mathematical models and working through their properties. While some of our material has been influenced by these orientations, the dominant perspective of this book is that of operational research (OR). The start point of OR should always be the real-life situation that is encountered. This means that it is essential to gain an in-depth understanding of inventory systems and how forecasts inform these decisions. Such an appreciation enables a sharper focus on forecasting requirements and the appropriate criteria for a 'good forecast'.

In this book, the first three chapters focus on the inventory management context in which forecasting occurs, including the inventory policies and the service level measures that are appropriate for intermittent demand. Recognising the interconnection between inventory policies, demand distributions, and forecasting methods, the next two chapters focus on demand distributions, including evidence from studies of real-world data. The following two chapters concentrate on forecasting methods, with discussion of practical issues that must be addressed in their implementation. We then turn to the linkage between forecasts and inventory availability, and review how forecast accuracy should be measured and how its implications for inventories should be assessed. We also look at how stock keeping units should be classified for forecasting purposes, and examine methods designed specifically to address maintenance and obsolescence. The next two chapters deal with methods that can tackle more challenging demand patterns. We conclude with a review of forecasting software requirements and our views on the way forward.

We are grateful to those pioneers who inspired us to study this subject, and who have given us valuable advice over the years, especially John Croston, Roy Johnston, and Tom Willemain. We would like to express our thanks to those who commented on draft chapters of this book: Zied Babai, Stephen Disney, Robert Fildes, Thanos Goltsos, Matteo Kalchschmidt, Stephan Kolassa, Nikos Kourentzes, Mona Mohammadipour, Erica Pastore, Fotios Petropoulos, Dennis Prak, Anna-Lena Sachs, and Ivan Svetunkov; and to Nicole Ayiomamitou and Antonis Siakallis who helped with the figures.

Lancaster and Cardiff
January 2021

John E. Boylan
Aris A. Syntetos

Glossary

ADIDA	aggregate–disaggregate intermittent demand approach
AIC	Akaike information criterion
AR	autoregressive
ARIMA	autoregressive integrated moving average
ARMA	autoregressive moving average
APE	absolute percentage error
BO	backorder
BoM	bill of materials
BS	Brier score
CDF	cumulative distribution function
CFE	cumulative forecast error
CSL	cycle service level (all replenishment cycles)
CSL^+	cycle service level (replenishment cycles with some demand)
CV	coefficient of variation
EDF	empirical distribution function
ERP	enterprise resource planning
FMECA	failure mode, effects, and criticality analysis
FR	fill rate
FSS	forecast support system
FVA	forecast value added
HES	hyperbolic exponential smoothing
INAR	integer autoregressive
INARMA	integer autoregressive moving average
INMA	integer moving average
IP	inventory position
KS	Kolmogorov–Smirnov (test)
LTD	lead-time demand
MA	moving average
MAD	mean absolute deviation
MAE	mean absolute error
MAPE	mean absolute percentage error
MAPEFF	mean absolute percentage error from forecast
MASE	mean absolute scaled error

ME	mean error
MMSE	minimum mean square error
MPE	mean percentage error
MPS	master production schedule
MRO	maintenance, repair, and operations
MRP	material requirements planning
MSE	mean square error
MSOE	multiple source of error
MTO	make to order
MTS	make to stock
NBD	negative binomial distribution
NN	neural network
NOB	non-overlapping blocks
OB	overlapping blocks
OUT	order up to
PIS	periods in stock
PIT	probability integral transform
RMSE	root mean square error
rPIT	randomised probability integral transform
S&OP	sales and operations planning
SBA	Syntetos–Boylan Approximation (method)
SBC	Syntetos–Boylan–Croston (classification)
SCM	supply chain management
SES	single (or simple) exponential smoothing
SKU	stock keeping unit
SLA	service level agreement
SMA	simple moving average
sMAPE	symmetric mean absolute percentage error
sMSE	scaled mean square error
SOH	stock on hand
SOO	stock on order
SSOE	single source of error
TSB	Teunter–Syntetos–Babai (method)
VZ	Viswanathan–Zhou (method)
WMH	Wright Modified Holt (method)
WSS	Willemain–Smart–Schwarz (method)

About the Companion Website

This book is accompanied by a companion website.

www.wiley.com/go/boylansyntetos/intermittentdemandforecasting

This website includes:

- Datasets (with accompanying information)
- Links to R packages

1

Economic and Environmental Context

1.1 Introduction

Demand forecasting is the basis for most planning and control activities in any organisation. Unless a forecast of future demand is available, organisations cannot commit to staffing levels, production schedules, inventory replenishment orders, or transportation arrangements. It is demand forecasting that sets the entire supply chain in motion.

Demand will typically be accumulated in some pre-defined 'time buckets' (periods), such as a day, a week, or a month. The determination of the length of the time period that constitutes a time bucket is a very important decision. It is a choice that should relate to the nature of the industry and the volume of the demand itself but it may also be dictated by the IT infrastructure or software solutions in place. Regardless of the length of the time buckets, demand records eventually form a time series, which is a sequence of successive demand observations over time periods of equal length.

On many occasions, demand may be observed in every time period, resulting in what is sometimes referred to as 'non-intermittent demand'. Alternatively, demand may appear sporadically, with no demand at all in some periods, leading to an intermittent appearance of demand occurrences. Should that be the case, contribution to revenues is naturally lower than that of faster-moving demand items. Intermittent demand items do not attract much marketing attention, as they will rarely be the focus of a promotion, for example. However, they have significant cost implications for a simple reason: there are often many of them!

Service or spare parts are very frequently characterised by intermittent demand patterns. These items are essentially components or (sub-) assemblies contributing to the build-up of a final product. However, they face 'independent demand', which is demand generated directly from customers, rather than production requirements for a particular number of units of the final product. In the after-sales environment (or 'aftermarket'), we deal exclusively with 'independent demand' items. Service parts facing intermittent demand may represent a large proportion of an organisation's inventory investment. In some industries, this proportion may be as high as 60% or 70% (Syntetos 2011). The management of these items is a very important task which, when supported by intelligent inventory control mechanisms, may yield dramatic cost reductions.

Intermittent Demand Forecasting: Context, Methods and Applications, First Edition.
John E. Boylan and Aris A. Syntetos.

Companion Website: www.wiley.com/go/boylansyntetos/intermittentdemandforecasting

Industries that rely heavily on after-sales support, including the automotive, IT, and electronics sectors, are dominated by intermittent demand items. The contributions of the after-sales services to the total revenues of organisations in these industries have been reported to be as high as 60% (Johnston et al. 2003). This signifies an opportunity not only to reduce costs but also to increase revenues through a careful balancing of keeping enough in stock to satisfy customers but not so much as to unnecessarily increase inventory investments. There are tremendous economic benefits that may be realised through the reappraisal of managing intermittent demand items.

There are also significant environmental benefits to be realised by such a reappraisal. Because of their inherent slow movement, intermittent demand items are at the greatest risk of obsolescence. The problem is exacerbated by the greatly reduced product life cycles in modern industry. This affects the planning process for all intermittent demand items (both final products and spare parts used to sustain the operation of final products). Better forecasting and inventory decisions may reduce overall scrap and waste. Furthermore, the sustained provision of spare parts may also reduce premature replacement of the original equipment.

The area of intermittent demand forecasting has been neglected by researchers and practitioners for too long. From a business perspective, this may be explained in terms of the lack of focus on intermittent demand items by the marketing function of organisations. However, the tough economic conditions experienced from around 2010 onwards have resulted in a switch of emphasis from revenue maximisation to cost minimisation. This switch repositions intermittent demand items as the focus of attention in many companies, as part of the drive to dramatically cut down costs and remain competitive. In addition, the more recent emergence of the after-sales business as a major determinant of companies' success has also led to the recognition of intermittent demand forecasting as an area of exceptional importance.

Following a seminal contribution in this area by John Croston in 1972, intermittent demand forecasting received very little attention by researchers over the next 20 years. This was in contrast to the extensive research conducted on forecasting faster-moving demand items. Research activity grew rapidly from the mid-1990s onwards, and we have now reached a stage where a comprehensive body of knowledge, both theoretical and empirical, has been developed in this area. This book aims to provide practitioners, students, and academic researchers with a single point of reference on intermittent demand forecasting. Although there are considerable openings for further advancements, the current state of knowledge offers organisations significant opportunities to improve their intermittent demand forecasting. Numerous reports, to be discussed in more detail later in this chapter, indicate that intermittent demand forecasting is one of the major problems facing modern organisations. Specialised software packages offer some forecasting support to companies but they often lag behind new developments. There are great benefits that have not yet been achieved in this area, and we hope that this book will make a contribution towards their realisation.

There are three main audiences for this book:

1. Supply chain management (SCM) practitioners, broadly defined, who wish to realise the full benefits of managing intermittent demand items.

2. Software designers wanting to incorporate new developments in forecasting into their software.
3. Students and academics wishing to learn and incorporate into their curricula, respectively, the state of the art in intermittent demand forecasting.

In summary, business pressures to reduce costs and environmental pressures to reduce scrap (often introduced in the form of prescribed policies imposed by national governments or the EU for example) render intermittent demand items, and forecasting their requirements, one of the most important areas in modern organisations.

There are great benefits associated with forecasting intermittent demand more accurately, and those benefits are far from being realised. This may be explained by the well reported innovation–adoption gap, which arises from the divergence between innovations and real-world practices. Organisational practices typically lag behind software developments, and software developments typically lag behind the state of the art in the academic literature. It is the aim of this book to bridge these gaps and show how intelligent intermittent demand forecasting may result in significant economic and environmental benefits.

In the remainder of this chapter, we first discuss in more detail the potential benefits that may be realised through improved intermittent demand forecasting. We then provide an overview of the current state of supply chain software packages and enterprise resource planning (ERP) solutions with regard to intermittent demand forecasting. This is followed by a section where we elaborate on both the structure of this book and the perspective that we take regarding the material presented here. We close with a summary of the chapter.

1.2 Economic and Environmental Benefits

Intermittent demand for products appears sporadically, with some time periods showing no demand at all. Moreover, when demand occurs, the demand size may be constant or variable, perhaps highly so, leading to what is often termed ‘lumpy demand’. Later in this chapter, we discuss why forecasting sporadic and lumpy demand patterns is a very difficult task. Specific characterisations of intermittent demand series are considered in detail in Chapters 4 and 5.

1.2.1 After-sales Industry

Intermittent demand items dominate service and repair parts inventories in many industries (Boylan and Syntetos 2010). A survey by Deloitte Research (2006) benchmarked the service businesses of many of the world’s largest manufacturing companies with combined revenues reaching more than $1.5 trillion; service operations accounted for an average of 25% of revenues. In addition to their contribution to revenues, these items present a distinct opportunity for cost reductions. Maintenance, repair, and operations (MRO) inventories typically account for as much as 40% of the annual procurement budget (Donnelly 2013). Increased revenues and reduced costs naturally lead to increased profits. Many organisations have repeatedly testified to the importance of after-sales services for their businesses and the profits they generate. Companies such as Beretta, Canon, DAF Trucks, Electrolux, EPTA, GE Oil & Gas, and Lavapiu have reported contributions of the after-sales services to their total profit of up to 50% (Syntetos 2011). Comparable numbers have been reported by Gaiardelli et al. (2007), Kim et al. (2007), and Glueck et al. (2007), while after-sales service has been identified as a key profit lever in the manufacturing sector (Manufacturing Management 2018).

Intermittent demand items are at the greatest risk of obsolescence. Many case studies (e.g. Molenaers et al. 2012) have documented large proportions of 'dead' (obsolete) stock in a variety of industries, with serious environmental implications. However, under-stocking situations may be as harmful, given the potentially high criticality of the items involved. In civil aviation, for example, lack of spare parts is one of the major causes of 'aircraft on ground' events (problems serious enough to prevent aircraft from flying). Badkook (2016) found that a quarter of the aircraft in an (un-named) airline's Boeing 777 fleet were affected by such aircraft on ground events over a year.

1.2.2 Defence Sector

Defence inventories, which are highly reliant on spare parts, have been repeatedly identified as a high risk area with a direct impact on a nation's economy. In the United States for example, the Department of Defense (DoD) manages around five million secondary items. These include repairable components, subsystems, assemblies, consumable repair parts, and bulk items. They reported that, as of September 2017, the value of the inventory was $93 billion (GAO 2019). Although a matter of concern, there had been no substantial reductions in inventory values over the previous decade (being, for example, $95 billion in 2013 and 2010; GAO 2012, 2015).

A major determinant of the performance of an inventory system is the forecasting method(s) being used to predict demand. Inaccurate forecasts lead to either excess inventory or shortfalls, depending on the direction of the forecast error. Over-forecasting can lead to holding stocks that are simply not needed. According to the US Government Accountability Office (GAO 2011, p. 11), 'Our recent work identified demand forecasting as the leading reason why the services and DLA [Defense Logistics Agency] accumulate excess inventory'.

Unfortunately, progress in improving forecasting and inventory management has been slow in many industries, with the defence industry being a case in point. The GAO of the United States reported, 'Since 1990, we have identified DoD [Department of Defense] supply chain management as a high-risk area due in part to ineffective and inefficient inventory management practices and procedures, weaknesses in accurately forecasting the demand for spare parts, and other supply chain challenges. Our work has shown that these factors have contributed to the accumulation of billions of dollars in spare parts that are excess to current needs' (GAO 2015, p. 2). Progress in inventory management has been made since then, especially with regard to the visibility of physical inventories, receipt processing, and cargo tracking (GAO 2019). These improvements in information systems have led to inventory management being removed from the list of high-risk areas. However, it is notable that no claims have yet been made for corresponding improvements in demand forecasting.