The Application of Material Requirements Planning (MRP) System to Aircraft Parts Inventory

By

Adel Abulgassem Ghobbar

A thesis submitted for the Degree of Doctor of Philosophy

Department of Aeronautical, Civil and Mechanical Engineering

City University

London

July, 2001

ABSTRACT

As the title implies, the application of MRP into an aviation context is the response to the huge cost of parts holding in an ever-expanding industry. The nature of intermittent parts demand (unpredictable parts), typical of maintenance and overhaul inventory parts control, is investigated both to illustrate the deficiency of traditional ROP systems for dependent-demand inventory and other applications in the area of lot sizing and forecasting with a specific exploration into sources of demand lumpiness.

In order to investigate current inventory procedure, we surveyed 175 *airline operators* and *maintenance service organisations*, to explore the status of MRP and ROP worldwide. This response showed current inventory practice to be less than effective and that better systems were required, leading us to investigate specific problems experienced namely; lot-size and forecasting methods used within the MRP concept. MRP had made some inroads into the aviation sector, but a number of factors have prevented its general uptake.

Through a case study of KLM-uk's workshop practices within overhaul and repair, we apply various solutions to lot-size and forecasting methodology in order to realise best practice, putting forward a small scale MRP-spreadsheet as a working tool. In the process we present two predictive models; a Lot-size Predictive Cost Model, *LPCM*, and a Predictive Error-Forecasting Model, *PEFM*. The models in their present form use seventeen lot-size and thirteen forecasting methods respectively, simplifying material management through appropriate estimates of costs and planning needs. Within lot-sizing, we found that under almost all operations conditions the WWA and MSM2 methods give the best performance. Similarly the WMA method followed by the Holt and the Croston methods work best for forecasting intermittent demand parts.

To Allmighty God

To my mother, Massuda, and my father, Abulgassem, for their love, support and patience.

Their continual belief in me,

has been the main source of inspiration and strength in my life.

Acknowledgements

I would first and foremost like to thank my supervisor, Dr Chris H. Friend to whom I am greatly indebted for his invaluable guidance and strong support during the course of this research. He made substantial contributions to this work by actively participating and creating new ideas. The completion of this work would not have been possible without his detailed advice, constructive criticism, encouragement and patience.

I am also extremely grateful to Dr Louise Swift school of Maths and Statistics at the University of East Anglia, whose invaluable knowledge, experience and moral support proved to be of inestimable value to the completion of this thesis.

The willing participation of 175 different aviation companies in our initial survey is to be acknowledged and they are listed individually in the Appendix A. The contribution of Royal Dutch Airlines (KLM-uk) staff however was vital. In particular I would like to thank Ian Bartholomew in logistics, Barry Tabbanor from purchasing and supply and Alan Dolphin their workshop superintendent. They spent a considerable amount of time to provide us with valuable data and insights.

I express my sincerest gratitude to my teachers, lecturers, tutors and advisors throughout my studies, from primary school to university, too numerous to mention by name, who encouraged and inspired me and presented me with the means to achieve things beyond my horizons.

A special indebtedness is due to my family, especially my loving parents, my wife Salma, my sisters and my brothers, who have always done their utmost to support and encourage me.

I would also like to thank my friends Abdarrazzak Goodall, Shan Barclay and Stephen Barrett for their support and assistance.

Finally, I thank God for his mercies and blessings every step of the way.

Declaration

LIST OF CONTENTS

Chapter 5

Chapter 8

LIST OF FIGURES

Chapter 7

Chapter 8

LIST OF TABLES

Chapter 2

Chapter 3

Chapter 4

Chapter 7

Chapter 8

GLOSSARY OF TERMS

AD	Average Demand
ADI	Average inter-Demand Interval
AMASS	Advanced Materials Allocation Scheduling System
ANOVA	Analysis Of Variance
AO	Airline Operator
AOG	Aircraft-On-Ground
APICS	American Production and Inventory Control Society
ARRSES	Adaptive-Response-Rate Single Exponential Smoothing
ASPL	Advance Spares Provisioning List
ATA	Air Transport Association
AUR	Aircraft Utilization Rate
AUV	Annual Usage Value
AW	Additive Winter
BAe	British Aerospace
BOM	Bill Of Materials
BTH1	Bookbinder & Tan Heuristic One
BTH2	Bookbinder & Tan Heuristic Two
CAA	Civil Aviation Authority
CC	Carrying Cost
CM	Condition-Monitoring
CMA	Component Maintenance Assembly
COL	Component's Overhaul Life
CPA	Critical Path Analysis
CPP	Cumulative Part-Periods
CV^2	Square Coefficient of Variation on Demand
CVD	Coefficient of Variation in Demand
DES	Double Exponential Smoothing
EDI	Electronic Data Interchange
EIP	End Item Plans
EOQ	Economic Order Quantity

EPP	Economic Part-Period
EWMA	Exponentially Weighted Moving Average
FAA	Federal Aviation Administration
FHs	Flying Hours
FLs	Flying Landings
FOP	Fixed Order Period
FOQ	Fixed Order Quantity
FPR	Fixed Period Requirements
FSN	Fast, Slow and Non-moving
GLM	General Linear Model
HML	High, Medium, Low
HT	Hard-Time
IATA	International Air Transport Association
IC	Item Cost
ICA	Incremental Approach
IIC	Incremental Inventory Cost
IIT	Issue Interval Technique
IOQ	Incremental Order Quantity
IP	Inventory Position
IPC	Illustrated Parts Catalogues
IPD	Initial Provisioning Data
IPP	Incremental Part-Periods
IPPA	Incremental Part-Period Algorithm
JAR	Joint Aviation Requirements
JIT	Just In Time
KLM	Royal Dutch Airlines
LALB	Look-Ahead/Look-Back
LFL	Lot For Lot
LPCM	Lot-size Predictive Cost Model
LPD	Logistic Planning Document
LS	Lot-Size
LT	Lead-Time
LTC	Least Total Cost

LUC	**L**east **U**nit **C**ost
MAD	**M**ean **A**bsolute **D**eviation
MAPE	**M**ean **A**bsolute **P**ercentage **E**rror
ME	**M**ean **E**rror
MEL	**M**inimum **E**quipment **L**ists
MEMIS	**M**aintenance and **E**ngineering **M**anagement **I**nformation **S**ystem
MHs	**M**an-**H**ours
MMEL	**M**aster **M**inimum **E**quipment **L**ist
MO	**M**aintenance Service **O**rganizations
MOQ	**M**inimum **O**rder **Q**uantity
MPE	**M**ean **P**ercentage **E**rror
MRO	**M**aintenance **R**epair and **O**verhaul
MRP	**M**aterial **R**equirements **P**lanning
MRP II	**M**anufacturing **R**esource **P**lanning
MS	**M**aster **S**chedule
MSG	**M**aintenance **S**teering **G**roup
MTBF	**M**ean **T**ime **B**etween **F**ailure
MTBO	**M**ean **T**ime **B**etween **O**verhaul
MTBR	**M**ean **T**ime **B**etween **R**emoval
MTBUR	**M**ean **T**ime **B**etween **U**nscheduled **R**emoval
MSE	**M**ean **S**quare **E**rror
MSM1	**M**odified **S**ilver-**M**eal **O**ne
MSM2	**M**odified **S**ilver-**M**eal **T**wo
MW	**M**ultiplicative **W**inter
OC	**O**rdering **C**ost
OEM	**O**riginal **E**quipment **M**anufacturers
OH	**O**n-**H**and
OLS	**O**rdinary **L**east **S**quare
ORR	**O**rder **R**eleases **R**eport
PEFM	**P**redictive **E**rror-**F**orecasting **M**odel
PH	**P**lanning **H**orizon
PMP	**P**rimary **M**aintenance **P**rocess
POQ	**P**eriod **O**rder **Q**uantity

PPA	Part Period Algorithm
PPB	Part Period Balancing
Qty	Quantity
RAM	Random-Access Memory
RMSE	Root Mean Square Error
ROL	Re-Order Level
ROP	Re-Order Point
RSPL	Recommended Spares Provisioning Listing
SAE	Society of Automotive Engineers
SES	Single Exponential Smoothing
SDE	Scarce, Difficult and Easy to Procure
SKUs	Stock Keeping Units
SM	Silver-Meal
SPL	Seasonal Period Length
SRM	Seasonal Regression Model
SS	Safety Stock
SSE	Sum of Squared Errors
TAES	Trend Adjusted Exponential Smoothing
TAT	Turn Around Time
T_{EOQ}	EOQ divided by the average weekly demand
USAF	United State Air Force
VBA	Visual Basic for Applications
VED	Vital. Essential and Desirable
WCDR	Weighted Calculation of Demand Rates
WMA	Weighted Moving Averages
WRDF	Weighted Regression Demand Forecasters
WWA	Wagner-Whitin Algorithm

1. INTRODUCTION

The aim of this Chapter is to provide an introduction to the thesis and to propose the viability of adapting the Material Requirements Planning system, MRP, to aircraft parts inventory, with specific applications in the area of lot sizing and forecasting. The Chapter ends with the layout of the thesis.

1.1 The context

Service parts are a major expense for companies in all sectors, one that often exceeds annual profits. The commercial aviation industry, for instance, holds an estimated $45 billion in spare parts worldwide. A conservative estimate for the cost of holding this inventory is $6.1 billion dollars per year, more than four times the combined profits of the world's airlines between 1995 and 1997, and even this is probably understated. A reduction in inventory by operators could free up huge amounts of capital and reduce operating expenses.

Maintenance and inventory control problems have been a focus area for many who work in the area of airline operations research; of particular interest is the application of quantitative techniques to control the cost of component maintenance, or repairable parts, and to improve overall equipment utilization. When focusing research efforts on aircraft component maintenance, airlines must determine the method of repair required in order to lower cost, maintain quality, and keep aircraft utilization high. Quite simply, when an aircraft component is removed for maintenance, it will usually be replaced on the aircraft by a like component taken from stock. Having the component in stock will allow the aircraft to be returned to service quickly but will cause measurable cost to be incurred. Whether from an in-house shop or a maintenance vendor, the quicker and more predictably the spares are repaired and returned, the fewer the component spares that need to be carried in stock while at the same time not incurring the probability of an out-of-stock situation.

The aircraft spare-parts industry is unsure of itself. While some companies enjoy growth, others face uncertain futures and many no longer see the sense in sitting on huge inventories of spare parts when they can turn those assets into cash or task out storage and upkeep to others. The airlines industry, having risen rapidly in the last few years from the floor of recession, has been seeking alternative ways to manage its spare parts and overhaul shops, while start-up airlines have been seeking a complete service in this area. There is a huge, pent-up demand by airlines who want their spare-parts inventories managed in a more efficient way. Most airlines have far more inventory than they need. The past view of 'if we need it, get three', became extremely expensive and in their effort to be masters of their own destinies, and in their over-riding fear of an aircraft being late, the airlines built up a ten-year supply of spare parts. However, overheads like paying for property taxes, storage costs, heat, lighting, together with their management, just to keep spares on the shelf probably add 30% a year to the price of the part, so all airlines are now focused on reducing their inventory stock. For this reason there are several challenges facing the airline industry that make the use of more sophisticated inventory control systems essential. The chronic unreliability of historical data, rapidly changing products, equipment, fleets of aircraft that are ageing and the introduction of regulatory changes are all impacting on the reliability of traditional data.

For various reasons however, most manufacturers, especially smaller ones, have clung to older methods of reordering component-parts. The method favoured is usually some form of the traditional Reorder Point system, ROP, in combination with a Bill of Materials explosion, BOM. ROP plans for routine replenishment of parts, while the BOM explosion is performed for the purpose of generating parts-shortage lists for components needed in support of the current Master Schedule, MS. Since ROP continues to be in wide use in the aviation industry, it warrants the attention we give it, yet the deficiency of ROP for planning dependent-demand inventories has been demonstrated by many operators. The ROP is deficient in that it results in an unnecessary excess of parts or stockouts.

Few companies can boast that they achieve the maximum benefits from their parts investments which are notoriously difficult to manage. Demand is variable and hard to predict, lead times for replenishment parts are often erratic, stockout costs are difficult to measure and the lot size of part inventories usually requires large order quantities.

Unpredictable parts, which form sporadic or intermittent[1] demand patterns with highly skewed distributions, are common in parts inventory, and much available inventory control methodology is not appropriate for such items. The issue of intermittent demand in inventory management is too often neglected. Handbooks describe ROP based on normal demand distribution. Many other standard software packages for inventory management and control also take normality of demand for granted. We take issue with this.

With inventory problems arising when periodic overhauls are scheduled, how many spare parts should be stocked at the aircraft maintenance centre in order to meet demands, and as the demand requirement becomes intermittent, how effective is it to use such classical inventory methods as the ROP method? Of late, we have seen airlines start moving towards a system preferred by many aerospace manufacturers, the Materials Requirements Planning system, MRP. Since its advent, advocates of MRP have claimed that the system is better designed to handle intermittent demand patterns. This argument is developed in this study.

1.2 Research methodology

To investigate the current inventory procedure used by *airline operators* and *maintenance service organisations*, we developed an extensive questionnaire, to explore the current status of MRP and ROP in companies today. With responses from 175 out of 283 airline operators and maintenance service organisations worldwide, the survey looks at the benefits and costs incurred through their implementation and any resultant problems. The response to the survey led us to investigate further issues experienced by those companies, namely; lot-size and forecasting methods used within the MRP concept. Typically experienced problems were high inventory costs and poor delivery performance, poor selection of lot-size methods and forecasting settings. Despite the importance of MRP input parameters, the effects are not well understood, and few prescriptive methods for setting them exist in the airline industry. This study aims to clarify the effect inputs have on MRP performance.

---

[1] Intermittent demand is synonymous with terms such as lumpy, sporadic and erratic demand. Throughout the thesis we come across these words.

1.3 Research objectives

The objective of this study is to look at the problems facing the aviation industry today and how the MRP application, commonly used in manufacturing planning and control can benefit it. In addition, this study intends to address two further research issues regarding intermittent demand:

- As the degree of demand lumpiness varies, how is the performance of MRP lot-size and forecasting affected by this variation? Do we expect that an increase in demand lumpiness would lead to a better performance for those methods already used by airline operators?
- After evaluating the impact of demand lumpiness on MRP performance (lot-size and forecasting), can a general pattern be derived for the main sources of intermittence?

1.4 Data sources

The logical extension of MRP to spreadsheets is developed in this study using data from Royal Dutch Airlines (KLM-uk, formally Air UK). Sample data of repairable parts from their fleet of Fokker, BAe and ATR aircraft were kept, with records of weekly demand levels for each component, then grouped in monthly and quarterly intervals of demand usage. Data from a total of thirty-five components was collected during a span of three to ten years from January 1989 to June 2000. Only recurring demands, *hard time*, *HT*, and *condition monitoring*, *CM*, components, which could be expected to occur routinely as a result of aircraft utilisation, have been considered in this study. In addition to demand data, aircraft operation data i.e. flying hours and number of aircraft in service was also collected for the same time periods.

1.5 Predictive models proposed

Owing to the unpredictable nature of demand for aircraft maintenance repair parts, airline operators are still looking for superior forecasting and lot-size methods that can provide more economical and smoother planning procurement. This study puts forward two models, namely; a Lot-size Predictive Cost Model, *LPCM*, and a Predictive Error-Forecasting Model, *PEFM*, aimed to benefit airline operators and other maintenance service organisations. The models in their present form use seventeen lot-size and thirteen forecasting methods respectively, giving the material manager an estimate of costs and planning needs. This approach is consistent with the purpose of this study, which aims to evaluate different lot-size and forecasting methods when faced with intermittent demand and which better meets a cyclical demand for parts. The models are applied to the data provided by KLM-uk.

1.6 Thesis layout

Chapter two is an overview of aircraft regulation and spare parts control, in which a general description of relevant literature is cited.

Chapter three begins with a brief description of the ROP inventory system, followed by a survey examining the relative success of this system.

Chapter four describes the background of MRP, its features and how it is related to aircraft maintenance. A survey analysis follows, to examine the benefits and costs incurred, the nature of the implementation process used and problems faced during implementation.

Chapter five presents an overview of the airline operator KLM-uk participating in this research. It looks into its background and the current inventory system used.

Chapter six presents an MRP-spreadsheet using a Visual Basic for Application, VBA, as an easily implementable and reliable application for material planning. The spreadsheet model is based on the results of an MRP survey of airline companies, many of whom found standard MRP systems impossible to implement both financially and environmentally.

Chapter seven presents the results of an investigation into the relative performance of each lot-size method, followed by a description of our developed lot-size predictive cost model. *LPCM.*

Chapter eight presents the results in two parts. The first part, deals with the sources of this intermittent demand data collection as a function of airline operational factors. The second part presents the results of the utilisation of these factors in forecasting intermittent demand, followed by a description of the developed predictive error-forecasting model, *PEFM.*

Chapter nine draws principal conclusions from the preceding Chapters and recommendations are made for further work.

In addition to this layout, and owing to space limitations, some of the results are presented in the attached CD disk at the back of this thesis.

2. AIRCRAFT MAINTENANCE REGULATION AND CATEGORISATION OF PARTS

2.1 Introduction

In the early days of aviation, maintenance requirements were determined by a few experienced engineers in collaboration with the manufacturer. As aircraft became more technically advanced, it was recognized that a more sophisticated method for developing maintenance programmes and parts control was needed.

Soon after their inception, both the Civil Aviation Authority, CAA, and Federal Aviation Administration, FAA introduced the concept of *Airworthiness*, defined as "the continuing capability of the aircraft or component part to perform in a satisfactory manner through a range of operations determined by the CAA or FAA, and the flight operations for which it was designed". Each aircraft off the line receives an airworthiness certificate attesting to the fact that it conforms to the type certificate and is safe to fly [30].

Regulatory control on aircraft and equipment inevitably impinges on a natural tendency within the airline companies to economise on spare part inventory owing to the significant investment this involves. In this Chapter we intend to discuss these issues in detail with specific reference to component parts management and stock control, together with a basic introduction to the terminology used in inventory control in the aviation industry.

2.2 Airline maintenance requirements

The aircraft maintenance workload is generated through a continuous airworthiness maintenance program. These programs include: aircraft inspections which deal with routine inspection, minor services and tests performed on the aircraft at prescribed intervals; scheduled maintenance that includes replacement of life-limited items, periodic overhauls and special inspection, and unscheduled maintenance which is usually generated by inspections, pilot reports and failure analysis.

In order to perform the maintenance work, production maintenance is organized into three levels [75]. The first level is the first line which deals with inspection, testing and minor maintenance tasks. The second line maintains major tasks, e.g. overhaul and replacements of limited-life equipment. The third line or depot maintenance is used for major jobs which cannot be handled by the first and second lines.

To conform with CAA guidelines, some companies have adopted maintenance policies that call for routine inspections at least every four days. The first major check (denoted as 'A' check), mandated by the CAA, occurs every 65 flight hours, or about once a week. 'A' checks involve a visual inspection of all major systems such as landing gear, engines, and control surfaces. 'B' checks are performed every 300 to 600 flight hours, and entail a thorough visual inspection plus lubrication of all moving parts such as horizontal stabilizers and ailerons. 'C' and 'D' checks are done about once every one to four years respectively, and require taking the aircraft out of service for up to a month at a time.

The CAA is responsible for certifying carriers and overseeing maintenance operations. Inspectors are assigned to each airline and monitor compliance with airworthiness directives and general maintenance procedures. With the exception of unscheduled repairs, aircraft maintenance takes place by a series of checks of increasing thoroughness. The frequency of these checks depends on a combination of flight hours and number of take-off and landing cycles, and may be performed at any site appropriately equipped. Because each aircraft type has different inventory requirements, few savings can be achieved by combining facilities for the different fleets.

2.2.1 Air operators' certificates for maintenance support

The CAA has provide most airline operators and maintenance service organisations with some scheme guidelines known as CAP 360 [32], which may be summarised under the following headings specific to inventory control:

- Account must be taken of the operator's Minimum Equipment Lists, MEL to ensure that essential spares to support the rectification of defects in systems required for operation are placed where they are most likely to be needed and in such numbers as to ensure that successive defects will be promptly addressed.

- The CAA may require the examination of spares provisioning arrangements and any agreements entered into to ensure that adequate support for defect rectification is being made. Where necessary the CAA may require additional provisions to be made.
- The necessary material to perform the scope of work, which means readily available raw material and aircraft components in accordance with manufacturer's recommendations unless the organisation already has an established spares provisioning procedure. This was also specified by the Joint Aviation Requirements, JAR [68].

2.3 The development of a maintenance steering group, MSG-3

In mid-1968, representatives of various airlines developed the "Handbook MSG-1, Maintenance Evaluation and Program Development," which included decision logic and inter-airline/manufacturer procedures for developing a maintenance program for Boeing 747 aircraft. It was subsequently decided that experience gained on the 747 project should be applied to all newly developed aircraft. In order to do this, the decision logic was updated and certain procedures specific to the 747 were deleted. That universal document resulted in MSG-2. In mid-1979, the Air Transport Association, ATA, with the intention of further updating procedures, formed a task force to analyse MSG-2 and make recommendations for change and improvements. These revisions were published by the ATA and approved by the FAA in late 1993 as an acceptable method for developing scheduled maintenance requirements for new model transport-category aircraft. This is known as MSG-3.

While MSG-3 has become a mainstay of commercial aviation, business aircraft manufacturers, corporate operators and repair firms, serving that market, have resisted such reliability centred maintenance, believing it to be safer to replace components at regular intervals rather than to inspect them regularly and to replace when necessary [105].

Implementation of the recommendations generated through MSG-3 analysis is the major role of an airline operator in developing a maintenance program. The accuracy and clarity of the MSG-3 process provides a smooth transition for the airline to determine its manpower, parts, tooling, ground equipment, and other related requirements [23, 93]. MSG-3 is based on a consistent and rigorous application of questions for each aircraft component. It is decision tree analysis at work. The first question MSG-3 asks is: "What's the consequence of a specific hardware/component failure for the entire aircraft?" Once this consequence is assessed, MSG-3 offers a choice of applicable tasks and evaluates each one's effectiveness. Once a task is chosen, its frequency is patterned after frequencies adopted for similar hardware. If no comparison can be made, a conservative frequency is initially adopted and adjusted as experience is gained.

This work [75] resulted in the recognition of a third, primary maintenance process called *condition-monitoring*, a process applying to components with specific design characteristics but not involving *hard-time* or *on-condition* checks.

2.4 Primary maintenance process, *PMP*

The three primary maintenance processes recognised by the CAA [30, 51] are; hard-time, on-condition, and condition-monitoring. In general terms, the first two both involve actions directly concerned with preventing failure, whereas condition monitoring does not. However, the condition monitoring process would be expected to lead to preventive action if shown to be necessary. These categories of component maintenance are defined as follows:

2.4.1 Hard-time, HT

This is defined as a preventive process in which known deterioration of an item is limited to an acceptable level by the maintenance actions carried out periodically according to time in service. This time may be calendar time, the number of cycles, or the number of landings. The prescribed actions normally include servicing, full or partial overhaul and/or replacement according to the instructions in relevant documentation so that the item is restored to suitable condition for use for a further specified period. *HT* requires that a component be overhauled after a pre-set usage time, regardless of the component's condition, and assumes a relationship between failure and age.

2.4.2 On-condition, OC

This is also a preventive process, but one in which the item is inspected or tested at specified periods to an appropriate standard in order to determine whether it can continue in service. The inspection or test may reveal a need for servicing action. The fundamental purpose of *OC* is to remove an item before its failure in service. It is not a philosophy of 'use until failure'. *OC* requires checks and tests of components at fixed intervals, with parts such as wires, bulbs, brackets, covers and bearings etc, being replaced during overhaul.

2.4.3 Condition monitoring, CM

This is not a preventive process, having neither hard-time nor on-condition elements, but one in which information on items is collected from operational experience, then analysed and interpreted on a continual basis as a means to implement corrective procedures.

It is convenient here to classify *information*, z, into two classes; namely, direct information and indirect information. Direct information is where z measures a variable which directly determines failure, for example the thickness of a brake pad, or the wear in a bearing. Indirect information z on the other hand provides associated information which is influenced by the component condition, but is not a direct measure of the failure process, for example, an oil analysis or a vibration frequency analysis. In both cases, the point of concern is to predict, given information z, the subsequent and conditional failure time distribution as an input to modelling maintenance practice.

The CAA has imposed a continual report requirement on all such components with each carrier having a certain latitude which it can exercise in managing its own program, Table 2.1 summarises the overhaul control category.

Category	Maintenance Action	Requirements / Restrictions
Hard-Time	Overhaul/Replace item at specified time interval.	Overhaul will 'zero time' the item.
On-Condition	- *OC* checks at specified time intervals. - Regularly scheduled collection of *OC* data. Overhaul required when item exceeds specified limits for *OC* check or *OC* data.	- *OC* check must give reasonable assurance of satisfactory operation until the next check. - *OC* data must ascertain continuing airworthiness and/or show reliability degradation – failure imminence.
Condition - Monitoring (No overhaul control)	- No scheduled overhaul or repair. - Item is operated to failure.	- Failure must have no direct adverse effect on flight safety. - Hidden functions must have regularly scheduled verification tests. - Data collection / evaluation program required for overhaul surveillance.

Table 2.1 Overhaul control category summary.

2.5 Aircraft inventory categorisation

The items that are typically found in aircraft components inventory are listed in Table 2.2 (consumable, repairable and critical spares). They are grouped to illustrate the types and variety of demand for aircraft maintenance parts. Spares are subjected to both random and dependent demand. The random demand is generated by failures that can result in the need for emergency repairs, while dependent demand for spares is generated by schedules for the off-line repair of the parent aircraft item that uses that part. There are three major groups of spares recognised by the majority of the airlines. These are: *Components*, *Recoverables* and *Expendables*.

2.5.1 Components

These include Rotables and Repairables.

2.5.1.1 Rotables

A rotable is an item that bears an individual serial number either assigned by the airline or by the manufacturer. Rotables (e.g. hydraulic pump) are assemblies which are subject to replacement on the aircraft or engine, on a Time Between Overhaul, TBO, (either *HT* or *OC*) basis. After a rotable is removed from the aircraft or engine it is normally routed to an overhaul shop for inspection and repair or overhaul and re-certification of serviceability according to established procedures. In this way rotables extend their life expectancy. Under normal conditions their life is equal to that of the aircraft or engine.

2.5.1.2 Repairables

A repairable spare is an item that is economically repairable over a period that is less than the life of the aircraft or engine. Repairables are usually units with a detailed parts breakdown. Repairable items can be economically reconditioned for a limited number of times. Repairables are items conditioned to original state by using parts and known repair processes.

2.5.2 Recoverables

These spares do not have a detailed parts breakdown but are put into a serviceable condition one or more times by a refurbishing service type operation such as recharging, refilling or content replacement.

2.5.3 Expendables

Spares whose cost of repair is higher than the cost of a new item are called expendables. Expendables (consumables) items which are discarded and replaced as recommended by the manufacturer, these items are subject to only one time use with no authorised repair procedure existing. Expendables are further classified into the following four groups:

- Mandatory (100%) replacement.
- On-Condition replacement item.
- Miscellaneous hardware items.
- Bulk material.

Aircraft Spares		Economically Recoverable	Authorized Repair	Serial Number	Depreciated	Comparative Unit Cost
Component	Rotable	Yes	Yes	Yes	Yes	Highest
	Repairable	Yes	Yes	No, but Rarely Yes	Yes	Higher
Recoverable		Yes	No	No	No	High
Expendable		No	No	No	No	Generally Low

Table 2.2 Characteristics of aircraft spares.

The airline stock control problem is somewhat non-standard. mainly because of:

- Wide variations in unit cost;
- Low and/or unpredictable demand,
- Lengthy delivery lead-times.
- Although. from a financial aspect. the amount of capital invested in the establishment of a stock of expendable spares is far less than for rotables and repairables. the range and quantities of expendables are far greater.
- The types of expendable spares generally dealt with fall mainly into three distinct categories:
  - » Line maintenance items (on aircraft); a part which is replaced on the aircraft or engine during aircraft maintenance.
  - » Shop maintenance item (off aircraft); a part which is required to repair a unit which has been removed from the aircraft for repair and which can be returned to service without its full overhaul/repair cycle.
  - » Overhaul item; a part which is required for overhaul or repair of an aircraft, engine, rotable or repairable unit.

Some expendable spares are individual in their application to either requirement, and some occasionally meet more than one situation. The penalties involved by shortages of expendable spares are not usually as serious as being out of stock with a rotable/repairable/recoverable item. This is because an expendable shortage can often be met by:

- Either the fitting of the next higher assembly, or
- Local manufacturing, or

- Removal from the next higher assembly, as a last resort.

2.6 Parts classification

Before computers, paying equal attention to all inventory parts was not feasible. The focus would be on a few expensive and fast-moving parts. Parts were categorised into homogeneous groups based on their particular characteristics. This is the principle of selective inventory control. Several procedures for classifying parts into homogeneous groups are available, a few of which have been listed in Table 2.3.

Technique	Description	Basis for formulation
ABC	Pareto rule	Annual usage value of the parts
VED	Vital, essential and desirable	Criticality of the parts
FSN	Fast, slow and non-moving	Usage rate of the parts
HML	High, medium, low	Unit price of the parts
SDE	Scarce, difficult and easy to procure	Procurement lead-times

Table 2.3 List of selective inventory control procedures.

Several non-cost criteria have been identified as important in the management of maintenance inventories [43]. Among them are lead-time, obsolescence, availability, substitutability, and criticality. In discussions with managers this final concept of criticality seemed to sum up their feelings about most aspects of maintenance items. It takes into account such factors as the severity of the impact of running out, how quickly the item could be purchased and whether there was an available substitute. It remained to be seen whether it would be feasible to distinguish degrees of criticality in practice.

The purpose of spares classification is to provide quick identification of aircraft spares either within a single airline or in conjunction with other airlines. To provide material support for the maintenance and overhaul of such a variety of equipment, over a million items are stocked. These items are classified under rotables, (class A), repairables, (class B), and expendables, (class C). The inventory parts classifications are shown in Table 2.4.

Class	Type	Description
A	Spares	Aircraft rotables (serialised and life-controlled)
B	Spares	Aircraft repairables, ground equipment, components
C	Spares	Aircraft expendables, ground equipment, consumables
C	Maintenance stocks	Standard items (bolts, nuts, washers, etc.)
C	Maintenance stocks	Sealants, paints, oils and greases
C	Raw materials	Bulk items (carpets, sheet metals, vinyls, etc.)
C	General supplies	Commercial items (rags, detergents, inspection fluids)
C	Tools	Aircraft tools, commercial tools

Table 2.4 Inventory types and classifications.

2.6.1 The nature of the ABC analysis

The ABC analysis illustrated in Table 2.5, is an application of the Pareto principle, named after a 19th Century Italian economist. The goal of the ABC analysis is to assign all inventory to one of three categories[1]. Each category brings with it different requirements in terms of the degree of control and requirements. In general, we use two attributes when describing the categories. The first is the percentage of part numbers or Stock Keeping Units, SKUs. The second is the percentage of inventory value accounted for by that category of inventory. Inventory value is defined in terms of two traits: the quantity demanded per period of time; usually a year, and the cost per unit. Typically, we express the three categories as follows:

Groups	Quantity % Of SKUs	Value % Of $	Degree of Control	Types of Records	Safety Stock	Ordering Procedures
A items	10-20%	70-80%	Tight	Complete Accurate	Low	Careful, accurate; frequent reviews
B items	30-40%	15-20%	Normal	Complete Accurate	Moderate	Normal ordering; some expediting
C items	40-50%	5-10%	Simple	Simplified	Large	Order periodically: 1 to 2 year supply

Table 2.5 Characteristics of the ABC classification system.

[1] The survey shows that some companies may use more than three categories.

2.6.2 Master minimum equipment list, MMEL

This is a list of items that are permitted to be temporarily inoperative on an aircraft while still maintaining the desired level of safety at the time of despatch on revenue operations whilst operating within a controlled and sound programme of repairs, replacement and servicing.

The MMEL is a list which may be produced by the aircraft manufacturer or by the Airworthiness Authority, and covers all aircraft of a specified type. This is described more fully in CAP 549 [31, 51].

For an operator to develop a Minimum Equipment List, MEL, applicable solely to his own operation, he must use MMEL. The MEL must be no less restrictive than the applicable MMEL but may include additional advisory material and define any additional or modified operational procedures. MEL determination is regarded as a matter principally for flight operation departments with engineering input. Engineering has responsibility for ensuring that aircraft are kept to MEL standards. This may be known to some operators as *criticality* and/or *essentiality*, which can be categorised into three codes as follows:

1. A flight cannot be dispatched for commercial service with the part inoperative.
2. A flight can sometimes be dispatched for commercial service with the part inoperative.
3. A flight can always be dispatched for commercial service with the part inoperative.

2.6.3 Lead-time, LT

The distance of an airline from the supply source has a strong bearing on the ultimate lead-times involved in stock replenishment. It is important, therefore, in establishing initial stocks that this factor is interpreted in terms of time and that it is added to the manufacturers' lead-times.

2.6.4 Insurance spares

These are items held by either the airlines or the manufacturer purely as a precaution against serious delay of the aircraft should an accident occur. Examples include, control surfaces, landing gear doors, wing tips etc. Because these items are expensive they should be held either by the manufacturer or by a pool of airlines operating the same routes. Insurance spares can be recoverable or expendable components, but are different from airline spares holdings.

Most applications found in the literature make use of a combination of selective inventory control procedures because classification or categorisation of parts based on just one criterion is inadequate for managing the maintenance components. There follow two examples of applications involving such a combination.

Ramani and Krishnan Kutty [100] have utilised an ABC * VED classification technique where not only the annual value of the usage of the part is taken into account, but also the parts are classified into nine categories. For each of the nine categories, a range of service levels is specified.

There are several ways by which the criticality of a part can be defined. A part may be called critical if the loss of operation caused by non-availability of the part is very high. If a substitute part is readily available then the part may be less critical. Flores and Whybark [43, 44] have identified several non-cost criteria for management of spare part (maintenance) inventories. Among them are obsolescence, availability and substitutability. They have developed a 'policy-driven' approach to categorising spare parts. By this method, policies for all the categories in which the parts fall are first established. After this the maintenance manager is allowed to determine which policy is best suited for each of the categories.

2.7 Summary

The basic purpose of this Chapter was to provide the necessary background to, and present in a proper perspective the need for, spare parts control. Firstly the various types of parts in selective inventory control procedures and their characteristics in terms of CAA and FAA regulations were explored. Then the terminology for selective control was introduced explaining the commonly used methods, and the work done by researchers in the area of spare parts management was discussed. This Chapter provides a foundation for those which are to follow.

3. REORDER POINT, ROP

3.1 Introduction

Continuously monitored and periodic systems are, by themselves, essentially only *order launching* techniques. With a tendency to look *back* at historical averages rather than *ahead* to a forecast of parts requirements, they nevertheless they are still widely used by aviation companies as a basis for releasing orders because they answer the basic questions of *how much* to order and *when*. This is often satisfactory for independent demand inventories, but is usually unsatisfactory for aviation parts inventories.

In order to make an assessment of the current inventory systems used by the aviation industries today, we introduce the background to the ROP system with its particular features in order to contrast it with the MRP system. An analysis of ROP formed the rationale of our survey to the airlines. The second part of this Chapter introduces the survey responses to ROP in both airline operators (hereafter AO) and maintenance service organizations (MO). The survey shows that many companies, unsatisfied with their existing system, were looking for alternative concepts along the lines of the MRP system which is the subject of the next Chapter.

3.2 Inventory control system

In this section we start with a description of type of demand characteristics in order to proceed with the mechanism of the ROP system.

3.2.1 Demand type characteristics

Dependent demand is the demand for components derived from the demand for other items, or occurs when the need for a component is triggered by some specific event. In the aviation industry, this event is typically the requirement for an assembly that uses this component (e.g. component-parts and raw material).

Independent demand occurs when the demand for the component is not related to other components or events (e.g. spare parts and finished goods).

3.2.2 The ROP concept

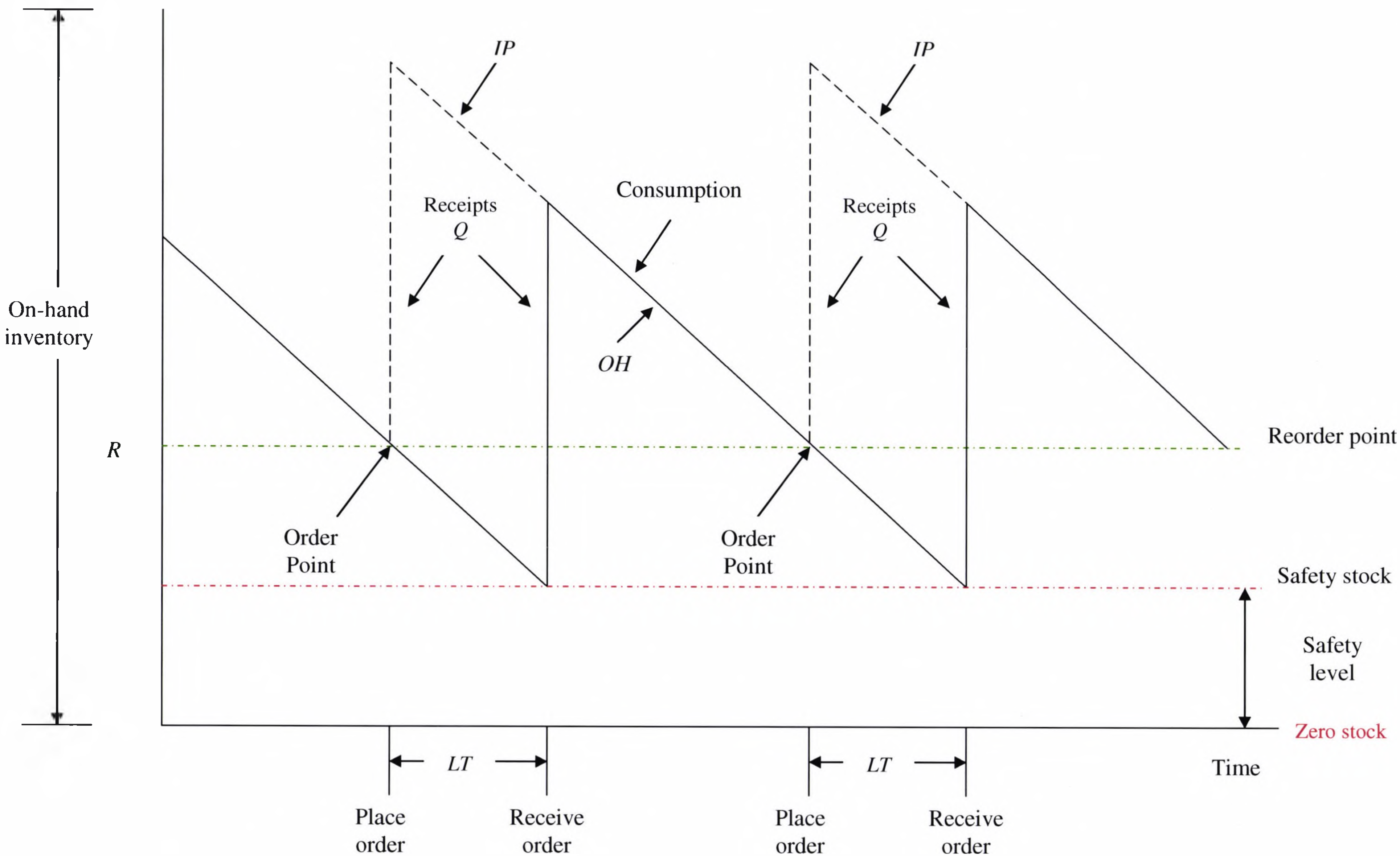
The traditional inventory control systems are classified as either continuously monitored or periodic. As space does not permit a detailed description of the numerous types of inventory control system in use today, we take only a brief look at continuously monitored systems.

The *continuous review system* is that in which the remaining quantity of an item is reviewed each time a withdrawal is made from inventory and determines whether it is time to reorder or not. In practice these reviews, rather than being done continuously may be done only frequently, such as on a daily basis, rather than upon each withdrawal. This type of system, illustrated in Figure 3.1, lends itself to the use of the EOQ purchasing methods. The system requires continuous monitoring of inventory levels. This continuous review system is sometimes called *Q* system, or fixed order quantity system as well as the *reorder point system, ROP*.

As the Figure 3.1 shows, the downward sloping line represents the on-hand, *OH*, inventory, which depletes at a fairly steady rate. When it reaches the reorder point *R*, (the horizontal line), a new order for *Q* units is placed. The on-hand inventory continues to drop throughout lead-time, *LT*, until the order is received, at which time the end of lead-time, the on-hand inventory jumps vertically by *Q* units.
The *inventory position*[1], *IP*, is also shown in Figure 3.1. It corresponds to the on-hand inventory, except during the lead-time. Just after a new order is placed, marking the start of the lead-time, *IP* increases by *Q*, the size of the new scheduled receipt (dashed line). *IP* exceeds *OH* by this same margin throughout the lead-time. At the end of the lead-time, when the scheduled receipts convert to on-hand inventory, *IP* = *OH* once again. The key point here is simple: Compare *IP*, not *OH*, with *R* in deciding whether to reorder.

[1] Measures the item's ability to satisfy future demand, relying only on scheduled receipts, and is defined as the inventory on hand, plus on order, minus back orders.

Figure 3.1 Continuous review system (reorder point system) layout.



3.2.3 Selecting the reorder point

The reorder point R equals the *demand during lead-time*, with allowance for safety stock, SS. More formally, the reorder point is

$$R = \bar{D}_{LT} + SS \qquad 3.1$$

where R is the reorder point, $\bar{D}_{LT}$ is the average demand during lead-time LT and SS is the safety stock. Since $\bar{D}_{LT}$ is externally determined, the real decision to be made when selecting R concerns the safety stock level SS.

3.3 Inventory measuring procedures

Where inventory is necessary to the aircraft maintenance operation, or inventory results as a natural consequence of the operating system in place, companies will normally have overall inventory measurements by which the total inventory is measured against an established target [77]; these may be expressed in the form of average aggregate inventory value, weeks of supply and inventory turnover. The following section describes each of those tool measurements.

3.3.1 Average aggregate inventory value

Is the average total value of all items held in inventory over some time period. It is found by multiplying the number of units of each item on hand by its per unit value to obtain the value of each item and then adding the values of all the items. This total value tells managers how much of a firm's assets are tied up in inventory. To some extent, managers can evaluate average aggregate inventory value by historical or industry comparison or by managerial judgement.

3.3.2 Weeks of supply

Weeks of supply equal the average aggregate inventory value divided by weekly issues, where managers also want to know the demand rates by using the weeks or months of supply measures.

3.3.3 Inventory turnover

Equal to annual issues divided by average aggregate inventory value. The higher the turnover, the less inventory for the same amount of issues: lower inventory levels result in lower inventory carrying costs.

3.4 Limitations of the ROP inventory system

Independent demand inventory systems are very widely used. Since they were introduced in the 1920s they have proved a valuable and flexible tool for management. Nonetheless, there are some circumstances in which they do not perform well. In these circumstances we can list weaknesses of independent demand systems as follows.

- They assume that demand for all items is independent. In reality the demand for parts depends on the component-parts (end-item) overhaul assembly such as BOM.
- They assume that demand is relatively stable and uniform, or can be accurately forecast.
- Independent demand systems cannot be used for forward planning. The calculations for reorder level, reorder quantity and so on are all based on historic figures rather than future plans, even when these plans are known with some certainty.
- Reorder level calculations assume lead-time demand follows a fixed distribution. In reality, the lead-time can be varied by expediting procedures or stressing the urgency of an item.

These observations reinforce the view that independent demand systems do not work well in the aircraft parts inventory environment. There can also be weaknesses in specific situations. The reorder cost, for example, may be very high and the economic quantity suggests order sizes which are so large that units become obsolete before they are used. Schonberger [110] has reached the same conclusions.

3.5 The methodology of aviation industry survey

The companies used in this survey vary significantly in geographical location, size and method of operation (by AO and MO) as shown in Figures 3.2 & 3.3. The survey covered 283 aviation companies, 62% of whom replied (see Appendix A). First we examined the use of the ROP system and examined current problems faced by companies, including strategies for change. Secondly it reviewed those companies already utilising MRP and described its advantages.

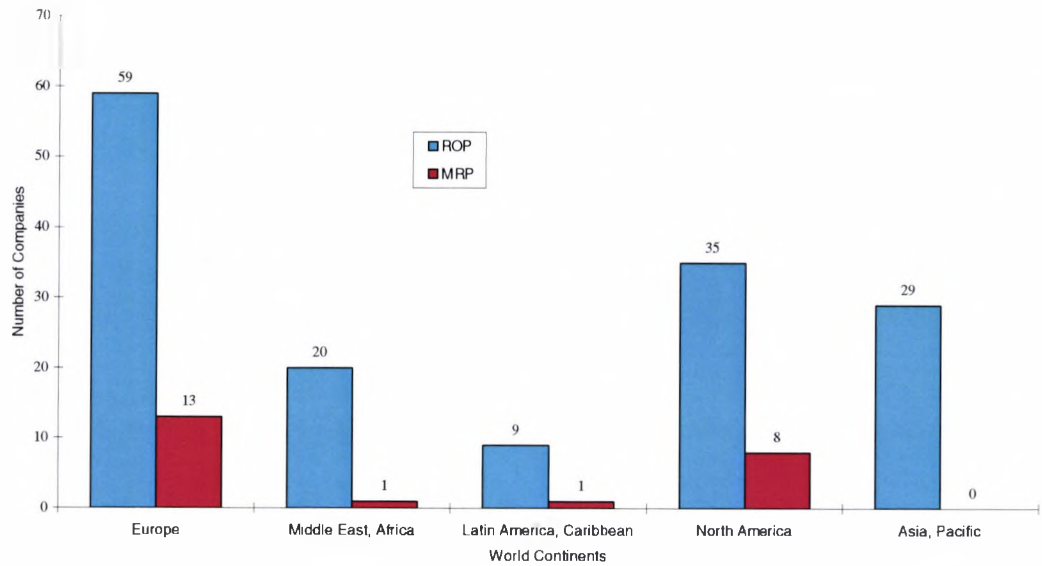


Figure 3.2 The implementation of MRP & ROP systems by continent.

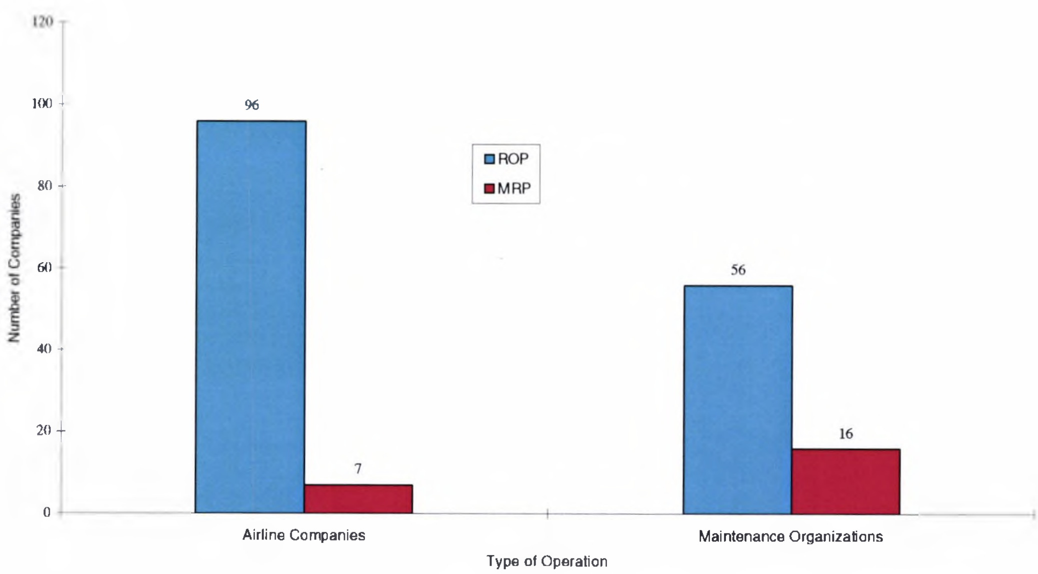


Figure 3.3 The implementation of MRP & ROP systems by type of operation.

3.6 Analysis of survey findings

The following results are based on a survey of 96 airline operators and 56 maintenance service organizations.

3.6.1 Reasons for not using MRP

A large number (66% of MO : 57% of AO) were aware of MRP but had neither used nor investigated it further. The survey showed that 21% of MO and 15% of AO believed the system was more suited to other manufacturing industries. Fourteen percent of both sectors indicated that MRP was under review as existing systems became outdated or unsatisfactory; 16% of AO already used some elements of the MRP system compared to 5% of MO. Yet the survey showed that 16% of MO and 7% of AO of interviewed companies believed MRP to be unsuitable for their businesses because:

- There was only a small technical department with no large industrial needs.
- Their commercial business was mainly ad hoc.
- Due to uncertain factors, and/or unpredictable consumption of parts.
- No bill of materials (BOM) could be developed economically.
- Each job was unique with a different work scope and BOM.
- As they were a service organizations, their workload fluctuated.

Five percent of both organizations believed that MRP was more suitable for predictable work since:

- Most of the 'parts requirement' was unscheduled.
- The majority of aircraft components underwent 'on-condition' maintenance.
- Airframe parts demand was unpredictable.
- Heavy maintenance and line maintenance inventories were not readily predicted.
- Very few spare parts requirements could be forecast in advance.

Eight percent of both organizations were satisfied with their existing system. Three percent of both organizations were unable to implement the MRP system for various reasons i.e.

- Financial resources.
- Inadequate staff training for MRP implementation.
- Time or other resource constraints
- Lack of manpower.

- Lack of support for project.

Three percent of AO said that the MRP system was too time consuming and the setting up of a data base too complicated. Three percent of both organizations believed that an investment in an MRP system was not warranted at that time.

3.6.2 Other types of inventory control used

It was necessary to know which other type of inventory system the companies used. The survey showed that the most used inventory system was 'safety stock' which accounted for about 66% of MO and 77% of AO. About 5% of companies mentioned one other system, that of 'inventory forecasting', and 3% used various systems such as:

- Kanbans (pull systems) known as JIT.
- Scrap.
- Significant traceability as required by law, i.e.

  ⇒ Rotable pool of spares on aircraft ⇒ Unserviceable

  ⇒ Quarantine stores ⇒ Repair facility ⇒ Serviceable tag

  ⇒ Into inventory ⇒ On to aircraft.

The survey results showed that most companies had difficulty in forecasting demand for parts. Some of these companies were looking for a better forecasting system to identify their needs. They estimated future demand by considering available maintenance contract information and looking at scheduled maintenance plans. Some companies prepared manual forecasts for expensive items (rotables/repairables) or they used scheduled maintenance programmes.

3.6.3 Methods of inventory monitoring

Economic material provisioning is normally measured by the turnover of stock and is a widely used financial tool to know how well an organization is managing its inventory [20] especially in high usage parts over a given period. Companies which are located near vendors and dealers will usually have a greater turnover of stock, while those companies which are at a considerable distance from supply sources will tend to keep larger stocks and hence have a lower stock turnover.

The survey indicated that about 39% and 54% of MO and AO respectively used 'average aggregate inventory value'. Seven percent of MO and 14% of AO used 'weeks of supply'. Inventory turnover was used by about 50% of both types of companies. Examples of the most common formulas used by those companies are:

- Average aggregate inventory value = average value of inventory not charged to maintenance and not in-house repair pipeline.
- Inventory turnover = receipts per aircraft type ÷ aircraft type inventory value (average).
- Weeks or months of supply = average aggregate inventory value ÷ weekly or monthly consumption.

Eighteen percent of companies opted for an alternative to the measuring systems mentioned above. One company stated that they calculated average aggregate inventory value from the purchase ledger, recording all trading transactions, with a computer calculating the value once the program had run. Other companies stated that they measured their inventory performance on a monthly review based on the following:

- Balance on-hand vs. forecasted balance on-hand.
- Service level.
- Inventory turnover = money issued ÷ number of weeks × balance on-hand.

The remainder were using an inventory ratio, which is equal to the inventory value (acquisition cost) divided by aircraft value. This is a set percentage where it is possible to have a low inventory, but the risk of shortage is high for different classes of inventory.

3.6.4 Action taken when a 'stockout' occurs

This survey question aimed to establish what type of action would be taken when the stock of spare parts was depleted. Normally companies first determined which classification of stock had depleted. If the item was a consumable (expendable), the company would expedite it; if the item had already been ordered, or was being repaired, it would then issue a new order, if the stock item was relatively inexpensive. If there was a time constraint, the company would need to 'borrow' or 'loan' stock. In the case of classifications such as rotables or repairables, mostly expensive items, issuing an order would not be necessary. More appropriate action such as expedition would firstly be taken, then borrowing, if no items were already under order. The course of action taken would depend upon the circumstances, whether the item required was urgent or not.

The survey results indicated that 36% of MO compared with 45% of AO used *expedite*, *borrow*, *loan*, or *buy*, depending on the specific circumstances of the item. Even so we noticed that some companies expedited only when they ran out of stock (13% of MO and 7% of AO); Schmahl and Anand [109] stated that the expediting function showed the greatest reduction in inventory. Twenty-three percent of MO compared to 9% of AO, used 'expedite' and 'buy' only; while about 16% of MO and 7% of AO used buying exclusively. It was found that those actions applied to maintenance service organizations rather than the airline operators, as maintenance organizations did not hold a large inventory. They ordered only what was needed and did not hold expensive items, as the inventory requirements depended upon the contract with the customer.

3.6.5 Degree of automation of the ordering system

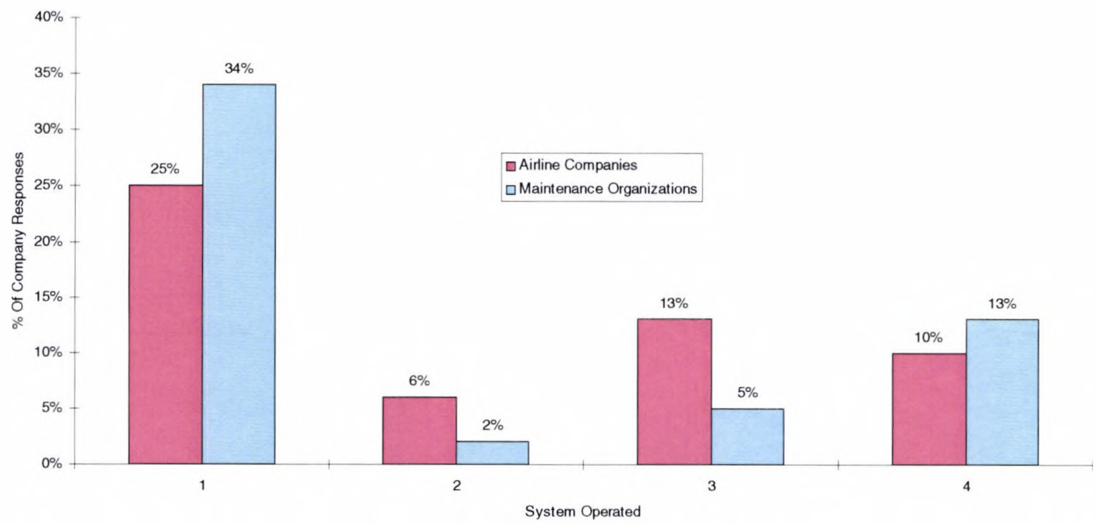
Companies were asked about the degree of system automation. Unfortunately it was difficult to classify the replies due to varying interpretations of terminology. Some replies mentioned only the actual ordering, and others were concerned with the complete system. For this reason we divided the answers into two groups, either by percentage or system description, as shown in Table 3.1 and Figure 3.4

Table 3.1 shows that 19% of companies in the first group operated an automatic system (90 - 100% automatic). Thirteen percent of companies had approximately 50% to 80% of their system automated, and about 11% of the companies still had systems which were almost totally varied between 90% to 100% manually operated. Four percent of companies had a system predominantly manual (between 60% - 80%).

Degree of automation	99 - 100% Automated	90 - 95% Automated	70 - 80% Automated	50 - 60% Automated	90 - 100% Manual	60 - 80% Manual
MO responses %	7	14	4	11	7	4
AO responses %	5	13	8	3	13	4

Table 3.1 Degree of automation and manually carried out work.

Figure 3.4, shows the second group and by looking at the graph we can see that the highest percentage belongs to those companies whose orders were generated automatically, as material reached the reorder level, ROL, but who were concerned with orders that were reviewed and released manually. The lowest figure (6% of AO and 2% of MO) represented the few companies who used the electronic data interchange, EDI, system which is designed to eliminate the physical handling of paperwork associated with ordering, shipping, receiving and invoicing [62, 90, 125].



No.	Description
1	All orders are generated automatically as material reaches ROL, but orders are reviewed and released manually.
2	All orders are generated automatically as material reaches ROL, but orders are reviewed manually and released automatically via EDI system.
3	Low cost parts (consumables) are reordered automatically, and high cost parts (rotables) are reordered manually.
4	The system is only capable of doing a stock check, therefore all work is manually performed.

Figure 3.4 Work done purely automatically & manually.

3.6.6 Capacity planning and scheduling

Normally companies develop their capacity requirements plan either by man-hours per flying hour, or by monthly budget. The survey showed that 30% of MO and 38% of AO used a monthly budget; whereas 26% of AO used man-hours per flying hour, and only

5% of MO utilised man-hours per flying hour. Two percent of MO and 7% of AO stated that they used both methods. Some companies indicated other methods for capacity planning which included;

- Flying hours and check cycles.
- Forecasting based on past history or usage consumption (i.e. historical data).
- A ratio system.
- Contract related decisions made through the marketing department dependent on contract requirements.

As this question was more appropriate for airline operators than for maintenance service organizations, not surprisingly 42% of the latter thought it inappropriate and with their maintenance contracts differing it was difficult to plan or forecast on an ad hoc basis.

3.6.7 Degree of satisfaction with the existing inventory system

About 97% of companies questioned used a computerised inventory system. Fifty-seven percent of MO and 83% of AO were using a reorder point system. Not all of these companies were satisfied with their existing system. Fifty percent of companies believed that their inventory system was appropriate, while 22% were happy with their system but were looking to improve it. The remainder of the companies were dissatisfied with their inventory control system, representing about 28% of the total. These companies provided various reasons for their dissatisfaction, as shown in Figure 3.5. Less than 5% said that it was due to sector and environmental changes such as regulation, deregulation, self-regulation, recession. growth, consolidation, initial provisioning, and ageing aircraft programs. Two to five percent did not have an integrated system, and were looking for a single joint system, with others saying that their system was out of date, either because of its age or because the company had grown and their methods no longer provided good results, and as the aviation market tended to change quickly, an inventory strategy based on history became less usable. Less than 6% represented companies who gave other reasons, not specified above, e.g.

1. Difficulties in expedite handling, unused items, return and disposal.
2. Their system was based on a fixed service level rather than an optimum service level.

3. High inventory cost build-up as their system worked with EOQ which incurred a high level reorder point with safety stock.
4. The system generated a lot of paper work which was not utilised by the planners.
5. High value 'A' items were still ordered manually.
6. There were no BOM or MRP facilities.
7. Reporting routines were inadequate.
8. Stock management facilities were inadequate.
9. A more expeditious system to reduce inventory and order just-in-time was needed.

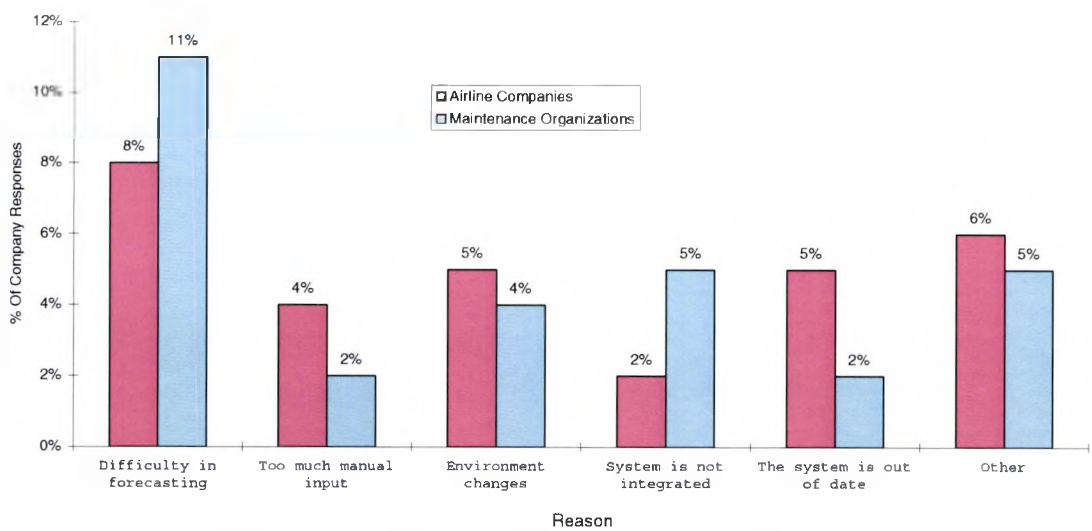


Figure 3.5 Reasons for inappropriateness of inventory system.

3.6.8 Spare parts classification

The survey showed that the most common classification was the '*standard airline system*' (ATA or IATA classification) which designates consumables, repairables and rotables. Sixty percent of AO used this method, while only 20% of MO did (Figure 3.6). Even so, there were still other classifications used by companies, (representing less than 9%), and examples of these classifications are as follows:

1. Source of the parts.
2. Low MTBR & MTBUR.

3. Based on individual requirements of maintenance, engineering or material management (i.e. 'hard time', shelf life or modification status).
4. An overhaul system:
   - aircraft standard part
   - non-stocked (Boeing, Airbus, MD, etc.) parts
   - stocked (Boeing, Airbus, MD, etc.) parts
   - commercial items etc.
5. By function of the component:
   - electronics (airframe)
   - non-electronics (airframe)
   - engine
6. Spares insurance for lease and rental.

Twenty percent of maintenance service organizations believed this question was inappropriate for their companies as they carried out contract work.

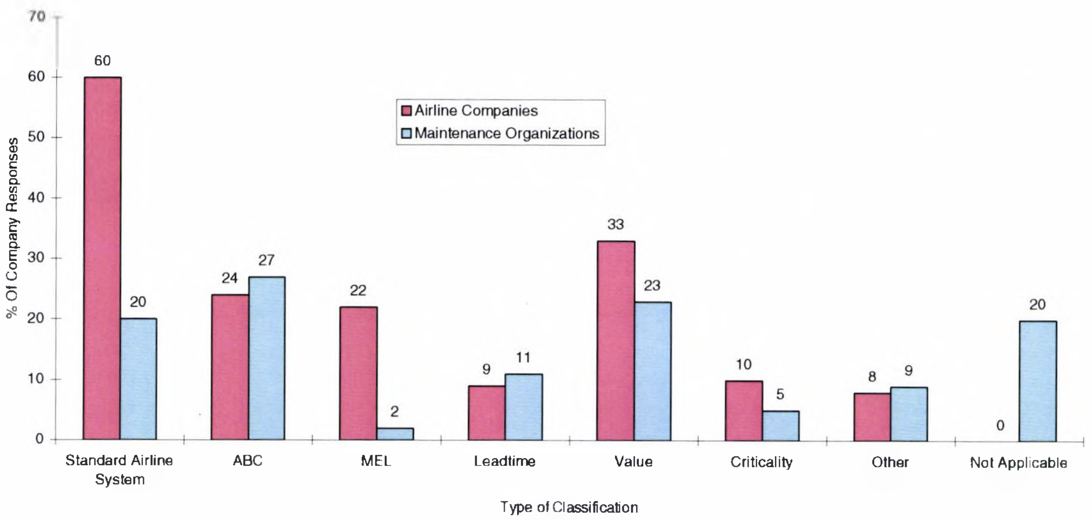


Figure 3.6 Component system's classification.

3.6.9 Component repair contracts

Once spare parts have been sent for repair to a contractor (workshop), control is no longer within the company with regard to time and progress of the repair. Normally there is an agreed upon repair time in the contract.

The survey showed that more than 55% of both organizations worked to an agreed time only, as illustrated in Figure 3.7. Less than 6% of companies worked with an agreed time penalty clause (guaranteed/warranted). This penalty could be in the form of financial cost (compensation) or by supplying the airline with a replacement component free of charge until the faulty one was repaired. Six percent of AO, compared to 13% of MO, relied solely on the contractor as there was no advance agreement concerning a time limit or penalties if the repair time was not met.

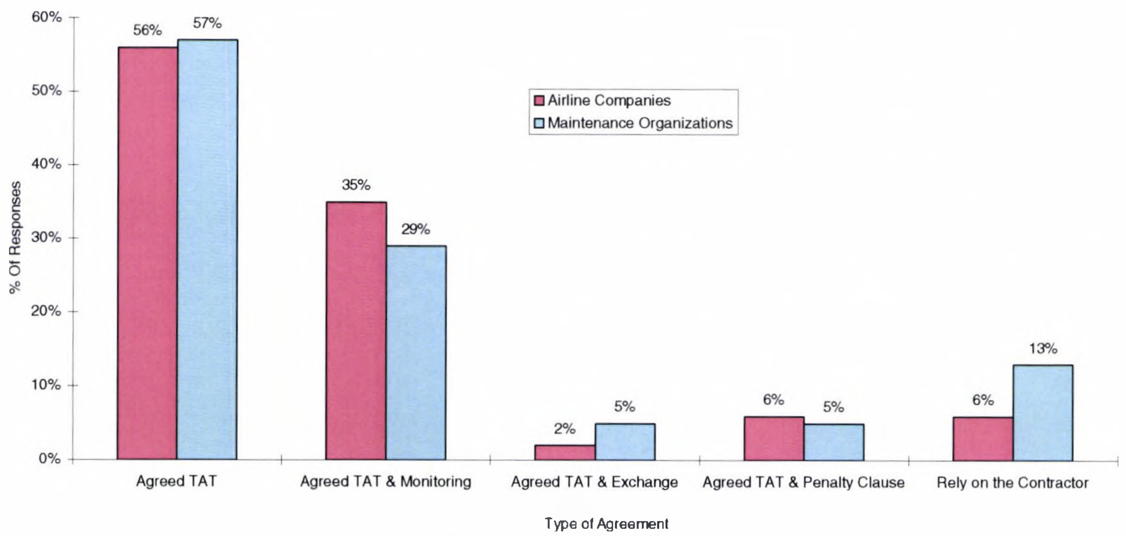


Figure 3.7 Repair contract agreements.

3.6.10 Changing the fleet size

When new types of aircraft are introduced, the manufacturer normally provides the airline with initial provisioning data, *IPD*, e.g. advance spares provisioning list, *ASPL*, recommended spares provisioning list, *RSPL,* and logistic planning document, *LPD.* These references for initial provisioning, usually indicate the main base float required to maintain aircraft. The original equipment manufacturers, *OEM*, also provide overhaul manuals for components fitted to the aircraft, which enable an assessment of the piece parts required based on reliable information, and specified component operation and life limits. The cost of operating older aircraft will continue to decline because parts availability becomes greater and the price for those parts becomes less [94]. The survey (Figure 3.8) showed the following courses of action taken :

- In most cases companies asked the manufacturer for initial provisioning data, *IPD*, when new aircraft were introduced, or they used their own experience of previous types of the same aircraft to calculate the quantity of parts required.
- As this question is more appropriate for airline operators than maintenance service organizations 14% of those maintenance companies believed that this question did not apply to their business, either because they carried out other operator's aircraft maintenance, or because they believed the manufacturer's data was not reliable. These companies did not operate flights or own their own fleet.

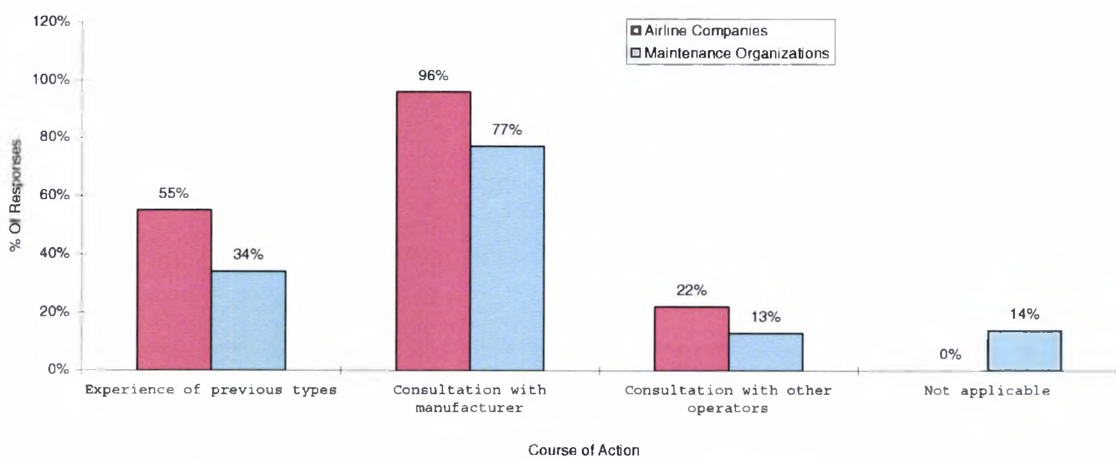


Figure 3.8 Changing the fleet size or adding new type of aircraft.

3.7 Summary of conclusions

The results analysis of the ROP system survey can be summarised into the following points.

- Twenty-nine percent of companies surveyed agreed that there was a potential for the implementation of MRP. These companies had either considered using MRP, were currently using part of it, or would have liked to implement it, but were unable to do so for financial reasons. As opposed to this 35% believed that the MRP system was not appropriate for aircraft maintenance.

- Safety stock was found to be the most common inventory system used, specifically for immediate replacement to minimise the aircraft's on-ground time [57].

- When 'stockout' occurs, survey replies indicated that the majority of the airlines expedite, borrow or buy stock, depending upon the item concerned, i.e. consumables (expendables), or rotables (repairables), and the lead-time involved.

- A large percentage of companies had a fully automatic system (60%) and 40% of companies had a manual system. Expendable/consumable parts were all automatically reviewed whereas top value items, such as repairables/rotables, were 100% manually processed.

- Fifty-nine percent of the companies were still using man-hours per flying hour, monthly budget, or both, whereas the remainder used different methods based on consumption history or contract.

- At least 50% of companies were dissatisfied with their system, or despite being satisfied were still looking for improvements; 14% were currently reviewing their system and considering implementing an MRP system.

- The most common classification analysis used by airline companies was 'standard airline system plus value' and ABC analysis which has a bias toward those parts that have the greatest annual expenditure and has more flexibility in responding to component shortages [72, 139]. Thus companies should classify components based on their requirements (AOG, MEL) and not necessarily by cost, since a low cost part could just as easily cause flight interruptions. Maintenance organizations did not appear to classify components in relation to the type of work they performed as contractors.

- In the case of fleet size changes;
  (a) Companies relied solely on their experience and statistics, and the system's parameter had to be changed to meet requirements.
  (b) Historical data had to be used to identify the parts to purchase and the order quantity.
  (c) Spares inventory levels and rotables float levels had to be reviewed.

- In the case of a new type of aircraft brought into service, companies followed recommendations of the aircraft manufacturer, which included such details as:
  (a) Cost, removal rate and essentiality.
  (b) Illustrated parts catalogues, *IPC*, which identifies parts required for overhaul or repair.
  (c) Guidelines about items and quantities that the companies should have in stock (MEL, AOG).
  (d) MTBUR and MTBF data for repairable and rotable parts, to calculate expected failure rates.

- If historical data was unavailable, the manufacturer's data was used, or the customer would provide them with the historical data (in the case of maintenance organizations).

- The fewer the types of aircraft the operators own, the lower the maintenance costs will be. When different types of aircraft are added, a greater number of parts must be stocked [117].

Finally, such conclusions reinforce the view that the ROP does not work well in the aircraft parts inventory environment. In order to overcome the problems expressed, we moved to adapt the MRP system to this complex environment and MRP is the subject of the following Chapters.

4. MATERIAL REQUIREMENTS PLANNING, MRP

4.1 Introduction

Manufacturing companies began by controlling their parts through the reorder point technique. Gradually, they recognized that some of these components had dependent demand and they evolved an MRP technique to control the dependent items more effectively. In the last Chapter we discussed independent-demand inventory control systems; however, component-parts that are assembled to meet repair plan requirements for parent parts have a dependent demand. Such parent-component dependent relationships, which are expressed in bills of materials, greatly increase the complexity of inventory management. As a result, MRP needs to be adapted specifically to aid the management of dependent-demand inventory and scheduling replenishment orders.

We begin this Chapter with a basic description of the MRP background and its features followed by a brief comparison of an MRP and a traditional ROP system. However, in order to investigate to what extent the MRP system can be applied, within the context of aviation operation and maintenance, we introduce our extensive MRP survey of aviation companies.

4.2 MRP background

Recent advances in computer technology and software development have changed maintenance and repairs from being isolated activities in a production system to becoming integrated functions within the entire system. Computer packages begin life with specific applications to certain industries or jobs. People then look for other ways of using them and start altering the packages to accommodate new requirements, as happened with the *Critical Path Analysis, CPA*. When CPA first appeared it was not used for applications like aircraft maintenance, but rather for very large projects where data over a very long time scale was wanted. People then started looking at the CPA for requirements other than those normally served. New CPA software features appeared to allow them to do these jobs. So it was that CPA became more common in many other fields. The same we believe will happen to MRP. At the moment MRP is sold for manufacturing applications, but it could well be adopted to become more useful in other sectors such as in aircraft parts inventory.

The standard argument against using a manufacturing inventory system within the aircraft maintenance environment is the two industries' essential differences. Both manufacturing and aircraft maintenance are subject to changes in demand resulting from product or component changes. Manufacturers have to contend with changes in orders because of reengineering resulting in design changes and process changes. And in the case of the airline maintenance environment, modification programs are common occurrences. Fourcaud [46] found that there are more similarities than differences between repair/remanufacturing and standard manufacturing, both environments are comparable in planning, execution, and operational characteristics.

4.3 The MRP concept

MRP is a technique for determining the quantity and timing of the acquisition of dependent demand items needed to satisfy master schedule requirements. It is a scheduling technique that has, as one of its main objectives, keeping the due date equal to the need date, meaning material shortages are eliminated and excess stocks are avoided.

MRP breaks a component into its many parts and subassemblies and then plans for all those parts to come into stock when needed. As such MRP relates each individual component or subassembly to every other part and to the completed component as a whole. The key ingredients of MRP are; bill of material, master schedule and inventory records.

4.3.1 Bill of material, BOM

BOM is a diagram or record that shows all the components of an item, the parent-component relationships and usage quantities. It is a listing of all components (subassemblies and materials) that go into an assembled item and frequently includes the part numbers and quantity required per assembly. Since any of several individual parts can be responsible for end-item (component) failure, it is important for the material manager to know the bill of materials for each component. This will allow him to determine which parts are subject to failure and which are critical to the operation of the component. Knowledge of the BOM will also help in establishing which parts (100% replacement) should be stocked as spare parts to support the component overhaul. There are two types of BOM formats, each serving to display the BOM in a different way:

- A single-level bill specifies requirements for only the immediate or next level parts that are needed to assemble a parent component; it specifies the parts quantity required, including the part numbers.
- A multi-level bill shows the parent and all of its components at all levels down to the purchased parts.

In this study we only intend to use single-level BOM for components overhaul assemblies.

4.3.2 Master schedule, MS

The master schedule drives MRP and is thus the key input into the MRP process. Any errors within the MS, such as high forecasting error, will result in poor MRP performance. The MS is a statement of what the company plans to order. It is the planned build schedule, by quantity and date, for the developed BOM needs.

4.3.3 The MRP inventory records

MRP inventory records in hierarchical order are:

1. Gross requirements
2. Scheduled receipts
3. Projected on-hand inventory
4. Net requirements
5. Planned order receipts
6. Planned order release.

Gross requirements; the total needs from all sources.

Scheduled receipts, the materials already on order from a vendor. The MRP shows both the quantity and projected time of receipt.

Projected on-hand inventory, the on-hand balance less allocations, reservations and back orders.

Net requirements, the net figure after allowing for available inventory (from the basic logic of MRP that gross requirements, minus the balance on hand and the scheduled receipts, yield the net requirement).

Planned order receipts; the materials that will be ordered from a vendor. Otherwise it is similar to a scheduled receipt.

Planned order release; indicates when an order for a specified quantity of an item is to be issued. The release date is the receipt date minus the lead-time. This process of using planned order releases to calculate gross requirements may continue on down through the bill of material for many levels until we arrive at the purchase level for every part needed in the assembly of our component. This process is known as an *explosion*. So the planned order releases at one level, then produces gross requirements at the next level in the case of multi-level BOM.

The logic of MRP calculation will be discussed later in Chapter six followed by an actual illustration.

4.4 MRP parameters

Several parameters must be pre-assigned to each inventory record, sometimes known as planning factors, they include;

1. The planning horizon
2. Lead-time and safety stock.
3. Lot-sizing considerations.

4.4.1 Planning horizon, PH

The planning horizon refers to the span of time from the current date to some future date, over which material plans may be generated. The planning horizon may be 10 weeks, 26 weeks, or even 52 weeks, depending upon the type of firm and the components involved. It should equal or exceed the cumulative lead-times for the longest time sequence required by any parent-component relationship, otherwise it will be inadequate, resulting in late orders and costly or disruptive expediting activities.

4.4.2 Lead-time and safety stock

Lead-time, LT, is the supply time, or number of time buckets between releasing an order and receiving the parts (MRP uses planned lead-times for scheduling order releases).

Time bucket refers to the units of time into which the planning horizon is divided, and is usually represented in weeks, days or months.

Safety stock, *SS*, is the quantity of stock maintained in inventory to protect against unexpected fluctuations in demand and/or supply. In this sense, safety stocks can be considered as a type of insurance policy to cover unexpected events, whether such events be the failure of a vendor to meet a promised delivery date or an unexpected increase in demand for the component to be repaired.

MRP can include planning of safety stock, but this is not recommended and is not common practice. When included, the quantity of safety stock is either subtracted from the on-hand quantity or added to gross requirements; the former is common. When safety stock is added to MRP, the resulting overstated requirements and false timing of order release and due dates destroy its credibility [98].

4.4.3 Lot-sizing Considerations, LS

Lot-size is the process of specifying the order size. MRP logic requires that a lot-sizing method be pre-assigned to each item before the system can compute planned receipts and planned order releases. The parameters of lot-size methods will be discussed later in Chapter seven.

4.5 The MRP replanning systems

Re-planning is the MRP system process, which tells the planner what should be done. It expects the planner to react and resolve conflict by providing a set of exception messages to alert the planner to order, increase, defer, cancel, decrease or expedite. These can be summarised as;

- Orders which should have been received but have not.
- Orders already placed but which are now needed earlier.
- New orders needed in less than the planning lead-time.

Namely, there are two basic approaches to re-planning within MRP systems; top-down planning and bottom-up re-planning

4.5.1 Top-down planning

Has two tools; Regenerative and Net Change.

Regenerative; all requirements and due dates are totally recomputed in a batch job that is run at specified intervals in time, and the original plan is discarded and replaced by a new plan. This involves rescheduling any open orders that have invalid due dates and creating planned order releases for future requirements that cannot be met from current inventory and open orders. The regenerative approach thus involves a complete re-analysis of each and every item identified in the MS. Regenerative systems are typically operated in weekly and occasionally monthly re-planning cycles.

- Starts from latest version of MS.
- Re-explodes right through MRP system process.
- Limited frequency of re-planning.

Net change MRP: is an on-line system that continuously reacts to changes in the master schedule, inventory additions, and other transactions. It uses the same type of MRP logic, but net change systems re-plan only those items that are changed or were not previously planned. However they may take more computer time and generate too many action notices, sometimes referred to as *system nervousness*.

- On-line material requirements plan.
- Explodes only net changes.
- Processing on-line or overnight.
- More reactive, but more nervous.

4.5.2 Bottom-up re-planning

Also has two tools; Pegged Requirements and Firm Planned Order.

Pegging requirements allow the user to identify the sources of a particular component's gross requirements. These gross requirements typically originate either from its parent assemblies or from independent demand in the MS or from the demand for spare parts. The technique of pegging is useful in that it allows the user to retrace the MRP systems planning steps in the event of an unexpected event, such as a supplier being unable to deliver in the planning lead-time. By retracing the original calculations the user can detect what orders are likely to be affected and perhaps identify appropriate remedial action.

Firm planned orders allow the materials planner to force the MRP system to plan in a particular way, thus overriding lot-size or lead-time rules. This technique can aid planners working with MRP systems to respond to specific material and capacity problems. It is also used to reduce the system`s nervousness.

Action notice; is a computer-generated memo indicating the need to release an order or adjust the due date of a scheduled receipt, an action notice can simply be a list of part numbers for items needing attention.

Action bucket; if there is a non-zero quantity in the first week's entry of the planned order release row, they call it the action bucket and the computer issues an action notice. An order in the action bucket is the call to release the planned order.

4.6 ROP versus MRP system

The two approaches have different patterns of stocking component-parts. With MRP, stocks are generally low but rise as deliveries are made, just before component overhaul starts. Stock is then used during overhaul and the amount held declines until it returns to a normal, low level. This pattern is shown in Figure 4.1 (a). With ROP, stocks are not related to maintenance plans, so higher levels must be maintained. These are reduced during overhaul, but are replenished as soon as possible, to give the pattern shown in Figure 4.1 (b).

In a study conducted by Ritzman et al [103], they conclude that as the number of levels in the BOM increase, MRP increasingly surpasses ROP in terms of lower total inventory for the same level of end item service, and also, as lot-sizes are increased, the relative superiority of MRP also increases. Bregman [22] found in his study comparing MRP and ROP systems that when the temporal penalty is large, forecasts of future requirements used in ROP systems will often reflect outdated and possibly obsolete information which may result in backorder or excessive inventory conditions.

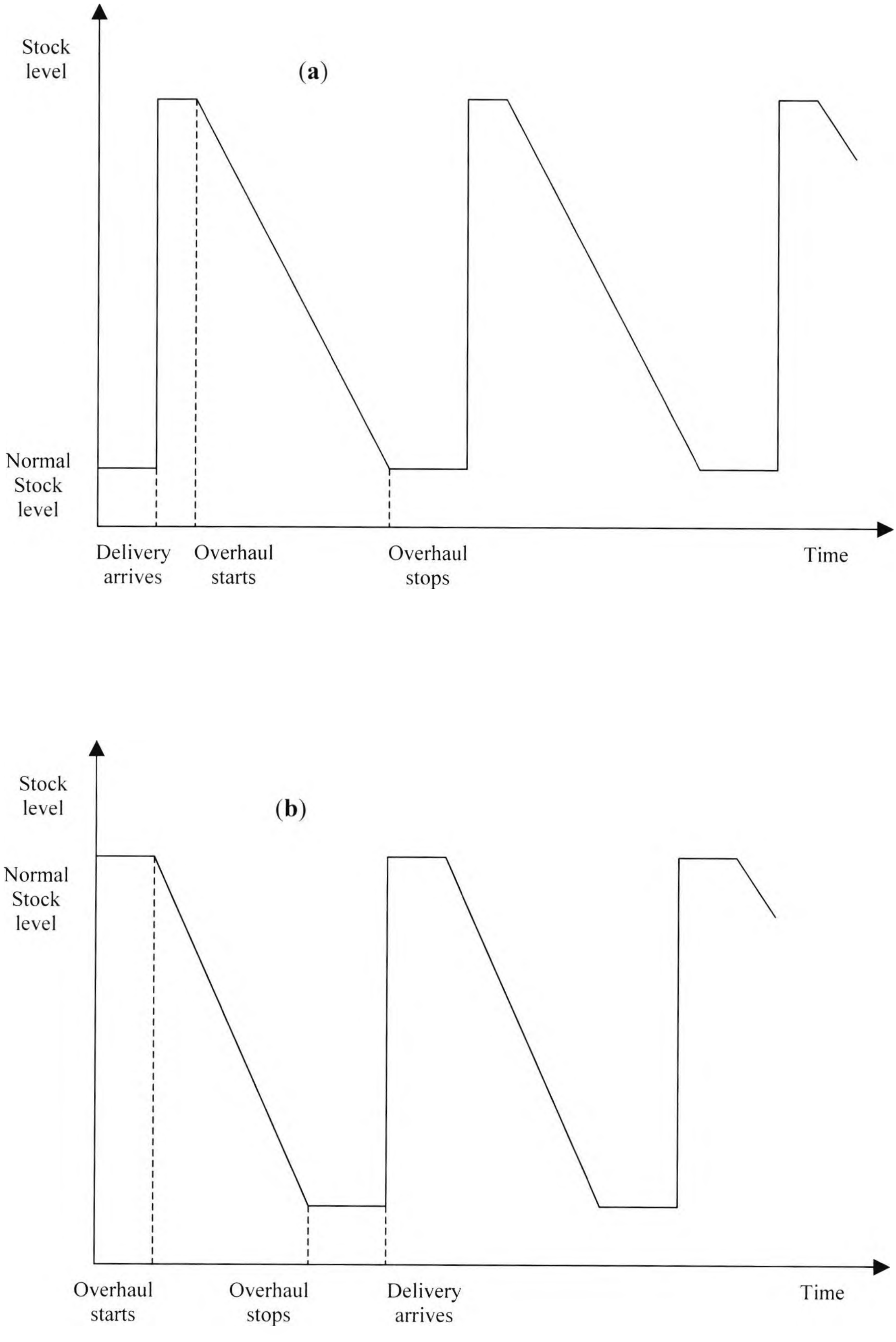


Figure 4.1 Comparison of stock levels. (a) Stock level of parts with MRP. (b) Stock level of parts with ROP system.

When the demand for an item can be calculated through its dependence on another item, as in the case of aircraft component overhaul, the best technique to use is MRP because it looks forward, anticipating future orders based on sharp fluctuations in demand, whereas the ROP uses historical averages and triggers one order at a time. This may be summarized as follows (Table 4.1).

Main features comparison	ROP	MRP
Deals with	Used averages.	With lumpy demand.
Looks	Back (past).	Forward (future).
Demand uses	Smooth, uniform, continuous.	Sharply fluctuating demand.
Requires BOM?	No.	Yes.
Inventory is	Maintained.	Run out.
Recommends orders dates to	Start.	Complete.
Activates for an order	One order at a time based on expected run-out.	Periodically, plans multiple orders based on need dates.
Shows future orders	None.	All in horizon.
Can be re-planned?	No.	Yes.

Table 4.1 Comparison of ordering techniques of the ROP and MRP systems.

4.7 The methodology of the aviation industry survey

As we mentioned earlier in Chapter three, this survey is based on responses from 175 out of 283 airline operator and maintenance service organisations worldwide. It emerged that 152 aviation companies were currently using the Reorder Point system, ROP, whilst 23 had adopted the MRP system. The intention behind this survey was to examine the experience and successes of those 23 companies which were using the MRP system. The survey indicates that MRP is now being taken seriously in aircraft parts inventory. However, it is more difficult to implement in the aircraft maintenance environment than in a commercial environment, as the need for spare parts is unpredictable. But if the obstacles are understood and a sound plan realised by good management, MRP can be successfully implemented. The benefits can be substantial.

The survey consists of eight airline operators and fifteen maintenance service organisations who acknowledged the implementation of MRP. After a thorough analysis of replies from the twenty-three companies, the following headings aptly represent the main features of the MRP system.

4.7.1 MRP software and inventory records

The survey shows in Table 4.2 that at the time of our investigation, different packages of the MRP system were being used; fifteen companies were using recognised software packages supplied by a vendor, and eight had developed an in-house system, (within an MRP conception) designed by a consultant to satisfy company requirements.

It was thus important to know if those companies used the same inventory records. Nineteen used the same. But four companies had introduced additional inventory records, which are listed below:

- Service level 94 - 96% (that meant on average 95% of demand should be satisfied).
- Consumption forecast based on extrapolation of last two years' consumption.
- Trend analysis (i.e. statistical analysis of the demand).
- Time gates:
  a. Asset check alternatives.
  b. Parts groups (to enable pre-modification stock to be used up).
- For *on-condition* materials, a replacement index was used as an expected percentage of removals (additional planning factor).

4.7.2 MRP output report statement

Some computer packages occasionally give extraordinary answers either because of the way the package does the calculation, or because of the data supplied to it.

The survey showed that eight companies accepted a computer statement, and a further fifteen only accepted a computer statement after having reviewed it. None of these companies used manual calculations alone.

4.7.3 Lead-time purchasing agreement

As global competition increases, contractors are forced to compete not only in the areas of cost, quality, and technology, but also on the basis of time delivery. This time-based competition has become increasingly important. Lead-times for purchased items are determined following discussions and negotiation between the purchasers, within the company and with its suppliers.

The survey showed that thirteen of the companies interviewed arrived at their lead-time by *agreement*. Five of the companies used past data, based on their knowledge and experience of the market and up-dated it if change occurred. Some companies (a total of five) used both methods.

No.	Company name	Type of operation	Software name
1	Aeromexico	Airline operator	In-house developed
2	AGUSTA	Maintenance organisation	SAP/R2
3	Airwork	Maintenance organisation	In-house developed
4	Bristol Aerospace	Maintenance organisation	COPICS
5	British Airways	Airline operator	MAC PAC D
6	Crossair	Airline operator	AMOS
7	Dee Howard Co.	Maintenance organisation	PRO III
8	Delta Airlines	Airline operator	In-house developed
9	Deutsche Lufthansa	Airline operator	In-house developed
10	Dowty Aerospace	Maintenance organisation	CINCOM
11	Hunting Aircraft	Maintenance organisation	UNIPLAN
12	TAT European Airlines	Airline operator	In-house developed
13	Lockheed A/C Service	Maintenance organisation	AMAPS-G
14	MTU Maintenance	Airline operator	In-house developed
15	National Airmotive	Maintenance organisation	BAMCS
16	Normalair-Garrett	Maintenance organisation	MAS (MCS)
17	OGMA	Maintenance organisation	In-house developed
18	Parker Bertea Aero.	Maintenance organisation	In-house developed
19	Rolls-Royce Services	Maintenance organisation	MERLIN
20	Shannon Aerospace	Maintenance organisation	SAP
21	Simera	Maintenance organisation	MAS II
22	Sundstrand Aerospace	Maintenance organisation	MRP II
23	Swissair	Airline operator	SAP 5.0

Table 4.2 MRP software packages used by aviation companies.

4.7.4 The MRP time bucket

Anderson's survey [2] suggests that the vast majority (70.4%) of MRP users work in time buckets of one week. But our survey revealed rather a different picture. In the case of five companies the MRP time bucket was shown in months, traditionally, budgeting is calculated on a monthly basis since flying hours for a season are forecast by the month. Only six applied weekly time buckets, because of the many thousands of items involved, or they used weekly time buckets for 'short jobs' and monthly, for 'longer jobs'. Significantly twelve companies stated that they worked in days. They felt that this reflected the batch quantity of their workload demand and therefore covered an appropriate period.

4.7.5 The MRP planning horizon

The survey shows that the most popular planning horizon amongst companies was one year or less, while only five used a 3-year horizon and another five used a one-to-six month period. Only two companies used a two-year planning horizon (Figure 4.2), whereas Anderson's survey [2] showed that the average length of the planning horizon used in MRP systems was of the order of 40 weeks. A study by Blackburn et al [10] concluded that as the horizon increases, nervousness decreases and cost performance improves.

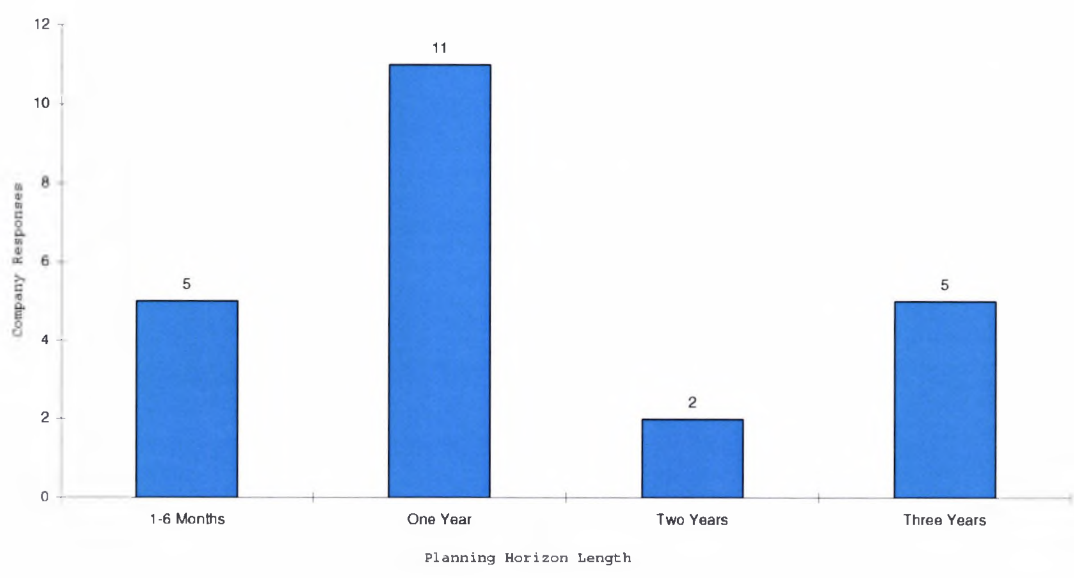


Figure 4.2 MRP planning horizons length.

4.7.6 MRP lot-size methods

In order to enable MRP to carry out its explosion, the formulas or methods for lot-sizing must be accessible to or part of its computer program. The survey showed most companies used more than one method and the breakdown is as follows:

- *Economic order quantity, EOQ*, this method was used by twelve companies.
- The *lot for lot, LFL*, technique is probably the simplest of the variable ordering techniques, and eleven companies were using this method.
- Since *fixed order quantity, FOQ*, does not exactly match requirements, as it generates high inventory and creates inventory remnants, only four companies used this method.
- The *fixed period requirements, FPR*, orders a supply for a given number of periods each time (for example: a 2-month supply). The survey showed that four companies applied FPR, using regular orders especially for consumable parts. They thus knew what to order, when it was needed and what quantities were required.
- *Fixed order period, FOP*, sets a fixed time between orders, and orders the amount required to meet the demand in that period. This was used by three companies.
- The *part-period algorithm, PPA*, only two companies used this method.
- As for *period order quantity, POQ*, the survey showed that no company applied this method.
- For the *least unit cost, LUC*, approach, the survey indicated that three companies used this method.
- *Wagner-Whitin Algorithm, WWA*, in fact none of the companies appeared to be using this method.
- One company used *part-period balancing, PPB*.

Maintenance organisations believed these methods were not applicable to them as they dealt with small quantities, so they preferred to pursue minimum inventory and also small lot-size.

4.7.7 MRP safety stock

The survey showed that four companies did not use safety stock, while nineteen had already applied safety stock to their MRP system. Figure 4.3, shows that thirteen out of twenty-three were applying safety stock procedures, depending on material significance and cost. Only one applied safety stock methods at all levels while six companies were using them at low-level, and seven restricted safety stock controls to end item (component) level. In Wemmerlov's [129] survey of thirteen MRP installations, three companies used safety stock at all levels, five used them only on low-level items and five companies applied safety stocks strictly to the end item or finished goods level.

A large number of companies used safety stock control, which in theory could be calculated from experience, simply by guessing or taking an average. However, the survey showed that most companies used a variety of methods, with nine companies using statistical methods, eight calculating from their own experience, and four taking an average by reviewing historical usage. The survey also indicated that in fact no company simply guessed. It was also found that for three companies it did not apply because they were maintenance organizations which ordered parts based on contracts received, and thus safety stock was not used.

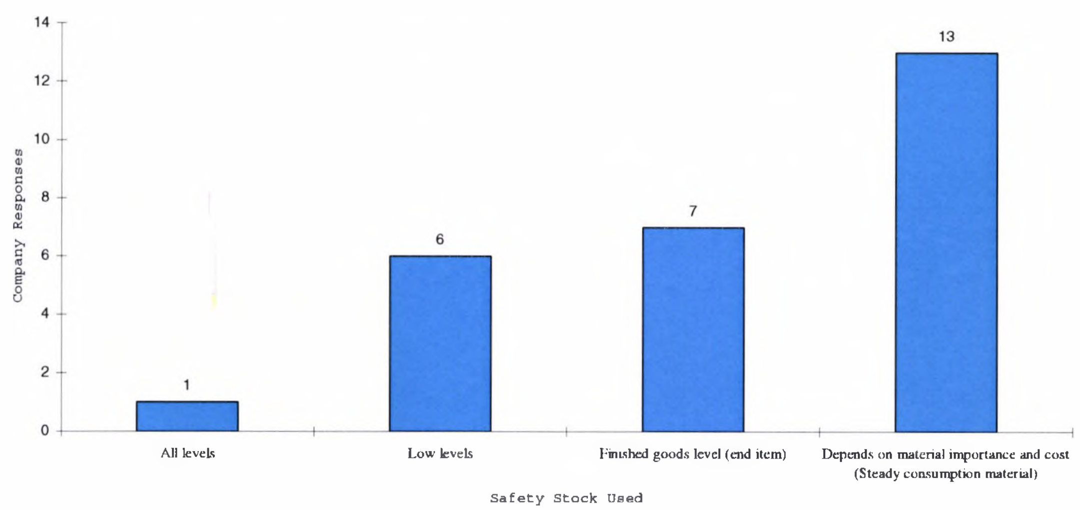


Figure 4.3 Safety stock levels.

4.7.8 The bill of materials

The bill of materials processor (software package) links the BOM file with the inventory status file so that the requirements explosion correctly accounts for the current inventory levels of all components. The survey showed that nineteen companies applied

BOM software packages. Four did not use the BOM software package, as it was not applicable to their business.

The two methods of specifying component requirements are as follows: A single-level BOM and multi-level BOM. The survey replies showed that:

- Six used a single-level BOM.
- Nine were using multi-level BOM.
- Five used both methods.
- Three did not use any of those methods, in which case they were classified as not applicable.

4.7.9 MRP replanning systems

The survey showed that nineteen used top-down planning and four used both systems. Furthermore, of the twenty-three companies surveyed, twenty-one used a regenerative MRP system and two did not. With the regenerative MRP system, replanning was usually done on a weekly basis, but the diagram shown in Figure 4.4 indicates that different time bases were being used. The most common was a once-a-week period (13 - or 52%), with the next, daily (4 - or 17%). According to the survey conducted by Hamid et al [60] 75% of respondents were updating their system by using a regenerating method. A further study by Anderson [2] found that 56.7% of MRP users updated their MS on a weekly replanning cycle, while 16.4% updated the MS on a daily basis. The La-Forge and Sturr study [79] found that 45% updated their MS on a weekly basis, while 24% did so daily.

With regard to the Net change MRP system, the survey of 433 companies using MRP conducted by Anderson [2] indicated that 30.3% of those studied were using the net change approach. The later study by LaForge and Sturr [73] found that 38% were using net change. In our survey with aviation companies we found that 14 of the 23 used net change MRP based on weekly replanning.

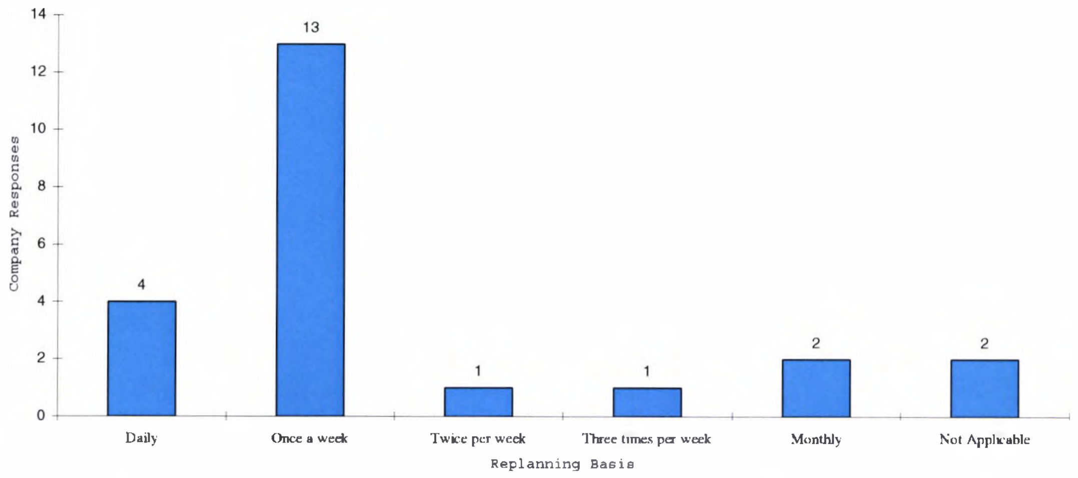


Figure 4.4 MRP replanning frequency.

4.7.10 MRP & MRP II

With the extension of master scheduling to deal with all master planning and the support of business planning in financial terms, and through the addition of certain financial features to the closed loop system, MRP was labelled *Manufacturing Resource Planning*, or *MRP II*. Responses to our survey show that:

- Eleven used MRP
- Eight were using MRP II
- Four were using both systems

4.7.11 Degree of automation of the ordering system

As mentioned earlier in Chapter three, it was sometimes difficult to classify replies as not all of them referred to the same set of criteria. For this reason we have also here divided the answers into two groups, as shown in Figures 4.5 & 4.6.

Figure 4.5 indicates that nine companies had between 90% and 100% of their system operating automatically while five had approximately 50% - 80% of their system automated. Figure 4.6 indicates that three companies said their orders were generated automatically as material reached the reorder level, but manually when the orders were reviewed and released. Three companies operated fully automatically for low cost parts (consumables), and manually for high cost parts (rotables) and the remainder of companies (a total of two) had a fully automatic system with all orders as material reached the reorder level, but whose orders were reviewed manually and released automatically via an EDI[1] system. Such a system benefited the company by its direct impact on the financial performance for a number of years [61, 138], but at the time of writing this thesis, many airline purchasing managers are finding that EDI is largely outmoded. The Internet has opened up new opportunities for changing the way airlines manage their supply chains [91].

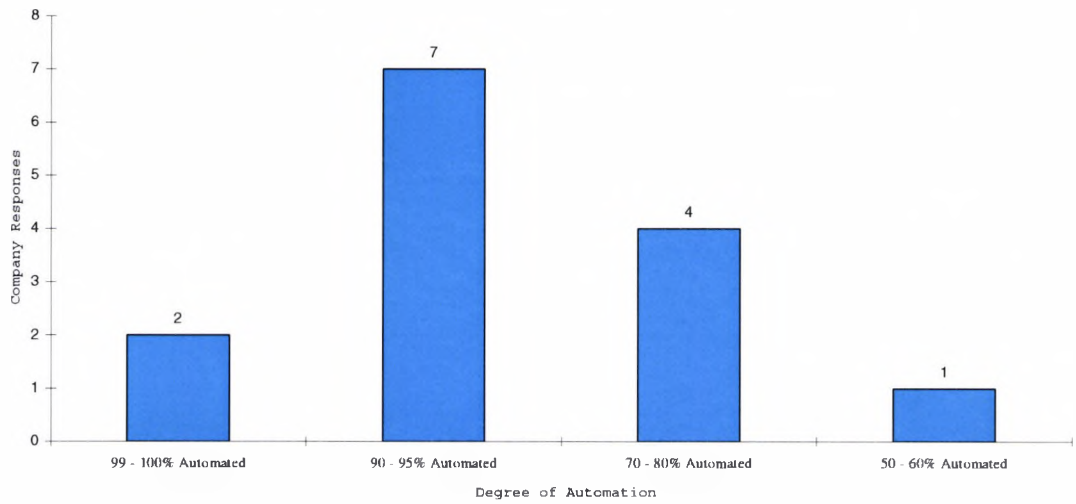
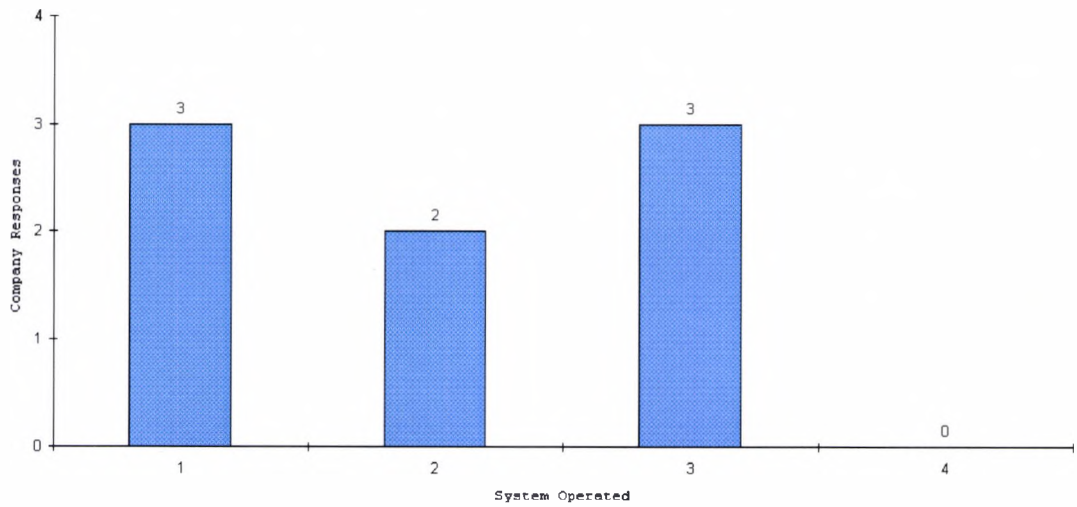


Figure 4.5 Degree of work done purely automatically.

[1] EDI is the computer-to-computer exchange of business documents such as purchase orders.



No.	Description
1	All orders are generated automatically as material reaches ROL, but orders are reviewed and released manually.
2	All orders are generated automatically as material reaches ROL, but orders are reviewed manually and released automatically via EDI system.
3	Low cost parts (consumables) are reordered automatically, and high cost parts (rotables) are reordered manually.
4	The system is only capable of doing a stock check, therefore all work is manually performed.

Figure 4.6 Work done purely automatically & manually.

4.7.12 Spare parts classification

The survey showed that the most common classification was the 'ABC' analysis (Pareto analysis). Thirteen companies used this method, six used *standard airline system* which designated consumables, repairables and rotables, while six companies used MEL, sometimes known as *essentiality* or *criticality* for flight dispatch and considering the importance of the component as to whether it was an AOG item or not. The next group represents companies who may have applied lead-time blocks (or the availability of the ordering item from the supplier) but in fact none of the companies used this method. There were seven companies who used '*value*' or '*average unit price*'. Apart from these, there were still other classifications used by three companies, and examples are as follows:

- Sub category A-Z depending on target service level for each item (by service level).
- Warranty liabilities; new parts are issued with warranties.
- Insurance for slow and fast moving stock.

Three companies believed this question was not appropriate since they only carried out contract work.

4.7.13 Component repair contracts

The survey shows that sixteen companies worked to an agreed time only. Five others worked to an agreed time but also monitored progress when the due date approached. None of the companies worked to an agreed time plus exchange, with only two companies working with an agreed time penalty clause. None of the companies relied solely on a contract where there was no agreement in advance concerning a time limit.

4.7.14 Changing the fleet size

"What happened when the airline changed the fleet size or brought a new type of aircraft into service and what action would be taken when historical data was not recorded?" Figure 4.7, shows a variety of courses of action taken:

- Fourteen companies used their experience of previous types of the same aircraft, or related the manufacturer's initial provisioning data, to calculate how many parts would be required and which. In most cases they integrated the information received from the manufacturer with their own experience.
- Eighteen companies asked the manufacturer for initial provisioning data, mostly when new aircraft were introduced.
- Seven companies used or consulted other operators using the same aircraft and engine type.
- Two companies believed that this question did not apply to their business, either because they carried out other operators' aircraft maintenance or because they believed the manufacturer's data was not reliable.

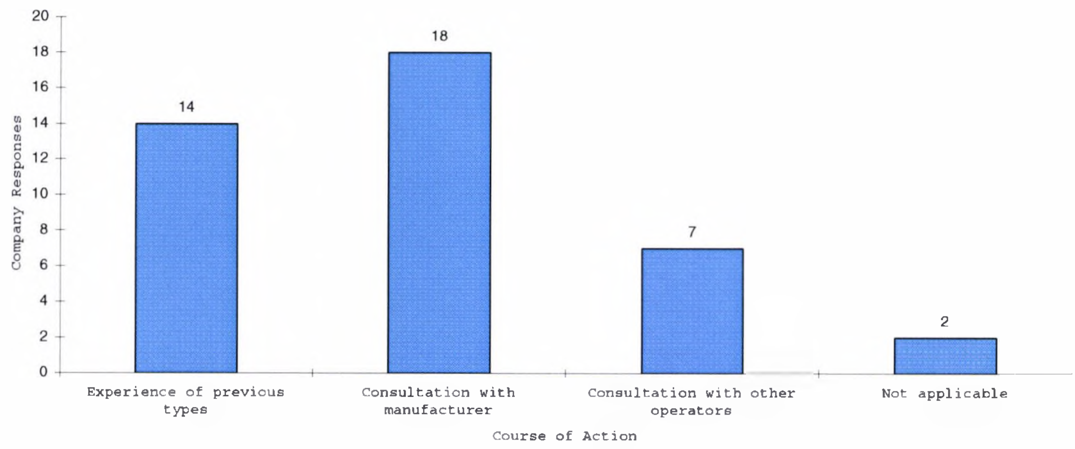


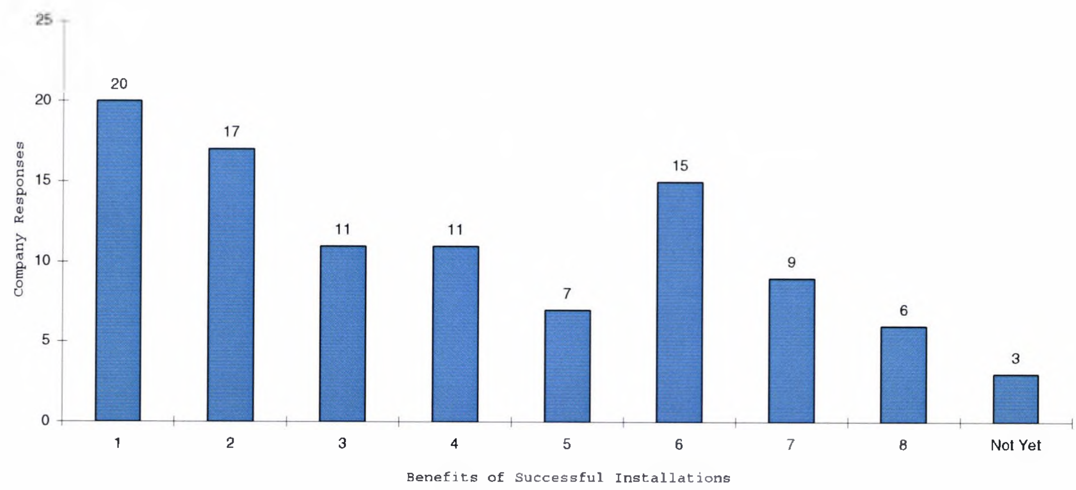
Figure 4.7 Effect of change in fleet size or introduction of a new type of aircraft into service.

4.7.15 Benefits of successful installation of MRP

The survey indicated that twenty-two companies were pleased with the results of MRP usage, and a further one had only recently installed the system and had not therefore had time to assess its merit. Nineteen saw an improved service, and four were still in the process of discovering its use. These then were some of the benefits identified following the successful installation of MRP, illustrated by Figure 4.8 and also referred to in previously published articles [34, 76].

To summarise, the survey showed that the most common benefits gained by companies were: reduction of inventory costs, improved scheduling effectiveness and the reduction of component shortages by (20, 17 and 15) respectively. The survey indicated also that there were other benefits not targeted in our questionnaire. These were:

- Achieving better turn-around-time.
- Shelf stock was drastically reduced and inventory turns increased.
- The inventory turnover rate was increased.
- MRP minimised outlay which optimised cash flow.



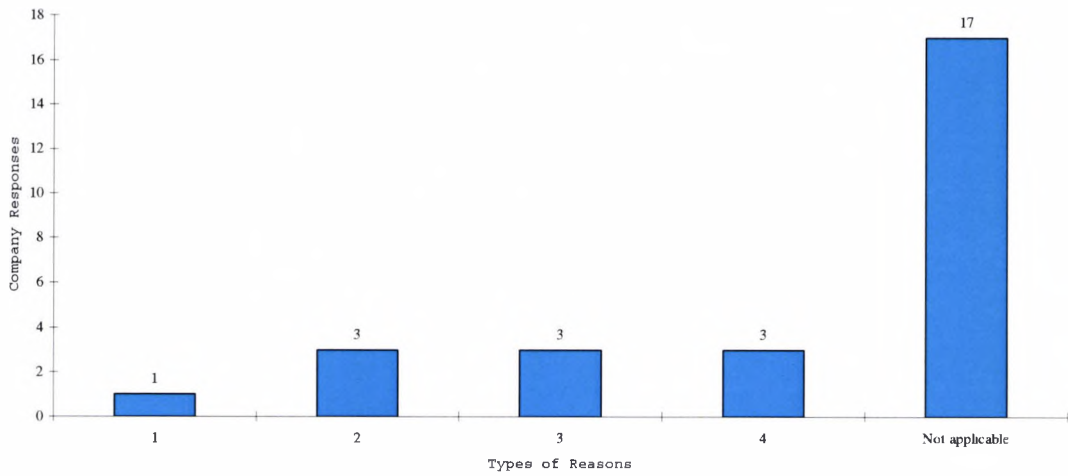
No.	Description
1	Reduction in inventory costs .
2	Improvement in scheduling effectiveness.
3	Ability to respond more quickly to market demands.
4	Increase in on-time customer deliveries.
5	Reduction in over-time costs.
6	Reduction of component shortages.
7	Reduction of the use of indirect labour
8	Reduction of the use of direct labour.

Figure 4.8 Benefits of MRP.

4.7.16 Reasons for the unsuccessful use of MRP system

If for any reason an MRP system failed, it was for the reasons shown in Figure 4.9. stated by Clode [34]. Blood [14] believed that most of those companies who had feelings of despair about MRP had trouble with its execution, not lying with the MRP system itself. More recommendations and improvements are mentioned by Lengyel [81].

The survey showed only six out of twenty-three companies with problems. Most companies indicated that the reason for not realising the full potential of the MRP system was mainly due to lack of training, unrealistic MS and inaccurate data, particularly BOM and inventory data. One company believed the reason was lack of top management commitment to the project. The survey also showed that there were some companies who did have problems in the early days of implementation, but had ultimately overridden these obstacles.



No.	Description
1	Lack of top management commitment to the project.
2	Lack of education (training) in MRP for those who will have to use the system.
3	Unrealistic master schedule.
4	Inaccurate data, particularly BOM data and inventory data.

Figure 4.9 Reasons for unsuccessful use of MRP system.

4.8 Discussion and conclusions

The MRP survey shows that the system is now being used in a small but significant number of airline operators and maintenance service organisations around the world.

Airlines in particular believe that their industry's uniqueness comes from a combination of four market characteristics:

a. Parts needed worldwide.
b. Demand unpredictability.
c. Traceability of parts for safety reasons.
d. The high cost of not having a part (AOG).

One of the main purposes of this Chapter has been to investigate how the MRP system is being applied in aircraft maintenance and inventory control. It is our belief that the items needed for scheduled maintenance can be controlled accurately and efficiently and that the MRP system can be used to control the inventory of these items, and greatly reduce the possibility of stock shortages.

Presently, only 23 companies use the MRP system and of the 152 companies who still use the ROP system, it is clear that approximately 50% of these were dissatisfied, and were considering implementing the MRP system.

There were many issues raised by the companies in response to both surveys, associated with implementing or controlling spare parts within MRP. However the MRP survey showed only six out of twenty-three companies as having problems.

The ROP and MRP survey response suggests the need to classify these problems into two types, as raised by those organisations implementing the MRP system, namely; problems arising from management in contrast to those arising from technical sources.

Firstly, the management sources cited by companies as the reason for MRP system failure were;

- Inadequate staff training for MRP implementation.
- Time or other resource constraints.
- Lack of manpower.
- Lack of support for the project.
- Financial resources.

The first four reasons can only be solved or overcome within the company itself, and as the implementation of the MRP system in an aircraft maintenance environment does require entire reorganisation of the plant, careful planning and total commitment is essential. Survey findings indicate that a key factor to the success of implementation lay in a comprehensive MRP education and training program prior to and during implementation.

In the event of insufficient financial resource, in Chapter six we intend to produce a small scale MRP-spreadsheet, which could act as an alternative for small businesses unable to incorporate larger and more comprehensive MRP systems.

Secondly, the technical sources of difficulty of implementing MRP cited were varied; reasons ranged from the unpredictable consumption of parts, through most parts requirements being unscheduled (i.e. *on-condition* maintenance), to the fact that many companies also had difficulty forecasting with such unpredictable parts, an issue to be dealt with in Chapter eight where we discuss the forecasting of intermittent demand in relation to these primary maintenance processes.

Added to these difficulties experienced by companies already using MRP was the fact that most companies were unsatisfied with their method of lot-size calculation. The survey results showed that the most common methods used by companies were EOQ, LFL and FOQ, which clearly produced very high inventory costs, especially in the case of intermittent demand. Another reason given was that no BOM could be developed economically as each job was unique, with its different work scope. The survey showed that nineteen companies applied BOM software packages in order to overcome this problem. For this reason single-level lot-size methods will be discussed in detail later, (see Chapter seven).

Finally, we end this Chapter by summarising the MRP survey finding as follows.

1. Planning horizon length; the survey showed that it varied between companies depending on the type of work in hand, in accordance with their planning forecast. We intend to look at the effect of this factor on the MRP lot-size in conjunction with the demand variation.

2. After each repair it is necessary, for a multi-level BOM to be updated (modification programs were common occurrences in aviation industries), with the amending of the *end item plans, EIP,* and the building of new BOMs using all available data from the manufacturer or other operators. Multi-level BOM was found to be a good method for rotables repair but was not easy for airframe work. Replacement parts and other repair material could be entered into the BOM

structure as order dependent demands. This step would provide improved inventory and cost control of repairs along with the collection of maintenance information for review and analysis.

3. We found that the regenerative MRP system was most commonly used on a weekly basis. Barrett [4] suggests that inventory may increase with more frequent MRP re-planning and that the widely accepted practice of making weekly MRP runs may not always be the best alternative. This method updates the data plan each time a change is posted and exploded through the system.

4. Credibility in the MRP system can only be achieved when a high level of visible management commitment exists, with continuous monitoring and consistently accurate data essential to achieving excellent results from MRP.

5. Software vendors and client companies alike must recognise that no purchased MRP software product can exactly meet the client company's needs, and any system not designed by a user will only be half effective.

6. Safety stocks should only be considered if necessary for immediate replacement to minimise the aircraft on ground time and for highly critical items (e.g. MEL, AOG, No-Go-Items).

7. *Open repair* orders must be controlled by a reminder system based on agreed time and warranties in some cases.

The application of MRP will provide the framework and feedback mechanisms needed for parts inventory.

5. KLM-uk profile

5.1 Introduction

The aim of this Chapter is to provide an overview of the airline company which participated in this research study from the beginning. We start with a brief profile of KLM-uk, followed by a basic outline of their current inventory system and other technical features.

5.2 Company background

Air UK Limited was established in January 1980, with the amalgamation of British Island Airways, Air Anglia and Air West. The Company formed part of the British and Commonwealth Shipping Company's conglomerate, but in July 1988 became a separate division of Bricom Group plc. A further change of ownership in April 1989 left Air UK Limited as one of a group of companies within the holding company, *British Air Transport Holding Limited, BATH*. The capital ownership of Air UK Holdings Limited was shared 55% by *BATH* and 45% by KLM, with the ownership shared between Caledonia Investments and Yattendon Investment Trust. After an ownership deregulation within European airlines in July 1997, an agreement was reached between *BATH* and KLM, whereby KLM acquired the 55% shareholding held by *BATH* in Air UK Holdings Limited, resulting in KLM owning 100% of Air UK Holdings Limited.

Initially, the engineering function was carried out by a separate division of the Air UK Limited Airline. However, in January 1990, as development continued, Air UK Engineering Limited was established as a wholly owned subsidiary of the Air UK Group. Furthermore, in April 1999, to continue the close association with KLM, Air UK Engineering Limited was renamed 'KLM-uk Engineering Limited'. As of 31 March 2001, KLM-uk Engineering employed 344 personnel at its main base in Norwich, 80 at Stansted, 65 at Schiphol and 8 on the Edinburgh Line Station.

The prime function and purpose of KLM-uk Engineering was initially to provide engineering support to KLM-uk to enable it to profitably operate scheduled and nonscheduled commercial air services throughout the UK and Europe. However, KLM-uk Engineering has gone through a major investment programme with new hangar facilities at Schiphol, Stansted and Norwich airports. Schiphol and London Stansted are primarily used for line and light maintenance aircraft input with the main base facilities at Norwich. The investment within KLM-uk Engineering has allowed an expansion into the aircraft maintenance market sector with extended workshop facilities for the repair and service of third parties. This includes an on-site paint facility, two new three-bay hangars, office accommodation and technical and logistical support departments in Norwich.

KLM-uk Engineering has become a successful 'one stop shop' for aircraft maintenance on Boeing 737-300/400/500 series, BAe146/RJ series, Fokker F28 Mark 100, Fokker F27 Mark 50 and ATR42/72 aircraft. This service is provided 24 hours a day, seven days a week for 364 days of the year. Norwich also boasts a JAR147 approved technical college, offering training courses from basic *ab initio* training up to degree level on all the above aircraft types, together with ancillary courses.

5.3 Workshop issues and parts control

KLM-uk's engineering workshops are fully equipped for the overhaul and rectification of airframes, undercarriages, pneumatics, hydraulics, electrical instrumentation, radio, avionic components, wheels and brake units.

The Planning department's duty is to control the maintenance requirements of the aircraft. The Technical Records department logs every aircraft component onto computer, so that when a part needs replacing it can be called up in advance. In this way, preparations can be made for aircraft scheduled for repair work.

We derived the following points of practice in the KLM-uk workshop from a recorded interview with David Goddall *workshop advisor*, and Peter Read, *Parts Supply*. The difficulties with a fairly outmoded system are evident.

- KLM-uk's workshop commences with the disassembly of the whole component, and then makes a list of parts needed to be replaced. Those lists will be checked for availability of stock through a computer link to the main store in Norwich (see Figure 5.1).

AirUK engineering

COMPONENTS USED SHEET

UK/W/438
Issue 4
Sept 1994

Work Order Number		Manual Ref.	Date	Job Card Ref.
50107773		DUNLOP DM1184 PT2 CHAP 36	5/1/94	

Description	Part Number	Serial Number	Sheet
BRAKE CONTROL VALVE	IN:- AC61342 OUT:- AC63880	D 24472	1 of 1

Qty	Part Number	Description	GRN	Avail.	Priority	Pick List Number	R.T.S
2	AC043389	SEAL	0362361			130044777	
1	ACO43390	SEAL	0362362			L	
1	ACO43391	SEAL	0362363			⌐	
1	AC043392	SEAL		N/S	12/1/95	60123459	
1	AC043393	SEAL		N/S	\	60123460	
1	AC043394	SEAL		N/S	L	60123461	
1	ACO43395	SEAL				130044778	
1	AC021463	SPRING		N/S	12/1/95	60123462	
1	AC038541	MAIN SPRING	0360879			130044778	
1	ACM26494	FORK END	0364870	N/S	12/1/95	60123465	
1	AC038546	PEG	0364869	N/S	⌐	60123466	
1	AC038539	FORK END RETAINER	0364864	N/S	1	60123468	
1	AC038537	RING NUT	0195315	N/S	⌐	60123469	
1	AC038540	WASHER	0340391	N/S	⌐	60123470	
1	AC038535	BUSH	0340390	N/S	⌐	60123471	
1	AC042274	PLUNGER	0364858	N/S	⌐	60123472	
1	ACM26493	BODY	0364866	N/S	1	60123473	
1	AC038536	PLUG	0364871	N/S	⌐	60123474	
3	AC038532-1	SHIM	0260795	N/S	.	60123475	
3	AC038532-2	SHIM	0362153			130044778	
4	DSR124-10	SCREW	0364863	N/S	12/1/95	60123476	

CERTIFICATE OF RELEASE TO SERVICE

Certifies that the work specified except as otherwise specified was carried out in accordance with JAR 145 and in respect to that work the aircraft/aircraft component is considered ready for release to service.

Stamp/signature for final clearance of sheets ....
Air UK Engineering Ltd
CAA Approval Ref: CAA 00127

Date ....

Figure 5.1 – Overhaul component parts log (Brake Control Valve).

- For parts which have nil stock, a message will be sent to the purchasers within the main store in order to proceed with an order action. In the case of an urgent situation, an AOG procedure is expedited, but this still depends on a decision taken by the supplier manager.

- The percentage availability of parts once the component has started the overhaul process (i.e. dismantled) differs; for example, 50% of undercarriage parts listed are stocked, for engine parts a figure of 80% availability was given, whereas for avionics it depended on the parts type, though in most cases 60% of parts were reported in stock. Brake units and wheels assembly had a 90% parts availability within the store, having a high consumption rate.

- The consequences of not having parts ready when needed had a major effect on the whole workshop, as work would be delayed until the parts were ordered. Problems regularly occurred with few improvements having been made to what was reportedly the outdated system currently used.

- Due to component-part dependence, in most cases the component overhaul could not be started until all parts required were available. While this work was put on hold through shortage of parts, another job was set in process, resulting in many jobs being backlogged.

- Short lead-times were another matter for concern as KLM-uk preferred long lead-times to get the best value for money. With lead-times varying from 60 to 80 days there is less chance of a cancelled order incurring a penalty.

- With all these problems, overhaul targets were not always met, apart from for brake units and wheel components.

- Finally, the *Line Maintenance* areas had more complaints of non-stock problems than did the workshops, with more deadlines to meet, constantly having to get the aircraft ready to fly.

5.4 Inventory control system used

The stock replenishment of aircraft expendables is activated by computer-generated demands received from the inventory controller. The control or setting of reorder levels within the inventory system and the establishment of maximum and minimum stock levels, is the responsibility of the inventory control section staff whose authority is to add, delete or amend reorder levels on the inventory system. The procedure for setting the reorder level for expendables and rotables is as follows:

- Any item with an annual usage of one or less will not have a reorder level except where the item is critical to the operation of aircraft and a reorder level is approved by the planning and logistics manager.

- The reorder level is calculated as (quantity used during average lead-time) plus 1/12 (annual quantity used) but it should not exceed one half of annual usage. The maximum stock level for expendables will be set at ¼ times the annual usage.

- There will be a reorder level set for zero against rotables to generate nil requisition. The maximum stock level for rotables will be set at a figure equal to the stock holding, less the sum of all outstation holdings.

- Where the ROP falls within the above criteria, or where the ROP is zero, the supplies officer should proceed to place a purchase order either through the inventory system or manually.

- The quantity ordered will be determined by the following rules:
    a. The total order quantity may exceed ¼ of annual usage, plus the quantity on open and unfulfilled requisitions.
    b. The first delivery on any order should not exceed 1/12 annual usage plus the quantity on any open and unfulfilled requisitions.
    c. The second and subsequent deliveries should not exceed 1/12 annual usage.

- Deliveries should be planned so that stock does not exceed 1/6 annual usage at any time, also taking into account any existing open purchase orders and their due delivery dates when planning deliveries against the next purchase order.

Ultimately, the material requirement is listed and submitted to various KLM-uk approved suppliers in order to obtain the required delivery dates and best commercial price.

5.5 Summary

KLM-uk believes that its current inventory system is inadequate and incurs high inventory costs. With the merger with the *Royal Dutch Airlines*, there is now, a strong possibility of investment through the establishment of a new material supply chain which has some elements of the MRP system, with a link between the Norwich base component overhaul workshop and the main parts store at Schiphol. For the time being, all parts required have to come on a daily basis from Amsterdam.

Whatever the nature of the KLM-uk inventory management system they were able to provide us with detailed data, the analysis of which will provide the subject matter for the next three Chapters.

6. MRP-SPREADSHEET CALCULATIONS

6.1 Introduction

This Chapter presents an MRP-spreadsheet using *Visual Basic for Applications*, *VBA*, as an easily implemented and reliable application for material planning. The work is based on the results of an MRP survey of airline companies, many of which found standard MRP systems impossible to implement, both financially and environmentally. This study will demonstrate how MRP-spreadsheets could work as an alternative for a small business unable to incorporate a larger and more comprehensive MRP system. It will show their effective use as a first step in the search for continuous improvement in maintenance and inventory control. The results and evaluations are presented later in this Chapter.

6.2 Background

Our survey (see Chapter three, [55]) has shown that many AO and MO are either already using some elements of MRP or are weighing the advantages of an MRP system against its cost. But, and the point was emphasised by Schroeder [111], the expense is substantial. The average cost of an MRP system installation ranges from $93,000 for small companies to $1,633,000 for larger companies.

During the last few years, the use of electronic spreadsheets as a solution to engineering and science problems has increased with the advancements in spreadsheet software and computer hardware, see [74, 89]. The introduction of electronic macro programs has added problem-solving capabilities to spreadsheet applications. They can carry out complex manipulations and numerical computations. This growing use of spreadsheet programs stems from their ability to perform repetitive sophisticated calculations in real time and the availability of built-in procedures desirable for presentations.

System tools have been steadily moving from mainframe and minicomputer platforms to the microcomputer. There are several reasons for this transition; the increased power of the microcomputer relative to the minicomputer and the mainframe, users' familiarity, the decreasing cost of computers, and the availability of new specialist software packages and approaches [112]. The MRP-spreadsheet is not a discrete MRP package. It is designed to do quick and limited "what-if" analyses and various other MRP-related tasks and to operate within a spreadsheet program such as Lotus 1-2-3, Novell Quattro Pro, or Microsoft Excel. Using computer spreadsheets for capacity planning and production scheduling has been shown to be an excellent method for achieving immediate results [8], incorporating spreadsheet software, written macros, and specialised menus. It allows the user to change the maintenance order and assess what would happen for as many scenarios as are needed [87]. A spreadsheet-like grid tool can be used in cases of multiple transactions, focussing on the analysis and presentation of information in a form more understandable to management, through a simulation using visual representation for each step [36, 104].

For small firms that find commercial MRP packages too expensive, such an alternative MRP-spreadsheet [112, 118], which on today's hardware can easily handle a few thousand parts—and on tomorrow's, several thousand, has the great advantage of saving on hardware and software costs [119]. Sponseller [120] has indicated that a spreadsheet model using overlapped scheduling can significantly improve the overall efficiency of a production operation. And, according to Frazer [47], the availability of spreadsheet programs, their low cost, and managers' growing familiarity with them has raised expectations for their being the solution in the MRP environment.

6.3 Workbook features

The workbook, the electronic equivalent of a three-ring binder, is the normal document or file type within the Microsoft Excel program. Workbooks can contain multiple worksheets, charts, and Visual Basic for Applications, VBA, modules. Each sheet's name appears on a tab at the bottom of the workbook. The default workbook opens with three numbered worksheets. But the number of sheets is limited only by available memory, the maximum in the most recent workbook being 255. With workbooks, users can switch between sheets easily and enter data on more than one sheet at a time, naming the sheets separately for easy distinction. No longer do workbooks have to be created with contents pages, bound or unbound sheets for viewing, naming or saving separately; instead, all sheets may be accessible at all times and the entire workbook saved on command. The smaller the number of worksheets within the workbook, the greater the speed and the lower the RAM requirement [119].

VBA tailored by Microsoft to act as a macro language that permits the automation of repetitive tasks by recording user keystrokes, which allows the writing of more complex applications, offers a more flexible way to read and write macros and it contains the tools to make Microsoft Excel fit customer-specific needs.

6.4 MRP Workbook design

Our MRP-spreadsheet program has been written using VBA. The VBA system runs across the Microsoft product family (e.g., Excel spreadsheet, Access database, Word word-processing). The Visual Basic Model[1] was successfully tested on Kaimann and Berry's Data [7, 69].

MRP starts by determining what parts are required to fulfil the master schedule and whether there is any need for service spare parts. To do so, MRP requires a bill of material to obtain a list of the parts in the master schedule or inventory data so that what is in stock and/or on order can be determined. Processing this information, it calculates when existing orders need to be expedited and what new material has to be ordered.

Let us see how this could be implemented on our spreadsheet model, where the software used is Microsoft Excel 2000 for Windows. In reality, the MRP-spreadsheet is several worksheets that perform a variety of tasks: *component maintenance assembly*, *CMA*, *bill of material*, *BOM*, *master schedule*, *MS*. *order releases report*, *ORR*, and a calculation of each component's requirements on separate worksheets so that the user can simply move between sheets by clicking the mouse on the appropriate tab at the bottom of each sheet (see Figure 6.1 to 6.5).

The nine different components[2] tested in this MRP-spreadsheet calculation vary from electrical instrumentation and avionics components to wheels and brake units, with each component having its own inventory data file, BOM, and MS. Notice that the periods represent weeks, chosen to simplify the calculation of carrying costs per period. The lot-size and record of the projected on-hand balances are computed as though the beginning balance on-hand period is always at zero. Lead-time for the supply is given in all cases,

[1] For consecutive running of MRP-spread sheet see Appendix E. for detailed function descriptions see Appendix B.
[2] From KLM-uk components overhaul workshop.

with no overdue orders for simplicity. The main aspects of the MRP-spreadsheet calculations are reviewed in the following subsections.

6.4.1 Component maintenance assembly

Figure 6.1 is a view of the complete component assembly (end item), which includes 100% replacement parts. Indexed components with the numbers 18 through 73, for example, listed in the MS, were all scanned from the main component maintenance manual for the nine spare parts used. These were then tested.

6.4.2 Bill of materials

The BOM, or parts list, is an ordered list of all the parts needed to assemble a particular component. The BOM (Figure 6.2) shows the levels of materials used, with level zero referring to the final component (unit or end item) and level one to the constituent parts. The numbers on the right of the part names show the quantities needed to assemble each component. This example shows a relatively simple bill of material; however, a BOM is usually much more complicated, involving many more levels.

6.4.3 Master schedule

The MRP-spreadsheet uses a master schedule, MS, to give an accurate assessment of demand for parts needed to overhaul components. The first stage of the process is to "explode" the MS using a BOM sheet. Figure 6.3 shows a typical example of an *Inverter Unit Assembly's* MS. In this case the MS describes each component in terms of its part number, time between overhauls, repair time needed to accomplish the work, aircraft type, and operator's name. There is other information more closely related to MRP input spreadsheet calculations: lead-time, safety stock selected by the operators themselves, *minimum order quantity*, *MOQ*, and part or *item cost*, *IC*, provided by the supplier.

6.4.4 Main MRP-spreadsheet calculation

To run the MRP calculation, the user must dedicate every sheet by name to one of the spare parts listed in the MS. In MRP, the master schedule for components (or major assemblies) is exploded downward, using the BOM to derive the dynamic demand requirements for the component parts and listing the gross requirements for each period in the planning horizon. After adjustments for safety stock, on-hand inventories, and scheduled receipts, the resulting net requirements need to be grouped into planned orders. The process of determining these order quantities (commonly referred to as *lot sizing*) in turn leads to the requirements at the next, lower level. An example will be given later in this Chapter; the spreadsheet layout is shown in Figure 6.4.

6.4.4.1 MRP inventory record

The MRP inventory record in Figure 6.4 records the following: planning factors, gross requirements, scheduled receipts, projected on-hand inventory, shortage, net requirements, planned order receipts, beginning inventory, ending inventory, average inventory, planned order releases, carrying cost, ordering cost, and total cost. The body of the record divides the future into time periods called *time buckets*, which normally represent weeks, but which can be expressed in days or months.

The part number and description identify the particular record. The pre-assigned lead-time, the lot-size method, and the safety stock figure provide planning factors. The minimum order quantity, the carrying and ordering costs, and the planning horizon will be selected each time a different lot-size method is applied from the MRP menu. Management must select those quantities in advance. An inventory planner updates the factors whenever conditions, such as lead-time, change. An explanation of rows 7 to 19 follows:

Gross requirements (row 7). Gross requirements are the total forecasting demand derived from the component's parent assembly.

Scheduled receipts (row 8). Sometimes called open orders, scheduled receipts are orders that have been placed but not yet completed. For a purchased spare part, the scheduled receipt could be in one of several stages toward completion, that is, actually being processed by the vendor or being inspected by the purchaser's receiving department.

Figure 6.1 Component maintenance assembly worksheet.

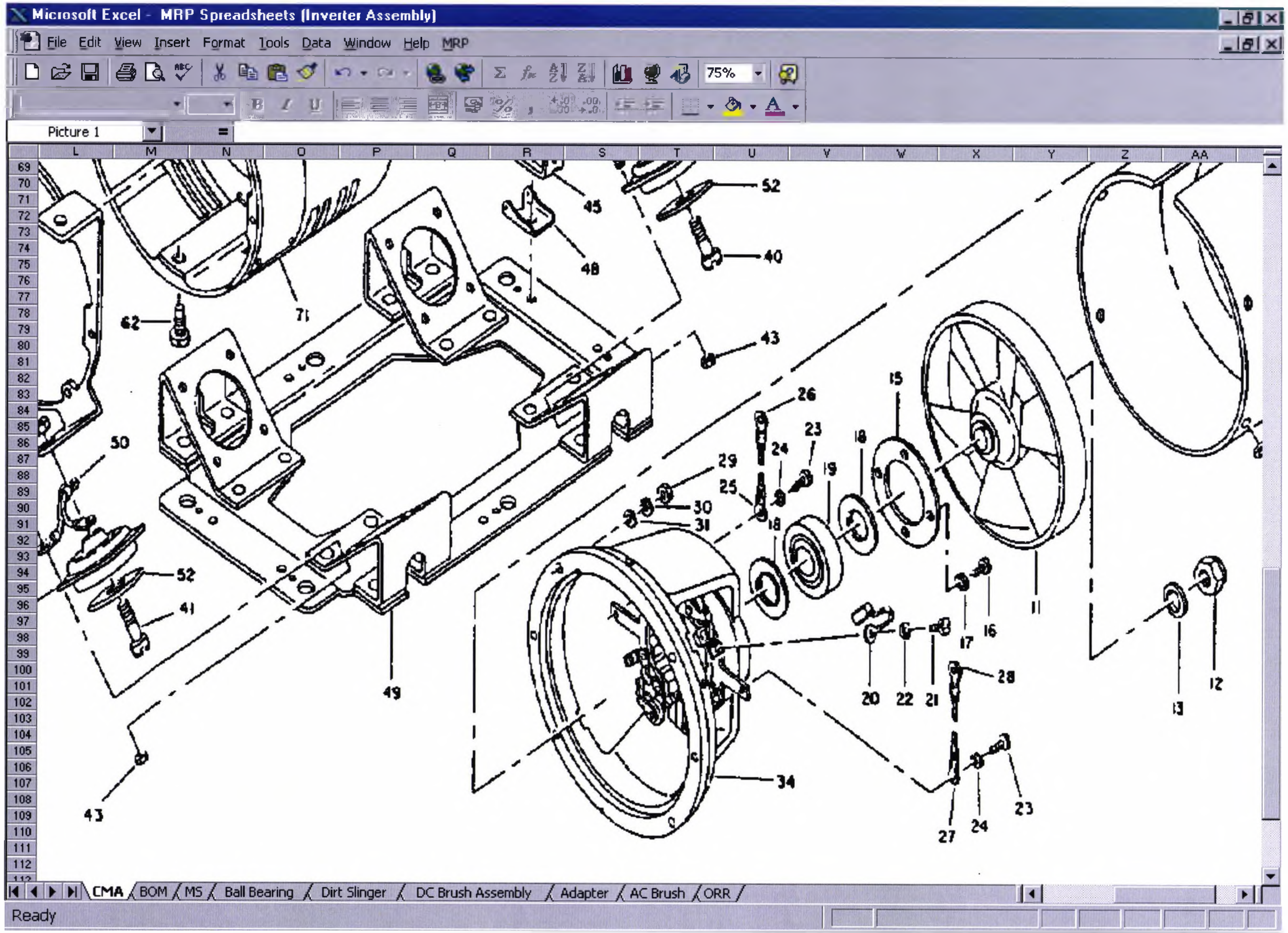


Figure 6.2 Bill of materials layout.

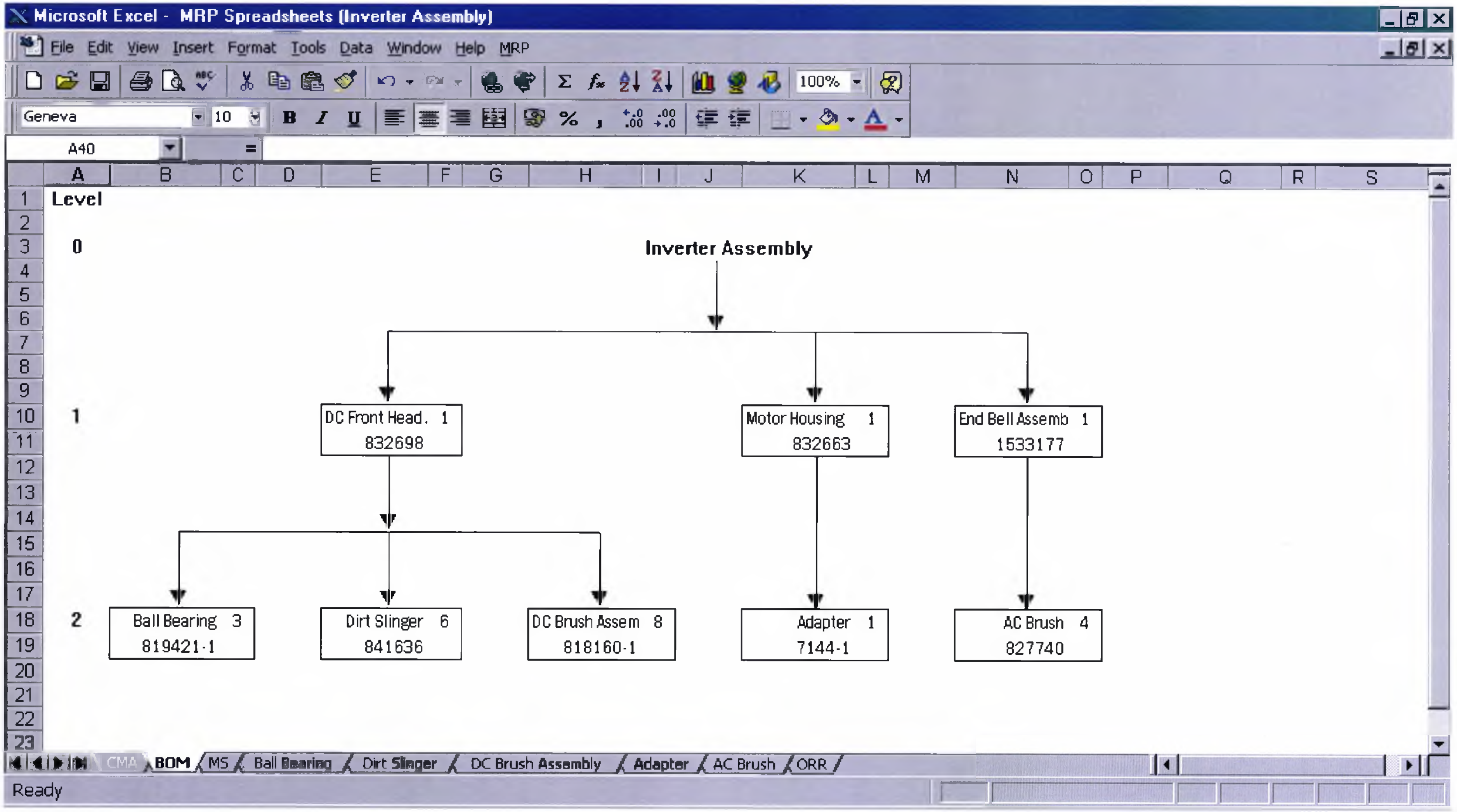


Figure 6.3 Master schedule worksheet - ** Owing to limited space the period from 29 Sep. to 29 Jun. has been hidden (Format-Row-Hide).

Microsoft Excel - MRP Spreadsheets (Inverter Assembly)

Description	Inverter Assembly
Part Number	1518-8-C
Overhaul	2700 Hours
Repair Time	17 MHs
Aircraft Type	Fokker 27
Operator	KLM-uk

QTY	Part Number	Description	Index No.	Lead Time in Weeks	Safety Stock	Minimum Order Quantity	Item Cost	Level
1	832698	DC Front Head Assembly	38	44	0	1	£ 8,482.43	1
3	819421-1	Ball Bearing	19	1	0	1	£ 49.80	2
6	841636	Dirt Slinger	18	1	12	5	£ 3.56	2
8	818160-1	DC Brush Assembly	35	24	40	2	£ 33.44	2
1	832663	Motor Housing	73	14	0	1	£ 6,955.40	1
1	7144-1	Adapter	56	1	4	2	£ 18.97	2
1	1533177	End Bell Assembly	34	31	0	1	£ 6,500.00	1
4	827740	AC Brush	20	1	20	1	£ 30.95	2

Period	Demand 1994	Demand 1993	Demand 1992		
18-Aug	3	4	3		
25-Aug	5	0	3		
01-Sep	0	0	1		
08-Sep	5	3	4		
15-Sep	3	2	2		
22-Sep	1	0	1	**	
06-Jul	1	0	4		
13-Jul	3	1	2		
20-Jul	2	3	3		
27-Jul	2	5	1		
03-Aug	2	4	4		
10-Aug	2	1	2		
	81	152	109	Total	
	1.56	2.03	1.62	Standard Deviation	STD
	1.56	2.92	2.10	Average	AVE
	1.00	0.69	0.77	Coefficient of Variation	CV

CMA / BOM / MS / Ball Bearing / Dirt Slinger / DC Brush Assembly / Adapter / AC Brush / ORR

Ready

Figure 6.4 Inverter unit assembly-Ball Bearing (MRP spreadsheet calculation layout).

Microsoft Excel - MRP Spreadsheets (Inverter Assembly)

File Edit View Insert Format Tools Data Window Help MRP

Geneva 10 100%

A30 =

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	*Part Number*	819421-1			*LotSize*	PPA			*MSD*	01/01/95		*OC*	£ 40		T_{EOQ}	4.28	weeks		
2	*Part Name*	Ball Bearing			*MOQ*	1			*Level*	2		*EPP*	80.3213		*PH*	52			
3	*Safety Stock*	0			*IC*	£ 50	EA		*STD*	2.03		*Max Qty*	80.3213		*AD*	8.76923			
4	*Lead Time*	1	week		*QTY*	3			*CC*	£ 0.01		*EOQ*	38						
5		**Period**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**
6			**06-Jul**	**13-Jul**	**20-Jul**	**27-Jul**	**03-Aug**	**10-Aug**	**17-Aug**	**24-Aug**	**31-Aug**	**07-Sep**	**14-Sep**	**21-Sep**	**28-Sep**	**05-Oct**	**12-Oct**	**19-Oct**	**26-Oct**
7	Gross Requirements		0	3	9	15	12	3	12	0	0	9	6	0	3	6	21	18	18
8	Scheduled Receipts																		
9	Projected On-	0	0	-3	15	0	-12	12	0	0	0	-9	9	9	6	0	-21	0	-18
10	Shortage?		No	Yes	No	No	Yes	No	No	No	No	Yes	No	No	No	No	Yes	No	Yes
11	Net Requirements		0	3	9	15	12	3	12	0	0	9	6	0	3	6	21	18	18
12	Planned Order Receipts			27			27					24					39		36
13	Beginning Inventory		0	27	24	15	27	15	12	0	0	24	15	9	9	6	39	18	36
14	Ending Inventory		0	24	15	0	15	12	0	0	0	15	9	9	6	0	18	0	18
15	Average Inventory		0	25.5	19.5	7.5	21	13.5	6	0	0	19.5	12	9	7.5	3	28.5	9	27
16	Planned Order Releases		27			27					24					39		36	
17	Carrying Cost		£ 359																
18	Ordering Cost		£ 560																
19	Total Cost		£ 919																
20																			

CMA / BOM / MS / **Ball Bearing** / Dirt Slinger / DC Brush Assembly / Adapter / AC Brush / ORR /

Ready

Projected on-hand inventory (row 9). As with scheduled receipts, each actual withdrawal and receipt must be entered into the MRP database. The revised inventory can then be produced, typically once per week. Equation 6.1 shows this calculation. Other entries in the row show the inventory expected in future weeks. The record thus takes into account the inventory left over from the previous week, scheduled receipts, planned receipts, and gross requirements. Mathematically this relationship is expressed as:

$$I_t = I_{t-1} + SR_t - GR_t + PR_{t-1} \qquad 6.1$$

C9 = B9 + C8 - C7 + B12

where

I_t Projected on-hand inventory balance at the end of week t

SR_t Scheduled receipt (open order) due in week t

GR_t Gross requirements in week t

PR_{t-1} Planned receipt in week t-1

Shortage (row 10). The projected on-hand inventory of the current week is checked against the selected safety stock B3. If it is less than B3, a "Yes" sign will appear in the current week; if it is greater than or equal to it, then a "No" will appear. This test is written by the formula = IF(C9 < B3, "Yes", "No") .

Net requirements (row 11). Occurring only when components available total less than safety stock, net requirements show the amount needed to return goods available to the safety stock level. In practice, net requirements are equivalent to the projected on-hand inventory plus scheduled receipts, less the gross requirements together with planned receipts.

Planned order receipts (row 12). *Planned order receipts*, *PORs*, are new part orders not yet released. Planning the receipt of such new orders keeps the projected on-hand balance from dropping below the designated safety stock level. If no safety stock is necessary, often the case with intermediate parts, the purpose of *PORs* is to offset a negative projected on-hand balance in the inventory record. This factor is programmed and controlled by VBA and is activated as soon as the lot-size is formalised.

Beginning inventory (row 13). The beginning inventory is equal to the inventory left over from the previous week (ending inventory), plus planned order receipts, plus scheduled receipts for the current week.

Ending inventory (row 14). Ending inventory is equal to the projected on-hand inventory plus planned order receipts for the current week.

Average inventory (row 15). Average inventory is the sum of both ending and beginning inventory divided by two.

Planned order releases (row 16). Planned order releases indicate when an order for a specified quantity of the part is to be issued. The release date is the receipt date minus the lead-time. A VBA Module was introduced to carry out this operation based on the lead-times given by the supplier as shown on the top left of the spreadsheet (Figure 6.4). The planned order releases depend on the lot-sizing method, and planned lead-time could easily be assigned individually to each part.

Carrying cost (row 17). Carrying cost was programmed by VBA to calculate the total carrying cost for the selected planning horizon.

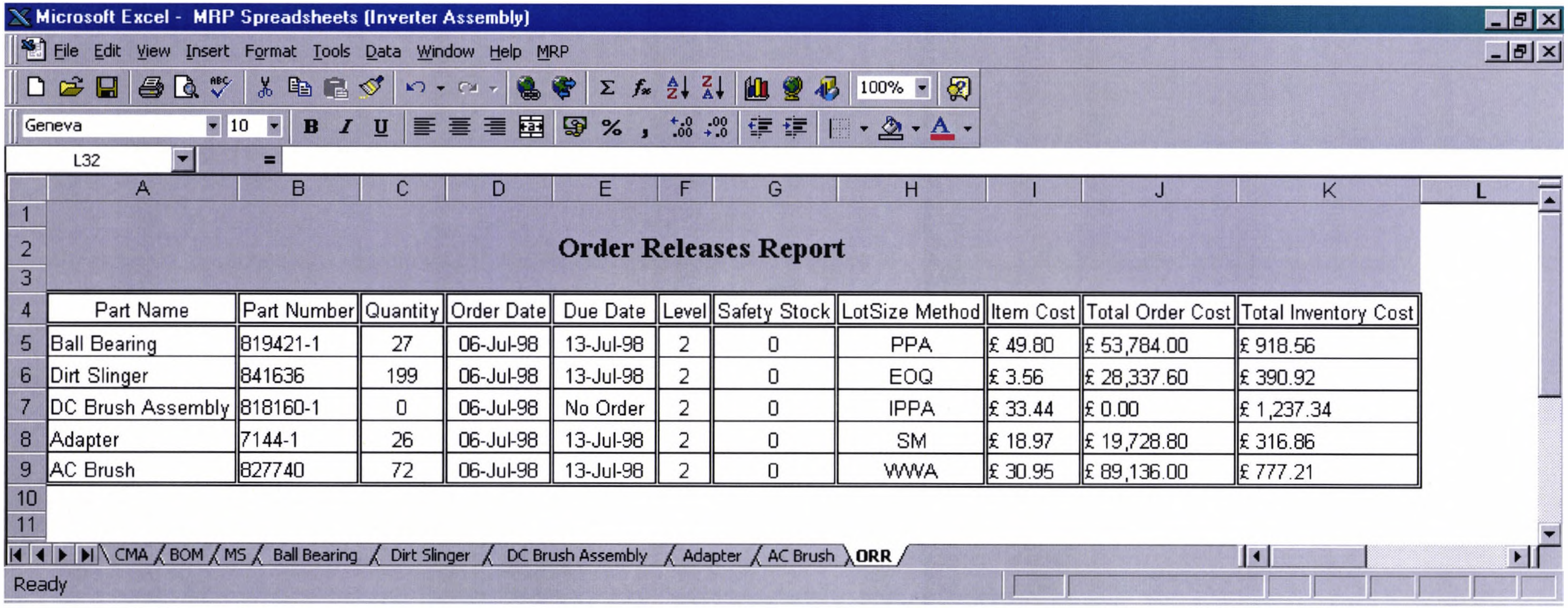
Ordering cost (row 18). Ordering cost was programmed by VBA to calculate the total amount of ordering costs for the entire planning horizon.

Total cost (row 19). Total cost is the sum of both carrying and ordering costs.

6.4.5 Order release report

MRP inventory records are compiled for every part appearing on bills of materials. These records together represent the current material requirements plan, which can be printed out in hard copy or displayed on a computer screen as an order releases report, *ORR*. Inventory planners use the computer-generated reports and view the full records for those parts, making the necessary decisions about releasing new orders and expediting open orders. The *ORR* throws up a spare part description together with the part number, quantity required, level, order and due dates, plus the total cost of the particular order, as shown in Figure 6.5.

Figure 6.5 Order releases report contents.



Order Releases Report

Part Name	Part Number	Quantity	Order Date	Due Date	Level	Safety Stock	LotSize Method	Item Cost	Total Order Cost	Total Inventory Cost
Ball Bearing	819421-1	27	06-Jul-98	13-Jul-98	2	0	PPA	£ 49.80	£ 53,784.00	£ 918.56
Dirt Slinger	841636	199	06-Jul-98	13-Jul-98	2	0	EOQ	£ 3.56	£ 28,337.60	£ 390.92
DC Brush Assembly	818160-1	0	06-Jul-98	No Order	2	0	IPPA	£ 33.44	£ 0.00	£ 1,237.34
Adapter	7144-1	26	06-Jul-98	13-Jul-98	2	0	SM	£ 18.97	£ 19,728.80	£ 316.86
AC Brush	827740	72	06-Jul-98	13-Jul-98	2	0	WWA	£ 30.95	£ 89,136.00	£ 777.21

6.5 Illustrative example

The following example illustrates how at the single component level a spreadsheet can greatly simplify the inventory planning process. Figure 6.4, an example of an *Inverter Unit Assembly*, can be used to demonstrate the overall approach of MRP-spreadsheets. The analysis begins with the top level parts from the bill of materials linked through the MS worksheet to each component's requirements on separate worksheets. The result provides us with the gross requirements for each constituent part required to build the component. In this particular example, a planning horizon of 52 weeks and a time bucket of one week were used. The information was formalised on the basis of the MRP airlines survey (see, Chapter four, [52]).

The maintenance planning forecast shows that the time interval for taking in one Inverter Assembly for overhaul is almost weekly (viz. demand 1992). This information together with the bill of material allows us to calculate the quantity of spare parts needed. For the sake of clarity, at this stage the focus will be on *Ball Bearing* part number 819421-1 only.

Once the gross requirements are known, the netting process takes place; gross requirements are matched against the projected on-hand balance and the scheduled receipts status. Once those two elements are taken into consideration, the net requirements can be determined. The first line (row 7 of Figure 6.4) shows the first gross requirements for the assembly to be 3 units, starting in week 29. The second line (row 8) displays the scheduled receipts. In practice, there may be parts already in stock, or orders for materials already placed due to arrive in time to meet the gross requirements. In this example the safety stock has been set to zero with no scheduled receipts pre-planned. The first formula to be calculated is the projected on-hand inventory, which is equal to the previous period's on-hand balance together with the scheduled receipts, less gross requirements, plus any planned receipts. Whenever the projected availability is less than zero (i.e., the safety stock level), a planned order is scheduled for receipt in that particular week. As long as projected on-hand (row 9) remains positive, no replenishing action is necessary. If a negative quantity is encountered (out-of-balance condition) as in week 29, the MRP-spreadsheet reacts by generating computer-planned orders. If these are subtracted from the net requirements, the number of parts still to be ordered, as shown in row 11, can be found. At the same time, the MRP-spreadsheet will let us know whether there is a shortage or not (row 10).

In the event of a shortage, the planned order receipts will immediately be topped up with the sufficient quantity (lot size) via a planned order release (row 16).

The next step is to select the MRP lot-size method next to the *Help menu* from the worksheet, and choose *Part-Period Algorithm*, *PPA*, from the MRP lot-size methods list. The MRP method dialog box opens (see Figure 6.6a-b) after the lot-size method is selected. In the Planning Horizon box, type "52"; in the Carrying Cost box, type "0.01"; in Ordering Cost, type "40"; in Minimum Order Quantity, Type "1"; and then to choose "OK". The dialog box closes and the lot-size quantities will be added to cells, since the MRP-spreadsheet VBA recognised a net need of 3, 9, 15, 12, 3, 12, 9, 6, 3, 6, 21, and 18 parts from week 29 to 43. A computer planned order receipt for 27 was scheduled in week 29, for 27 parts again in week 32, for 24 parts in week 37, and for 39 parts in week 42. Once quantities to be received have been calculated, the next step is to find the time when orders should be placed. A VBA Module has been introduced to carry out this operation automatically, according to the lead-times given by the supplier (as shown on the top left of the spreadsheet, lead-time equals one week). The planned order release row shows that the final date to place orders of 27, 27, 24, and 39 parts is in weeks 28, 31, 36, and 41, respectively.

These computer planned orders will now be used to create other gross requirements if there are lower-level parts linked with the next worksheet, assuming our example is multileveled with two components being required for each next assembly. Therefore, the orders for 27, 27, 24, and 39 parts are multiplied by 2, giving a projected gross requirement of 54, 54, 48, and 78.

The calculation for the rest of the spare parts in the master schedule is similar and is presented on the following worksheets within the same workbook. The VBA coding used to produce Figure 6.4 with regard to the MRP calculation spreadsheet for the other nine components, incorporating most lot-size methods from a total of seventeen, is on the attached CD disk at the back of this thesis

Figure 6.6a MRP pull-down menu.

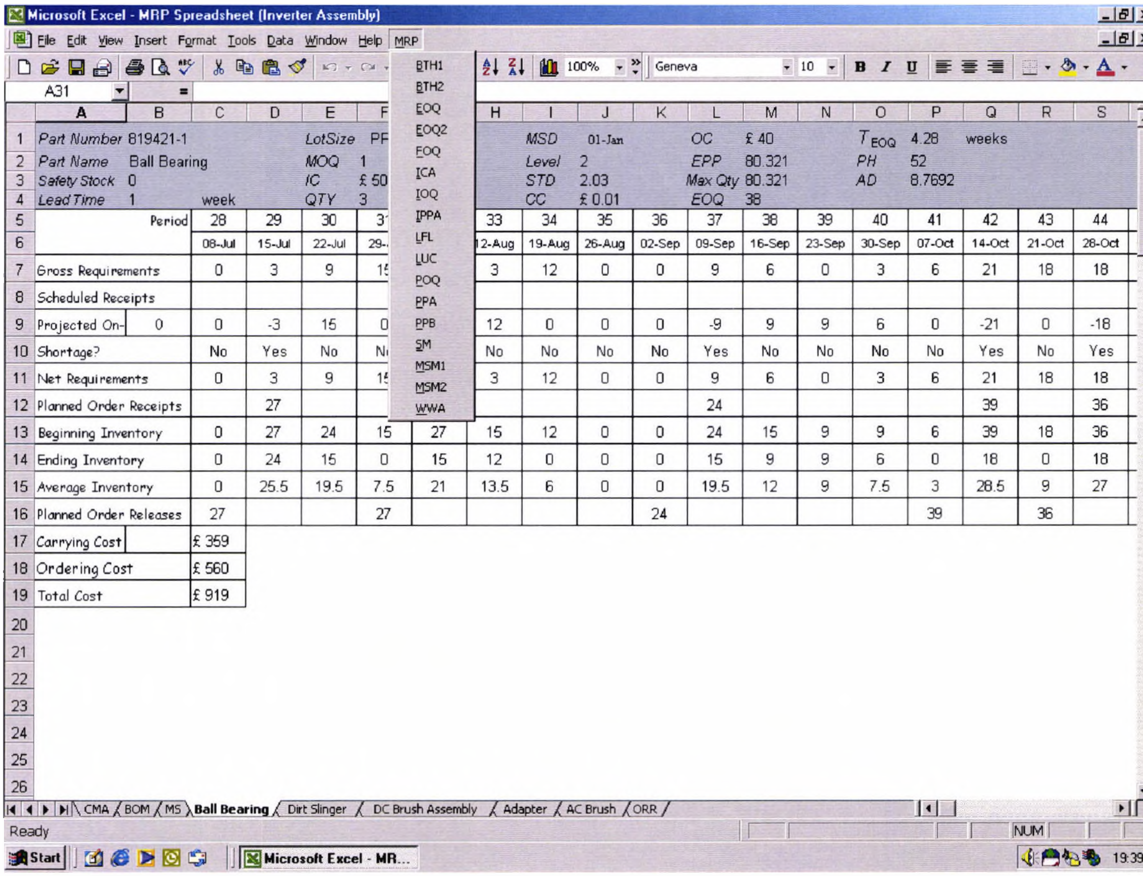
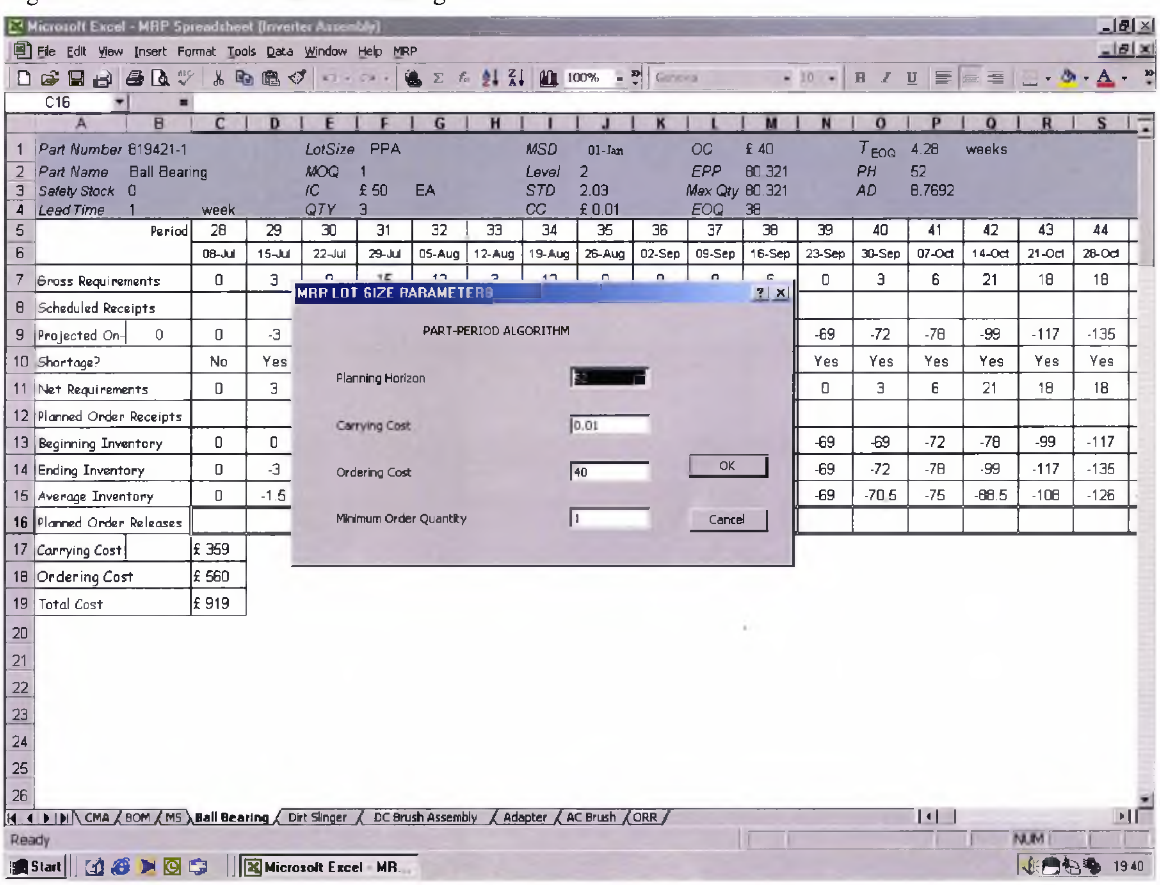


Figure 6.6b MRP lot-size methods dialog box.



6.6 Advantages of MRP-spreadsheets

The computing environment in general, especially in PC-based applications, is ever becoming more user-friendly. Interfaces are becoming easier to learn and use and almost all applications developed today feature pull-down menus, on-line help facilities, and easily obtainable outputs [82]. As a result, MRP-spreadsheets may be applicable to parts inventory control. The following are some advantages of MRP-spreadsheets:

- Hardware and software costs are lower compared with a full-blown MRP system; this is the greatest advantage.
- Users can custom-design the screen display of spreadsheets in a variety of ways most suited to meet the needs of their companies.
- A spreadsheet can create better charts and graphs than typical MRP software [119], showing trends and comparisons more easily.
- MRP-spreadsheets provide some basic reports, the most valuable of which is a list of needed parts (purchased or self-manufactured).
- Macros allow automated processing and eliminate keying errors [39].
- The high availability of microcomputers and spreadsheet software is making production-scheduling techniques much more accessible to the average user [112].
- The successful application of spreadsheets to microcomputers in various other applications has demonstrated that the software can also reliably solve problems in the MRP environment [47].
- Spreadsheets are compatible with other software programs, for example, accounting and purchasing, which can share common data.
- The major advantage of using spreadsheets for an application such as rough-cut capacity planning is that considerable time is saved by computerising what were previously manual methods. "What-if" is simplified once the spreadsheet has been created [13].

6.7 Disadvantage of MRP-spreadsheets

Spreadsheets may be perceived as too limited or too slow for large or complex applications, or such applications could require excessive (macro) programming to be implemented in the spreadsheet. It may simply be easier to use an established specialised package rather than a spreadsheet for certain types of problems. While many authors extol the virtues of spreadsheets, some warn that certain applications are suitable for spreadsheet treatment and others are not [49]. The following disadvantages of MRP-spreadsheets may be noted:

- Unlike most modern MRP systems, the MRP-spreadsheet on Microsoft Excel was not designed as an integrated database MRP system. As such it is limited in regard to the number of parts it can handle. This depends on the machine's speed and its RAM capacity.

The above-mentioned limitation has been resolved to a large extent through the constant upgrading of PC's and the extension of RAM memory.

6.8 Evaluation and conclusion

Given their advantages and disadvantages and bearing in mind their widespread availability, comparative low cost, high performance, and the desirable features of spreadsheets, the efforts of MRP-spreadsheet practitioners to determine the extent of VBA applicability and the acceptance of MRP-spreadsheets in aircraft maintenance and inventory control, could lead to the implementation and further development of the approach we have been investigating.

Anyone with a basic knowledge of computer programming can develop a versatile MRP system on spreadsheets [118]. The system described in this Chapter has been designed to meet the scheduling needs of small companies with spreadsheet experience and limited resources. Some companies could use it as a stop-gap system before installing a full-featured MRP system.

The MRP-spreadsheet is a good way to obtain some basic material planning information. Although it is not a complete, integrated system like many on the market, the output is generally reliable and useful. It could provide most benefit to small organisations handling relatively few components, or in a make-to-order environment in which on-hand inventory is minimal.

As many companies believe that an MRP operation needs a large investment (Chapter three, [55]), perhaps the greatest benefit of a system like this one is that it is an inexpensive introduction to the concept of MRP. It requires the user to organise bills of material, inventory records, and planning information such as safety stocks, lead-times, and component costs. Our proposal should provide companies with a good foundation;

as they grow and gain resources, they can then adapt to larger and more comprehensive systems.

We are now able to proceed to the assessment of lot-size methods in the following Chapter.

7. MRP LOT-SIZING METHODS

7.1 Introduction

The simple act of purchasing is becoming the complex issue of supply management in the airline industry. It has become a matter of determining the cost of owning the part and which method to use to reduce the cost of logistics and thereby reduce overall costs. Purchasing managers are increasingly required to make order quantity decisions for parts that have irregular usage patterns. Classical economic order quantity, EOQ, formulae are of less value in this case, as they assume relative constancy of demand over the planning period. The acceptance of the MRP system by many airline operators and maintenance services has caused us to question the validity of many of the lot-size methods used, particularly with respect to the assumption of intermittent demand.

In this Chapter, we study the performance of *single-level lot-size* methods in the inventory environment of aircraft maintenance. A total of seventeen lot-sizing methods have been considered. What follows is a comparison of alternative methods for determining appropriate purchase quantities within an MRP system. Actual historical demands from airline component overhaul workshops have been used to determine how lot-sizing methods respond to different combinations of operating parameters within aviation maintenance. Visual examination of the results is our first focus of analysis, and subsequently these visual observations on the experimental results are examined and clarified through statistical analysis, using the general linear model.

Finally, a useful tool has been developed through this study; namely, lot-size predictive cost model, which may prove useful to a range of material managers, particularly those dealing with erratic demands, when evaluating either lot-size method or the potential effects of such operating factors on lot-sizing performance. A simple example is presented to illustrate the performance of the mathematical model, and a set of recommendations are included to enable airline inventory practitioners, amongst others, to choose an appropriate lot-size method for their particular operating parameters.

7.2 Literature review

The nature of the overhaul of assemblies and subassemblies, dictates that 100% of all possibly required parts are available at the time the overhaul is started. This may result in a large number of parts being returned to stock later via technical inspection and credit to the inventory balance. Thus carriers that continue to manage their own spare-part inventories keep stocks as lean as possible to minimise carrying costs. Inventory costs and supply are critical elements for airlines seeking to minimise expenses while adhering to leasing conditions and local civil aviation authority rules. Many small airlines have responded by stocking only essential parts to meet minimum equipment list requirements, MEL.

Lot-sizing in an MRP environment has received considerable attention in the inventory control literature [64, 66]. Several methods have been tested with data demand generated randomly from a normal distribution [15, 64]. Not until now though has data from airline operators or maintenance service organisations been fully addressed. The demand for spare parts in most aircraft maintenance is unpredictable and characterised by a degree of 'lumpiness', due to natural seasonal fluctuations in the airline business. This is in contrast to normal industry where demands are known in advance and supply is more constant.

Since the introduction of MRP, the problem of determining economic order quantities, EOQ, has shifted from square-root formulae with assumptions of average usage rates, to calculations using discrete period demands. In lot-sizing studies, Toelle [124] suggested that batch-sizing decisions are real and critical, but should be "schedule based" rather than "economically based", while Coleman [35] has stated that the choice of lot-sizing technique, whether by approximation or optimising, should be based on considerations other than speed of computation. Several studies have evaluated the performance of these methods under various conditions. One of the factors is the length of the planning horizon, which can influence the evaluation of lot size relative performance. Blackburn [11] stated that the choice of the number of periods can have a strong influence on a method's cost performance, Bregman [21] also suggested that the length of the planning horizon and the value of the carrying cost can significantly affect the choice of the best lot size method, whereas Gaither [54] found that the length of the requirements schedule was an unimportant factor in choosing among lot-sizing models. On the other hand, Nydick and Weiss [95] recommended the use of the *Part-Period Balance, PPB*, and *Silver-Meal, SM*, methods as neither are adversely affected by a long planning horizon.

The increase in requirement lumpiness has a substantial effect too on the performance of the lot-sizing method. Bobko and Whybark [15] indicated in their results that the coefficient of variation in demand is quite a robust measure. Choi [27], reporting on their experimental simulation with high coefficients of variation, found that the *Least Unit Cost, LUC*, method performed better as the coefficient of variation increased. However, in follow-up studies, Ritchie and Tsado [102] found that the *Incremental Order Quantity, IOQ*, method performed much better as the coefficient of variation in demand increased, whereas Boe and Yilmaz [16] reported that the IOQ method generated lower costs and approximated to the optimal procedure of *Wagner-Whitin Algorithm, WWA*, very closely. Bookbinder and H'ng [17] in their studies, found that WWA tended to provide a more economical solution when the demand variability was high. On the other hand they maintain that a longer planning horizon would provide greater economy than a short one, whereas Chong [28], claims that when the planning horizon is long, WWA implementation is not practicable for MRP systems. Benton and Srivastava [6] also found *Part-Period Algorithm, PPA*, to be close to the WWA method as it was seen to perform well under conditions of lumpy demand. Blackburn et al [10, 12] concluded that Silver-Meal and the modified Silver-Meal method could, in some cases, outperform all other lot sizing methods, especially WWA.
Other studies [58, 96] have concluded that as the demand variability increases, the performance of the EOQ method remains poor. Blackburn et al [10] reported that *Lot for Lot, LFL*, and *Fixed Order Quantity, FOQ*, methods were questionable as both consistently created high cost and poor performance. On the other hand, Kanet [71] found that LFL appeared to provide better results than EOQ and EOQ2 when the item cost was high and planning horizon short.

7.3 Lot-sizing techniques

An extensive amount of work has been published on the subject of lot-size methods; the literature addressed in this section will primarily be confined to recent work relating to the MRP system. Seventeen lot-sizing methods are evaluated and these are classified into four groups according to the kind of lot-sizing criteria they are based on. Throughout this Chapter the following notation is used:

- IC is the standard spare part cost, in £s per part;
- n number of future periods whose demand requirements will be included in the order to be received in period i;
- d_i the amount demanded (projected net requirements) in period i, $i = 1, 2, ...n$;
- d_{i+n} the amount demanded (projected net requirement) in period i plus number of future periods;
- CC_i is the inventory carrying cost, expressed as a decimal fraction per part of the ending inventory in period i;
- OC_i is the ordering cost or cost of placing an order in period i;
- $F(i)$ is the minimum cost for periods 1 through i;
- d_j is requirements (demand) in a replenishment quantity, $j = 2, 3,.., T - 1$;
- T number of periods reached by the basic SM method, the time horizon:
- $\bar{d}$ is the average demand per period for the planning horizon, in units;
- S_j the profitable replenishment reached by the MSM1 at period j^* that gives the largest benefit (maximum occurrence and optimum time duration of the current replenishment);
- K is a constant whose value depends upon the length of the planning horizon:
- t_j the time (start of period) at which the last replenishment occurs;
- Q_j lot-size of the last replenishment to arrive at the beginning of week i;
- t_{j-1} time at which the jth (second-to-last) replenishment occurs;
- i the period in which an order is to be received;
- N number or orders placed in the interval $(0, H)$;
- H_n accumulative of carrying cost for length of the planning horizon;
- T_{n+1} length of the jth cycle;
- D_n accumulative of demand.

7.3.1 Group one - incremental holding costs

7.3.1.1 Incremental Approach, ICA

The Freeland and Colley [48] lot-sizing method works sequentially through increasing the lot-size by the requirements of successive periods until the *incremental inventory* *cost*, *HC* of carrying the next period's requirements as inventory exceeds the cost of ordering. This is based on applying the following equation:

$$HC = d_{i+n} \times n \times CC \qquad 7.1$$

7.3.1.2 Incremental Order Quantity Approach, IOQ

This method of lot-sizing, presented by Boe and Yilmaz [16], is very simple to compute and easy to understand. It includes the demand for period *i* if the incremental cost of carrying that period's demand is less than or equal to the order cost. Thus if this is the *ith* period under consideration, that period's demand is included in the current lot-size ordered for period one if:

$$OC > CC\,(i - 1)\,d_i \qquad 7.2$$

All requirements for periods in a given cycle are ordered at the beginning of that cycle.

7.3.2 Group two - minimising holding and ordering costs over the replenishment Interval

7.3.2.1 Wagner-Whitin Algorithm, WWA

This algorithm [127] was designed to find optimal ordering policies for parts with known demand and varying ordering and inventory carrying costs over an *n*-period planning horizon. The calculation procedure is based on looking ahead to the total planning horizon and working backwards to the present, developing lot-sizes for each period that achieve the "best" or optimum order schedule, once again by comparing order costs and inventory carrying costs. The outcome of the replenishment quantity decision for example at one point, has effects on possible replenishment action that can be taken at later decision times; i.e. whether or not we should replenish at the beginning of *March* say, depends very much on the size of the replenishment quantity at the beginning of *February*.

The method has been used as a standard for measuring the relative effectiveness of other lot-sizing techniques. The basic model, a generalised Wagner-Whitin model, has the following form:

$$F(i) = \min \left\{ \begin{array}{l} \min\limits_{1 \le j < i} [oc_j + \sum\limits_{h=j}^{i-1} \sum\limits_{k=h+1}^{i} cc_h \, d_k + F(j-1)] \\ oc_i + F(i-1) \end{array} \right\} \qquad 7.3$$

The computational effort, is significantly reduced because of the use of two key properties (derived by Wagner and Whitin) which the optimal solution must satisfy:

- *property one*: a replenishment only takes place when the inventory level is zero.
- *property two*: there is an upper limit as to how far before a period j we would include its requirements d_j in a replenishment quantity. Eventually, the carrying costs become so high that it is less expensive to have a replenishment arrive at the start of period j than to include its requirements in a replenishment from many periods earlier. However, if one is interested in computing the size of only the first replenishment quantity, it may not be necessary to go all the way out to the planning horizon. Using *property two* shows that, if for a period j the requirements are so large that:

$$d(j) > \frac{OC}{IC \times CC} \qquad 7.4$$

- then the optimal solution will be to have a replenishment at the beginning of period j, that is, the inventory must go to zero at this time. Therefore, the earliest period j, where this happens, can be used as a horizon for the calculation of the first replenishment.

The WWA has received extremely limited acceptance in practice. Managers often have difficulty understanding the method and frequently find that it can be too time consuming when applied [9, 116]. In this research study the WWA was found not to be too complex for practical use and was easily programmed into Visual Basic for Applications VBA (see Chapter six, [53]). A greater time horizon requires slightly more arithmetic, but the logic is no more complex as computation time is negligible with current computer technology [40, 45, 53, 108].

7.3.2.2 Silver-Meal, SM

The Silver-Meal method [114, 116] requires the determination of the average cost per period as a function of the number of periods the current order is to span, and stopping the computation when this function first increases. The procedure moves forward through the planning horizon and considers incorporating future material requirements in the current order. As each future period is examined, average total costs per period are computed as the sum of the ordering costs, plus the inventory charges for carrying future requirements, divided by the number of periods supplied by this order. Once average total costs per period increase, the order quantity is set equal to the sum of requirements up to the period where costs rise. The SM method has been found deficient in certain cases, namely when the demand pattern is sharply decreasing or when there are many periods of zero demand. Also the method requires a shorter forecast horizon to select the current replenishment quantity than the Wagner-Whitin algorithm [114]. Blackburn [12] demonstrates that when a firm has limited information about future demand, either the basic SM method or the modified SM method should be used instead of the WWA for reasons of cost effectiveness.

7.3.2.3 Modified Silver-Meal, MSM

The *modified Silver-Meal, MSM*, method [115] is designed to eliminate the high cost penalties of the original SM method in conditions of sharply decreasing demand or a high number of periods with no demand. (The first modification, denoted MSM1, deals with the conditions of sharply decreasing demand). The basic Silver-Meal method will often suggest a single replenishment to cover requirements of the entire horizon. Modification one examines whether total costs can be reduced by introducing another properly-timed replenishment. If T is the number of periods reached thus far by the SM method, a second replenishment will be implemented at the beginning of period j if

$$S_j = (j-1)\sum_{t=j}^{T} d_t > \frac{oc}{cc} \qquad j = 2,3,\ldots,T-1 \tag{7.5}$$

$$T_{EOQ} = \sqrt{\frac{2 \times oc}{cc \times \bar{d}}} \tag{7.6}$$

The following summarises the logic of modification one.

Step 1: Initialisation

Calculate T_{EOQ} from equation 7.6 and select K, where K = 1.25 if the length of planning horizon is smaller or equal to 30 periods, and K = 1.50 if the length of planning horizon is more than 30 periods.

Step 2:

Perform the basic Silver-Meal heuristic calculation for the current T value. If the heuristic finds a local minimum, use the T value as the time duration of the current replenishment. If not, is the current $T \geq k\,T_{EOQ}$ and is it larger than 2?

if Yes ... go to step 3.

if No ... loop back through step 2 with T increased by a unit (i.e., continue with the basic SM method).

Step 3: Modification procedure

Using equation 7.5 calculate S_j for j = 2,3, ..., max. If one or more S_j exceed OC/CC , let the maximum occur for j^*. Then the time duration of the current replenishment is j^* periods. If no S_j exceeds OC/CC , then return to step 2 with T increased by a unit.

In cases of frequent periods with no demand, the SM method tends to replenish more frequently than necessary. To eliminate this unnecessary replenishment, a modification is made to eliminate the very last replenishment by combining it with the preceding lot, a modification denoted *MSM2A*. More generally, it attempts to eliminate each lot in turn, working back in time - this modification is termed *MSM2B*.

The modification logic is summarised as follows:

Step 1: (Modification MSM2A)

The initial timing of replenishments is specified by the output of modification one. Evaluate the cost savings of eliminating the last replenishment as follows:

$$savings = OC - CC \times Q_j(t_j - t_{j-1}) \qquad 7.7$$

Are the savings > 0 ?

if Yes ... combine Q_j with the replenishment at time t_{j-1} and go to step 2.

if No ... go to step 2.

Step 2:

Is modification 2B to be used?

if No ... stop the procedure.

if Yes ... go to step 3 and consider the second-to-last replenishment.

Step 3: (Modification 2B)

Are we now considering the very first replenishment?

if Yes ... then stop because, by definition, the first replenishment cannot be eliminated.

if No ... evaluate the cost savings of eliminating the replenishment currently under consideration. To do this use the equation 7.7, where t_j is now the time of the current replenishment, Q_j is the size of the current replenishment and t_{j-1} is the time of the immediately preceding replenishment.

Are the savings > 0 ?

if Yes ... combine Q_j with the replenishment at time t_{j-1} and recycle through step 3 considering the replenishment at time t_{j-1} .

if No ... recycle through step 3 considering the replenishment at time t_{j-1} .

7.3.2.4 Least Unit Cost, LUC

This algorithm [38, 56] attempts to compute for various order sizes the costs per part chargeable to orders and storage. That order size is selected for which the total cost per part is minimised. The LUC is an iterative trial-and-error approach, determining the order quantity by asking whether it should equal only the first period's net requirements, or should be increased to cover the next period's requirement and the one after that and so on. A "part cost" is calculated for each step by dividing the total of ordering and carrying costs by the cumulative lot quantity at that step. The final decision is based on the lowest part cost. The process is then repeated, starting at period $i+n$ and continuing until the end of the planning horizon is reached. The advantage of this method is that it allows us to compare the ordering costs to the carrying costs on a period-by-period basis. It is applicable to spare parts with high cost.

7.3.2.5 Bookbinder and Tan Heuristic One, BTH1

Heuristic 1 (H1)'s stopping rule is based on later periods' demands [18] and is derived by examining the SM stopping rule, (see equation 7.8), and applied in difficult cases where there is sharply decreasing demand. So when the SM method determines a lot-size for period i to cover the demands of the next n periods, one has

$$[oc + cc\sum_{i=2}^{n+1}(i-1)d_i]/(n+1) > [oc + cc\sum_{i=2}^{n}(i-1)\,d_i]/n \qquad 7.8$$

The "stopping rule" of the SM method can thus be written

$$oc < n^2 \times cc \times d_{n+1} - cc\sum_{i=2}^{n}(i-1)\, d_i \qquad 7.9$$

For the difficult demand pattern $d_i = [oc/cc]/(i\text{-}1)$, $i = 2, 3, 4,....$, the relation (7.9) is

$$oc < n^2 \times cc\,[(oc/cc)/n] - cc\sum_{i=2}^{n}(i-1)[(oc/cc)/(i-1)] = 0 \qquad 7.10$$

The stopping rule for the SM method will never be satisfied by such a demand pattern. Thus the heuristic will suggest using a single order to cover the requirements for the entire time-horizon and discards the term $cc\sum_{i=2}^{n}(i-1)d_i$ from the equation 7.9, thus the setting stopping rule for H1 is:

$$oc < n^2 \times cc \times d_{n+1} \qquad 7.11$$

A summary of the H1 is shown in Table 7.1a.

$Step1: Let\, n = 1, T_1 = 1.$
$Step2: 2a. If\, d_{n+1} = 0, goto Step2b. Otherwise, goto Step2c.$
$2b. Let\, T_{n+1} = T_n\, and\, goto Step3.$
$2c. Let\, T_{n+1} = T_n + 1\, and\, goto Step3.$
$Step3: 3a. If\, (T_{n+1} - T_n) oc \geq cc \times n T_n d_{n+1}, goto Step3b. Otherwise, goto Step4.$
$3b. Let\, n = n + 1\, and\, goto Step2.$
$Step4: Let\, the\, lot\, size\, be \sum_{i=1}^{n} d_i\, and\, Stop.$

Table 7.1a Heuristic 1 of Bookbinder and Tan.

7.3.2.6 Bookbinder and Tan Heuristic Two, BTH2

Heuristic 2 (H2) is based on a combined SM and LUC method [18]. Its form (see Table 7.1b) is partially suggested by the LUC, which has done well in certain cases troublesome to SM. The LUC criterion function is total relevant cost per unit quantity:

$$TRCUQ(n) = [oc + cc\sum_{i=2}^{n}(i-1)d_i] / \sum_{i=1}^{n} d_i \qquad 7.12$$

Because there are examples of other simulated tests in which the LUC method did not do well [38, 130], Heuristic 2 attempts to combine the merits of both SM and LUC while eliminating their respective drawbacks. The criterion function for H2 is thus divided into two parts, one part retaining some features of the SM criterion function and the other some features of that of the LUC. The portion retained from the SM method is $f_1(n) = oc/n$. The other part, $f_2(n)$, retains the term $\sum_{i=1}^{n} d_i$ for the denominator, as in LUC. To agree dimensionally with $f_1(n)$, $f_2(n)$ is taken to be

$$f_2(n) = \{cc\sum_{i=2}^{n}[(i-1)/i]d_i\sum_{j=1}^{i} d_j\} / \sum_{i=1}^{n} d_i \qquad 7.13$$

The criterion function for Heuristic 2 is thus

$$F_2(n) = f_1(n) + f_2(n) \qquad 7.14$$

$$F_2(n) = oc/n + \{cc\sum_{i=2}^{n}[(i-1)/i]d_i\sum_{j=1}^{i} d_j\} / \sum_{i=1}^{n} d_i \qquad 7.15$$

Its stopping rule is derived by requiring $F_2(n+1) > F_2(n)$, which leads to

$$oc < n^2 d_{n+1} \times cc - [n(n+1)]cc \times d_{n+1}\{\sum_{i=2}^{n}[(i-1)/i]d_i\sum_{j=1}^{i} d_j\} / (\sum_{i=1}^{n+1} d_i)(\sum_{i=1}^{n} d_i) \qquad 7.16$$

$Step1: Let\, n = 1,\, T_1 = 1,\, D_1 = d_1,\, H_1 = 0,\, F_1 = oc.$

$Step2: Let\, n = n + 1.$

$Step3: 3a.\ If\ d_n = 0,\ go\,to\,Step3b.\ Otherwise,\ go\,to\,Step\,3c$

$3b.\ Let\, T_n = T_{n-1}\ and\ go\,to\,Step\,4.$

$3c.\ Let\, T_n = T_{n-1} + 1\ and\ go\,to\,Step\,4.$

$Step4: 4a.\ Let\, D_n = D_{n-1} + d_n.$

$4b.\ Let\, H_n = H_{n-1} + cc[(n-1)/T_n]d_n \times D_n.$

$4c.\ Let\, F_n = oc/T_n + H_n/D_n.$

$Step5: If\, F_n > F_{n-1},\ go\,to\,Step6.\ Otherwise,\ go\,to\,Step2.$

$Step6: Let\ the\ lot\ size\ be\ D_{n-1}\ and\ Stop.$

Table 7.1b Heuristic 2 of Bookbinder and Tan.

7.3.3 Group three - equal ordering and holding costs

7.3.3.1 Part-Period Algorithm, PPA

The part-period algorithm has received considerable attention in contemporary production/operations management literature because it is rational, cost effective and has the important advantages of simplicity and ease of implementation [38, 78]. Each order that is placed and received creates what is known as *part-periods* of inventory. Part-periods are a measure of inventory accumulation that is computed by multiplying the number of parts in inventory by the number of periods for which the parts have to be carried. The term part-period refers to one part carried for one period, usually a week. Computation of the part-periods is as follows:

1. The additional number of part-periods created by including the demand requirements of the *nth* future period with a present order will be referred to as the *incremental part-periods, IPP,* and is calculated as follows:

$$IPP = d_{i-n}(n + 0.5) \qquad 7.17$$

2. The total number of part-periods created by combining future requirements into a single order is identified as *cumulative part-periods, CPP*, this quantity is simply the sum of the *IPP* values:

$$CPP = \sum IPP \qquad 7.18$$

3. Grouping future demand requirements into the same order is satisfactory as long as the *CPP* created is less than a predetermined "critical" value. The critical value is called the *economic part-period, EPP*, and is defined as that quantity of a part which, if carried in inventory for one period, would result in a carrying cost equal to the cost of ordering. It is computed as follows:

$$EPP = \frac{oc}{cc \times ic} \qquad 7.19$$

4. The order is successively increased as long as the following condition is satisfied:

$$CPP \leq EPP \qquad 7.20$$

When a future demand requirement increases the *CPP* beyond the critical value that period's requirement is excluded and the order is closed. The offending quantity and period become the starting point for determining the next order size. In effect, the procedure is to increase each order size until the cumulative carrying cost that is created exceeds the cost of placing a separate order.

7.3.3.2 Incremental Part-Period Algorithm, IPPA

This is an incremental version and a modification of the original part-period balancing method. IPPA is easy to use for both establishing the order schedule and determining the sensitivity to order quantity [3, 126]. It examines the incremental costs/savings generated by combining future demand requirements with current requirements in the same order, as long as the additional or *incremental* carrying cost created by its inclusion is less than the cost of placing a separate order for that period's requirement. This can be accomplished easily by continually increasing the order size as long as the following condition is satisfied:

$$IPP \leq EPP \qquad 7.21$$

The IPPA assumes that, for a given planned order, trial lot-sizes are generated by iteratively adding the projected requirements of future periods to the order. Each trial lot-size is evaluated to determine if it is acceptable. If a trial lot-size is acceptable, the iterations continue and the requirement of the next future period is tentatively added to the lot-size (order quantity). If a trial lot-size is unacceptable, the last requirement added becomes the starting point for creating a new planned order.

7.3.3.3 Part Period Balancing, PPB

The part-period balancing algorithm DeMatteis [38], is a lot-sizing method suitable for discrete and time-varying demand data; it is sometimes referred to as the *Least Total Cost, LTC*, method. This PPB technique selects that order quantity at which the part-period cost nearly equals the *EPP*. An adjustment routine included in PPB, called *Look-Ahead/Look-Back, LALB*, is intended to prevent stock covering peak requirements from being carried for long periods of time and to keep orders from being brought in too early in periods with very low requirements. The adjustments are made only when the conditions exist that LALB corrects. The look-ahead test is always made first. If covering an additional period is uneconomical, the look-back test is made. This checks the desirability of cutting the lot-size, adding the requirements in the last period covered by the order to the next lot. The primary advantage of part period balancing is that the LALB feature tends to group the orders together at points of large lumps of demand. This method is applicable to high-priced spare parts that enjoy sporadic demand. The disadvantage of the method is its complexity, making it hard to understand while paradoxically easy to programme. On the other hand, when MS changes take place many components may be affected, generating a nervousness problem. LALB will multiply these problems, affecting both quantities and timing of orders [98]. The LALB feature consists of a series of tests. The tests are carried out by doing limited searches around each replenishment period determined by PPB, checking whether local cost savings can be achieved by moving the replenishment period forward or backwards.

7.3.3.4 Periodic Order Quantity, POQ

The POQ lot-size equals the total of the future net requirements for *n* weeks or time periods, beginning with the week of the receipt, plus any desired safety stock, minus the projected on-hand balance from the previous week (periods with zero requirement are ignored). This amount restores the safety stock and exactly covers *n* weeks' worth of net requirements, where the projected on-hand inventory should equal the desired safety stock in the *nth* week. One way to select an *n* value T_{EOQ} is to divide the EOQ by the average weekly demand as shown in equation 7.22. The value of T_{EOQ} is rounded off to the nearest integer value greater than zero. This procedure also defaults to the LFL method when the POQ is less than or equal to one.

$$T_{EOQ} = n = \frac{EOQ}{Average \;\; Weekly \;\; Usage} \qquad 7.22$$

The technique has several good features. For example, it reduces the amount of on-hand inventory by adjusting lot-sizes as requirements increase or decrease and should leave no residues or remnants of unused lot-size inventory [98]. Note that a periodic order quantity of *n* periods does not mean that an order is placed every *n* periods. It means *n* periods are totalled, beginning with the first period having a requirement. This avoids receiving a lot-size in a period, which has no demand for the part. The total cost is, computed by the total number of orders and the average inventory level. If an initial inventory exists, the carrying costs for this inventory are added to the total cost.

7.3.3.5 Economic Order Quantity, EOQ

The EOQ which balances the inventory carrying and order costs is based on an assumption of continuous, steady-rate demand, and is still an aid to good performance when the actual demand approximates this assumption. The more discontinuous and non-uniform the demand, the less effective EOQs will be. To apply the EOQ formula, we need three inputs: the average demand rate, $\bar{d}$, the carrying cost rate, CC and the ordering cost, OC. The formula is stated as:

$$EOQ = \sqrt{\frac{2 \times \bar{d} \times oc}{cc \times ic}} \qquad 7.23$$

The basic idea of this method is to find the order quantity which minimises the total cost per unit per period and best balances the costs related to the number of orders placed against the costs related to the size of the orders placed. When these costs have been balanced properly, the total cost is minimised. However, in an MRP environment it may not give the best results, because the typical MRP situation does not meet some of the basic assumptions of the model. When this method is applied, some important points should be taken into account, such as the avoidance of multiple orders in one period or excessive carrying costs from ordering in earlier periods. If the quantity on-hand together with the order quantity is not sufficient to meet the period's demand, the order to be placed will be increased to meet demand [7]. The VBA programme has been set to check if no parts are on-hand and the demand is zero for that period, then no order is placed in that period, but moved ahead to the period in which a positive demand first occurs. A check is made to see if the EOQ equals or exceeds current demand. If so, the order quantity is the EOQ. If the EOQ is less than the current demand, then the order quantity is increased to meet the current demand to prevent shortages. As the EOQ makes no attempt to finish the end of the planning horizon with on-hand inventory at zero, the total cost is computed by the total number of orders and the average inventory level.

7.3.3.6 Modified Economic Order Quantity, EOQ2

This modification is based on the classical *economic order quantity* and also known as EOQ-MRP [92, 113], which allows the EOQ to examine the demand pattern before the placement of the order. As it covers the demand for an integral number of periods, a demand is accumulated until a total closest to the EOQ is found, the order quantity is then determined by first using equation 7.23 to compute EOQ, and rounded to an integer value. Demand is accumulated until cumulative demand exceeds the EOQ.
Let period n be the period in which this first occurs. Let the order point, the time period in which we are trying to determine the order quantity, be denoted by q while d_i denotes the demand in period i. Then the order quantity is Q_1 or Q_2, depending on whichever is closer to EOQ. If EOQ is exactly halfway between Q_1 and Q_2, the order quantity is chosen to be Q_2, as shown in equation 7.24 and 7.25.

$$Q_1 = \sum_{i=q}^{n} d_i, \quad Q_1 > EOQ \tag{7.24}$$

$$Q_2 = \sum_{i=q}^{n+1} d_i, \quad Q_2 < EOQ \tag{7.25}$$

7.3.4 Group four - set lot-size to current period demand

7.3.4.1 Lot for Lot, LFL

LFL is an order quantity technique which generates planned order receipts in quantities always equal to the net requirements in each period, where no attempt is made to group net requirements together to trade off the order and carrying costs [25, 83, 98]. The LFL method, sometimes called *discrete ordering* or *one-for-one*, is the simplest and most straightforward of all of the lot-sizing methods. The LFL method provides period-by-period coverage of net requirements, which minimises inventory carrying cost, but maximises the number of orders placed. As there are no remnants left over at the end of the period, the balance will fall to zero, in which case the total cost is determined by the number of orders over the planning horizon. This method is most applicable to expensive parts with small or negligible ordering costs.

7.3.4.2 Fixed Order Quantity, FOQ

FOQ is an order quantity technique applicable to a situation where the same quantity is to be ordered each time [25, 83, 98]. The net requirements are checked against the assigned fixed lot-size. If the net requirements are less than or equal to the lot-size, then the amount specified in the lot-size is ordered, otherwise the order size is equal to the net requirements. A fixed lot-size is always constant for each part, which is usually derived from some restriction in the method of supply such as quantity discount level or *minimum order quantity, MOQ*. The FOQ method generates a higher level of average inventory since it creates inventory remnants, as it does not exactly match the requirements.

7.4 Experimental factors and assumptions

In this Chapter we examine the effect of seventeen lot-sizing methods on the aircraft maintenance inventory system in an experiment incorporating a variety of environmental factors and under widespread demand variation. The experiment was run on nine different components of a Fokker 27 and Fokker 100 aircraft fleet, providing as they did, a large amount of data on historical demand. Data included actual estimated requirements, costs and lead-times being collected for each of 66 actual purchased parts. All of the lot-sizing methods employed in this study were designed to follow conventional MRP decision-making procedures [53]. These resulted in 1,704 observations per lot-size giving a total of 28,968 runs to measure the method's cost performance.

The following five environmental factors were included in the experiment: the *ordering cost, OC, planning horizon length, PH, annual usage value, AUV, coefficient of variation in demand, CVD*, and *minimum order quantity, MOQ*. Since actual values for *AUV, CVD* and *MOQ* were used, they are taken as covariate factors, whereas *OC* and *PH* are selected as categorical factors. The factor levels may be different from those of other research studies since, as this study is concerned with aviation maintenance, most variables were covariates rather than categorical variables. Table 7.2 summarises the five factors and a description follows.

Factor	Description	Levels	Values	Units
OC	Ordering cost	4	40, 80, 120, 180	Sterling £
PH	Planning horizon	2	12, 52	Months, weeks
AUV	Annual usage value	-	2.7 to 67728.0	Sterling £
CVD	Coefficient of variation	-	0.65 to 2.05	-
MOQ	Minimum order quantity	-	1 to 100	Each

Table 7.2 Environmental factors, (-) indicates covariates factor

7.4.1 Ordering cost, OC

Cost structure ratio is not a relevant factor in *analysis of variance, ANOVA* if the performance measure is total cost. The main effect will clearly be significant since ordering cost per item cost both creates and costs out each result [131]. Those ordering costs are activated per-part per-period, which as a result, affects the performance of lot-size methods. In this study, the ordering costs are: 40, 80, 120 and 180 per order.

7.4.2 Planning horizon length, PH

This is the number of periods for which the forecast is known. The most popular planning horizon used by aviation companies [52] is one year or less, while a few use a 3-year horizon. In this study the planning horizon *PH* factor determines the independent variable carrying cost *CC*. The *CC* was set to 37% per year which is equal to 0.01 per-part per-period carrying cost, so planning horizons of 12 and 52 periods have been selected in conjunction with a carrying cost of 0.03 and 0.01 respectively for each lot-sizing method. The dynamic-demand was collected in static horizons of 52 weeks.

7.4.3 Coefficient of variation in demand, CVD

The *CVD* captures the degree of lumpiness (intermittence) in the dependent demand for a purchased part in an MRP environment. It is equal to the standard deviation of period requirements divided by the average period requirements. A *CVD* of 0.02 represents a relatively smooth demand rate, while a *CVD* of 1.20 depicts a rather lumpy demand environment with periods of zero demand. As the coefficient of variation increases, the lumpiness and the number of periods with zero requirement increases (i.e. orders decrease). This increase in requirement lumpiness has a substantial effect on the performance of the lot-sizing procedures [15].

7.4.4 Annual usage value, AUV

Annual usage value defines the financial importance of the part and is the first dimension, which makes use of the ABC classification criteria such as fast, slow and non-moving categories (see Chapter two). *AUV* is equal to annual usage times the item cost. This gives the total annual use of items in terms of value. *Item cost*, *IC* is also varied in this study for each component, as each of the nine components contain several different spare parts $£0.08 \leq IC \leq £1047.50$.

7.4.5 Minimum order quantity, MOQ

This factor has been hitherto ignored or insufficiently dealt with in the literature; *MOQ* does not apply for some components and is only used for the FOQ method. Its values range from one to one hundred in this research (see Table 7.2).

In addition to several varying factors described previously, there are important factors that are held as constant in the base experiments. The following assumptions are made throughout this research:

1. The replenishment lead-time is known and varies for each component. Once the ordering decisions are made, they can be offset to allow for the lead-time, so that shortages will not occur.
2. There are no quantity discounts.

3. The inventory carrying cost per part per time period is constant over the planning horizon based on ending inventory levels and is calculated for stock carried over from one period to another. Inventory levels at the beginning of period one are zero for all spare-parts.
4. An ordering cost is incurred in the period in which the order is placed.
5. Total inventory costs during the planning horizon are the sum of the total carrying costs plus the total ordering costs.

7.5 Experimental results and analysis

The results of this section are divided into two parts. The first part of the analysis discusses the comparison of lot-size methods in terms of averaged total cost (Tables 7.3 to 7.5), and subsequently these visual observations on the experimental results are examined and clarified through statistical analysis. Analysis of variance, ANOVA, is used to explain the variation attributable to the various experimental factors and their interactions. Tables 7.6 and 7.7 present a summary of the *general linear model*, *GLM*, results and report the *p-values* for each of the main factors and their two-way interactions. Due to space limitations, the GLM output results and the performance rankings of the lot-sizing methods under each of these are not presented here. However they are available on the attached CD disk at the back of this thesis (see Appendix E).

7.5.1 Analytical comparisons of lot-sizing methods

The mean total cost averaged over several runs is given in Table 7.3, which compares the performance in terms of the total cost for each method. A summary of the cost differences and percentage increase in total costs compared to the values determined by the Wagner-Whitin Algorithm, WWA is also provided in Table 7.3 since the WWA is often taken as a benchmark against which to measure the cost performance of other methods.

Rank	Lot-size method	Average total cost	% increase
1	WWA	762.86	0.00
2	MSM2	774.33	1.50
3	BTH2	822.96	7.88
4	PPA	833.00	9.19
5	BTH1	837.99	9.85
6	SM	846.46	10.96
7	MSM1	850.59	11.50
8	PPB	854.43	12.00
9	LUC	871.75	14.27
10	EOQ2	902.33	18.28
11	IOQ	931.17	22.06
12	IPPA	931.23	22.07
13	POQ	960.01	25.84
14	EOQ	968.92	27.01
15	ICA	996.87	30.68
16	FOQ	1897.61	148.75
17	LFL	2248.16	194.70

Table 7.3 Summary of methods' average total cost.

The survey of MRP users in the aviation sector [52], shows that the most commonly used lot-size methods are; EOQ, LFL, FOQ, LUC, PPB and PPA, 52%, 48%, 17%, 13%, 13% and 9% respectively, with little or no appreciation of other lot-size methods. In other sectors, Haddock and Hubicki [59] made similar findings. Their survey also reported that the most popular lot-sizing methods employed by MRP users (ranking from most popular to least popular) were LFL, FOQ, EOQ, POQ, PPA and finally LUC and SM. In this study we intend to examine the performance of those methods already used by the aviation industry and what would be achieved by using other methods which are almost ignored. Maintenance companies commonly believe that these methods are not applicable to them as they deal in small quantities, preferring to pursue minimum inventory and also small lot-sizes.

Tables 7.4a to 7.4c, describe the relationship between levels of lot-size factors and total cost. Visual examination of these results shows that in line with general expectation, as order cost increases, the total inventory cost also increases; this fact was corroborated by all methods. It was observed that as item costs increase, total costs increase. Another point noticed was that the higher the item cost, the greater the differences in the total cost performance of the lot-size methods. Further, a planning horizon of 52 weeks usually incurs higher costs than a planning horizon length of 12 months.

Due to the large number of methods tested in this study, we mainly concentrate our results analysis with those methods, which are commonly applied by airline operators, starting with the EOQ method, which seems to be the poorest (Table 7.3). The high variability of demand within the data used in this research would account for this. It is concluded that as the demand variability increases, the performance of the EOQ method remains poor. One big reason for this is that EOQ incurs high levels of ordering quantity thus building up inventory cost, but EOQ is readily adaptable to MRP systems and widely used as indicated in the survey total, where 52% of companies used it.

The LFL technique is probably the simplest of the variable ordering techniques as it minimises inventory's carrying costs and can be effective for highly discontinuous demand while maximising the number of orders placed. The survey indicates that almost 48% of the airline companies were using LFL methods. This study shows that LFL and FOQ methods were the poorest total cost methods (Table 7.3). However LFL did perform slightly better than WWA in certain limited cases (see Table 7.4a and 7.4b). Earlier in the survey [52] we found that most companies used LFL for type "A" & "B" class items (items with high annual usage or forecasted usage over specified cost amounts), whereas EOQ was used for "C" class items.

FOQ generates a higher level of average inventory as it creates inventory remnants, which occur because the FOQ does not exactly match requirements. We expected a small percentage of airline companies to use it; in fact 17% did. In this study, the FOQ method appears to provide better results than WWA when the item cost is low and for both lower and high demand as a short planning horizon length of 12 months was selected, and as *MOQ* rose, FOQ again outperformed the WWA method. This was observed for the long planning horizon of 52 weeks, for lower item cost as higher *CVD* occurred, with no limit to the ordering cost (Table 7.4c).

Table 7.4a. Lot-sizing total cost performance.

Lot-size Methods	Low *CVD* *MOQ* = 1 Low *IC*								Low *CVD* *MOQ* = 1 High *IC*							
	OC = 40		*OC* = 80		*OC* = 120		*OC* = 180		*OC* = 40		*OC* = 80		*OC* = 120		*OC* = 180	
	PH = 12	*PH* = 52	*PH* = 12	*PH* = 52	*PH* = 12	*PH* = 52	*PH* = 12	*PH* = 52	*PH* = 12	*PH* = 52	*PH* = 12	*PH* = 52	*PH* = 12	*PH* = 52	*PH* = 12	*PH* = 52
BTH1	14.57	17.52	24.53	29.50	34.61	41.62	48.19	57.95	1312.61	1578.44	1812.45	2179.51	2178.11	2619.23	2595.50	3121.14
BTH2	11.45	14.85	19.66	25.51	28.34	36.76	42.24	54.79	1479.29	1686.08	1918.14	2186.27	2217.55	2527.53	2602.99	2966.85
EOQ	14.37	15.65	25.83	28.12	38.42	41.83	59.07	64.32	1723.06	1876.19	2232.09	2430.46	2578.16	2807.28	2989.83	3255.53
EOQ2	11.07	13.08	19.11	22.58	27.17	32.11	40.92	48.36	1559.45	1842.73	2030.59	2399.46	2322.41	2744.29	2663.50	3147.34
FOQ	341.07	525.78	638.08	983.63	942.33	1452.64	1399.16	2156.86	**(806.60)**	2572.53	1509.00	4812.71	2228.51	7107.50	3308.86	10553.11
ICA	11.52	12.90	**(17.91)**	**(20.05)**	**(24.40)**	**(27.33)**	**(35.27)**	**(39.50)**	1658.83	2300.16	2158.77	2993.38	2513.16	3484.79	2897.66	4017.95
IOQ	12.35	13.22	19.11	20.47	26.15	28.00	37.72	40.39	1491.27	2192.84	1961.92	2884.90	2302.60	3385.86	2649.17	3895.47
IPPA	12.34	13.19	19.15	20.48	26.12	27.93	37.68	40.29	1491.09	2198.73	1950.70	2876.47	2302.31	3394.94	2648.84	3905.93
LFL	360.80	1564.50	738.43	3442.83	1154.98	5420.25	1773.28	8432.49	821.66	2347.60	**(1383.56)**	4250.39	**(1956.76)**	6050.71	2810.13	8804.98
LUC	11.61	13.75	19.33	22.89	27.61	32.70	41.07	48.64	1474.97	1746.88	1972.41	2336.03	2285.30	2706.60	2636.95	3123.09
POQ	12.56	**(12.24)**	21.18	20.64	30.74	29.96	46.79	45.60	1379.56	1889.77	1762.95	2414.95	2010.73	2754.37	**(2287.59)**	3133.62
PPA	11.99	14.01	20.12	23.52	28.91	33.80	42.55	49.74	1426.81	1667.88	1924.87	2250.09	2240.02	2618.49	2606.46	3046.84
PPB	**(10.75)**	12.76	19.19	22.77	28.06	33.30	41.49	49.24	1527.97	1813.20	1922.16	2280.98	2204.67	2616.22	2581.71	3063.64
SM	12.61	17.26	21.93	30.02	30.50	41.75	42.92	58.74	1299.48	**(1529.24)**	1783.22	2098.51	2119.59	2494.35	2548.78	2999.42
MSM1	12.56	17.23	21.80	29.91	30.36	41.65	42.59	58.44	1306.48	1535.91	1799.97	2116.06	2132.53	2507.02	2572.26	3023.97
MSM2	11.06	12.85	19.23	22.34	28.10	32.65	42.61	49.50	1365.82	1586.64	1794.32	2084.41	2084.57	2421.58	2411.72	2801.63
WWA	11.05	12.66	19.33	22.15	28.28	32.41	42.95	49.23	1363.61	1562.99	1788.41	**(2049.91)**	2074.11	**(2377.39)**	2406.96	**(2758.90)**

( ) indicates lowest method TC performance (shown in bold).

Table 7.4b Lot-sizing total cost performance - continued.

Lot-size Methods	High *CVD* *MOQ* = 1 Low *IC*								High *CVD* *MOQ* = 1 High *IC*							
	OC = 40		*OC* = 80		*OC* = 120		*OC* = 180		*OC* = 40		*OC* = 80		*OC* = 120		*OC* = 180	
	PH = 12	*PH* = 52	*PH* = 12	*PH* = 52	*PH* = 12	*PH* = 52	*PH* = 12	*PH* = 52	*PH* = 12	*PH* = 52	*PH* = 12	*PH* = 52	*PH* = 12	*PH* = 52	*PH* = 12	*PH* = 52
BTH1	21.30	25.61	35.87	43.13	50.60	60.85	70.45	84.72	660.77	794.59	912.39	1097.17	1096.46	1318.52	1306.57	1571.18
BTH2	19.93	23.30	34.22	40.01	49.32	57.67	73.51	85.95	722.12	741.81	936.35	961.88	1082.51	1112.03	1270.66	1305.31
EOQ	25.39	27.65	45.63	49.69	67.88	73.91	104.36	113.63	893.65	973.07	1157.66	1260.54	1337.14	1455.97	1550.65	1688.45
EOQ2	18.38	19.67	31.72	33.94	45.11	48.26	67.94	72.69	844.47	903.50	1099.60	1176.47	1257.63	1345.54	1442.33	1543.16
FOQ	227.95	207.72	426.45	388.61	629.79	573.91	935.10	852.13	**(539.08)**	1016.35	1008.51	1901.40	1489.39	2808.02	2211.42	4169.31
ICA	19.58	18.64	33.15	31.55	48.36	46.03	73.31	69.78	678.97	800.14	962.09	1133.79	1199.11	1413.11	1449.99	1708.77
IOQ	20.93	19.33	35.48	32.76	51.62	47.67	78.93	72.90	581.00	736.88	**(836.92)**	1061.46	1044.76	1325.06	1274.21	1616.08
IPPA	21.09	19.28	36.49	33.36	52.02	47.56	79.55	72.73	581.01	732.56	846.86	1067.74	1044.78	1317.30	1274.24	1606.59
LFL	322.94	494.42	660.94	1088.02	1033.77	1712.93	1587.19	2664.86	624.86	**(630.35)**	1052.18	1141.26	1488.08	1624.66	2137.06	2364.21
LUC	19.90	21.12	33.12	35.16	47.32	50.23	70.38	74.70	773.17	820.66	1033.93	1097.43	1197.94	1271.52	1382.27	1467.17
POQ	**(16.20)**	**(15.79)**	**(27.31)**	**(26.62)**	**(39.63)**	**(38.62)**	**(60.34)**	**(58.80)**	984.48	1348.58	1258.08	1723.36	1434.90	1965.58	1632.47	2236.21
PPA	20.22	21.53	33.95	36.14	48.78	51.93	71.79	76.43	698.74	743.89	942.65	1003.57	1096.99	1167.88	1276.44	1358.93
PPB	18.44	19.64	32.91	35.04	48.13	51.24	71.16	75.76	787.24	838.11	990.33	1054.33	1135.89	1209.29	1330.14	1416.10
SM	21.52	33.81	37.43	58.81	52.05	81.78	73.24	115.08	676.33	913.78	928.10	1253.93	1103.16	1490.46	1326.54	1792.26
MSM1	21.56	33.85	37.42	58.76	52.10	81.81	73.10	114.79	677.20	911.18	932.99	1255.35	1105.37	1487.29	1333.30	1793.97
MSM2	20.01	21.39	34.78	37.18	50.83	54.34	77.06	82.39	657.92	703.44	864.33	924.13	1004.15	1073.62	1161.74	1242.12
WWA	20.24	21.47	35.42	37.57	51.82	54.97	78.71	83.49	643.89	682.97	844.49	**(895.73)**	**(979.39)**	**(1038.82)**	**(1136.56)**	**(1205.53)**

( ) indicates lowest method TC performance (shown in bold).

Lot-size Methods	High *CVD* *PH* = 52		Low *IC* *MOQ* = 100	
	OC = 40	*OC* = 80	*OC* = 120	*OC* = 180
BTH1	25.61	43.13	60.85	84.72
BTH2	23.30	40.01	57.67	85.95
EOQ	27.65	49.69	73.91	113.63
EOQ2	19.67	33.94	48.26	72.69
FOQ	**(10.88)**	**(20.35)**	**(30.05)**	**(44.63)**
ICA	18.64	31.55	46.03	69.78
IOQ	19.33	32.76	47.67	72.90
IPPA	19.28	33.36	47.56	72.73
LFL	494.42	1088.02	1712.93	2664.86
LUC	21.12	35.16	50.23	74.70
POQ	15.79	26.62	38.62	58.80
PPA	21.53	36.14	51.93	76.43
PPB	19.64	35.04	51.24	75.76
SM	33.81	58.81	81.78	115.08
MSM1	33.85	58.76	81.81	114.79
MSM2	21.39	37.18	54.34	82.39
WWA	21.47	37.57	54.97	83.49

( ) indicates lowest method TC performance (shown in bold).
Table 7.4c Lot-sizing total cost performance - continued.

In this research, LUC was found to perform better than WWA under conditions of low item cost and high coefficient variation when order costs start to increase (see Table 7.4b). The survey found that 13% of companies used this method. The PPB method was found to outperform the method WWA under a situation of lower item cost, *CVD* and *OC* with a *PH* of 12 months (Table 7.4a). In Kanet's experimental study [71] it was found that the PPB method was better limited to parts with high order costs and relatively lumpy demand.

Finally, for the PPA method the survey showed that 9% of aviation companies used these methods, but our results showed PPA to be amongst the top lot sizing methods in providing the lowest total cost of all the seventeen methods. Further observation showed that PPA outperformed the WWA method under conditions of lumpy demand

and low item cost, for both planning horizon of 12 and 52 weeks when order cost was high.

The performances of the rest of the methods are summarised in Table 7.5, which briefly describes the factor level in which the best method could be exploited.

Methods	Low *OC*	High *OC*	*PH* 12	*PH* 52	Low *IC*	High *IC*	Low *CVD*	High *CVD*
WWA	poor	good	poor[1]	good	poor	good	poor[1]	good
MSM2	good[2]	good[2]	good	poor	good	poor	poor	good
MSM1	good	poor	poor	good	poor	good	good	poor
SM	good	poor	poor	good	poor	good	good	poor
BTH2	poor	good	poor	good	poor	good	> 0.8	good
BTH1	good	poor	good	good	poor	good	1:1.3	poor
EOQ2	good	good	good	poor	good	poor	> 0.7	good
IOQ	good	poor	good	poor	poor	good	poor	good
IPPA	poor	good	good	poor	good	poor	< 0.7	poor
POQ	good	good	good	good	good	poor[1]	poor[1]	good
ICA	poor	good	good	good	good	poor	good	poor

Superscript [1] indicates that the method performs better under certain conditions.

Superscript [2] indicates order costs between 80 and 120.

Table 7.5 A summary of lot-size method performance within parameters levels.

7.5.2 General linear model approach

Table 7.6 shows the general linear model, GLM results for the total cost as the dependent variable and the independent variables *OC*, *PH*, *AUV*, *CVD* and *MOQ* where appropriate, to investigate the significance of lot size factors and their interactions. For all methods the 3rd and 4th order interactions were found to be insignificant and as such were eliminated from this analysis. Table 7.6 presents a summary of the GLM results and reports the *p-values* for each of the main factors and their two-way interactions. In this study we have devised a new approach to lot-size evaluation. This new model compares and evaluates the lot-size methods based on their factor levels. A description of the model and of its function will be discussed later in this Chapter (section 7.6). Firstly, however, the experimental results need further clarification through a multi-factor analysis of variance. A natural logarithm transformation of the dependent variable was used to overcome the problem of non-constancy of error variance in linear models, see [50].

Tables 7.7a to 7.7c give the significant coefficients of the fitted GLMs. In Table 7.6, all factors except for *PH* had significant main effects for all methods in terms of the performance criterion. *PH* was significant for most methods. For IOQ and IPPA (p = 0.079) and POQ (p = 0.080) however, it was not significant but the *p-values* were small. This shows that all the experimental factors, *OC*, *PH*, *AUV*, *CVD* and *MOQ* have a significant effect on the lot-size methods' total cost. That is, different values of the independent variables give different performance values for the dependent variable.
A significant interaction between factors A and B indicates that the effect of A on the mean value of the dependent variable differs for the various levels of B. For example, the $PH \times CVD$ interaction indicates that the coefficient of *CVD* depends on the level of *PH*. So a significant interaction implies that an appropriate combination of independent variables could be selected in such a way that the performance criterion (the cost) is minimised.

Table 7.6 also indicates that the interaction $OC \times PH$ for all methods was not significant except for the LFL method where it was found to be significant at the 0.01 level. For all methods except FOQ, the interaction $OC \times AUV$ was significant at the 0.01 level while for FOQ it was only marginally significant (p = 0.073). $OC \times CVD$ was found to be only significant with the three methods ICA, IOQ and IPPA, while for all other methods it was insignificant. The $PH \times AUV$ interaction was not significant for the following methods: EOQ, EOQ2, LUC, PPA, MSM2, BTH1, WWA. The PPB method however was marginally significant (p = 0.065) while for all other methods it was significant at 0.01 level. For methods other than EOQ and POQ, the interaction $PH \times CVD$ was significant at the 1% or 5% levels. Finally the interaction of $AUV \times CVD$ was highly significant for all methods except for FOQ.
The FOQ method has an additional independent variable, *MOQ*. The main effect of *MOQ* was significant, and there were other significant interactions: $PH \times MOQ$, $AUV \times MOQ$ and $CVD \times MOQ$. That is, the coefficient of *MOQ* depends on the values of *PH*, *AUV* and *CVD*

Table 7.6 A summary of unbalanced ANOVA (GLM) results for lot-size parameters (p-values).

Factors	BTH1	BTH2	EOQ	EOQ2	FOQ	ICA	IOQ	IPPA	LFL	LUC	POQ	PPA	PPB	SM	MSM1	MSM2	WWA
OC	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]
PH	0.000[1]	0.000[1]	0.002[1]	0.003[1]	0.000[1]	0.009[1]	0.079	0.079	0.000[1]	0.001[1]	0.080	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.002[1]	0.000[1]
AUV	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]
CVD	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]
MOQ	-	-	-	-	0.000[1]	-	-	-	-	-	-	-	-	-	-	-	-
OC * PH	0.477	0.842	0.871	0.992	0.552	0.698	0.463	0.499	0.000[1]	0.946	0.460	0.946	0.912	0.521	0.546	0.850	0.952
OC * AUV	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.073	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]
OC * CVD	0.461	0.947	0.091	0.355	0.938	0.012[5]	0.005[1]	0.007[1]	0.718	0.269	0.340	0.198	0.424	0.328	0.328	0.171	0.230
OC * MOQ	-	-	-	-	0.107	-	-	-	-	-	-	-	-	-	-	-	-
PH * AUV	0.235	0.009[1]	0.371	0.389	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.492	0.000[1]	0.962	0.065	0.001[1]	0.001[1]	0.486	0.724
PH * CVD	0.029[5]	0.006[1]	0.085	0.033[5]	0.000[1]	0.000[1]	0.001[1]	0.000[1]	0.000[1]	0.010[5]	0.326	0.014[5]	0.001[1]	0.000[1]	0.000[1]	0.045[5]	0.027[5]
PH * MOQ	-	-	-	-	0.000[1]	-	-	-	-	-	-	-	-	-	-	-	-
AUV * CVD	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.949	0.000[1]	0.000[1]	0.000[1]	0.016[5]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]
AUV * MOQ	-	-	-	-	0.000[1]	-	-	-	-	-	-	-	-	-	-	-	-
CVD * MOQ	-	-	-	-	0.000[1]	-	-	-	-	-	-	-	-	-	-	-	-

Superscript [1] indicates significance at the 0.01 level.

Superscript [5] indicates significance at the 0.05 level.

No superscript denotes a lack of significance at both levels (at 0.01 and 0.05 level).

(-) indicates interactions inapplicable to lot-size methods (the model for FOQ contains additional terms to the models for the other methods).

Table 7.7a Coefficients of fitted models: a main effects.

Methods	*Log AUV* coefficient	*CVD* coefficient	Ordering cost coefficient levels				*PH* coefficient		*OC* * *PH*							
									OC = 40		*OC* = 80		*OC* = 120		*OC* = 180	
			OC = 40	*OC* = 80	*OC* = 120	*OC* = 180	*PH* = 12	*PH* = 52	*PH* = 12	*PH* = 52	*PH* = 12	*PH* = 52	*PH* = 12	*PH* = 52	*PH* = 12	*PH* = 52
BTH1	**0.46673**	**0.34596**	**-0.70799**	**-0.12742**	**0.27696**	**0.55845**	**-0.14213**	**0.14213**	0.01024	-0.01024	-0.00818	0.00818	-0.00514	0.00514	0.00308	-0.00308
BTH2	**0.49421**	**0.44777**	**-0.73893**	**-0.14438**	**0.24288**	**0.64043**	**-0.16057**	**0.16057**	0.00694	-0.00694	0.00038	-0.00038	-0.00199	0.00199	-0.00533	0.00533
EOQ	**0.48501**	**0.49239**	**-0.75135**	**-0.10941**	**0.24136**	**0.61940**	**-0.08749**	**0.08749**	0.00341	-0.00341	-0.00393	0.00393	-0.00486	0.00486	0.00538	-0.00538
EOQ2	**0.50143**	**0.40505**	**-0.70551**	**-0.11681**	**0.23548**	**0.58684**	**-0.08661**	**0.08661**	-0.00154	0.00154	0.00150	-0.00150	-0.00181	0.00181	0.00185	-0.00185
FOQ	**0.11774**	**-0.47371**	**-0.96096**	**-0.12747**	**0.31750**	**0.77093**	**-0.30476**	**0.30476**	0.02300	-0.02300	-0.00365	0.00365	-0.00666	0.00666	-0.01269	0.01269
ICA	**0.53991**	**0.49917**	**-0.55303**	**-0.13396**	**0.15927**	**0.52772**	**-0.08392**	**0.08392**	-0.00729	0.00729	-0.00491	0.00491	0.00108	-0 00108	0.01112	-0.01112
IOQ	**0.53110**	**0.50815**	**-0.54841**	**-0.13749**	**0.16222**	**0.52368**	-0.05296	0.05296	-0.01196	0.01196	-0.00319	0.00319	0.00228	-0.00228	0.01287	-0.01287
IPPA	**0.53157**	**0.51498**	**-0.54731**	**-0.14078**	**0.16331**	**0.52478**	-0 05406	0.05406	-0.01314	0.01314	0.00034	-0.00034	0.00110	-0.00110	0.01170	-0.01170
LFL	**0.04706**	**-0.43959**	**-0.94710**	**-0.12774**	**0.31323**	**0.76161**	**-1.02611**	**1.02611**	**0.03048**	**-0.03048**	**-0.00578**	**0.00578**	**-0.00905**	**0.00905**	**-0.01565**	**0.01565**
LUC	**0.49970**	**0.42860**	**-0.69923**	**-0.10829**	**0.23472**	**0.57280**	**-0.09502**	**0.09502**	0.00011	-0.00011	-0.00353	0.00353	-0.00147	0.00147	0.00489	-0.00489
POQ	**0.46817**	**0.22297**	**-0.67917**	**-0.13365**	**0.20589**	**0.60693**	0 05343	-0.05343	-0.01495	0.01495	0.00255	-0.00255	0.00250	-0.00250	0.00990	-0.00990
PPA	**0.49611**	**0.42683**	**-0.69959**	**-0.10154**	**0.23765**	**0.56348**	**-0.10077**	**0.10077**	-0.00078	0.00078	0.00052	-0.00052	-0.00410	0.00410	0.00436	-0.00436
PPB	**0.50078**	**0.43079**	**-0.75487**	**-0.10681**	**0.25519**	**0.60649**	**-0.15271**	**0.15271**	0.00230	-0.00230	-0.00135	0.00135	-0.00556	0.00556	0.00461	-0.00461
SM	**0.47536**	**0.51417**	**-0.71188**	**-0.06460**	**0.23650**	**0.53998**	**-0.13228**	**0.13228**	0.00994	-0.00994	0.00174	-0.00174	-0.00863	0.00863	-0.00305	0.00305
MSM1	**0.47693**	**0.51788**	**-0.71019**	**-0.06561**	**0.23850**	**0.53730**	**-0.13436**	**0.13436**	0.00987	-0.00987	0.00133	-0.00133	-0.00823	0.00823	-0.00297	0.00297
MSM2	**0.49731**	**0.48624**	**-0.68711**	**-0.14199**	**0.21406**	**0.61504**	**-0.07967**	**0.07967**	-0.00520	0.00520	-0.00179	0.00179	0.00033	-0.00033	0.00666	-0.00666
WWA	**0.49810**	**0.49995**	**-0.70331**	**-0.13928**	**0.22260**	**0.61999**	**-0.09355**	**0.09355**	-0.00279	0.00279	-0.00230	0.00230	0.00086	-0.00086	0.00423	-0.00423

Significant interactions shown in bold.

Table 7.7b Coefficients of the fitted models - continued.

Methods	*OC * Log AUV*				*OC * CVD*				*PH * Log AUV*		*PH * CVD*		*Log AUV * CVD*
	OC = 40	*OC* = 80	*OC* = 120	*OC* = 180	*OC* = 40	*OC* = 80	*OC* = 120	*OC* = 180	*PH* = 12	*PH* = 52	*PH* = 12	*PH* = 52	
BTH1	**0.02781**	**0.00671**	**-0.01079**	**-0.02373**	0.02316	-0.00248	-0.03115	0.01047	0.00271	-0.00271	**0.02744**	**-0.02744**	**-0.07518**
BTH2	**0.03809**	**0.00936**	**-0.01241**	**-0.03504**	0.00863	-0.00815	-0.00826	0.00778	**0.00638**	**-0.00638**	**0.03712**	**-0.03712**	**-0.08964**
EOQ	**0.04226**	**0.00906**	**-0.01324**	**-0.03808**	-0.02422	-0.03947	0.00622	0.05747	0.00236	-0.00236	0.02508	-0 02508	**-0.08643**
EOQ2	**0.03757**	**0.00919**	**-0.01152**	**-0.03524**	-0.01301	-0.02291	-0.00932	0.04524	-0.00231	0.00231	**0.03140**	**-0.03140**	**-0.07899**
FOQ	0.02142	0.00096	-0.00780	-0.01458	0.02920	-0.01228	-0.00477	-0.01215	**-0.03588**	**0.03588**	**0.18775**	**-0.18775**	-0.00088
ICA	**0.02651**	**0.00896**	**-0.00658**	**-0.02889**	**-0.07846**	**-0.01767**	**0.03106**	**0.06507**	**-0.01054**	**0.01054**	**0.05809**	**-0.05809**	**-0.10041**
IOQ	**0.02519**	**0.00913**	**-0.00600**	**-0.02832**	**-0.08103**	**-0.01626**	**0.02781**	**0.06948**	**-0.01566**	**0.01566**	**0.05282**	**-0.05282**	**-0.10368**
IPPA	**0.02540**	**0.00850**	**-0.00579**	**-0.02811**	**-0.08414**	**-0.00694**	**0.02471**	**0.06637**	**-0.01587**	**0.01587**	**0.05593**	**-0.05593**	**-0.10428**
LFL	**0.02210**	**0.00105**	**-0.00816**	**-0.01499**	0.01780	-0.01289	-0.00037	-0.00454	**0.02059**	**-0.02059**	**0.37181**	**-0.37181**	**-0.01149**
LUC	**0.03307**	**0.00921**	**-0.01018**	**-0.03210**	0.00445	-0.03410	-0.01208	0.04173	-0.00174	0.00174	**0.03606**	**-0.03606**	**-0.08353**
POQ	**0.03798**	**0.01076**	**-0.01089**	**-0.03785**	-0.02777	-0.02514	0.01108	0.04183	**-0.01770**	**0.01770**	-0.01534	0.01534	**-0.04171**
PPA	**0.03244**	**0.00865**	**-0.01051**	**-0.03058**	0.00060	-0.03694	-0.00871	0.04505	0.00012	-0.00012	**0.03359**	**-0.03359**	**-0.08722**
PPB	**0.04323**	**0.00742**	**-0.01499**	**-0.03566**	-0.00679	-0.02912	-0.00217	0.03808	0.00486	-0.00486	**0.04736**	**-0.04736**	**-0.08480**
SM	**0.02983**	**0.00378**	**-0.01006**	**-0.02355**	0.01125	-0.03406	-0.00579	0.02860	**0.00746**	**-0.00746**	**-0.04932**	**0.04932**	**-0.08373**
MSM1	**0.02947**	**0.00402**	**-0.01031**	**-0.02318**	0.01150	-0.03384	-0.00640	0.02874	**0.00762**	**-0.00762**	**-0.04821**	**0.04821**	**-0.08442**
MSM2	**0.03648**	**0.01017**	**-0.01076**	**-0.03589**	-0.03835	-0.01583	0.01370	0.04048	-0.00168	0.00168	**0.02666**	**-0.02666**	**-0.09328**
WWA	**0.03757**	**0.01000**	**-0.01138**	**-0.03619**	-0.03228	-0.01705	0.00955	0.03978	0.00085	-0.00085	**0.02920**	**-0.02920**	**-0.09562**

Significant interactions shown in bold.

As reported above, the significant terms were similar for most methods except LFL and FOQ. In the next few sections we examine, for each method, the effects of each factor on the total cost.

7.5.2.1 The effect of annual usage value

From Table 7.7a the coefficient of log *AUV* is positive and similar for all methods (approximately 0.5), except FOQ and LFL. However, for these methods this positive coefficient is offset by a negative coefficient of log $AUV \times CVD$, i.e. as *CVD* increases this effect reduces. For FOQ and LFL the coefficient of log *AUV* is much lower (0.12 and 0.05 respectively) but there is no such offset. For all methods there are minor differences only in coefficients of log *AUV* for each level of *PH* and *OC*. The coefficient of log *AUV* is lower for higher ordering costs.

7.5.2.2 The effect of ordering cost

The coefficients of *OC* increase with ordering cost as expected. The increase is non-linear. In particular, the difference between *OC's* 40 and 80 is larger than between other adjacent ordering costs (Table 7.7a). $OC \times PH$ is only significant for LFL. The next interaction $OC \times \log AUV$ shows that the coefficient of log *AUV* decreases as *OC* increases (Table 7.7b). This is to be expected as ordering cost becomes a smaller proportion of item cost. This is because the *AUV* is a result of annual demand times the item cost which strictly depends on whether the part is so expensive as to mean that a higher *OC* is needed to order this part.

7.5.2.3 The effect of the coefficient of variation on demand

In this study the coefficient of *CVD* is positive, i.e. a higher *CVD* gives higher total costs. However, the positive coefficient is offset by a negative coefficient of log $AUV \times CVD$, i.e. for larger *AUV*s the coefficient of *CVD* becomes negative. It is suggested that the reason that this may differ from other (previous) studies is that in our study actual data were used. In other words, the actual nature of demand variability and lumpiness in the aircraft maintenance environment behaves differently from findings and results where factors and demand data are based on simulation. Table 7.7b shows that there are minor differences in these coefficients for each level of *OC* and *PH* where they are significant, but the coefficient of *CVD* increases with *OC* where significant, and is usually higher for *PH* equal to12. So as ordering cost increases *CVD* has more impact and *CVD* makes more difference for a shorter planning horizon. Only LFL and

FOQ give a negative *CVD* coefficient, but these are less negative for *PH* equal to 12 and more negative for *PH* equal to 52. The interaction of *OC*× *CVD* was found to be only significant with the ICA, IOQ and IPPA methods. This is because those methods are based on the incremental version of measurement of part-periods as all examine the incremental costs/savings generated by combining future demand requirements with current requirements in the same order as long as the additional or *incremental* carrying cost created by their inclusion is less than the cost of placing a separate order for that period's requirement.

7.5.2.4 The effect of planning horizon

A planning horizon of 12 months reduces total cost on average, compared with *PH* equal to 52 weeks, but the benefit is usually less as *CVD* increases, indicating that, for very intermittent demand, the advantage of a short planning horizon is reduced. For LFL the pattern is the same but is exaggerated. There is a similar story for FOQ, but any advantage of *PH* equal to12 is offset by a large *CVD* or a large *MOQ*.

7.5.2.5 The effect of minimum order quantity

The FOQ method includes another factor, *MOQ*, so we report its results separately. In Table 7.6 all the main effects, including *MOQ*, are highly significant and the significant interactions are *PH*× *MOQ*, log *AUV*× *MOQ* and *CVD*× *MOQ*. Further analysis of those interactions are shown in Table 7.7c, and demonstrate that the higher the *MOQ*, the lower the total cost will be, more so with higher log *AUV* and *CVD*.

Table 7.7c Coefficients of model fitted to FOQ data - continued.

Method	*MOQ* coefficient	*OC* * *MOQ*			
		OC = 40	*OC* = 80	*OC* = 120	*OC* = 180
FOQ	**-0.03986**	0.00136	-0.00009	-0.00048	-0.00079

PH * *MOQ*		Log *AUV* * *MOQ*	*CVD* * *MOQ*
PH = 12	*PH* = 52		
0.00197	**-0.00197**	**0.00197**	**0.00385**

Significant interactions shown in bold.

7.6 Lot-size predictive cost model, *LPCM*

The lot-size predictive cost model, as its name suggests, is thus a model whereby the optimum cost of any item selected together with its most efficient parameters are found. By entering in the prepared dialog box, the lot size factors of a specific item [e.g. *OC*, *PH*, *AUV*, *CVD* and *MOQ*, (see Figure 7.1)], the adapted visual basic for applications, VBA, runs through a complex series of calculations of prepared coefficients. The linear statistical procedure GLM fitted to the data for each method allowing estimation of the log total cost for any given set of factors and covariates are included. The coefficients used are slightly different to those given in Table 7.7 as non-significant terms are eliminated one by one. These coefficients are presented in tabular form for each of the seventeen lot-size methods. The predictive cost model then selects the most appropriate lot-size method based on the lowest total cost. The whole process takes less than a second. The process may be demonstrated by the following example:

7.6.1 Illustrative example

For this example, the FOQ method is selected as it has the additional factor *MOQ*, and assumes factor values of: *OC* = 80, *PH* = 52, *AUV* = 2400 log *AUV* = 7.7832, *CVD* = 1.50 and *MOQ* = 100.

Table 7.6 reminds us that the FOQ method has five significant interactions: Log *AUV*, *CVD* and *MOQ*, all interact with *PH*. This means that log *AUV*, *CVD* and *MOQ* factors will all depend on the level of the planning horizon (52 or 12); and *MOQ* interacts with both log *AUV* and *CVD*. The constant term in the fitted GLM is 7.04101. The other estimated parameters follow.

Effect of *OC* = £80 is given by -0.13717

Effect of *PH* = 52 periods is given by 0.30476

Coefficient of log *AUV* is 0.116696

Coefficient of *CVD* is -0.47946

Coefficient of *MOQ* is -0.039891

Additional coefficient of log *AUV* for *PH* of 52 = 0.035885

Additional coefficient of *CVD* for *PH* of 52 = -0.18775

Additional coefficient of *MOQ* for *PH* of 52 = -0.001973

Coefficient of log $AUV \times MOQ$ = 0.004158

Coefficient of $CVD \times MOQ$ = 0.003874

The estimated log total cost is then given as:

$$\text{Log TC} = 7.04101 + (-0.13717) + (0.30476) + (0.116696 \times 7.7832) + (-0.47946 \times 1.50) + (-0.039891 \times 100) + (0.035885 \times 7.7832) + (-0.18775 \times 1.50) + (-0.001973 \times 100) + (0.004158 \times 7.7832 \times 100) + (0.003874 \times 1.50 \times 100)$$
$$= 7.02632$$

The log total costs estimated in this way for these values of the input variables are displayed in ascending order, as in Figure 7.1 (for consecutive running of model see Appendix E, and for detailed function descriptions see Appendix C).

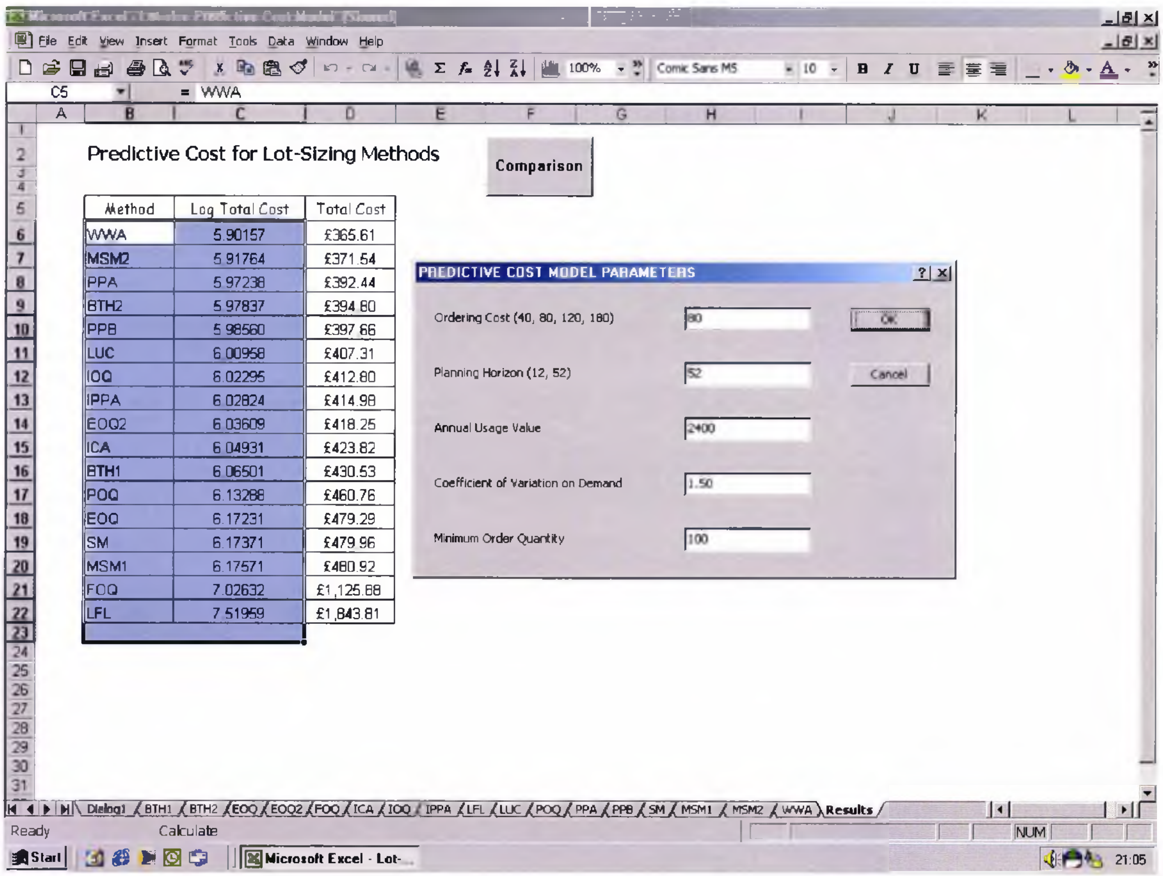


Figure 7.1 Predictive cost model dialog box.

7.7 Discussion and conclusions

The results of this investigation lead us to important conclusions. Furthermore we do believe that our conclusions will assist in the selection of the proper lot-size method and factors for the demand likely to be encountered in practice.

7.7.1 Methods evaluation

A large number of airline companies still use earlier methods [52] specifically; EOQ, LFL, FOQ, LUC, PPA and PPB with little or no appreciation for the other lot-size methods used in this study. Indeed, simplistic, demand driven lot-sizing techniques, such as LFL, EOQ and FOQ, are the most commonly embraced by airline companies, who believe that the implementation of any other lot-size method within their environment would build-up an unnecessary inventory. The present study offers clear evidence that the use of the LFL, FOQ and EOQ methods is not efficient for the aircraft maintenance industries where a high variation of demand typically occurs as those methods consistently create high cost and poor performance, with their performance remaining poor as the demand variability increases. This is in particularly true of the EOQ method, while many airline operators still maintain its efficiency (52% of companies). Accordingly, it is recommended that companies reconsider utilisation of these methods. We find that the LFL technique is more suitable in environments of high-cost items, already realised by a few aviation companies, with the cost performance of EOQ deteriorating as *CVD* increases. The LFL has the largest performance improvement as demand becomes lumpier and with a higher *AUV* and low order cost, it even outperforms the WWA and MSM2.

Evidence emerges indicating that the implementation of the WWA and MSM2 methods would be the most beneficial order method, as examination of most of the results reveals that both methods were consistently the best. Such an excellent performance was most pronounced when demand patterns were more variable ($CVD \geq 1.20$). The selection of other methods might still be useful though, as different methods have certain strengths under differing environmental factors.

7.7.2 Statistical analysis and predictive cost model

In addition, this research shows that the level of appropriate factors has an effect on the total inventory cost. The results indicate that the impact of demand variability, *CVD*, on cost is significant, that as demand variability and lumpiness increase, so the cost increases. *CVD* has more effect with a long planning horizon of 52 weeks than with a short one of 12 months. This was observed in most methods except for the POQ, SM and MSM1. The annual usage value factor too has a significant main effect in terms of lot-sizing performance. Generally, an increase in *AUV* increases total cost as might be expected, however the effect reduces as *CVD* increases.

Finally, as many aviation companies were found to be dissatisfied with their current use of lot-size method calculations [52, 55] this study has taken a step in the direction of defining the relationship between the total cost of lot-size methods and their factors in order to enable the management practitioners to select the method that best suits the demand fluctuations. As such a model was presented in this Chapter that, as described earlier, could be of great benefit to airline operators and other maintenance service organisations. It will enable them to select in advance the appropriate lot-size method that best meets their cyclical demand for parts. The adaptability of the model to variations of factor input, for example in the case of fleet or product change, is assured. One direction of further research however would be the inclusion of a *Quantity Discounts* (Purchase Discounts) factor and an examination of the impact of this additional parameter on lot-sizing method performance. Such a study could enhance the model presented here.

Although we have used data from one particular airline operator, it is suggested that these findings may be applicable elsewhere as other manufacturing sectors have similar demand patterns as airlines.

8. SPARE PARTS FORECASTING

8.1 Introduction

Demand forecasting is one of the most crucial issues of inventory management. Forecasts, which form the basis for the planning of inventory levels, are probably the biggest challenge in the repair and overhaul industry, as the one common problem facing airlines throughout the world is the need to know the short term part demand forecast with the highest possible degree of accuracy. The high cost of modern aircraft and the expense of such repairable spares as aircraft engines and avionics, constitute a large part of the total investment of many airline operators. These parts, though low in demand, are critical to operations and their unavailability can lead to excessive down time costs. Most airline materials managers deal with intermittent demand, which tends to be random and has a large proportion of zero values. This topic has received extremely limited study within the aviation industry.

Forecasting the demand for parts with highly variable demand patterns is one of our main objectives since some of the traditional forecasting methods generate results with such large error margins that, in many cases, as they create too many stock-outs managers find them useless. In our recent survey (see Chapter three and four [52, 55]) of *airline operators* and *maintenance service organisations* several common problems were mentioned in relation to developing service part forecasts. Firstly, it showed that most companies felt the service part forecasts they received were never realistic and as such they tried to outguess the forecast. Secondly, for those companies which did implement the MRP system, the service part forecast was loaded directly into the system without any review; and finally, firms most commonly cited problems in the development of reliable forecasts owing to the relatively high percentage of items which experienced erratic or lumpy demand.

The main specific objectives in this research study are:

- To analyse the nature and sources of a lumpy demand.
- To compare the performance of forecasting methods and therefore to identify their domain of applicability according to level and type of demand lumpiness, when

applied to a common sample (*HT*, *CM* {see, Chapter two}) of aircraft components.

- To analyse the behaviour of different forecasting methods when dealing with lumpy and uncertain demand; we argue that the performance of a forecasting method should vary with the level and type of lumpiness (i.e., with the sources of lumpiness).
- Finally, based on the forecast accuracy measurements and the results of their statistical analysis, a predictive model is developed successfully for each of the thirteen forecasting methods analysed.

8.2 Literature review

This section involved two distinct focuses which will be presented separately. The first part will consider the variety of literature relating to the forecasting of intermittent demand. The second will discuss the practicalities of coping with such irregularities in demand in the airline industry.

8.2.1 Related research

In order to determine suitable spare part inventory levels, one must know maintenance schedules and parts forecasting that feed into the MRP system. However, forecasting demand is reported as a major problem by some companies [52, 55, 133] who have implemented the MRP system. This is due to the nature of demand pattern variation in the airline sector where such an intermittent demand produces a series of random values that appear at random intervals, leaving many time periods with no demand. The literature includes a relatively small number of proposed forecasting solutions to this demand uncertainty problem [5, 37, 101, 136]. Watson [128] found that the increase in average annual inventory cost resulted from fluctuations in the forecast demand parameters of several lumpy demand patterns. The single exponential smoothing and the Croston methods are the most frequently used for forecasting low and intermittent demand [37, 136]. In practice, the standard method for forecasting intermittent demand is the single exponential smoothing method, although some production management texts suggest the lesser-known alternative of the Croston method. In their experimental study, Johnston and Boylan, [67] using a wide range of simulated conditions, observed an improvement in forecast performance using the Croston method when compared with the straight Holt (EWMA) method. On the other hand, Bartezzaghi et al [5] in their experimental simulation found that EWMA appears applicable only with low levels of lumpiness. Willemain et al. [136] concluded that the Croston method is significantly superior to exponential smoothing under intermittent demand conditions. In addition, other methods such as the *Wilcox* [134] and *Cox Process* methods were used for forecasting intermittent demand. Both methods were shown to produce poor forecasting results [135] and for that reason neither is included in the study.

Zhao and Lee [141] concluded in their study that forecasting errors significantly increase total costs and reduce the service level within MRP systems, arguing that the selection of forecasting method has a significant impact on system performance. Their results show that forecasting errors increase as variations in the demand increase. The fact that the existence of forecasting error increases the total cost of MRP systems has been reported in several other studies [80, 121, 132, 141].

8.2.2 Airline forecasting systems review

Demand for air transport varies with time, as for many other goods. There are variations in daily, weekly, and annual demand, which result in peaks at popular times. The competitive market in which most operators now work results in their trying to meet these peaks as far as is reasonably possible. Aircraft availability has, therefore, to be maximised at these peaks and the maintenance fitted into a time when the planes are not required for commercial activities [51]. The context for this inventory forecasting in the *aircraft maintenance review* was based on our recent airline survey [52, 55] and the findings were potentially helpful for carrying out further studies.

The survey shows that a small number of companies did mention the inventory forecasting system; of those, 9% had difficulty in forecasting demand for parts. Some of these companies were looking for a better forecasting system. As is general within the aviation industry the usage patterns for most parts is unpredictable, and estimating future demand by considering available maintenance contract information and looking at scheduled maintenance plans, some companies prepare manual forecasts for expensive parts (rotables/repairables). Forecasts are generally based on past usage patterns such as flying hours or parts demand. On the other hand, the annual budgets for all departments in the technical division are taken into account: the number of forecasted flight hours/cycles, the number and type of checks planned for every aircraft, and the fleet size. With this data, the *purchasing department* tries to determine the quantity of stock necessary for the particular period. Alternatively, when new types of aircraft are introduced, the airframe and engine manufacturers normally provide a recommended spares provisioning listing, RSPL, based on the projected annual flying hours, which include forecast usage information on new aircraft and usually indicate the main base float to maintain aircraft. Also, the original equipment manufacturers, OEM, provide overhaul manuals for components fitted to the aircraft which enable an assessment of piece parts required based on reliability information and the specified components' operational and life limits. Other systems such as Maintenance and Engineering Management Information System, MEMIS, often mentioned, have built-in, forecast methods, which mainly use an exponential smoothing technique. Many operators also used Advanced Materials Allocation Scheduling System, AMASS. This is usually developed in-house and is a forecast based system.

The service life of components is another forecasting technique, where technical planning is based around flying hours. More companies are considering flying hours as the major factor for their forecasting of demand calculation. In general, the mean time between removal/overhaul, MTBR/O, is used for forecasting a failure rate.
Maintenance service organisations try to forecast with the help of their marketing department, e.g. every six months or one year, on all components for overhaul and repairs. With this information together with past usage they maintain inventory levels to support their turn around times.

It was found that most companies run their forecast on a monthly or quarterly basis. However forecasting systems generally depend on the category of part used. This is due to aircraft parts being defined either as life-limited, *predictable*, or condition-monitored, *unpredictable*. For "A" items forecast they look at what they may need. Some currently do this manually because they are only managing about 5% of the total parts purchased which makes up about 65% of the cost. Besides, for "on-condition" components they use an additional planning factor named the "*replacement index*" as an expected percentage of removals. Once they believe that they have received an accurate forecast from production departments, they start to order at regular intervals, but this represents only a few items such as wheels and brake parts. Even so, some companies still experience difficulties in relating insufficient data and appropriate forecasting methods to suit their work environment and needs. So our survey indicated that forecasting was the major problem, hence an inability to stock accurately, or the experience of a lack of "tie-in" to forecasts, especially in those companies that operate and support several major aircraft types and have large fleets. Others find that basically their system works but that they are looking for one that is more modern, flexible and integrated with MRP. A better forecasting system is still needed for those types of demand patterns.

8.3 Demand forecasting techniques

Thirteen forecasting methods have been considered in this study, which are grouped according to the kind of time-series type they are based on. The methods presented are designed to provide a means to analyse historical, and to project future, service part requirements or demand. The methods used in this study are as follows:

8.3.1 Seasonal demand

8.3.1.1 Winter's method AW, MW

Winter's method [86, 140] is a forecasting technique that we can apply to time-series exhibiting trend and seasonality. This method is similar to Holt's method but incorporates a number of adjustments for the possible effects of seasonality. There are two types of seasonal model: an *additive* version which assumes that the seasonal effects are of constant size and a *multiplicative* version which assumes that the seasonal effects are proportional in size to the local de-seasonalized mean level. We used Winter's method because we assume that either there is a rate of change or a seasonal effect; the rate of change being either an increase in airline fleet size or of flying hours.
To demonstrate this method, we let Seasonal Period Length *SPL* represent the number of seasons in the time-series (for quarterly data *SPL* = 4; for monthly data *SPL* = 12; and for weekly data *SPL* = 52). In the multiplicative case (which is the most commonly used), the updating equations are:

$$F_{t+k} = (E_t + kT_t)S_{t+k-p} \qquad 8.1$$

Where

$$E_t = \alpha \frac{D_t}{S_{t-p}} + (1-\alpha)(E_{t-1} + T_{t-1}) \quad 8.2$$

$$T_t = \beta(E_t - E_{t-1}) + (1-\beta)T_{t-1} \quad 8.3$$

$$S_t = \gamma \frac{D_t}{E_t} + (1-\gamma)S_{t-p} \quad 8.4$$

We can use the forecasting function in equation 8.1 to obtain k time period forecasts into the future where k = 1, 2, ... SPL. The forecast for time period $t+k\,(F_{t+k})$ is obtained in equation 8.1 by multiplying the expected base level at time period $t+k\,(given by E_t + kT_t)$ by the most recent estimate of the seasonality associated with this time period $(given\ by S_{t+k-p})$ the smoothing parameters $\alpha, \beta and\, \gamma\,(gamma)$ in equations 8.2, 8.3, and 8.4 can assume any value between 0 and 1 $(0 \le \alpha \le 1, 0 \le \beta \le 1, 0 \le \gamma \le 1)$.

The expected base level of the time-series in time period $t(E_t)$ is updated in equation 8.2, which takes a weighted average of the following two values:

* $E_{t-1} + T_{t-1}$, Which represents the expected base level of the time-series at time period t before observing the actual value at time period $t(given\ by D_t)$.

* $\frac{D_t}{S_{t-p}}$, Which represents the deseasonalized estimate of the base level of the time-series at time period t after observing D_t.

The estimated per-period trend factor T_t is updated using equation 8.3, the estimated seasonal adjustment factor for each time period is calculated using equation 8.4, which takes a weighted average of the following two quantities:

* S_{t-p}, Which represents the most recent seasonal index for the season in which time period t occurs.

* $\frac{D_t}{E_t}$. Which represents an estimate of the seasonality associated with time period t after observing D_t.

Equations 8.1 to 8.4 can readily be adapted for the additive case. 8.3 stays the same, but 8.1, 8.2 and 8.4 become

$$F_{t+k} = E_t + kT_t + S_{t+k-p} \quad 8.5$$

$$E_t = \alpha(D_t - S_{t-p}) + (1-\alpha)(E_{t-1} + T_{t-1}) \quad 8.6$$

$$S_t = \gamma(D_t - E_t) + (1-\gamma)S_{t-p} \quad 8.7$$

8.3.1.2 Seasonal Regression Model, SRM

The Seasonal Regression Model [99] is another common method that is used in time series for modelling data with seasonal effects. Using regression analysis to find a linear function $f(t)$ that describes the trend component of the time series data. An estimate of adjustment factors S_t for each season is made by averaging the ratio of each observation to its trend estimate for observations in like seasons (i.e. week, month or quarters of the year). The following model is then used to make estimates of the time series variable Y_t (where S_t is the seasonal adjustment factor associated with time period t),

$$Y_t = f(t)S_t + \varepsilon_t \quad 8.8$$

$$f(t) = B_0 + B_1 t \quad 8.9$$

Where ε_t represents a random disturbance term.

Using a linear trend function in equation 8.9, the parameters for the linear regression function were computed using ordinary least square, OLS, regression.

Here again, the results we obtain using this approach can be improved upon by using *Excel's Solver*. In particular, with *Solver* it is possible to determine *simultaneously* the least square estimates of the coefficients in the linear trend model and the seasonal adjustment factors as well.

8.3.2 Component service life (replacement) techniques

The uses of service life techniques require estimates of the service life characteristics of the part (MTBR & MTBO), derived from historical data (flying hours or number of landings). Future spares demand is then assumed to be affected by fleet planning and flying hours.

8.3.2.1 MTBR and MTBO

Mean time between removals is a statement of a part's performance, its reliability and the summation of its demand performance; the MTBR estimate may come from the manufacturer or the airline's own engineering department. These estimates frequently vary widely, and can be used for developing component and end unit forecasts. The basic model [19] calculation used in this study is based on many variables and parameters:

$$D = \frac{(\#\, of\ aircraft) \times (average\ flight\ hours) \times (quantity\ per\ aircraft)}{MTBR \times (length\ of\ time\ over\ which\ the\ flight\ hours\ are\ averaged)} \qquad 8.10$$

The demand history (flying hours) is the mathematics model performance indicator. The denominator must always correspond to the length of time over which the flight hours are averaged. Averaged flight hours may range from one day to a month. In this study we assumed that *SPL* equal to 4, 12 and 52. Table 8.1; illustrate values of MTBO and MTBR ranges.

Many airline operators have different MTBR and MTBO data depending on their operational usage. This would include how often their aircraft are used per day, the length of the runway (harder use of brakes and wheels which decrease life) and ambient temperatures. Some operators perform modifications to the component, e.g. the original overhaul life of the *Alternator's* bearing was 1250 hours, but following a modification to the bearings, the overhaul life increased to 2000 hours with a brush at half-life. However, as a component gets older, this will of course have an effect on the MTBR. Thus, component failure rates increase as the part's age increases.

8.3.2.2 Weighted Calculation of Demand Rates, WCDR

The moving average forecasts are weighted demand rates [1]. A similar method, previously tested by Markland [88] and known as issue interval technique, IIT, was based upon the assumption of a constant demand rate over time where the relationship between past and future demand populations is a function only of the total program activity in each period. The total demand for a given part during an experience period is divided by the total activity of the aircraft during the same period to give an average forecast rate. The forecast for a future period is then obtained by multiplying the average forecast rate by the planned activity.

The total number of demands during the experience period is divided by the number of flying hours to give an average demand rate. The rate thus obtained is multiplied by the planned number of flying hours for the prediction period to obtain the predicted number of demands, so the current method calculates the demand rate as

$$Demand\ rate_{t+k} = \frac{\sum_{i=t-k}^{t} D_i}{\sum_{i=t-k}^{t} fh_i} \qquad 8.11$$

Where

D_i denotes the *ith* observed number of demands during the experience period,

fh_i observed flying hours during the experience period,

k the number of quarters, months or weeks into the future.

Forecasts are then made by simply multiplying this rate by the future program:

$$predicted\ demands_{t+k} = demand\ rate_{t+k} \times fh_{t+k} \qquad 8.12$$

fh_{t+k} predicted flying hours for the $t+k$ future period.

A simple way to make this model more responsive is to weight recent observations more heavily than older observations:

$$Demand\ rate_{t+k} = \frac{\sum_{i=t-k}^{t} w_i D_i}{\sum_{i=t-k}^{t} w_i fh_i} \qquad 8.13$$

A Kalman filtering approach [70] suggests weights of the form $w_i = \alpha^{t-i}$.

8.3.2.3 Weighted Regression Demand Forecasters, WRDF

This method [1] considers forecasts based on moving regressions. For a moving four or eight-quarter window, a regression model is fitted with the form

$$D_i = \beta_0 + \beta_1 fh_i \qquad 8.14$$

A model is then used to predict the demands for the following quarter, month or week. The dependent variable in this study is the forecasted demand for spare parts D_i. The independent variables are assumed to have affected the dependent variable and thereby "caused" the results observed in the past. In our case, the number of flying hours fh_i is the main independent variable. This may contribute to trends or seasonal patterns of data, as shown in equation 8.14, through the application of various exponential weights. The weighted regression forecaster is specified in the following algebra; supposing the observation of the most recent eight quarters of demand and past component's flying hours in the sequence $d_1, d_2, ..., d_8$, and $fh_1, fh_2, ..., fh_8$, respectively. So the weighting factors used would be $w_1, w_2, ...,$ and w_8 to assign greater weight to the more recent quarters by setting the $\{w_i\}$ equal to 0.75^{8-i}, $i = 1, 2, ..., 8$. Thus the weights are
$w_1 = 0.75^7 = 0.1335$, $w_2 = 0.75^6 = 0.1780$, $w_3 = 0.2373$, $w_4 = 0.3164$, $w_5 = 0.4219$, $w_6 = 0.5625$, $w_7 = 0.75^1 = 0.75$, and $w_8 = 0.75^0 = 1.0$.
The sum of $\{w_i\} = 3.5995$.
Let the notation $\sum_i$ be defined to mean the sum taken over eight quarters. The weighted mean demand, D^*, is given by

$$D^* = \frac{\sum_i w_i d_i}{\sum_i w_i} \qquad 8.15$$

and the weighted mean flying hours (item program), fh^*, by

$$fh^* = \frac{\sum_i w_i fh_i}{\sum_i w_i} \qquad 8.16$$

We define

$$\sum_{xy} = \left(\sum_i w_i\right)\left(\sum_i w_i d_i fh_i\right) - \left(\sum_i w_i d_i\right)\left(\sum_i w_i fh_i\right) \qquad 8.17$$

and

$$\sum_{xx} = \sum_i w_i \left[\sum_i w_i (fh_i)^2\right] - \left(\sum_i w_i fh_i\right)^2 \qquad 8.18$$

Then

$$\beta_1 = \frac{\sum_{xy}}{\sum_{xx}} \quad and \quad \beta_0 = D^* - \beta_1 fh^* \qquad 8.19$$

It is important to understand that the apparent superiority of the weighted regression demand forecasters over the weighted demand rate forecasters partially derives from the inclusion of a non-zero intercept in the model of demands as a function of flying hours. This feature is important, it departs from an assumption of strict proportionality between demand and flying hours [1].

8.3.3 Intermittent and erratic (lumpy) demand

8.3.3.1 Croston's method

Croston [37] developed a method for forecasting in circumstances of intermittent demand which he showed to be superior to single exponential smoothing. Croston's method forecasts the time between consecutive transactions p and the magnitude of the individual transactions z_t separately. At the review period t, if no demand occurs in a period then the estimates z_t^* and p_t^* remain unchanged. If a demand occurs so $y_t > 0$, then the estimates are updated by the equations 8.20 and 8.21 .

The classic work on intermittent demand forecasting is that of Croston [37], as corrected by Rao [101], wherein is described the purpose of exponential smoothing techniques for estimating demand size and demand frequency separately. He reports that this approach results in lower stock levels and fewer out of stock situations when compared to the use of exponential smoothing techniques for demand. The following notation parallels that of Croston. Let

x_t binary indicator of demand at time t ;

z_t size of demand;

$y_t = x_t z_t$ demand for an item at time t ;

μ mean value of demand when nonzero;

p average number of time periods between demands;

α smoothing parameter;

y_t' exponential smoothing estimate of mean demand for period;

y^* exponential smoothing estimate made immediately after a demand occurs;

q time interval since last demand;

p_t'' Croston's estimate of mean interval between demands;

z_t'' Croston's estimate of mean demand size;

y_t'' Croston's estimate of mean demand per period;

Croston's method makes separate exponential smoothing estimates of the average size of a demand and the average interval between demands. The method updates the estimates after demands occur; if a review period t has no demand, the method just increments the count of time periods since the last demand.

If $y_t = 0$,

$z_t'' = z_{t-1}''$

$p_t'' = p_{t-1}''$

$q = q + 1$

Else $y_t > 0$

$$z_t'' = z_{t-1}'' + \alpha\left(y_t - z_{t-1}''\right) \qquad 8.20$$

$$p_t'' = p_{t-1}'' + \alpha\left(q - p_{t-1}''\right) \qquad 8.21$$

$q = 1$.

Where α is a coefficient between zero and one $(0 \leq \alpha \leq 1)$, combining the estimates of size and interval provides the forecast of mean demand per period at time t,

$$y_t'' = z_t'' / p_t'' \quad 8.22$$

These estimates are only updated when demand occurs.

8.3.3.2 Single Exponential Smoothing, SES

Single exponential smoothing is claimed to be the method most frequently used for forecasting low and intermittent demand, because of its simplicity [85], sometimes known as simple exponential smoothing. This method of single exponential forecasting [86] takes the forecast for the previous period and adjusts it using the forecast error made in predicting the previous period's value $(\alpha(D_t - F_t))$. That is, the forecast for the next period is

$$F_{t+1} = F_t + \alpha(D_t - F_t) \quad 8.23$$

Another way of writing equation (8.23) is

$$F_{t+1} = \alpha D_t + (1-\alpha)F_t \quad 8.24$$

where the parameter *alpha* (in equation 8.24) can assume any value between 0 and 1 $(0 \leq \alpha \leq 1)$.

It can be seen that the new forecast is simply the old forecast with the added adjustment for the error that occurred in the last forecast.

Since the value for F_1 is not known, we can use the first observed value D_1 as the first forecast $(F_1 = D_1)$ and then proceed using equation 8.24 .

8.3.3.3 Exponentially Weighted Moving Average, EWMA (Holt's method)

This method, developed by Holt [65, 86] is usually called Holt's two-parameter model. This method is often an effective forecasting tool for time series data that exhibit a linear trend. We intend to use this method as we experienced some trend in our data due to increase in fleet size which meant an increase in the main flying hours and by extension the spare parts demand too. This method also was previously tested for intermittent demand [67].

After observing the value of the time series at period $t(F_t)$, Holt's method computes an estimate of the base level of the time series (E_t), and the expected rate of increase or decrease (trend) per period (T_t). The forecasting function in Holt's method is represented by:

$$F_{t+k} = E_t + kT_t \qquad 8.25$$

where

$$E_t = \alpha D_t + (1-\alpha)(E_{t-1} + T_{t-1}) \qquad 8.26$$

$$T_t = \beta(E_t - E_{t-1}) + (1-\beta)T_{t-1} \qquad 8.27$$

We can use the forecasting function in equation 8.25 to obtain forecasts k time periods into the future where $k = 1, 2, 3$, and so on. The forecast for time period $t+k$ or (F_{t+k}) is the base level at time period $t(given by E_t)$ plus the expected influence of the trend during the next k time periods$(given\ by\ kT_t)$. The smoothing parameters $\alpha\ and\ \beta$ in equation 8.26 and equation 8.27 can assume any value between 0 and 1 $(0 \le \alpha \le 1, 0 \le \beta \le 1)$.

8.3.3.4 Trend Adjusted Exponential Smoothing, TAES

This method [97] has been used successfully in several *maintenance repair* and *overhaul*, MRO, environments. It is relatively simple and straightforward and requires minimal calculations. The updated equations are:

$$F_{t+1} = SA_t + ST_t \qquad 8.28$$

$$ST_t = \alpha \times T_t + (1-\alpha) \times ST_{t-1} \qquad 8.29$$

$$T_t = SA_t - SA_{t-1} \tag{8.30}$$

$$SA_t = \alpha \times D_t + (1-\alpha) \times SA_{t-1} \tag{8.31}$$

where

- t current period
- t-1 previous period
- α alpha a weighting factor typically held $(0 \le \alpha \le 1)$.
- D actual current period demand
- SA smoothed average demand
- T the trend in the demand pattern
- ST the smoothed trend
- F forecasted average demand

8.3.3.5 Weighted Moving Averages, WMA

A moving average technique [86] is one in which all the past data used in calculating the average receive equal weighting. However, we can often obtain a more accurate forecast by assigning different weights to the data. The *weighted moving average* extrapolation technique is a simple variation on the moving average technique that allows for just such weighting to be assigned to the data being averaged. In the WMA, the forecasting function is represented by:

$$F_{t+1} = w_1 d_t + w_2 d_{t-1} + \ldots + w_k d_{t-k+1} \tag{8.32}$$

where $0 \le w_i \le 1$ *and* $\sum_{i=1}^{k} w_i = 1$. Although the WMA offers greater flexibility than the moving average, it is also a bit more complicated. In addition to determining a value for k, we must also determine values for the weights w_i in equation 8.32. However, for a given value of k, we can use *Excel's Solver* to determine the values for w_i that minimises the MAPE or other measuring accuracy methods.

8.3.3.6 Double Exponential Smoothing, DES

The double exponential smoothing technique, often referred to as *Brown's method,* [24] is used for forecasting time series data that have a linear trend. The basic concepts are similar to those of double moving averages. The double exponential smoothing technique is summarized by equations 8.33 through to 8.37. As the smoothed series values themselves are not the forecasts, the updated equations are easier to understand if the following notation is adopted.

A_t is the single exponentially smoothed value of d_t at time t

$A_t^{'}$ is the double exponentially smoothed value of d_t at time t

The single exponentially smoothed value is now computed using equation 8.33.

$$A_t = \alpha d_t + (1-\alpha)A_{t-1} \qquad 8.33$$

Equation 8.34 is used to compute the double exponentially smoothed value.

$$A_t^{'} = \alpha A_t + (1-\alpha)A_{t-1}^{'} \qquad 8.34$$

Equation 8.35 is used to compute the difference between the exponentially smoothed values.

$$a_t = 2A_t - A_t^{'} \qquad 8.35$$

Equation 8.36 is an additional adjustment factor, which is similar to a slope measurement that can change over the series.

$$b_t = \frac{\alpha}{1-\alpha}\left(A_t - A_t^{'}\right) \qquad 8.36$$

Finally, equation 8.37 is used to make the forecast k periods into the future.

$$F_{t+k} = a_t + b_t k \qquad 8.37$$

In order to apply formulas 8.33 and 8.34, values of A_{t-1} *and* $A_{t-1}^{'}$ must be available. However, when t = 1, no such values exist. Thus, these values will have to be specified at the outset of the method. This can be done by simply letting A_{t-1} *and* $A_{t-1}^{'}$ be equal to

d_t or by using some average of the first few values as a starting point. Alpha is a weighting factor typically held ($0 \leq \alpha \leq 1$).

8.3.3.7 Adaptive-Response-Rate Single Exponential Smoothing, ARRSES

This method [86] has an advantage over SES in that it allows the value of α to be modified in a controlled manner as changes in the pattern of data occur. The basic equation for forecasting with the method of ARRSES is similar to equation 8.24 (see SES) except that α is replaced by α_t:

$$F_{t+1} = \alpha_t d_t + (1-\alpha_t)F_t \qquad 8.38$$

where

$$\alpha_{t+1} = \left|\frac{A_t}{M_t}\right| \qquad 8.39$$

$$A_t = \beta E_t + (1-\beta)A_{t-1} \qquad 8.40$$

$$M_t = \beta|E_t| + (1-\beta)M_{t-1} \qquad 8.41$$

$$E_t = d_t - F_t \qquad 8.42$$

In equation 8.40, A_t denotes a smoothed estimate of forecast error, and is calculated as a weighted average of A_{t-1} and the last forecasting error E_t. Similarly, M_t denotes a smoothed estimate of the absolute forecast error, being calculated as a weighted average of M_{t-1} and the last absolute forecasting error $|E_t|$. Equation 8.39 indicates that the value of α_t used for forecasting period $(t+2)$ is defined as an absolute value of the ratio of A_t and M_t. Instead of α_{t+1} we could have used α_t in equation 8.39 . We prefer α_{t+1} because ARRSES is often too responsive to changes, thus by using α_{t+1} we introduce a small lag of one period which allows the system to "settle" a little and forecast in a more conservative manner. β is a parameter between 0 and 1 ($0 \leq \beta \leq 1$), and $|\ |$ denotes absolute values.

8.4 Forecast accuracy measuring techniques

The forecast error cost is defined to be the cost of carrying the safety stock required to satisfy the cycle service level. When forecast errors increase, they increase the required safety stock and the size of Master Schedule MS, changes, thereby increasing both the safety stock costs and the MS change costs. Total costs therefore increase and the increase in total costs appears to be dependent upon both the demand variations and the forecasting methods used. A common goal in the application of forecasting techniques is to minimize these deviations or errors in the forecast. These errors are defined as the difference between the actual value and what was predicted. A forecasting method's performance can be evaluated by computing any of a number of measures of forecast error. Fildes and Beard [41] suggest that a variety of error measures should be considered including relative error measures.

Most forecast-error measures can be divided into two groups: standard (absolute) and relative error measures [86]. The following is a collection of the more common accuracy measures. Specific suggestions with regard to their use follow.

If D_t is the actual value for time period t and F_t is the forecast error for the period t, the forecast error for that period is the difference between the actual value and the forecast:

$$e_t = D_t - F_t \qquad 8.43$$

When evaluating performance for multiple observations, say n, there will be n error terms. We can define the following *absolute* forecast-error measures:

Mean Error (Bias)
$$ME = \sum_{t=1}^{n} \frac{e_t}{n} \qquad 8.44$$

Mean Absolute Deviation
$$MAD = \sum_{t=1}^{n} \frac{|e_t|}{n} \qquad 8.45$$

Mean Square Error
$$MSE = \sum_{t=1}^{n} \frac{(e_t)^2}{n} \qquad 8.46$$

Root Mean Square Error $$RMSE = \left[\sum_{t=1}^{n} \frac{(e_t)^2}{n} \right]^{1/2}$$ 8.47

Sum of Squared Errors $$SSE = \sum_{t=1}^{n} e_t^2$$ 8.48

Next are some of the most common *relative* forecast-error measures.

Mean Percentage Error $$MPE = \sum_{t=1}^{n} \frac{PE_t}{n}$$ 8.49

Following the adjustment for zeros [106], the expression for PE in equation 8.49 would be rewritten as:

$$PE_t = \left[\frac{D_t - F_t}{D_t} \right] \times 100 \quad for\ all D_t > 0$$
$$PE_t = \left[\frac{F_t - D_t}{F_t} \right] \times 100 \quad for\ all D_t = 0$$ 8.50

Mean Absolute Percentage Error $$MAPE = \sum_{t=1}^{n} \frac{|PE_t|}{n}$$ 8.51

The mean absolute percentage error is one of the most popular error measures for both practitioners and academicians. One disadvantage of MAPE, however, is that the method has a bias for estimates that are below the actual value [106]. There are a few ways to correct this lack of symmetry. One way is by dividing the error $(D_t - F_t)$ by the average of both D_t and F_t which would be rewritten as:

$$APE_t = \left| \frac{(D_t - F_t)}{\left[\frac{(D_t + F_t)}{2} \right]} \right| \times 100$$ 8.52

The modification of MAPE may be the most appropriate way to meet theoretical and practical concerns and does so in a simple and meaningful way [84].

8.5 Experimental framework

This section is presented in two parts as follows:

8.5.1 Experimental design and data collection

The sample data used in this study consist of Fokker, BAe and ATR aircraft repairable parts which are unpredictable or random. The airline operator participating in this research kept records of weekly demand levels for each component (a sample of the demand data displayed on historical cards is shown in Figures 8.1 to 8.7) which were then grouped in monthly and quarterly intervals of demand usage. A total of thirty-six components were tested during a span of three to ten years from January 1989 to June 2000 as shown in Table 8.1. As the demand for these parts was assumed to be driven either by flying hours or flight landings, the time series varied greatly with regard to the amount of data available, and depended on flying hours and aircraft utilisation. We also limited the sample to parts that had valid demands (zero is a valid demand; missing is not). Only recurring demands, *hard-time*, *HT* and *condition-monitoring*, *CM*, which could be expected to occur routinely as result of aircraft utilisation, were considered in this study. As such, parts were stratified into two groups; *hard-time* and *condition-monitoring*. However, the nature of the data employed within this study exhibited trend, seasonal and irregular random fluctuation characteristics (see Table 8.2). In addition to demand data, aircraft operation data, in terms of flying hours and number of aircraft in service, were also collected for the same time periods (see the attached CD disk).

In this study we found it appropriate to use a *Microsoft Excel* spreadsheet, shown in previous studies [53, 123] to be practical and sufficient for a limited budget. The spreadsheets were designed (see Figure 8.8) for all time series based on the seasonal period length, *SPL*, (e.g., number of months, quarters or weeks in a year). The time series data were divided into an "initialisation" set and a "test" set. The initialisation set was then used to estimate any parameters and to initialise the method. Forecasts were made for the following test set. This procedure continued over the entire forecasting horizon. Accuracy measures are computed for the errors in the test set only.

As with any forecasting tool, its performance needs to be monitored. One statistic that performs an automatic comparison against the naive model in a slightly more complex way is Theil's *U*-statistic [86]. This statistic allows a relative comparison of formal forecasting methods with naive approaches and also squares the errors involved so that large errors are given much more weight than small errors. Mathematically, Theil's *U*-statistic is defined as

$$U = \sqrt{\frac{\sum_{t=1}^{n-1}(FPE_{t+1} - APE_{t+1})^2}{\sum_{t=1}^{n-1}(APE_{t+1})^2}} \qquad 8.53$$

where, forecast relative change $FPE_{t+1} = \frac{F_{t+1} - D_{t+1}}{D_t}$ 8.54

and actual relative change $APE_{t+1} = \frac{D_{t+1} - D_t}{D_t}$ 8.55

This provides results that fall into easily interpreted ranges. Simply they can be summarized as follows:

$U = 1$: the naive method is as good as the forecasting technique being evaluated.

$U < 1$: the forecasting technique being used is better than the naive method. The smaller the *U*-statistic, the better the forecasting technique is relative to the naive method.

$U > 1$: there is no point in using a formal forecasting method, since using a naive method will produce better results.

Before making predictions using a forecasting method, we want to identify optimal values for $\alpha, \beta, and\, \gamma$ that minimise the forecasting accuracy measures based on Theil's *U*-statistic range rules, therefore we applied the optimisation tool known as *Solver*. Since however, the demand fluctuations are typically random and sporadic in this study, choosing the right smoothing values was of vital importance. The issue of *Smoothing Constant Parameters* is beyond the scope of this research study, as this investigation was based on a crossed experimental factor rather then a nested factor.

AirUK engineering

BAY SERVICING RECORD SHEET

60064

Full nomenclature of Equipment: ATR 72 NOSE WHEEL
Permissible Life (if lifed item)

PART NO: AH54474

SERIAL NO: WJ093

WO	Date removed	TSO	Ex A/C	Reason for Unserviceability	Code	Remedial action taken/mods embodied	Date serviceable	Date Issued
50151952	29-5-98		STORES	FOR BUILD		NEW WHEEL ASSY BUILD -	4 JUN 1998	
50159494	3/8/98		G-UKTL	W-T-L		TYRE CHANGE	21 AUG 1998	
50162559	5-11-98		G-UKTK	W-T-L		[illegible]	11 NOV 1998	
50171248	18 8 99		G UTJ	W-T-L		TYRE CHANGE — NEW EXCLUDER	4 AUG 1999	
50177598	5/2/00		G-UKTK	W-T-L		TYRE CHANGE	28 FEB 2000	
50183064	24/7/00		G-UKTM	W-T-L		FULL OVERHAUL		

WJ093 AH54474

AirUK engineering

BAY SERVICING RECORD SHEET

60064

Full nomenclature of Equipment: ATR72 NOSE WHEEL
Permissible Life (if lifed item)

PART NO: AH54474

SERIAL NO: WHO49

WO	Date removed	TSO	Ex A/C	Reason for Unserviceability	Code	Remedial action taken/mods embodied	Date serviceable	Date Issued
50156242	29/4/98		STORES	1ST WHEEL BUILD		TYRE FITTED	01 MAY 1998	
50160125	29/9/98		G-UKTM	W-T-L		[illegible]	4-9-98	
50163798	14-12-98		G-UKTN	W-T-L		TYRE CHANGE	16 DEC 1998	
50167029	26 3 99		G UKTN	WTL		[illegible]	24 MAR 1999	
50168968	24 5	49	G UKTM	OVAL ?		tyre change	03 JUN 1999	
50172363	2 9 99		G-UKTL	W-T-L		[illegible]	09 SEP 1999	
50183065	27/7/00		G-UKTM	W-T-L		FULL OVERHAUL		

WHO49 AH54474

Figure 8.1 - ATR72 Nose Wheel overhaul service record cards.

AirUK engineering

BAY SERVICING RECORD SHEET

60064

Full nomenclature of Equipment	PART NO	SERIAL NO
146 NOSE WHEEL Permissible Life (if lifed item)	AHA 1349	NZ 018

40

WO	Date removed	TSO	Ex A/C	Reason for Unserviceability	Code	Remedial action taken/mods embodied	Date serviceable	Date issued
50125222	2-1-96		G-BVHD	WTL		Tyre Change, 1 Seal	12-1-96	
50120315	1-5-96		G-WAC	[illegible] INS		INS SAT	3-5-96	
50134071	24-7-96	-	G-BTTP	WTL		TE	6-8-96	
50143206	4-4-97		G-WISC	WTL		[illegible]	12-5-97	
50154539	8-3-98		G-BSNR	W-T-L		[illegible]	17-3-98	
50158518	8-7-98		G-UKID	W-T-L		TYRE CHANGE - NEW INBD BEARING	1 AUG 1998	
50163416	10-12-98		G-BTTP	WTL		TYRE CHANGE	21 DEC 1998	
50170555	8-8-99		G-BVHC	WTL		[illegible]	19 JUL 1999	
50176563	7-1-2000		G-WAC	WTL		TYRE CHANGE	21 JAN 2000	
50182823	26-7-00		G-BSNR	WTL	O/H			

NZ018 AHA1349

AirUK engineering

BAY SERVICING RECORD SHEET

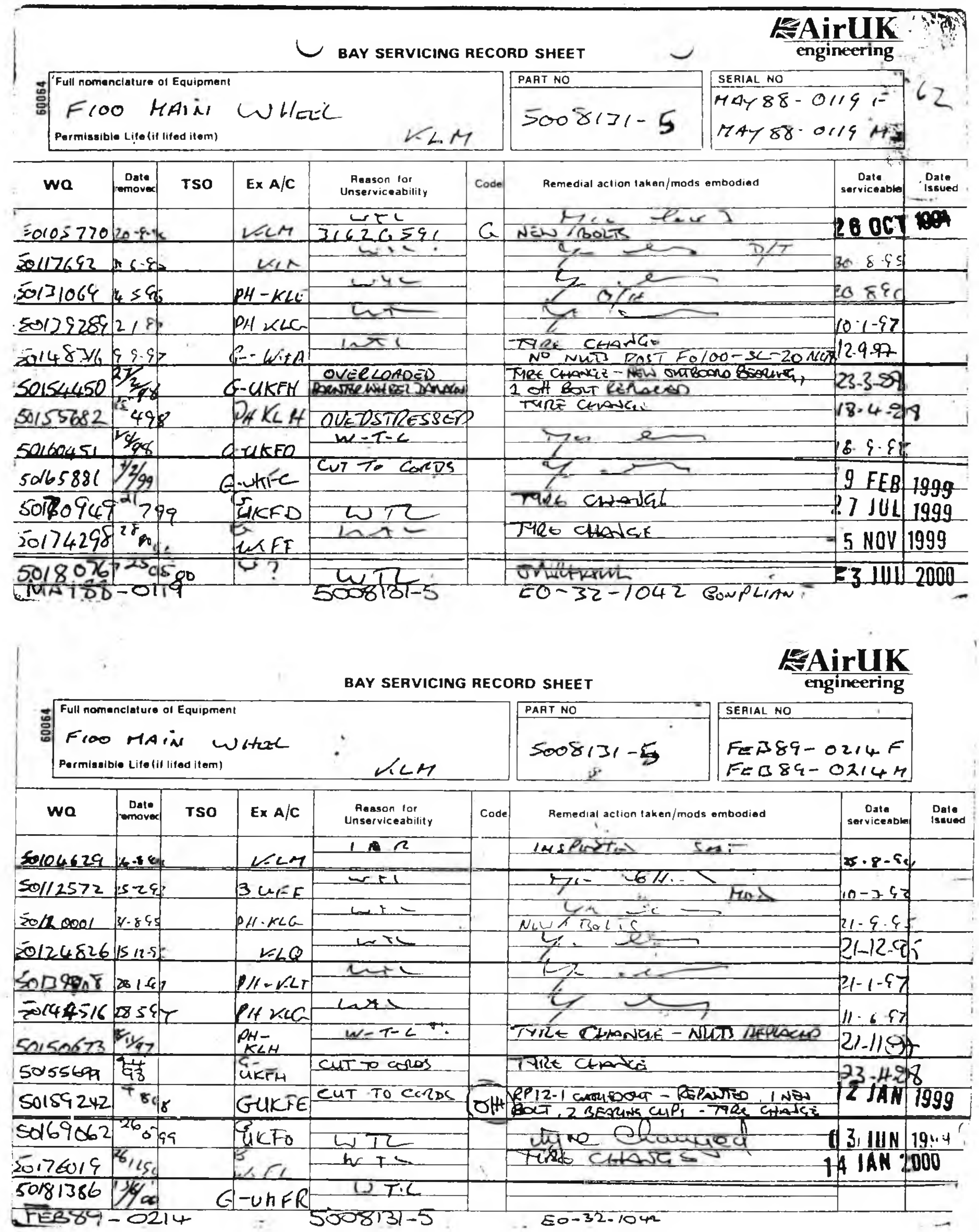
60064

Full nomenclature of Equipment	PART NO	SERIAL NO
146 NOSE WHEEL Permissible Life (if lifed item)	AHA 1349	HV 178

WO	Date removed	TSO	Ex A/C	Reason for Unserviceability	Code	Remedial action taken/mods embodied	Date serviceable	Date issued
50113224	8-7-95		G-BWHC	WTL		Tyre Change, Overhaul	5-5-95	
50120887	22-9-95		G-WISC	WTL		[illegible]	8-10-95	
50128223	4-3-96		G-WAG	WTL	M 28	[illegible] Seal, SAT [illegible]	11-3-96	
50130981	8-5-96		G-BWHC	[illegible] INS		[illegible]	5-5-96	
50134678	12-8-96		G-UKID	WTL		Overhaul	28-8-96	
50138355	25-11-96			VIBS ON RETRACTION		[illegible]	26-11-96	
50143637	1-5-97		G-WAC	WTL		[illegible]	23-5-97	
50147174	19-7-97		G-UKSC	WTL		TTL	15-8-97	
50154783	8-3-98		G-UKSC	W-T-L		TYRE CHANGE - NEW OUTBD BEARING SEAL - NEW INBD/OUTBD BEARINGS	23-3-98	
50160532	1-9-98		G-UKSC	WTL		INBOARD BEARING REPLACED - TYRE CHANGE	5 SEP 1998	
50168338	5-5-99		G-WAC	WTL		[illegible]	10 MAY 1999	
50171973	20-8-99		G-WHP	WTL		TYRE CHANGE	1 SEP 1999	

HV178 AHA1349

Figure 8.2 - BAe146 Nose Wheel overhaul service record cards.



AirUK engineering

BAY SERVICING RECORD SHEET

60064

Full nomenclature of Equipment	PART NO	SERIAL NO
F100 MAIN WHEEL KLM	5008131-5	MAY88-0119 F / MAY88-0119 H
Permissible Life (if lifed item)		

WO	Date removed	TSO	Ex A/C	Reason for Unserviceability	Code	Remedial action taken/mods embodied	Date serviceable	Date Issued
50105770	20-9-9[illegible]		KLM	WTL 3162G591	G	NEW BOLTS	26 OCT	1994
50117692	[illegible]		KLM	WTL		D/T	30-8-95	
50131064	4-5-96		PH-KLE	WTL		O/H	28-5-9[illegible]	
50139289	2/8[illegible]		PH KLC	WTL			10-1-97	
50148716	9-9-97		G-UKFA	WTL		TYRE CHANGE NO NUTS POST F0100-32-20 NUTS	12-9-97	
50154450	27/2/98		G-UKFH	OVERLOADED		TYRE CHANGE - NEW OUTBOARD BEARING, 1 OFF BOLT REPLACED	23-3-98	
50155682	15-4-98		PH KLH	OVERSTRESSED		TYRE CHANGE	18-4-98	
50160451	4/6/98		G-UKFO	W-T-L			18-9-98	
50165881	4/2/99		G-UKFC	CUT TO CORDS			9 FEB	1999
50170949	21-7-99		G-UKFD	WTL		TYRE CHANGE	27 JUL	1999
50174298	28-10[illegible]		G-UKFF	WTL		TYRE CHANGE	5 NOV	1999
50180767	25-05-00		G-?	WTL		O/HAUL	3 JUL	2000
MAY88-0119				5008131-5		E0-32-1042 COMPLIANT		

AirUK engineering

BAY SERVICING RECORD SHEET

60064

Full nomenclature of Equipment	PART NO	SERIAL NO
F100 MAIN WHEEL KLM	5008131-5	FEB89-0214 F / FEB89-0214 H
Permissible Life (if lifed item)		

WO	Date removed	TSO	Ex A/C	Reason for Unserviceability	Code	Remedial action taken/mods embodied	Date serviceable	Date Issued
50104629	4-8-94		KLM	IAR		INSPECTION SAT	25-8-94	
50112572	5-2-95		3 UKFE	WTL		MOD	10-3-95	
50120001	4-8-95		PH-KLG	WTL			21-9-95	
50124826	15-11-95		KLQ	WTL		NEW BOLTS	21-12-95	
50139908	28-1-97		PH-KLT	WTL			21-1-97	
50144516	28-5-97		PH KLC	WTL			11-6-97	
50150673	6/11/97		PH-KLH	W-T-L		TYRE CHANGE - NUTS REPLACED	21-11-97	
50155699	4-4-98		G-UKFH	CUT TO CORDS		TYRE CHANGE	23-4-98	
50159242	4-8-98		GUKFE	CUT TO CORDS	O/H	RP12-1 CARRIED OUT - REPAINTED, 1 NEW BOLT, 2 BEARING CUPS - TYRE CHANGE	12 JAN	1999
50169062	26-6-99		G-UKFO	WTL		tyre changed	3 JUN	1999
50176019	16-11-99		G-UKFI	WTL		TYRE CHANGE	14 JAN	2000
50181366	1/4/00		G-UKFR	WTL				
FEB89-0214				5008131-5		E0-32-1042		

Figure 8.3 - Fokker100 Main Wheel overhaul service record cards.

AirUK engineering

BAY SERVICING RECORD SHEET

60064

Full nomenclature of Equipment	PART NO	SERIAL NO
F100 NOSE WHEEL (KLM)	5008133-1	FEB96-1713

Permissible Life (if lifed item)

WO	Date removed	TSO	Ex A/C	Reason for Unserviceability	Code	Remedial action taken/mods embodied	Date serviceable	Date Issued
50128438	1-3-96		STORE	FOR BUILD		[illegible] FITTED	26-7-96	
50136987	23-10-96		PH-KLI	LEAKING		[illegible]	31-10-96	
50140691	11-2-97		PH-KLE	WTC		[illegible]	13-2-97	
50141308	13-3-97		G-UKFH	[illegible]		[illegible] SHC 100 Grease used	01-4-97	
50145657	21-6-97		G-UKFE	WTC		[illegible]	19-8-97	
50151809	12/12/97		G-UKFO	W-T-C		TYRE CHANGE	19.12.97	
50155529	8-4-98		G-UKFC	WTC		TYRE CHANGE	24-4-98	
50157518	15-6-98		G-UKFE	WTC		TYRE CHANGE	07 JUL 1998	
50163919	16/12/98		G-UKFR	WTC		[illegible]	04 JAN 1999	
50168075	25-4-99		G-UKFK	WTC		tyre changed	12 MAY 1999	
50170693	15-7-99		G-UKFC	WTC		OVERHAUL	2 AUG 1999	
50174109	25/10/99		G-UKFM	WTC	1	[illegible]	09 NOV 1999	

FEB96-1713 5008133-1

AirUK engineering

BAY SERVICING RECORD SHEET

60064

Full nomenclature of Equipment	PART NO	SERIAL NO
F100 NOSEWHEEL ASSY (KLM)	5008133	JAN89-0173

Permissible Life (if lifed item)

WO	Date removed	TSO	Ex A/C	Reason for Unserviceability	Code	Remedial action taken/mods embodied	Date serviceable	Date Issued
50146803	20/7/97		GUKFC	WTC		TYRE CHANGE	31-7-97	
50147833	21/8/97		G-UKFE	FLAT SPOT		[illegible]	1-9-97	
50156431	1/5/98		PH-KLH	VIBRATION		[illegible]	15-5-98	
50159724	10/8/98		G-UKFH	WTC		TYRE CHANGE	27 AUG 1998	
50164031	14/12/98		G-UKFB	W-T-C		[illegible]	04 JAN 1999	
50166783	19/2/99		G-UKFP	W.T.C		[illegible]	19 MAR 1999	
50169352	7-6-99		G-UKFO	WTC		[illegible] O/H	08 JUN 1999	
50174404	2-11-99		G-UKFK	WTC		[illegible]	08 NOV 1999	
50179988	17/5/00		G-UKFG	W-T-C		[illegible]	19 MAY 2000	
50182990	31/7/00		G-UKFK	WTC				

JAN89-0173 5008133

Figure 8.4 - Fokker100 Nose Wheel overhaul service record cards.

BAY SERVICING RECORD SHEET

AirUK engineering

1a

60064

Full nomenclature of Equipment	PART NO	SERIAL NO
F100 REFRIGERATION UNIT Permissible Life (if lifed item)	2203480 - 2	78-169

WO	Date removed	TSO	Ex A/C	Reason for Unserviceability	Code	Remedial action taken/mods embodied	Date Serviceable	Date Issued
50157834	19/6 98	(LH)	G- [illegible] UKFH	CLEANING/INSP (FOR REFIT)		TURBINE SN 77-172 U/S / NEW TURBINE SN. 116-134 FITTED	24/6/98	
50162644	5/11/98	3788-11	G LH UKFH	VERY NOISY IN OPERATION.		CLEANED, TURBINE SN 116-134 U/S NEW TURBINE FITTED SN 98-218	12/11/98	
50164749	13/1/99	4050.48 257 HOURS	LH G-UKFB	NOISY.		SERVICED. NO FAULT FOUND. SAME HEATEX & TURBINE HEATEX 17445 TURBINE 98-218	18/1/99	
50168674	11/5/99		LH G-UKFH	BROKEN TURBIN		NEW TURBINE FITTED 102-373-UGN	17/5/99	

78-169 2203480-2

ABS AUTHORISED DEVIATION NB1A5-108 AIR UK CON 4050/875

BAY SERVICING RECORD SHEET (TW) (7R32-2)

AirUK engineering

5

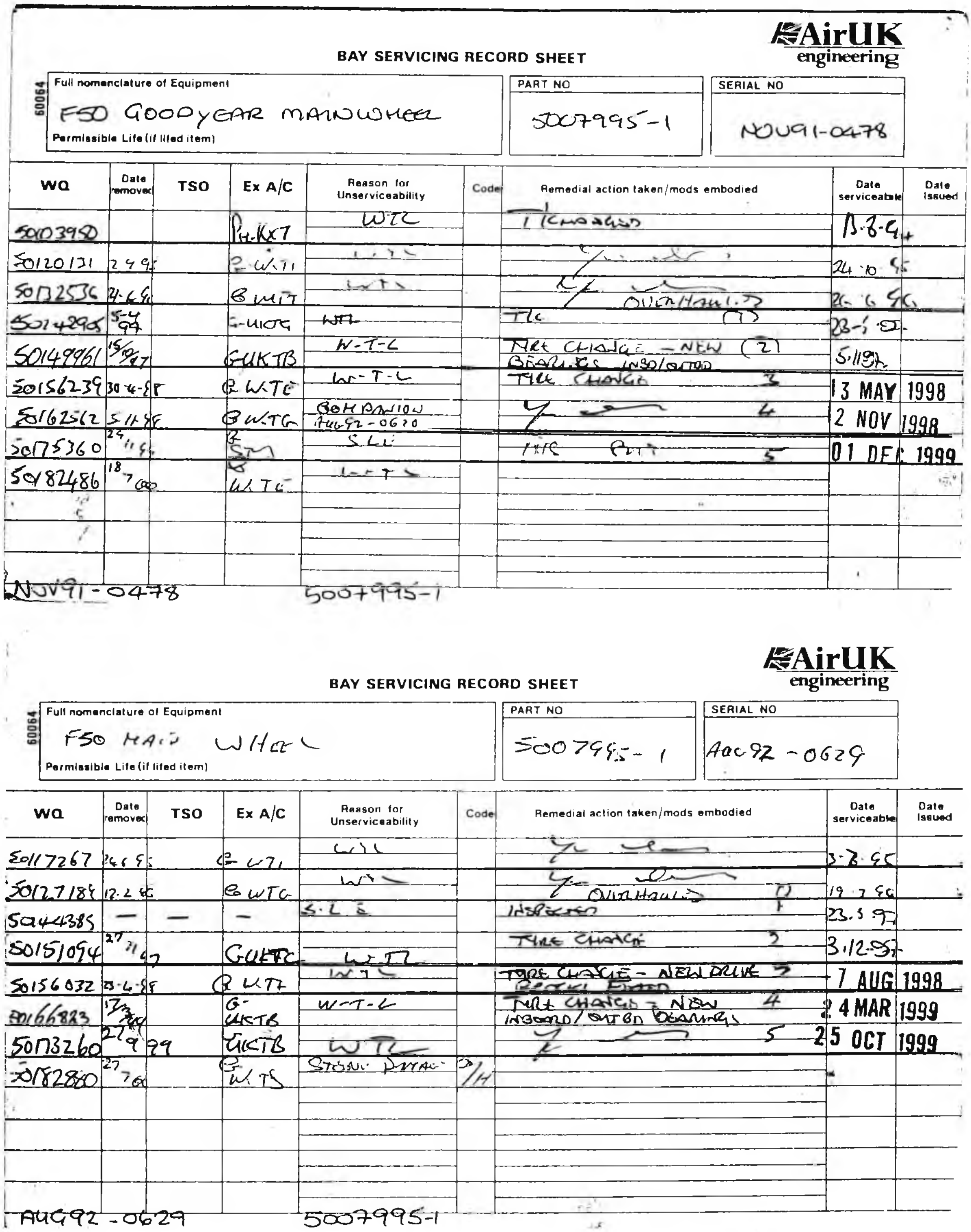
60064

Full nomenclature of Equipment	PART NO	SERIAL NO
F100 ABS BRAKE UNIT Permissible Life (if lifed item)	A5011809-2	JAN89-0054K

WO	Date removed	TSO	Ex A/C	Reason for Unserviceability	Code	Remedial action taken/mods embodied	Date serviceable	Date issued
50116518	3/6/95	-	FA	WTC	CP	UNIT OVERHAULED SB32-63 THICK STACK	31/7/95	
50122656	22/10/95	-	FG	SNATCHY	CP	UNIT LEAK + FUNCTION CHECKED	31/10/95	
50131465	10/5/96	-	FJ	LEAKING SHUTTLE VALVE	CP.	NEW SHUTTLE VALVE FITTED. CLEANED, LEAK + FUNCTION CHECKED.	23/5/96	
50137781	21/7/96	-	FG.	SHUTTLE VALVE LEAKING	CP.	SH. VALVE SPOOL RE-SEATED. CLEANED, LEAK + FUNCTION CHECKED.	31/10/96	
50146677	3/7/97	-	FI	DAMAGED UNION LOSS.	-	[illegible] GO2 [illegible] COST [illegible] [illegible] 5697-0882 04 NOV 1997		
50149813.	4/6/99	-	FG.	WTC	-2	HOUSING Q.P. [illegible] 503504-2 [illegible] VALVE [illegible] 0497-0429.	17 JUL 1999	

JAN 89-0054K (A5011809)-2

Figure 8.5 - Fokker100 Refrigeration and Brake Unit overhaul service record cards.



AirUK engineering

BAY SERVICING RECORD SHEET

60064

Full nomenclature of Equipment	PART NO	SERIAL NO
F50 GOODYEAR MAINWHEEL	5007995-1	NOV91-0478

Permissible Life (if lifed item)

WO	Date removed	TSO	Ex A/C	Reason for Unserviceability	Code	Remedial action taken/mods embodied	Date serviceable	Date issued
5003950			PH-KXT	WTC		TT changed	13-8-94	
50120131	2 4 95		G-UKTI	WTL		[illegible]	24-10-95	
50132536	24-6-96		G UKTI	WTL		Overhaul (1)	26-6-96	
50142965	5-4-97		G-UKTG	WTL		TTC (1)	23-5-97	
50149961	15/10/97		G UKTB	W-T-L		Tyre change – new (2) bearings inbd/outbd	5.11.97	
50156239	30-4-98		G WTE	W-T-L		Tyre change 3	13 MAY 1998	
50162562	5 11 98		G WTG	BOH [illegible] AUG92-0620		[illegible] 4	2 NOV 1998	
50175360	24 11 99		G SM	S.L.L		Tyre fit 5	01 DEC 1999	
50182486	18 7 00		G WTE	W-T-L				

NOV91-0478   5007995-1

AirUK engineering

BAY SERVICING RECORD SHEET

60064

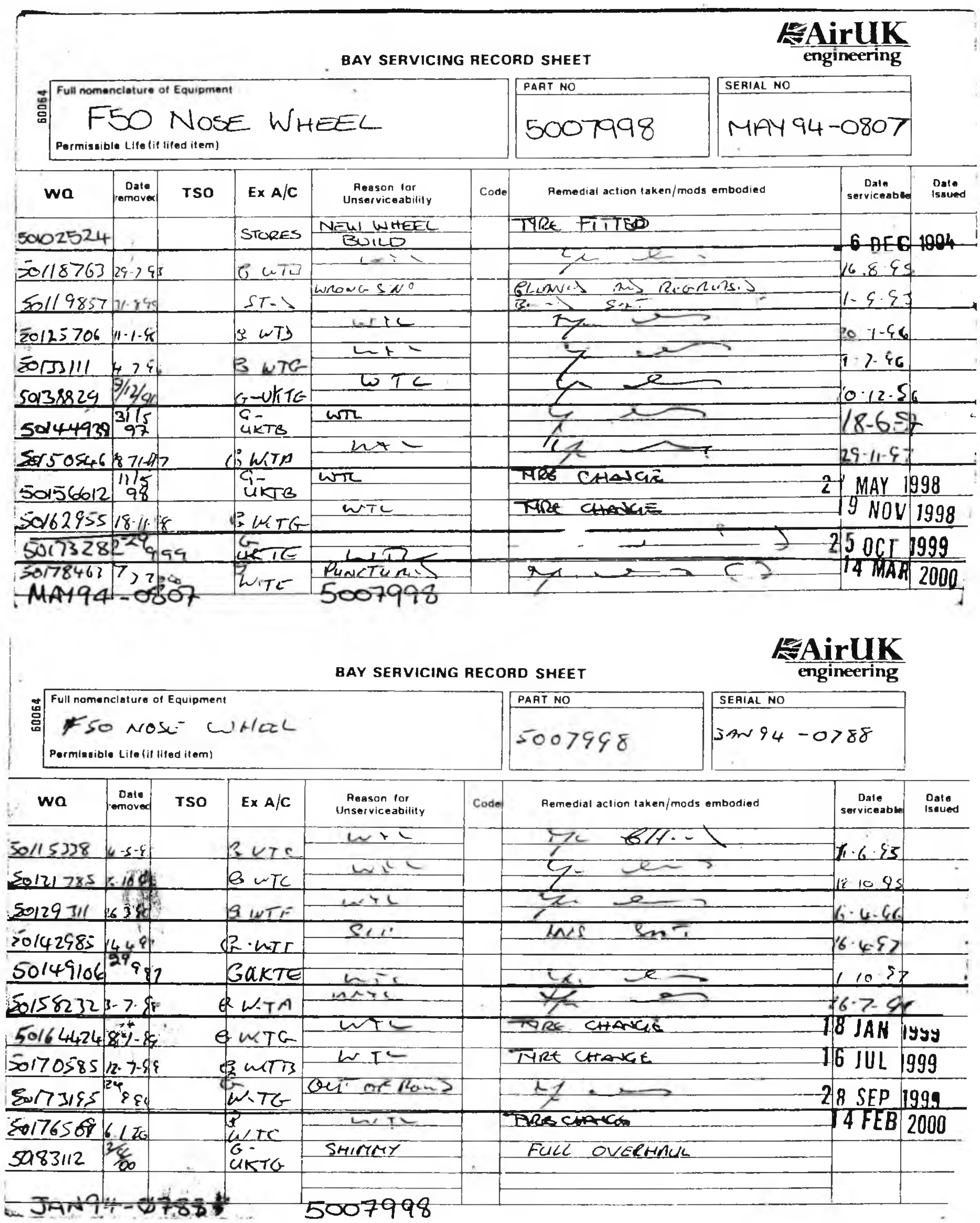
Full nomenclature of Equipment	PART NO	SERIAL NO
F50 MAIN WHEEL	5007995-1	AUG92-0629

Permissible Life (if lifed item)

WO	Date removed	TSO	Ex A/C	Reason for Unserviceability	Code	Remedial action taken/mods embodied	Date serviceable	Date issued
50117267	24 6 95		G WTI	WTL		[illegible]	3-8-95	
50127188	12.2.96		G WTG	WTL		Overhaul (1)	19 7 96	
50144385	—	—	—	S.L.L		Inspected	23.5.97	
50151094	27 11 97		G UKTC	WTL		Tyre change 2	3.12.97	
50156032	15-6-98		G WTL	WTL		Tyre change – new [illegible] bearing fitted 3	7 AUG 1998	
50166823	17 2 99		G-UKTB	W-T-L		Tyre change – new inboard/outbd bearings 4	24 MAR 1999	
50173260	27 9 99		UKTB	WTL		[illegible] 5	25 OCT 1999	
50182880	27 7 00		G WTS	Stone damage	D/H			

AUG92-0629   5007995-1

Figure 8.6 - Fokker50 Main Wheel overhaul service record cards.



AirUK engineering

BAY SERVICING RECORD SHEET

60064

Full nomenclature of Equipment: F50 NOSE WHEEL
Permissible Life (if lifed item)

PART NO: 5007998

SERIAL NO: MAY 94-0807

WO	Date removed	TSO	Ex A/C	Reason for Unserviceability	Code	Remedial action taken/mods embodied	Date serviceable	Date Issued
50102524			STORES	NEW WHEEL BUILD		TYRE FITTED	6 DEC 1994	
50118763	29-7-95		G-WTD	[illegible]		[illegible]	16-8-95	
50119857	31-8-95		ST-[illegible]	WRONG S/N°		[illegible]	1-9-95	
50125706	11-1-96		G-WTD	WTC		[illegible]	20-1-96	
50133111	4-7-96		G-WTG	WTC		[illegible]	9-7-96	
50138829	9/12/96		G-UKTG	WTC		[illegible]	10-12-96	
50144939	31/5/97		G-UKTB	WTL		[illegible]	18-6-97	
50150546	8-11-97		G-WTA	WTC		[illegible]	29-11-97	
50156612	11/5/98		G-UKTB	WTL		TYRE CHANGE	21 MAY 1998	
50162955	18-11-98		G-WTG	WTC		TYRE CHANGE	19 NOV 1998	
50173282	22-9-99		G-UKTE			[illegible]	25 OCT 1999	
50178463	7-?-00		G-WTE	PUNCTURE		[illegible]	14 MAR	2000

MAY94-0807 5007998

AirUK engineering

BAY SERVICING RECORD SHEET

60064

Full nomenclature of Equipment: F50 NOSE WHEEL
Permissible Life (if lifed item)

PART NO: 5007998

SERIAL NO: JAN 94-0788

WO	Date removed	TSO	Ex A/C	Reason for Unserviceability	Code	Remedial action taken/mods embodied	Date serviceable	Date Issued
50115338	4-5-95		G-UKTC	WTC		[illegible]	11-6-95	
50121785	[illegible]-10-95		G-WTC	WTC		[illegible]	18-10-95	
50129311	16-3-96		G-WTF	WTC		[illegible]	6-4-96	
50142985	14-4-97		G-WTF	[illegible]		[illegible]	16-4-97	
50149106	29-9-97		G-UKTE	WTC		[illegible]	1-10-97	
50158232	3-7-98		G-WTA	WTC		[illegible]	16-7-98	
50164424	8-1-99		G-WTG	WTC		TYRE CHANGE	18 JAN	1999
50170585	12-7-99		G-WTB	WTC		TYRE CHANGE	16 JUL	1999
50173195	24-9-99		G-WTG	OUT OF ROUND		[illegible]	28 SEP	1999
50176568	6-1-00		G-WTC	WTC		TYRE CHANGE	14 FEB	2000
50183112	3/4/00		G-UKTG	SHIMMY		FULL OVERHAUL		

JAN94-0788 5007998

Figure 8.7 - Fokker50 Nose Wheel overhaul service record cards.

Table 8.1 - A summary of KLM-uk workshop overhaul components.

#	Component Description	Part Number	Aircraft Type	Quantity Per Aircraft	Fleet Size	Maintenance Processes	Period MTBO	Period MTBR	Repair TAT	Time Series
1	Air Conditioning Unit	2203480-2	Fokker 100	2	17	HT	2000 FHs	854 FHs	20 MHs	95 - 99
2	Alternator Unit	No 406-3	Fokker 27	2	16	HT	2500 FHs	1250 FHs	20 MHs	92 - 94
3	Battery - Ultra pure	4078-8	Fokker 50	2	9	HT	1000 FHs	12 Weeks	5 MHs	95 - 00
4	Battery - distilled water	4608-1	Fokker 100	2	17	HT	1000 FHs	12 Weeks	5 MHs	94 - 00
5	Battery - Lead Acid	40678-2	ATR-72	1	5	HT	1000 FHs	12 Weeks	5 MHs	98 - 00
6	Brake Assembly (Heat Pack)	AH 52220	Fokker 27	4	16	CM	750 FLs	700 FLs	20 MHs	89 - 95
7	Brake Assembly (Brake Unit)	AH 52220	Fokker 27	4	16	CM	5000 FLs	1200 FLs	25 MHs	89 - 95
8	Brake Assembly Unit	AHA 2174-5	BAe 146	4	13	HT	9600 FLs	1500 FLs	24 MHs	90 - 99
9	Brake Assembly Unit	5011809-2	Fokker 100	4	17	CM	2500 FLs	2500 FLs	24 MHs	94 - 99
10	Brake Assembly Unit	5007996-1	Fokker 50	4	9	HT	3600 FLs	1200 FLs	18 MHs	95 - 99
11	Brake Control Valve	AC 61348	Fokker 27	2	16	HT	6600 FHs	3420 FHs	10 MHs	89 - 94
12	Combustion Chamber	RK 49159A	Fokker 27	2×7	16	CM	1200 FHs	1200 FHs	28 MHs	92 - 95

HT, Hard Time CM, Condition Monitored FHs, Flying Hours FLs, Flying Landings MHs, Man-Hours TAT, Turn Around Time

* Overhaul at every 5^{th} tyre change MTBO, Mean Time Between Overhaul MTBR, Mean Time Between Removal

Table 8.1 - A summary of KLM-uk workshop overhaul components ~ continued

#	Component Description	Part Number	Aircraft Type	Quantity Per Aircraft	Fleet Size	Maintenance Processes	Period MTBO	Period MTBR	Repair TAT	Time Series
13	DC Generator	30E02-21G1	Fokker 27	2	16	HT	2500 FHs	1104 FHs	28 MHs	92 - 94
14	Drag Strut Unit	200261001	Fokker 27	2	16	HT	12000 FLs	3620 FLs	30 MHs	89 - 94
15	Inverter Assembly	1518-8-C	Fokker 27	2	16	HT	2700 FHs	617 FHs	17 MHs	92 - 94
16	Lock Strut Unit	200260001	Fokker 27	2	16	HT	12000 FLs	4510 FLs	45 MHs	89 - 94
17	Main Undercarriage Unit	200223001	Fokker 27	2	16	HT	12000 FLs	2882 FLs	250 MHs	89 - 94
18	Main Wheel Overhauled	5008131-5	Fokker 100	4	17	HT	2500 FLs	1007 FLs	12 MHs	92 - 00
19	Main Wheel Tyre Changed	5008131-5	Fokker 100	4	17	CM	500 FLs	226 FLs	11 MHs	92 - 00
20	Main Wheel Overhauled	5007995-1	Fokker 50	4	9	HT	3500 FLs	1516 FLs	7 3/4 MHs	95 - 00
21	Main Wheel Tyre Changed	5007995-1	Fokker 50	4	9	CM	700 FLs	316 FLs	4 3/4 MHs	95 - 00
22	Main Wheel Overhauled	AHA 1489	BAe 146	4	13	HT	1600 FLs	1245 FLs	10 MHs	90 - 00
23	Main Wheel Tyre Changed	AHA 1489	BAe 146	4	13	CM	400 FLs	229* FLs	4 MHs	90 - 00
24	Main Wheel Overhauled	AHA 1890	ATR-72	4	5	HT	1800 FLs	1600 FLs	6 MHs	98 - 99

HT, Hard Time CM, Condition Monitored FHs, Flying Hours FLs, Flying Landings MHs, Man-Hours TAT, Turn Around Time

* Overhaul at every 5th tyre change MTBO, Mean Time Between Overhaul MTBR, Mean Time Between Removal

Table 8.1 - A summary of KLM-uk workshop overhaul components ~ continued.

#	Component Description	Part Number	Aircraft Type	Quantity Per Aircraft	Fleet Size	Maintenance Processes	Period MTBO	Period MTBR	Repair TAT	Time Series
25	Main Wheel Tyre Changed	AHA 1890	ATR-72	4	5	CM	450 FLs	133 FLs	6 MHs	98 - 00
26	Maxaret Anti Skid Unit	AC 63538	Fokker 27	2× 2	16	HT	4000 FLs	4000 FLs	16 MHs	89 - 94
27	Nose Undercarriage Unit	200490001	Fokker 27	1	16	HT	12000 FLs	3588 FLs	250 MHs	89 - 94
28	Nose Undercarriage Unit	201071001-3	Fokker 100	1	17	HT	20000 FLs	11495 FLs	220 MHs	96 - 00
29	Nose Wheel Overhauled	5008133-1	Fokker 100	2	17	HT	1250 FLs	1000 FLs	4.5 MHs	93 - 00
30	Nose Wheel Tyre Changed	5008133-1	Fokker 100	2	17	CM	250 FLs	122 FLs	3.5 MHs	93 - 00
31	Nose Wheel Overhauled	5007998	Fokker 50	2	9	HT	2500 FLs	906* FLs	3.5 MHs	95 - 00
32	Nose Wheel Tyre Changed	5007998	Fokker 50	2	9	CM	500 FLs	232 FLs	2.5 MHs	95 - 00
33	Nose Wheel Overhauled	AHA 1349	BAe 146	2	13	HT	1100 FLs	1100 FLs	5 MHs	90 - 00
34	Nose Wheel Tyre Changed	AHA 1349	BAe 146	2	13	CM	275 FLs	161 FLs	2 MHs	90 - 00
35	Nose Wheel Overhauled	AH 54474	ATR-72	2	5	HT	1200 FLs	527 FLs	6 MHs	98 - 00
36	Nose Wheel Tyre Changed	AH 54474	ATR-72	2	5	CM	300 FLs	135 FLs	3 MHs	98 - 00

HT, Hard Time CM, Condition Monitored FHs, Flying Hours FLs, Flying Landings MHs, Man-Hours TAT, Turn Around Time

* Overhaul at every 5th tyre change MTBO, Mean Time Between Overhaul MTBR, Mean Time Between Removal

Table 8.2 - Demand pattern categorisation: A summary of results

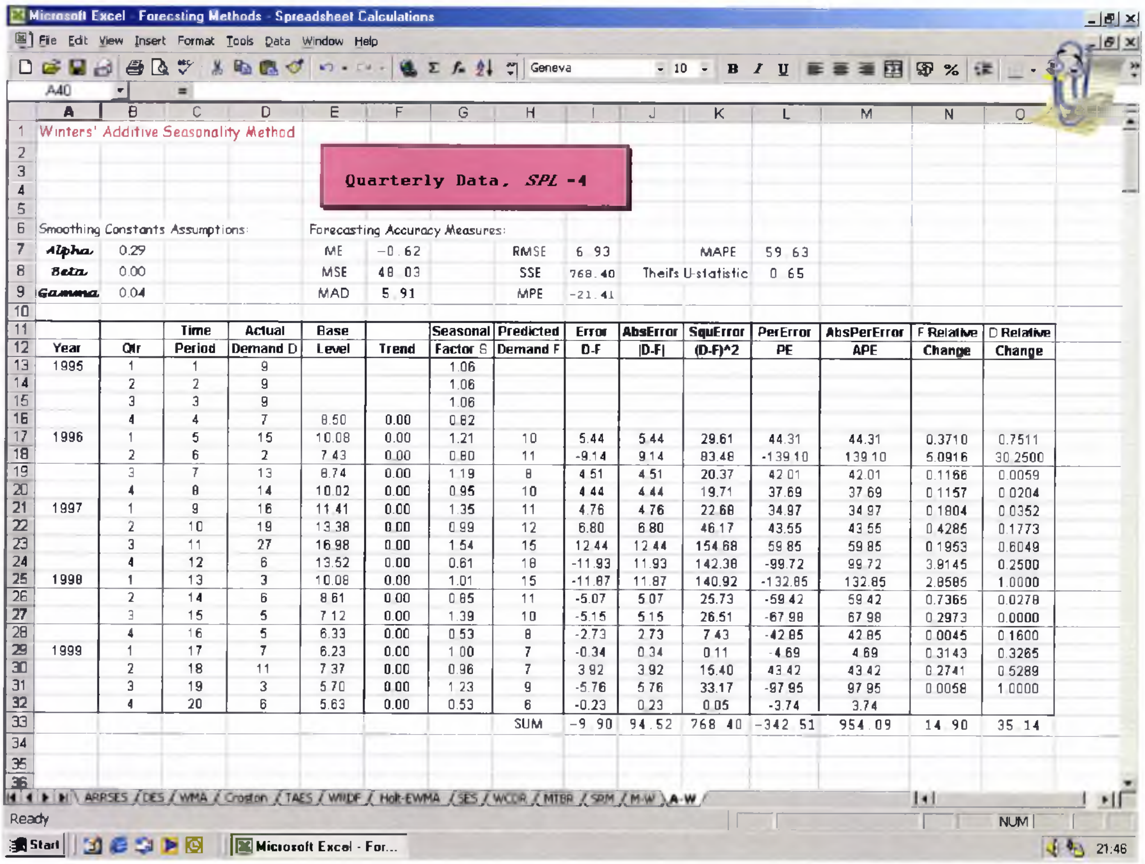
#	Component Description	Aircraft Type	weekly period ADI	weekly period CV^2	Demand Categorisation	monthly period ADI	monthly period CV^2	Demand Categorisation	quarterly period ADI	quarterly period CV^2	Demand Categorisation
1	Air Conditioning Unit	Fokker 100	2.5545	0.4466	erratic	1.1111	0.5029	intermittent	1.0000	0.3987	lumpy
2	Alternator Unit	Fokker 27	2.7636	0.3905	erratic	1.1667	0.3653	lumpy	1.0000	0.1886	lumpy
3	Battery - Ultra pure	Fokker 50	1.6358	0.2140	erratic	1.0000	0.2397	lumpy	1.0000	0.0321	lumpy
4	Battery - distilled water	Fokker 100	1.9314	0.2851	erratic	1.0685	0.3084	lumpy	1.0000	0.1156	lumpy
5	Battery - Lead Acid	ATR-72	1.9697	0.2655	erratic	1.0345	0.2284	lumpy	1.0000	0.1281	lumpy
6	Brake Assembly (Heat Pack)	Fokker 27	5.3529	0.1401	erratic	1.6471	0.3653	erratic	1.1200	0.3859	lumpy
7	Brake Assembly (Brake Unit)	Fokker 27	2.7923	0.2325	erratic	1.2000	0.3661	lumpy	1.0000	0.2285	lumpy
8	Brake Assembly Unit	BAe 146	2.8108	0.2479	erratic	1.2766	0.3516	lumpy	1.0500	0.3233	lumpy
9	Brake Assembly Unit	Fokker 100	2.5966	0.2564	erratic	1.2000	0.4711	lumpy	1.0400	0.2370	lumpy
10	Brake Assembly Unit	Fokker 50	1.9037	0.3348	erratic	1.0300	0.3902	lumpy	1.0000	0.1711	lumpy
11	Brake Control Valve	Fokker 27	4.1644	0.4633	erratic	1.4792	0.6414	smooth	1.0000	0.8090	intermittent
12	Combustion Chamber	Fokker 27	2.9420	0.3789	erratic	1.3429	0.5074	smooth	1.0667	0.4676	lumpy

Table 8.2 Demand pattern categorisation: A summary of results - continued

#	Component Description	Aircraft Type	weekly period *ADI*	*CV²*	Demand Categorisation	monthly period *ADI*	*CV²*	Demand Categorisation	quarterly period *ADI*	*CV²*	Demand Categorisation
13	DC Generator	Fokker 27	2.5172	0.3050	erratic	1.0625	0.3517	lumpy	1.0000	0.0539	lumpy
14	Drag Strut Unit	Fokker 27	5.3793	0.4727	erratic	1.8000	0.9444	smooth	1.2000	0.6233	intermittent
15	Inverter Assembly Unit	Fokker 27	1.3220	0.2873	erratic	1.0000	0.2182	lumpy	1.0000	0.1353	lumpy
16	Lock Strut Unit	Fokker 27	5.9600	0.4061	erratic	1.9714	0.5212	smooth	1.1000	0.5263	intermittent
17	Main Undercarriage Unit	Fokker 27	4.5882	0.2069	erratic	1.7561	0.4598	erratic	1.0900	0.4801	lumpy
18	Main Wheel Overhauled	Fokker 100	2.0000	0.4763	erratic	1.0900	0.5297	intermittent	1.0000	0.4328	lumpy
19	Main Wheel Tyre Changed	Fokker 100	1.1720	0.4609	lumpy	1.0100	0.2202	lumpy	1.0000	0.1152	lumpy
20	Main Wheel Overhauled	Fokker 50	3.3256	0.3080	erratic	1.4667	0.4485	erratic	1.1000	0.3799	lumpy
21	Main Wheel Tyre Changed	Fokker 50	1.3119	0.4063	lumpy	1.0000	0.2004	lumpy	1.0000	0.0620	lumpy
22	Main Wheel Overhauled	BAe 146	3.1034	0.2023	erratic	1.2500	0.4271	lumpy	1.0000	0.3825	lumpy
23	Main Wheel Tyre Changed	BAe 146	1.1793	0.5031	intermittent	1.0246	0.2052	lumpy	1.0000	0.1178	lumpy
24	Main Wheel Tyre Changed	ATR-72	1.6329	0.3027	erratic	1.0700	0.3392	lumpy	1.0000	0.2869	lumpy

Table 8.2 Demand pattern categorisation: A summary of results - continued

#	Component Description	Aircraft Type	weekly period ADI	weekly period CV^2	Demand Categorisation	monthly period ADI	monthly period CV^2	Demand Categorisation	quarterly period ADI	quarterly period CV^2	Demand Categorisation
25	Maxaret Anti Skid Unit	Fokker 27	1.4118	0.3960	erratic	1.0000	0.3072	lumpy	1.0000	0.1796	lumpy
26	Nose Undercarriage Unit	Fokker 27	7.7250	0.3542	erratic	2.3226	0.3186	erratic	1.2632	0.3030	lumpy
27	Nose Undercarriage Unit	Fokker 100	7.3125	0.0710	erratic	2.1600	0.1633	erratic	1.3846	0.3478	erratic
28	Nose Wheel Overhauled	Fokker 100	4.9367	0.6487	smooth	1.9149	0.6111	smooth	1.3043	0.4276	lumpy
29	Nose Wheel Tyre Changed	Fokker 100	1.2500	0.4597	lumpy	1.0100	0.2839	lumpy	1.0000	0.2033	lumpy
30	Nose Wheel Overhauled	Fokker 50	10.8846	0.2522	erratic	3.0000	0.3829	erratic	1.5714	0.5200	smooth
31	Nose Wheel Tyre Changed	Fokker 50	1.5294	0.3522	erratic	1.0200	0.2599	lumpy	1.0000	0.0439	lumpy
32	Nose Wheel Overhauled	BAe 146	7.2297	0.5148	smooth	2.8182	1.2321	smooth	1.6800	1.6522	smooth
33	Nose Wheel Tyre Changed	BAe 146	1.5648	0.4660	erratic	1.0413	0.3253	lumpy	1.0000	0.1281	lumpy
34	Nose Wheel Overhauled	ATR-72	20.8333	0.0000	erratic	5.8000	0.1111	erratic	2.5000	0.1111	erratic
35	Nose Wheel Tyre Changed	ATR-72	2.5000	0.3185	erratic	1.2083	0.3387	lumpy	1.0000	0.2636	lumpy


Winters' Additive Seasonality Method

Quarterly Data, *SPL* -4

Smoothing Constants Assumptions:

Alpha	0.29
Beta	0.00
Gamma	0.04

Forecasting Accuracy Measures:

ME	-0.62	RMSE	6.93	MAPE	59.63
MSE	48.03	SSE	768.40	Theil's U-statistic	0.65
MAD	5.91	MPE	-21.41		

Year	Qtr	Time Period	Actual Demand D	Base Level	Trend	Seasonal Factor S	Predicted Demand F	Error D-F	AbsError |D-F|	SquError (D-F)^2	PerError PE	AbsPerError APE	F Relative Change	D Relative Change
1995	1	1	9			1.06								
	2	2	9			1.06								
	3	3	9			1.06								
	4	4	7	8.50	0.00	0.82								
1996	1	5	15	10.08	0.00	1.21	10	5.44	5.44	29.61	44.31	44.31	0.3710	0.7511
	2	6	2	7.43	0.00	0.80	11	-9.14	9.14	83.48	-139.10	139.10	5.0916	30.2500
	3	7	13	8.74	0.00	1.19	8	4.51	4.51	20.37	42.01	42.01	0.1166	0.0059
	4	8	14	10.02	0.00	0.95	10	4.44	4.44	19.71	37.69	37.69	0.1157	0.0204
1997	1	9	16	11.41	0.00	1.35	11	4.76	4.76	22.68	34.97	34.97	0.1804	0.0352
	2	10	19	13.38	0.00	0.99	12	6.80	6.80	46.17	43.55	43.55	0.4285	0.1773
	3	11	27	16.98	0.00	1.54	15	12.44	12.44	154.68	59.85	59.85	0.1953	0.6049
	4	12	6	13.52	0.00	0.61	18	-11.93	11.93	142.38	-99.72	99.72	3.9145	0.2500
1998	1	13	3	10.08	0.00	1.01	15	-11.87	11.87	140.92	-132.85	132.85	2.8585	1.0000
	2	14	6	8.61	0.00	0.85	11	-5.07	5.07	25.73	-59.42	59.42	0.7365	0.0278
	3	15	5	7.12	0.00	1.39	10	-5.15	5.15	26.51	-67.98	67.98	0.2973	0.0000
	4	16	5	6.33	0.00	0.53	8	-2.73	2.73	7.43	-42.85	42.85	0.0045	0.1600
1999	1	17	7	6.23	0.00	1.00	7	-0.34	0.34	0.11	-4.69	4.69	0.3143	0.3265
	2	18	11	7.37	0.00	0.96	7	3.92	3.92	15.40	43.42	43.42	0.2741	0.5289
	3	19	3	5.70	0.00	1.23	9	-5.76	5.76	33.17	-97.95	97.95	0.0058	1.0000
	4	20	6	5.63	0.00	0.53	6	-0.23	0.23	0.05	-3.74	3.74		
							SUM	-9.90	94.52	768.40	-342.51	954.09	14.90	35.14

Figure 8.8 - The forecasting spreadsheet calculations for Air Conditioning Unit.

8.5.2 Experimental factors

In this research we examine the effect of thirteen forecasting methods on the aircraft maintenance inventory system in an experiment incorporating a variety of environmental factors and under widespread demand variations. These resulted in 1,365 observations per forecast accuracy measuring technique, giving a total of 9,555 runs to measure their forecasting performance (section 4, briefly summarises the philosophy of these techniques).

The following four environmental factors were included in the experiment: the seasonal period length, *SPL*; primary maintenance process, *PMP*; square coefficient of variation on demand, CV^2 and the average inter-demand interval, *ADI*. Since actual values for CV^2 and *ADI* were used, they are taken as covariate factors, whereas *SPL* and *PMP* are selected as categorical factors. The factor levels may be different from those of other research studies since, as this study is concerned with aviation maintenance, most variables were covariates rather than categorical variables. Table 8.3 summarises the four factors and a description follows.

Factor	Description	Levels	Values	Units
SPL	Seasonal period length	3	4, 12, 52	quarters, months, weeks
PMP	Primary maintenance processes	2	*HT*, *CM*	flight hours or landings
CV^2	Square coefficient of variation	-	0.0 to 1.65	-
ADI	Average inter-demand interval	-	1.0 to 20.83	-

Table 8.3 Environmental factors, (-) indicates covariates factor

8.5.2.1 Seasonal period length, SPL

This is the number of periods for which the demand pattern is forecasted. The most popular seasonal period length used by aviation companies [52, 55] is either a monthly or a quarterly one. The longer the time horizon of the forecasts, the greater the chance that established patterns and relationships will change, thereby invalidating forecasts. Thus forecasting accuracy decreases as the time horizon increases [63].

8.5.2.2 Primary maintenance process, PMP

The three primary maintenance processes recognised by the UK CAA [30] are hard-time, on-condition, and condition-monitoring (briefly discussed in Chapter two). In general terms, the first two both involve actions directly concerned with preventing failure, whereas the last does not. The condition-monitoring process is expected to lead to preventative action if shown to be necessary. The categories of component maintenance are as follows:

Hard-time, HT, which is defined as a preventive process in which known deterioration of an item is limited to an acceptable level by the maintenance actions carried out at periods related to time in service. This time may be calendar time, number of cycles, or number of landings. The prescribed actions normally include servicing, full or partial overhaul, or replacement according to instructions in the relevant documentation so that the item is restored to a condition suitable for use for a further specified period.

Condition-monitoring, CM, is not a preventive process, having neither hard-time nor on-condition elements, but one in which information on items, gained from operational experience, is collected, analysed, and interpreted on a continuing basis as a means of implementing corrective procedures. Models of decision aspects of condition-monitoring have concentrated upon cases where a direct measure of wear was available, such as the thickness of a brake pad in a braking system [29].

8.5.2.3 Demand size and average time interval factors, CV^2, ADI

Demand pattern classification, another distinguishing feature of this study, is when time series vary systematically according to their inherent variability. In this study the data demand patterns explicitly consider both the demand pattern and the size of demand when it occurs, which classify into four categories [122] based on modified Williams' criteria [137]. The definitions of the categories are as follows:

- *Intermittent demand* appears at random with many time periods having no demand.
- *Erratic demand* is (highly) variable. Erraticness relates to the demand size rather than demand per unit time period.
- *Slow moving demand* occurs at random with many time periods having no demand. Demand, when it occurs, is for single or very few units.
- *Lumpy demand* appears at random with many time periods having no demand. Moreover demand, when it occurs, is (highly) variable.

In this case the categorisation schemes have the following characteristics:

The "$ADI \leq x, CV^2 \leq y$" condition tries effectively to test for stock keeping units, SKUs, which are not very intermittent and erratic (i.e. faster moving parts or parts whose demand pattern does not raise any significant forecasting or inventory control difficulties).

The "$ADI > x, CV^2 \leq y$" condition tests for low demand items or intermittent demand patterns with constant, or more generally, no highly variable demand sizes (i.e. not very erratic).

The "$ADI > x, CV^2 > y$" condition tests for lumpy demand items, lumpy demand may be defined as a demand with great differences between each period's requirements and with a great number of periods with zero requests, and, finally

The "$ADI \leq x, CV^2 > y$" condition tests for erratic (irregular) demand items with rather frequent demand occurrences (i.e. not very intermittent).

Where x denotes the average inter-demand interval, *ADI*, cut-off value which measures the average number of time periods between two successive demands and y, the corresponding square coefficient of variation, CV^2, cut-off value, that is equal to the standard deviation of period requirements divided by the average period requirements. The four resulting demand categories are graphically presented in Figure 8.9 .

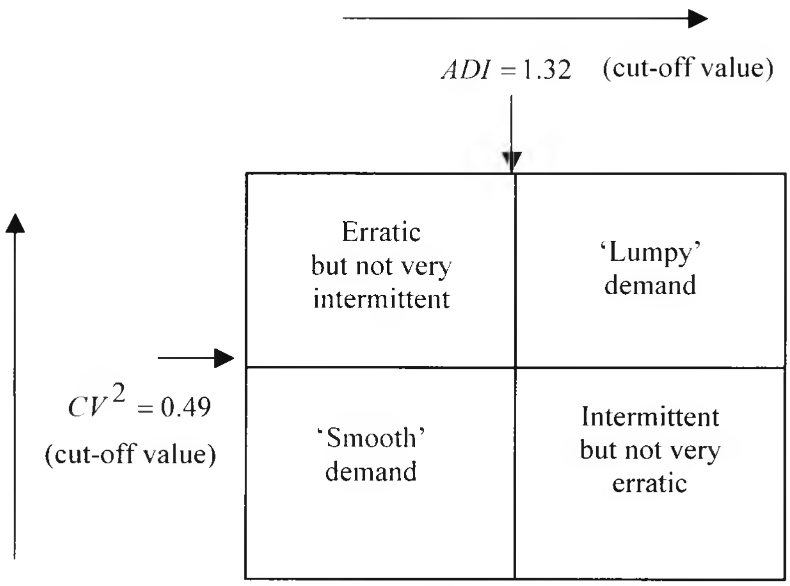


Figure 8.9 - Categorisation of demand patterns.

The cut-off values assigned in these criteria are the outcome of a numerical analysis conducted on the theoretical results [122]. The categorisation scheme should suggest in what different ways to treat the resulting categories. The objective in categorising demand patterns is the identification of the most appropriate forecasting and inventory control methods to be applied on the different demand categories. As such, categorisation schemes should explicitly suggest which methods should be used under which circumstances, and under what conditions one method is theoretically expected to perform more accurately than all the other methods. Willemain et al [136] conducted a comparative evaluation of Croston's method based upon the formally stated assumptions of independence (successive intervals are independent as are successive demand sizes, while intervals and sizes are mutually independent) and normality of the demand size. So if demand is modelled as the ratio of the demand size and inter-demand interval, then this ratio would not be a relevant factor in analysis of variance ANOVA as a performance measure. Therefore it is much more important to have two independent factors to indicate deviation of demand from the expected values, both in respect of demand size and inter-demand interval.

8.6 Sources of demand lumpiness in aircraft parts overhaul

The relationship between mean demand and flying hours/landings is not well understood. First, it is not at all clear that flying hours/landings are an appropriate "clock"; e.g., for landing gear what matters is not how long the aircraft is in the air, but how often it lands; also, some radar parts spend substantial amounts of time switched on and running while the aircraft is on the ground, so that flying hours understate the actual intensity of use. Second, there is no particular reason to assume that the relationship between flying hours and mean demands goes through the origin. Even if the aircraft simply sat in the hangars, some failures would inevitably occur. Thus in this section we investigate the sources of demand lumpiness based on several factors relating to the nature of airline operations, that may have certain effects on parts demand rate.

Airline operators are constantly faced with irregular operational problems that develop from severe weather patterns and unexpected aircraft or airport failures. This may result in the need to reschedule flight services and re-route aircraft. These actions cause flight delays and cancellations and disrupt aircraft maintenance scheduling [33]. Lumpiness may emerge as the consequence of such internal structural characteristics of the airline operations. Campbell [26] examined demand data from the USAF's maintenance, to explore relationships between demand and several operational variables. He concluded that demand seemed to be related to flying hours and sorties flown, with flying hours having the stronger relationship.

As any stock policy must operate implicitly or explicitly with some assumption of demand variability, it is important to note how sensitive stock requirements are in this area of airline operations. Unfortunately, there is a lack of research studies [26, 33] in the aviation sector on which to estimate the base demand variability and, more importantly, we have little understanding of the causes of such extreme fluctuations in demand. Clearly, we need to know more about the nature and causes of these fluctuations. It is hardly necessary to point out that this is a basic question, which from a management point of view is as important as choosing a specific target base fill rate.

The demand pattern for most spare parts (see, Table 8.2) tends to be erratic measured on a weekly basis. As such, even if the demand rate for a part is known for some past period, the future demand during a similar period cannot be predicted with accuracy. To reduce the occurrence of part shortages to a reasonably low level, it is not enough to predict (and use) average demand rates as most airline operators do [52, 55], but rather, it is necessary to know the source of these erratic demands. In this section we explore several factors that may have an effect on the main sources of lumpiness for aircraft parts' demand. Additional to previous factors (section 5.2), a further two factors, namely; *Aircraft utilization rate*, *AUR*, and *component's overhaul life*, *COL*, are examined in this section. Since actual values for *AUR* and *COL* were used, they are taken as covariate factors, whereas *PMP* is selected as a categorical factor. The additional two factors and their description follow.

8.6.1 Aircraft utilization rate, AUR

Aircraft do not generate revenue when they sit on the ground. Therefore, utilization is a variable that can affect successful operations, that is, the number of hours or cycles that an aircraft will fly, on average, e.g., 7.1 hours/day or 3.5 cycles/day. Over-utilisation of aircraft can lead to costly mechanical failure and may result in a shorter asset-life. So in most airlines with each aircraft capable of flying only a certain number of miles per working day, if for instance the total mileage scheduled is somewhat less than the maximum, they may be able to squeeze out a few more flights. This flight must be flown in the aircraft with the lowest number of flight miles and not necessarily the preferred aircraft. Most operators have an *Allowable limit* which is the maximum number of hours/cycles that an individual aircraft is allowed to fly between heavy maintenance[1] visits. When an aircraft crosses its allowable limit, it is grounded. Maintenance schedulers are closely involved in selecting aircraft for flight routes in order to control the movement of aircraft into maintenance.

8.6.2 Component's overhaul life, COL

Another factor, which may have an effect on producing lumpy demand is the overhaul life, for example; the undercarriage is a big item and has a long life. This is determined by flying hours/landings flow which helps the movement of aircraft parts into periodic maintenance tasks smoothly and systematically. This factor is controlled by MTBR and MTBO data. Each airline operator differs in the selection and setting of their overhaul

[1] Heavy maintenance inculds C and D checks (see Chapter two p.8).

data based on the recommendation provided by the component manufacture (see Table 8.1).

The above factors or characteristics of potential airline operation may be considered as sources of lumpiness which may occur separately or jointly. Hence beyond the general definition of lumpiness as irregular demand, lumpiness is actually a multidimensional phenomenon that may appear in different forms. Different sources of lumpiness may generate different types of irregularity in the demand. One may therefore argue that the approach to forecasting and managing a lumpy demand should depend on its source. In order to perform the experimental test, the demand generation process in this study was based on actual data collected from thirty-five components (a total of 2544 observations) and not simulated demand. Most studies simulate the demand per period from constituent events and probability density functions [5].

8.7 Experimental results and analysis

The results of this section are divided into three parts. The first part of the analysis discusses the main sources of demand lumpiness within aircraft parts inventory (Tables 8.4 to 8.5), followed by a further comparison of forecasting methods in terms of averaged MAPE (Tables 8.6 to 8.14), and subsequently these visual observations on the experimental results are examined and clarified through statistical analysis. Analysis of variance, ANOVA, is used to explain the variation attributable to the various experimental factors and their interactions. (Tables 8.16 to 8.22) present a summary of the general linear model, GLM, results and report the *p-values* for each of the main factors and their two-way interactions. For all methods, the 3rd and 4th order interactions were found to be insignificant and as such were eliminated from this analysis. A natural logarithm transformation of the dependent variable and some independent variables were used to overcome the problem of non-constancy of error variance in linear models, see [50].

Owing to space limitations, the GLM output results for all experimental factors are not presented here. However they are available on the attached CD disk at the back of this thesis (see Appendix E).

8.7.1 Sources of demand variability

Tables 8.4a and 8.4b present a summary of the general linear model (GLM) results for both square coefficient of variation, CV^2, and the average inter-demand interval, *ADI,* as dependent variables respectively and the independent variables *AUR*, *COL* and *PMP* where appropriate. *PMP* was a categorical variable and the others covariates. Table 8.5 give the significant coefficients of the fitted GLMs.

Factor	Type	Levels	Values
PMP	fixed	2	1 2

Analysis of Variance for CV^2, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
AUR	1	0.0508	1.5621	1.5621	38.26	0.000[1]
Log COL	1	3.9871	2.0200	2.0200	49.47	0.000[1]
PMP	1	0.0240	1.7041	1.7041	41.74	0.000[1]
AUR*Log COL	1	0.8510	1.2203	1.2203	29.89	0.000[1]
PMP*AUR	1	0.6114	2.0663	2.0663	50.61	0.000[1]
PMP*Log COL	1	0.4179	1.4710	1.4710	36.03	0.000[1]
PMP*AUR*Log COL	1	1.8162	1.8162	1.8162	44.48	0.000[1]
Error	2536	103.5439	103.5439	0.0408		
Total	2543	111.3024				

Table 8.4a - A summary of unbalanced ANOVA (GLM) results for CV^2 factors (*p*-values).

Factor	Type	Levels	Values
PMP	fixed	2	1 2

Analysis of Variance for ADI, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
AUR	1	7.810	3.943	3.943	5.51	0.019[5]
Log COL	1	109.464	1.097	1.097	1.53	0.216
PMP	1	72.022	1.808	1.808	2.53	0.112
AUR*Log COL	1	0.668	2.338	2.338	3.27	0.071
PMP*AUR	1	1.881	0.852	0.852	1.19	0.275
PMP*Log COL	1	1.388	0.801	0.801	1.12	0.290
PMP*AUR*Log COL	1	0.488	0.488	0.488	0.68	0.409
Error	2536	1815.519	1815.519	0.716		
Total	2543	2009.241				

Superscript [1] indicates significance at the 0.01 level.

Superscript [5] indicates significance at the 0.05 level.

No superscript denotes a lack of significance at both levels (at 0.01 and 0.05 level).

Table 8.4b - A summary of unbalanced ANOVA (GLM) results for ADI factors (*p*-values).

The demand lumpiness, measured by the square coefficient of variation, CV^2, (Table 8.4a) shows that all factors and their interactions were highly significant. From Table 8.5 the coefficient of *AUR* is positive, i.e. a higher *AUR* creates higher demand size. Also, log *COL* has a positive coefficient, i.e.; as the component's overhaul life is increased by the airline operator so the demand size pattern will increase as well. However, these two positive coefficients are offset by a negative coefficient of $AUR \times \log COL$, i.e. for larger *AURs* the effect of log *COL* reduces.

Primary maintenance processes, *PMP*, show that hard-time *HT* components have less effect in increasing average demand size, compared with condition-monitoring *CM*; this is because the *CM* concept allows a component to stay on the aircraft until it fails (unpredicted, e.g. tyre wear or brake pad thickness). The interaction of *PMP* with both *AUR* and log *COL* was found to be significant, indicating that as *AUR* increases the effect of *PMP* on demand size will increase for the hard-time and be reduced by condition-monitoring components. A similar story is found for log *COL;* as the component's overhaul life increases, the effect of *PMP* on demand size will increase with *HT* components and decrease for *CM*. The final significant interaction was $PMP \times AUR \times \log COL$. The interaction of these three factors indicates that hard-time components mediate the $PMP \times \log COL$ interaction with higher *AUR* (coefficients too small).

Demand lumpiness, measured by the average inter-demand interval, *ADI*, is a second dependent variable (response variable). Table 8.4b shows that only one factor *AUR* was found to be significant at the 5% level. This could be explained from Table 8.5, where the coefficient of *AUR* is negative, i.e. a lower *AUR* creates higher average inter-demand interval *ADI*. Further it was interesting to notice that there were no significant interactions, apart from $AUR \times \log COL$ which was only marginally significant (p = 0.071).

Response variables	AUR coefficient	log COL coefficient	PMP coefficients HT	CM	AUR * log COL
CV^2	**0.17986**	**0.18476**	**-1.2409**	**1.2409**	**-0.02187**
ADI	**-0.28580**	-0.13610	1.2783	-1.2783	0.03027

Significant factors and interactions shown in bold.

Response variables	PMP * AUR HT	CM	PMP * log COL HT	CM	PMP * AUR * log COL HT	CM
CV^2	**0.20686**	**-0.20686**	**0.15766**	**-0.15766**	**-0.026681**	**0.026681**
ADI	-0.13280	0.13280	-0.11640	0.11640	0.013830	-0.013830

Table 8.5 - Coefficients of fitted models: Sources of demand lumpiness (main effect).

Finally, this study shows that aircraft utilization rate *AUR* can be demonstrated to be a major source of lumpiness since it increases and decreases the square coefficient of variation CV^2, and the average inter-demand interval *ADI* respectively for the observed demand. This assumes a strictly linear relationship between demand and flying hours/landings. Thus if the planned flying hours programme increases inevitably the estimation of demand will increase too.

The data we tested in this study also shows a large change in the demand pattern; in particular for the Air Conditioning Unit in the last two years the 1998-99 periods (see Table 8.1and Figure 8.8), this was for many reasons. Firstly, faults on the component itself. Thus a modification was made on this component late in the year'97 which resulted in a reduction of component failure, where a decrease of demand for the part was observed. Secondly, the merger of the airline led the new operator to change and create new routes which technically had an environmental effect on the component function too. The other problem inside an airline is that the MTBF may change for some reason. The problem is that the true MTBF change continuously, as design, manufacturing, and quality control improve with experience. Thus replacement parts often have different failure characteristics to the originals. This type of failure may induce a certain amount of regularity to the demand pattern.

8.7.2 The evaluation of forecasting methods

The analysis of the results was mainly based on accuracy measurement techniques, which provide an indication of how large the forecast error is, in comparison to the actual values of the series. Tables 8.6 to 8.14 report averaged results for each accuracy measurement technique over the thirty-five components tested in this study.

These results were averaged based on the type of primary maintenance process, *PMP* (*HT & CM*). Tables 8.6, 8.8 and 8.10 indicate the results for *condition-monitored* components for quarterly, monthly and weekly *SPL* respectively. The WCDR method was shown to perform best for all accuracy measures except ME technique where Multiplicative Winter. MW was found to perform best for quarterly *SPL*. Similarly for a monthly *SPL*, we observed that the WCDR method in addition to the WMA and Croston methods were found to perform well in comparison with other accuracy measures. However, as *SPL* was selected for a weekly basis (i.e. increases in lumpiness), variations in accuracy measurement methods started to differ and give different results. The WMA method was found to be among the best performers.

Tables 8.7, 8.9 and 8.11, report the results for the *hard-time* components. For quarterly *SPL*, the SES method was found to perform best by most accuracy measurement techniques followed by MW and SRM methods. For a monthly *SPL*, the results show that the Croston and WMA methods and in addition SRM were found to perform well, while for a weekly *SPL* the performance of the methods starts to differ, and as such WMA and SES on average perform best.

Finally, Tables 8.12 to 8.14, report the overall results (combined for both components *HT* & *CM*), the WCDR method was found to perform best by most accuracy measurement techniques on a quarterly basis, where high seasonal data occurred MW and SRM were also found to perform better. On a monthly *SPL*, the results show that the Croston and WMA methods as well as SRM performed well, whereas for a weekly basis, the performance of the methods start to differ with WMA and WCDR also performing well.

For simplifying and segmenting the results in the previous Tables, we conducted an alternative approach by generating accuracy comparison results that indicate which estimation procedure performs better based on each of the four demand categories (see Figure 8.9). It is meaningful therefore to extend the analysis conducted here to propose rules which are valid across all the methods considered in this thesis. A summary of the test results made in this manner is presented in Table 8.15 . Henceforth, owing to limitations of space and its applicability to variability of demand we report only the MAPE analysis. Other studies in the research literature, including [42, 136] have used a similar procedure for measuring performance.

#	Forecast Methods	*ME*	*MSE*	*MAD*	*quarterly* *RMSE*	*SSE*	*MPE*	*MAPE*
1	ARRSES	-1.83316	89.780	6.35480	8.13008	1094.31	-15.90591	38.511
2	AW	-2.15385	80.175	6.25691	7.91477	872.80	-16.34224	38.885
3	Croston	-1.15909	94.930	6.58943	8.27850	1117.99	-12.87190	39.034
4	DES	-2.34768	96.687	6.76550	8.39672	1121.42	-18.43062	40.090
5	Holt	-2.07708	92.155	6.48624	8.31916	1089.55	-16.51038	37.678
6	MTBR	-5.21240	569.476	11.81045	13.28075	8181.93	-4.17905	52.398
7	MW	**0.21925**	98.395	6.83533	8.43033	1042.38	8.32041	54.702
8	SES	-1.48804	89.504	6.37000	8.08365	1072.07	-14.97428	38.429
9	SRM	-7.40750	420.808	12.23614	14.65469	4329.52	-23.87810	60.215
10	TAES	-1.12657	112.069	7.33312	8.90290	1289.05	-11.98082	44.946
11	WCDR	-0.54670	**47.774**	**4.77275**	**5.94394**	**628.74**	**0.61686**	**34.977**
12	WMA	-1.28487	94.843	6.68752	8.34094	1157.48	-13.18967	40.787
13	WRDF	-3.00120	111.848	7.08514	8.50862	1194.79	-16.86782	45.742

Table 8.6 A summary of average forecast accuracy measurement by quarterly period - condition monitored. (Best method performance shown in bold).

#	Forecast Methods	*ME*	*MSE*	*MAD*	*quarterly* *RMSE*	*SSE*	*MPE*	*MAPE*
1	ARRSES	-0.56741	30.78457	3.53099	4.67379	344.21	-17.081	66.763
2	AW	-0.65100	34.47485	4.17045	5.15090	360.90	-9.633	72.837
3	Croston	-0.39795	30.33611	3.55814	4.59743	320.01	-21.335	66.739
4	DES	-0.54346	31.0448	3.65025	4.68945	330.96	-19.388	69.388
5	Holt	-0.63963	31.97586	3.80935	4.70552	361.89	-16.273	66.519
6	MTBR	-4.63735	259.3701	7.94668	8.71314	1473.90	-26.588	83.104
7	MW	**-0.27614**	39.87631	4.60825	5.76963	456.02	14.800	83.702
8	SES	-0.69585	**28.21275**	**3.47240**	**4.48935**	**302.19**	-18.710	**61.353**
9	SRM	-0.49588	61.99974	5.37463	6.39834	666.92	**7.365**	94.675
10	TAES	-0.43284	29.3064	3.65201	4.67319	323.33	-16.001	71.543
11	WCDR	-0.95313	41.97934	3.97244	4.94106	352.17	-17.717	70.783
12	WMA	-0.84993	29.84904	3.60329	4.62571	329.96	-14.510	68.917
13	WRDF	-0.99069	30.88638	3.70015	4.65322	322.63	-24.649	66.752

Table 8.7 A summary of average forecast accuracy measurement by quarterly period - hard time.

#	Forecast Methods	*monthly* *ME*	*MSE*	*MAD*	*RMSE*	*SSE*	*MPE*	*MAPE*
1	ARRSES	-0.31206	20.338	3.23163	4.01264	769.25	-29.184	67.273
2	AW	-0.25716	24.262	3.44132	4.27537	879.04	-22.373	72.760
3	Croston	-0.42511	20.271	3.21247	3.96156	769.57	-30.366	**65.782**
4	DES	-0.52648	22.697	3.33935	4.17929	837.99	-27.988	70.269
5	Holt	-0.32595	24.690	3.40813	4.28342	890.24	-24.092	68.874
6	MTBR	-3.93557	95.761	5.78398	6.60694	4148.42	-42.316	82.760
7	MW	1.82661	39.365	4.36767	5.26855	1716.09	42.209	103.976
8	SES	-0.34225	21.005	3.33641	4.13087	821.83	-26.488	70.840
9	SRM	-0.67175	55.072	4.49799	5.51872	1851.26	-20.164	73.854
10	TAES	-0.22047	23.751	3.38010	4.24185	852.25	-20.473	70.292
11	WCDR	0.10121	**20.006**	**3.08545**	**3.79279**	**738.21**	-16.579	72.159
12	WMA	**-0.09733**	29.693	3.73959	4.69863	1083.28	**-14.401**	73.930
13	WRDF	-0.76983	20.558	3.33257	4.00185	751.69	-36.096	66.559

Table 8.8 A summary of average forecast accuracy measurement by monthly period - condition monitored.

#	Forecast Methods	*monthly* *ME*	*MSE*	*MAD*	*RMSE*	*SSE*	*MPE*	*MAPE*
1	ARRSES	-0.16430	6.73950	1.74566	2.32252	222.68	-49.766	103.117
2	AW	-0.12934	8.92558	2.02855	2.70911	272.43	-28.528	96.519
3	Croston	-0.16999	**5.76489**	**1.67160**	**2.17795**	**199.29**	-55.936	99.440
4	DES	-0.25133	6.70599	1.76612	2.36188	232.82	-38.012	95.780
5	Holt	-0.09255	6.81538	1.73130	2.32928	234.05	-44.869	102.943
6	MTBR	-1.81836	32.30787	3.16719	3.61958	593.56	-67.156	111.671
7	MW	0.11990	13.00342	2.57263	3.36291	373.86	24.398	105.166
8	SES	-0.26002	6.30776	1.71172	2.28779	219.24	-51.998	106.244
9	SRM	**-0.07529**	10.32488	2.15091	2.83530	318.27	**-11.502**	107.330
10	TAES	-0.09762	5.80430	1.67392	2.18372	201.57	-50.836	103.318
11	WCDR	-0.28552	6.97912	1.76585	2.28967	209.26	-54.069	103.839
12	WMA	-0.13547	7.58030	1.82495	2.48618	260.83	-20.977	**89.753**
13	WRDF	-0.27299	7.81361	1.79060	2.41773	256.25	-52.146	102.589

Table 8.9 A summary of average forecast accuracy measurement by monthly period - hard time.

#	Forecast Methods	*weekly*						
		ME	*MSE*	*MAD*	*RMSE*	*SSE*	*MPE*	*MAPE*
1	ARRSES	-0.05351	4.38122	1.39555	1.80688	728.34	-71.923	131.85
2	AW	-0.18779	3.86978	1.38277	1.81737	721.68	-35.992	102.83
3	Croston	-0.11363	3.85984	1.37623	1.70022	649.45	-78.376	125.81
4	DES	-0.02526	3.90925	1.33696	1.69906	656.49	-68.477	122.26
5	Holt	-0.13411	5.00006	1.41309	1.85392	763.80	-67.023	113.89
6	MTBR	-2.65351	18.96392	3.05082	3.48658	3305.41	-113.738	132.17
7	MW	-	-	-	-	-	-	-
8	SES	-0.15362	3.93904	1.40758	1.73028	654.08	-80.217	124.58
9	SRM	-0.97779	27.15801	2.40397	3.60342	5657.53	-53.114	113.63
10	TAES	-0.04914	**3.78549**	1.34457	1.67897	640.99	-76.811	127.01
11	WCDR	-0.01084	3.79876	**1.30650**	1.66569	**638.79**	-76.150	127.46
12	WMA	**-0.00365**	6.15989	1.51472	2.09385	1017.93	**-26.144**	**101.26**
13	WRDF	-0.19567	3.90698	1.40329	**0.0000**	643.21	-77.331	120.97

Table 8.10 A summary of average forecast accuracy measurement by weekly period - condition monitored. (-) indicates method was inapplicable, best method performance shown in bold.

#	Forecast Methods	*weekly*						
		ME	*MSE*	*MAD*	*RMSE*	*SSE*	*MPE*	*MAPE*
1	ARRSES	-0.04743	1.06211	0.68353	0.94695	156.73	-109.564	161.450
2	AW	-0.20076	2.22319	1.01012	1.39487	271.88	-63.774	127.544
3	Croston	-0.07601	1.01981	0.70062	0.91826	144.00	-94.151	159.541
4	DES	-0.05642	0.98642	0.67944	0.90800	138.17	-94.181	140.924
5	Holt	0.015627	1.03282	0.67571	0.91708	144.14	-107.754	160.469
6	MTBR	-0.67294	2.60241	1.10483	1.30326	296.79	-125.737	158.335
7	MW	-	-	-	-	-	-	-
8	SES	-0.03587	**0.96285**	**0.66383**	0.88980	**134.24**	-112.434	159.790
9	SRM	0.035474	1.67646	0.83556	1.20365	211.37	-46.077	119.736
10	TAES	-0.02948	0.97110	0.66890	0.89789	136.28	-112.211	159.422
11	WCDR	-0.06832	1.00026	0.67796	0.90309	136.78	-113.524	159.950
12	WMA	**-0.00093**	1.32010	0.69885	1.04156	183.95	**-25.398**	**91.914**
13	WRDF	-0.06173	0.98990	0.67832	**0.00000**	137.65	-106.337	152.680

Table 8.11 A summary of average forecast accuracy measurement by weekly period - hard time.

#	Forecast Methods	*quarterly* ME	MSE	MAD	RMSE	SSE	MPE	MAPE
1	ARRSES	-1.00138	51.012	4.49916	5.85881	601.39	-16.678	57.077
2	AW	-1.18142	50.605	4.90685	6.12639	541.57	-12.001	60.855
3	Croston	-0.65891	52.483	4.59744	5.85952	593.60	-18.433	57.240
4	DES	-1.16205	53.551	4.71833	5.96052	601.97	-19.060	59.343
5	Holt	-1.13247	52.609	4.72714	5.94448	611.37	-16.354	56.631
6	MTBR	-4.83451	365.692	9.27140	10.27918	3773.80	-18.905	72.576
7	MW	**-0.09600**	61.156	5.41810	6.73716	669.24	12.444	73.157
8	SES	-0.96746	49.227	4.46587	5.72168	566.15	-17.429	**53.493**
9	SRM	-2.93528	188.638	7.79634	9.31235	1959.60	**-3.662**	82.513
10	TAES	-0.67069	57.682	4.91411	6.12338	654.44	-14.623	62.424
11	WCDR	-0.81378	**43.966**	**4.24683**	**5.28491**	**447.00**	-11.431	58.507
12	WMA	-0.99905	52.133	4.66074	5.89951	613.68	-14.058	59.273
13	WRDF	-1.68001	58.645	4.86072	5.97507	621.65	-21.981	59.549

Table 8.12 A summary of average forecast accuracy measurement by quarterly period - overall results. (Best method performance shown in bold).

#	Forecast Methods	*monthly* ME	MSE	MAD	RMSE	SSE	MPE	MAPE
1	ARRSES	-0.21496	11.402	2.25514	2.90199	410.07	-42.710	90.828
2	AW	-0.17583	14.503	2.54229	3.27866	493.02	-26.290	87.880
3	Croston	-0.25746	**10.738**	**2.19990**	**2.78948**	394.81	-47.169	87.900
4	DES	-0.34567	12.189	2.30552	2.98499	440.30	-34.575	87.033
5	Holt	-0.17258	12.944	2.30622	2.99927	459.03	-37.746	91.262
6	MTBR	-2.54426	54.063	4.06438	4.64382	1812.37	-58.639	101.759
7	MW	0.86195	24.465	3.35309	4.19145	957.44	32.142	104.649
8	SES	-0.28821	11.347	2.26876	2.91971	425.84	-43.252	94.106
9	SRM	-0.28581	26.118	2.97929	3.78239	859.33	**-14.559**	95.515
10	TAES	-0.13974	11.958	2.25890	2.88937	424.66	-40.426	91.995
11	WCDR	-0.15293	11.446	2.21828	2.80503	**390.62**	-41.215	92.978
12	WMA	**-0.12239**	15.162	2.48140	3.24474	542.82	-18.723	**84.328**
13	WRDF	-0.44334	12.183	2.31927	2.96086	426.12	-46.643	90.236

Table 8.13 A summary of average forecast accuracy measurement by monthly period - overall results.

Table 8.14 A summary of average forecast accuracy measurement by weekly period - overall results.

#	Forecast Methods	*weekly*						
		ME	*MSE*	*MAD*	*RMSE*	*SSE*	*MPE*	*MAPE*
1	ARRSES	-0.04951	2.20009	0.92765	1.24178	352.71	-96.659	151.30
2	AW	-0.19512	2.93910	1.17215	1.57856	467.44	-51.695	116.80
3	Croston	-0.08891	1.99353	0.93226	1.18636	317.30	-88.743	147.98
4	DES	-0.04574	1.98854	0.90488	1.17922	315.88	-85.368	134.53
5	Holt	-0.03722	2.43303	0.93596	1.24774	362.85	-93.378	144.03
6	MTBR	-1.35200	8.21207	1.77203	2.05183	1328.32	-121.623	149.37
7	MW	-	-	-	-	-	-	-
8	SES	-0.07625	1.98326	0.91883	1.17796	312.47	-101.388	147.72
9	SRM	-0.33606	11.01970	1.41065	2.08357	2208.30	-48.657	117.50
10	TAES	-0.03622	**1.93604**	0.90056	1.16569	309.33	-100.074	148.31
11	WCDR	-0.04861	1.95975	**0.89346**	1.16455	**308.90**	-100.710	148.81
12	WMA	**-0.00187**	2.97946	0.97857	1.40235	469.89	**-25.654**	**95.12**
13	WRDF	-0.10766	1.99004	0.92689	**0.00000**	310.99	-96.392	141.81

(-) indicates method was inapplicable,
Best method performance shown in bold

Table 8.15 Evaluating forecast method performance through time by demand pattern categorisation.

#	Forecast Methods	*PMP* Type	weekly period *ADI range*	weekly period CV^2 *range*	*PMP* Type	monthly period *ADI range*	monthly period CV^2 *range*	*PMP* Type	quarterly period *ADI range*	quarterly period CV^2 *range*
1	ARRSES	HT	≥ 1.32[b]	0.21 : 0.29	CM	≤ 1.34[b]	0.33 : 0.51	CM	≤ 1.12[b]	0.20 : 0.47
2	AW	-	-	-	CM	1.65[b]	0.37	-	-	-
3	Croston	HT	≥ 1.41[b]	0.33 : 0.65	HT & CM	≤ 1.48[a]	0.22 : 0.94	-	-	-
4	Holt	CM	≥ 1.17[b]	0.14 : 0.50	HT	≤ 1.47[a]	0.22 : 0.64	HT	≤ 1.57[a]	0.11 : 0.81
5	MTBR	-	-	-	HT	1.80 : 2.82[b]	0.94 : 1.23	-	-	-
6	MW	-	-	-	-	-	-	HT	≤ 1.68[a]	0.03 : 1.65
7	SES	-	-	-	-	-	-	CM	1.00[b]	0.04 : 0.20
8	SRM	HT & CM	≥2.81[a]	0.00 : 0.51	-	-	-	HT	2.50[b]	0.11
9	TAES	-	-	-	CM	1.00 : 1.02[b]	0.20 : 0.28	-	-	-
10	WCDR	CM	1.53[b]	0.30 : 0.46	-	-	-	HT	≤ 1.20[b]	0.53 : 0.81
11	WMA	HT & CM	≥ 2.50[a]	0.00 : 0.65	HT	≥ 1.76[a]	0.11 : 1.23	HT	≤ 1.30[a]	0.03 : 0.53
12	WRDF	HT & CM	1.63[b]	0.21 : 0.40	CM	1.01 : 1.02[b]	0.20 : 0.33	-	-	-

(-) indicates method was inapplicable {poor performance}

(a) indicates method performance above average.

(b) indicates method performance below average.

Table 8.15, shows that *ARRSES* method performs well in all selected *SPL* aspects (quarterly, monthly and weekly) for average inter-demand intervals greater than or equal to 1.32 and a squared coefficient of variation taking values in the range (0.21 : 0.29). However, this performance was practical for weekly *SPL* and *HT* components only, and for monthly and quarterly *SPL* the ARRSES method was found to be practical only for *CM* components within average inter-demand intervals less than or equal to 1.34, 1.12 and a squared coefficient of variation taking values in the range (0.33 : 0.51, 0.20 : 0.47) respectively.

The *Additive-Winters* method performs well over a monthly *SPL* when average inter-demand intervals are equal to 1.65 and a squared coefficient of variation value of 0.37. This makes it suitable for *CM* components such as tyres and brakes which are more affected by high seasonal flying.

Croston's method is expected to show superior performance for high average inter-demand intervals (greater than or equal to 1.41) and a moderate squared coefficient of variation (0.33 : 0.65) on a weekly basis for *HT* components only. It also performed well with a monthly *SPL*, but for both components (*HT* and *CM*), based on low average inter-demand intervals (less than or equal to 1.48) and a squared coefficient of variation taking values in the range (0.22 : 0.94).

EWMA Holt's method was found to perform well in all selected *SPL* aspects (quarterly, monthly and weekly), for average inter-demand intervals greater than or equal to 1.17 and a squared coefficient of variation taking values in the range (0.14 : 0.50). This performance was practical on a weekly basis and for *CM* components only, but for monthly and quarterly *SPL*, the *EWMA* method was found to be sensible for *HT* components within average inter-demand intervals less than or equal to 1.47 , 1.57 and a squared coefficient of variation taking values in the range (0.22 : 0.64, 0.11 : 0.81) respectively. This practical performance can be explained by the fact that there is a rate of change being either an increase in airline fleet size or of flying hours, which may result in a mixture of trend pattern and intermittent demand.

MTBR procedure performs well for hard-time components on a monthly basis only. This is obvious as those components which have an overhaul life limit that is determined by hours flown which help in moving aircraft parts into periodic maintenance tasks smoothly and systematically, their *ADI* and CV^2 values varied as shown in Table 8.15.

The *Multiplicative-Winters* method was found to perform well on a quarterly *SPL* for the *HT* components only, and observed to perform very badly as the *SPL* for a monthly and weekly basis was selected. This could be explained by the fact that multiplicative seasonal factors cannot be calculated for situations where there are many periods with zero demand, which assumes that the seasonal effects are proportional in size to the local de-seasonalized mean level.

The *SES* method was observed to perform well on a quarterly *SPL* for condition-monitored components only, this performance was observed for low average inter-demand intervals equal to 1.00 and a moderate squared coefficient of variation (0.04 : 0.20). The rest of the methods in Table 8.15 could be explained in the same manner, whereas the *DES* method was found to perform less well than other methods in all cases.

In summarizing the above results and analysis, and testing across a wide range of demand patterns, an improvement was observed in forecast performance using the WMA and SRM methods when compared with other methods on a weekly *SPL*. This performance was found when the average inter-demand interval was greater than or equal to 2.50, corresponding to an average demand rate of less than 0.65 per period. The improvement increased as the average interval increased. Those methods are therefore recommended for many slow/fast-moving items (smooth & erratic). Conversely, for a monthly *SPL* an improvement was observed in forecast performance using the Croston, Holt and WMA methods. Finally, on a quarterly *SPL* the Holt, MW and WMA methods can produce better forecast performance when the average inter-demand interval is less than or equal to 1.68, corresponding to an average demand rate of less than 1.65 per period.

8.7.3 General linear model approach

In this study we have devised a new approach to forecasting evaluation. This new model compares and evaluates the forecasting methods based on their factor levels. A description and function of the model will be discussed later in this Chapter. Firstly however, the experimental results need further clarification through an analysis of variance of the experimental factor-design employing the forecast errors (measured in terms of MAPE) as the dependent criterion, as shown in Table 8.16, for the overall experimental, main factor and two-way interaction effects.

Tables 8.16 to 8.22, show the general linear model results for each accuracy measurement technique as the dependent variable and the independent variables *SPL*, *PMP*, CV^2 and *ADI* where appropriate, to investigate the significance of forecasting factors and their interactions. In addition, Tables 8.23 to 8.29 give the significant coefficients of the fitted GLMs.

Generally, in Table 8.16 all factors, except for *PMP* and CV^2, have significant main effects on all methods in terms of the MAPE accuracy measure. *PMP* is significant for most methods, except MW which is not significant ($p = 0.129$). CV^2 was also found to be significant for most methods, i.e. ARRSES, Holt and WCDR, (p = 0.076, 0.089 and 0.090 respectively) however, they are not significant where the p-values are small, for SRM is not significant ($p = 0.124$) which shows that all the experimental factors, *SPL*, *PMP*, CV^2 and *ADI* have a significant effect on the forecasting methods' error accuracy measuring MAPE. That is, different values of the independent variables give different performance values for the dependent variable.

Table 8.16 also indicates that the interaction $SPL \times PMP$ for all methods is not significant except for the DES, TAES and WRDF methods where they are found to be significant at the 0.05 level. The $SPL \times CV^2$ is not significant for all methods, while the interaction $SPL \times ADI$ is significant for all methods at the 0.01 levels except for the AW and SRM methods which were at the 0.05 level. The interaction $PMP \times CV^2$was significant for all methods too, at 0.01 level for methods (ARRSES, AW, Holt, MW and SRM) the rest of the methods were at 0.01 levels.

The $PMP \times ADI$ interaction was not significant for the AW and MW methods, however it was marginally significant ($p = 0.063$) for the Holt method while for all other methods it was significant for either level.

Finally the interaction of $CV^2 \times ADI$ was found to be only significant with the two methods DES and MW, while for all other methods it was insignificant.

As reported above, the significant terms were similar for most methods except AW, DES, Holt and MW. In the next few sections we examine, for each method, the effects of each factor on the accuracy of the MAPE measurement.

Table 8.16 A summary of unbalanced ANOVA (GLM) results for forecasting factors (*p*-values) - Log MAPE

Factors	ARRSES	AW	Croston	DES	Holt	MTBR	MW	SES	SRM	TAES	WCDR	WMA	WRDF
SPL	0.000[1]	0.006[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.017[5]	0.000[1]	0.000[1]	0.000[1]	0.000[1]
PMP	0.000[1]	0.004[1]	0.000[1]	0.000[1]	0.001[1]	0.000[1]	0.129	0.000[1]	0.001[1]	0.000[1]	0.000[1]	0.001[1]	0.000[1]
CV^2	0.076	0.049[5]	0.051[5]	0.022[5]	0.089	0.038[5]	0.000[1]	0.018[5]	0.124	0.017[5]	0.090	0.002[1]	0.016[5]
ADI	0.000[1]	0.021[5]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.051[5]	0.000[1]	0.000[1]	0.000[1]	0.000[1]
SPL * PMP	0.261	0.461	0.079	0.049[5]	0.250	0.351	0.969	0.063	0.297	0.019[5]	0.433	0.239	0.025[5]
SPL * CV^2	0.286	0.726	0.063	0.326	0.089	0.216	0.686	0.125	0.464	0.096	0.187	0.275	0.265
SPL * ADI	0.000[1]	0.016[5]	0.000[1]	0.000[1]	0.000[1]	0.001[1]	0.000[1]	0.000[1]	0.039[5]	0.000[1]	0.000[1]	0.000[1]	0.000[1]
PMP * CV^2	0.017[5]	0.021[5]	0.001[1]	0.001[1]	0.012[5]	0.000[1]	0.032[5]	0.001[1]	0.013[5]	0.000[1]	0.001[1]	0.008[1]	0.001[1]
PMP * ADI	0.006[1]	0.418	0.002[1]	0.000[1]	0.063	0.010[5]	0.260	0.001[1]	0.037[5]	0.001[1]	0.004[1]	0.032[5]	0.001[1]
CV^2 * ADI	0.246	0.591	0.072	0.043[5]	0.176	0.119	0.000[1]	0.139	0.573	0.088	0.100	0.646	0.263

Superscript [1] indicates significance at the 0.01 level.

Superscript [5] indicates significance at the 0.05 level.

No superscript denotes a lack of significance at both levels (at 0.01 and 0.05 level).

Table 8.17 A summary of unbalanced ANOVA (GLM) results for forecasting factors (*p*-values) - Log MAD

Factors	ARRSES	AW	Croston	DES	Holt	MTBR	MW	SES	SRM	TAES	WCDR	WMA	WRDF
SPL	0.001^{1}	0.126	0.000^{1}	0.000^{1}	0.000^{1}	0.000^{1}	0.789	0.000^{1}	0.001^{1}	0.000^{1}	0.000^{1}	0.000^{1}	0.000^{1}
PMP	0.230	0.547	0.344	0.403	0.207	0.489	0.025^{5}	0.249	0.816	0.535	0.645	0.302	0.468
CV^2	0.157	0.557	0.122	0.077	0.145	0.063	0.448	0.108	0.362	0.065	0.165	0.076	0.105
ADI	0.000^{1}	0.001^{1}	0.000^{1}	0.000^{1}	0.001^{1}	0.101	0.003^{1}	0.000^{1}	0.000^{1}	0.000^{1}	0.000^{1}	0.000^{1}	0.001^{1}
SPL * PMP	0.855	0.893	0.832	0.767	0.998	0.961	0.713	0.890	0.370	0.639	0.854	0.837	0.671
SPL * CV^2	0.895	0.424	0.694	0.861	0.729	0.138	0.864	0.872	0.702	0.821	0.747	0.822	0.880
SPL * ADI	0.001^{1}	0.010^{5}	0.000^{1}	0.002^{1}	0.005^{1}	0.002^{1}	0.404	0.003^{1}	0.001^{1}	0.002^{1}	0.000^{1}	0.004^{1}	0.004^{1}
PMP * CV^2	0.733	0.326	0.539	0.426	0.811	0.591	0.099	0.530	0.080	0.235	0.567	0.517	0.394
PMP * ADI	0.319	0.187	0.437	0.385	0.372	0.154	0.014^{5}	0.307	0.739	0.462	0.466	0.367	0.561
CV^2 * ADI	0.310	0.319	0.589	0.327	0.252	0.110	0.180	0.274	0.695	0.370	0.482	0.197	0.431

Superscript ^{1} indicates significance at the 0.01 level.

Superscript ^{5} indicates significance at the 0.05 level.

No superscript denotes a lack of significance at both levels (at 0.01 and 0.05 level).

Table 8.18 A summary of unbalanced ANOVA (GLM) results for forecasting factors (*p*-values) - Log MSE

Factors	ARRSES	AW	Croston	DES	Holt	MTBR	MW	SES	SRM	TAES	WCDR	WMA	WRDF
SPL	0.000[1]	0.072	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.734	0.000[1]	0.001[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]
PMP	0.276	0.635	0.310	0.397	0.284	0.651	0.018[5]	0.315	0.824	0.445	0.568	0.434	0.445
CV^2	0.062	0.526	0.054[5]	0.040[5]	0.056[5]	0.057[5]	0.399	0.053[5]	0.239	0.040[5]	0.079	0.040[5]	0.059[5]
ADI	0.001[1]	0.001[1]	0.000[1]	0.000[1]	0.002[1]	0.108	0.001[1]	0.001[1]	0.001[1]	0.001[1]	0.000[1]	0.001[1]	0.001[1]
SPL * PMP	0.849	0.702	0.853	0.805	0.907	0.987	0.733	0.881	0.364	0.711	0.867	0.776	0.718
SPL * CV^2	0.855	0.404	0.697	0.864	0.660	0.179	0.920	0.796	0.779	0.819	0.654	0.776	0.851
SPL * ADI	0.003[1]	0.009[1]	0.002[1]	0.002[1]	0.009[1]	0.005[1]	0.236	0.007[1]	0.004[1]	0.002[1]	0.001[1]	0.005[1]	0.003[1]
PMP * CV^2	0.765	0.283	0.540	0.384	0.654	0.706	0.080	0.444	0.090	0.277	0.610	0.398	0.400
PMP * ADI	0.516	0.308	0.406	0.390	0.495	0.196	0.008[1]	0.334	0.785	0.449	0.483	0.527	0.469
CV^2 * ADI	0.269	0.176	0.433	0.341	0.302	0.119	0.075	0.366	0.805	0.447	0.348	0.317	0.422

Superscript [1] indicates significance at the 0.01 level.

Superscript [5] indicates significance at the 0.05 level.

No superscript denotes a lack of significance at both levels (at 0.01 and 0.05 level).

Table 8.19 A summary of unbalanced ANOVA (GLM) results for forecasting factors (p-values) - Log SSE

Factors	ARRSES	AW	Croston	DES	Holt	MTBR	MW	SES	SRM	TAES	WCDR	WMA	WRDF
SPL	0.063	0.367	0.033[5]	0.035[5]	0.053[5]	0.018[5]	0.866	0.067	0.035[5]	0.046[5]	0.042[5]	0.099	0.077
PMP	0.083	0.164	0.096	0.122	0.086	0.887	0.020[5]	0.082	0.532	0.140	0.194	0.145	0.130
CV^2	0.119	0.494	0.113	0.094	0.110	0.085	0.855	0.110	0.152	0.092	0.151	0.091	0.109
ADI	0.000[1]	0.027[5]	0.000[1]	0.000[1]	0.001[1]	0.034[5]	0.016[5]	0.000[1]	0.001[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]
SPL * PMP	0.996	0.987	0.998	0.991	0.995	0.972	0.315	0.993	0.613	0.963	0.707	0.982	0.935
SPL * CV^2	0.842	0.881	0.716	0.861	0.681	0.234	0.945	0.798	0.784	0.822	0.685	0.792	0.845
SPL * ADI	0.001[1]	0.083	0.001[1]	0.001[1]	0.003[1]	0.002[1]	0.428	0.002[1]	0.001[1]	0.001[1]	0.001[1]	0.002[1]	0.001[1]
PMP * CV^2	0.564	0.622	0.745	0.909	0.660	0.831	0.538	0.819	0.506	0.959	0.694	0.908	0.904
PMP * ADI	0.395	0.409	0.314	0.296	0.377	0.335	0.038[5]	0.252	0.627	0.345	0.367	0.404	0.336
CV^2 * ADI	0.611	0.863	0.818	0.749	0.660	0.246	0.398	0.756	0.892	0.842	0.734	0.664	0.817

Superscript [1] indicates significance at the 0.01 level.

Superscript [5] indicates significance at the 0.05 level.

No superscript denotes a lack of significance at both levels (at 0.01 and 0.05 level).

Table 8.20 A summary of unbalanced ANOVA (GLM) results for forecasting factors (*p*-values) - ME

Factors	ARRSES	AW	Croston	DES	Holt	MTBR	MW	SES	SRM	TAES	WCDR	WMA	WRDF
SPL	0.130	0.032[5]	0.019[5]	0.077	0.026[5]	0.476	0.158	0.106	0.406	0.035[5]	0.316	0.019[5]	0.131
PMP	0.149	0.508	0.106	0.128	0.856	0.159	0.593	0.230	0.001[1]	0.319	0.891	0.018[5]	0.001[1]
CV^2	0.510	0.668	0.419	0.392	0.769	0.244	0.450	0.713	0.274	0.713	0.411	0.352	0.041[5]
ADI	0.335	0.023[5]	0.135	0.157	0.059[5]	0.287	0.875	0.124	0.745	0.140	0.131	0.144	0.547
SPL * PMP	0.099	0.413	0.518	0.014[5]	0.378	0.363	0.941	0.417	0.001[1]	0.809	0.623	0.332	0.004[1]
SPL * CV^2	0.942	0.763	0.722	0.682	0.974	0.626	0.477	0.902	0.644	0.712	0.915	0.888	0.604
SPL * ADI	0.337	0.059[5]	0.076	0.141	0.099	0.557	0.188	0.143	0.791	0.117	0.277	0.099	0.351
PMP * CV^2	0.033[5]	0.255	0.038[5]	0.011[5]	0.566	0.090	0.027[5]	0.072	0.000[1]	0.202	0.689	0.003[1]	0.000[1]
PMP * ADI	0.566	0.855	0.501	0.619	0.800	0.611	0.382	0.787	0.141	0.731	0.696	0.469	0.178
CV^2 * ADI	0.604	0.416	0.733	0.549	0.650	0.809	0.587	0.563	0.346	0.870	0.863	0.413	0.370

Superscript [1] indicates significance at the 0.01 level.

Superscript [5] indicates significance at the 0.05 level.

No superscript denotes a lack of significance at both levels (at 0.01 and 0.05 level).

Table 8.21 A summary of unbalanced ANOVA (GLM) results for forecasting factors (*p*-values) - MPE

Factors	ARRSES	AW	Croston	DES	Holt	MTBR	MW	SES	SRM	TAES	WCDR	WMA	WRDF
SPL	0.005[1]	0.466	0.656	0.028[5]	0.001[1]	0.469	0.029[5]	0.002[1]	0.985	0.004[1]	0.001[1]	0.111	0.034[5]
PMP	0.025[5]	0.371	0.417	0.018[5]	0.438	0.588	0.997	0.183	0.135	0.391	0.352	0.378	0.049[5]
CV^2	0.332	0.590	0.779	0.370	0.013[5]	0.798	0.276	0.104	0.678	0.242	0.104	0.585	0.859
ADI	0.000[1]	0.079	0.047[5]	0.002[1]	0.637	0.030[5]	0.185	0.421	0.783	0.044[5]	0.004[1]	0.242	0.001[1]
SPL * PMP	0.127	0.444	0.969	0.025[5]	0.952	0.748	0.972	0.683	0.222	0.749	0.952	0.709	0.210
SPL * CV^2	0.528	0.816	0.931	0.643	0.055[5]	0.274	0.366	0.104	0.977	0.450	0.659	0.240	0.887
SPL * ADI	0.001[1]	0.386	0.189	0.064	0.002[1]	0.223	0.007[1]	0.001[1]	0.874	0.008[1]	0.005[1]	0.244	0.002[1]
PMP * CV^2	0.179	0.355	0.762	0.471	0.613	0.464	0.308	0.717	0.107	0.928	0.497	0.378	0.289
PMP * ADI	0.028[5]	0.904	0.214	0.002[1]	0.250	0.157	0.969	0.128	0.189	0.248	0.210	0.737	0.032[5]
CV^2 * ADI	0.006[1]	0.121	0.125	0.001[1]	0.003[1]	0.804	0.333	0.003[1]	0.607	0.041[5]	0.048[5]	0.929	0.173

Superscript [1] indicates significance at the 0.01 level.

Superscript [5] indicates significance at the 0.05 level.

No superscript denotes a lack of significance at both levels (at 0.01 and 0.05 level).

Table 8.22 A summary of unbalanced ANOVA (GLM) results for forecasting factors (*p*-values) - Log RMSE

Factors	ARRSES	AW	Croston	DES	Holt	MTBR	MW	SES	SRM	TAES	WCDR	WMA	WRDF
SPL	0.000[1]	0.071	0.000[1]	0.000[1]	0.000[1]	0.000[1]	0.736	0.000[1]	0.001[1]	0.000[1]	0.000[1]	0.000[1]	0.000[1]
PMP	0.275	0.644	0.307	0.398	0.287	0.634	0.018[5]	0.280	0.822	0.444	0.572	0.433	0.438
CV^2	0.058[5]	0.528	0.054[5]	0.041[5]	0.057[5]	0.059[5]	0.399	0.054[5]	0.239	0.039[5]	0.080	0.039[5]	0.777
ADI	0.001[1]	0.001[1]	0.000[1]	0.000[1]	0.002[1]	0.105	0.001[1]	0.001[1]	0.001[1]	0.001[1]	0.000[1]	0.001[1]	0.001[1]
SPL * PMP	0.855	0.701	0.853	0.805	0.905	0.971	0.732	0.891	0.364	0.710	0.868	0.777	0.398
SPL * CV^2	0.835	0.407	0.698	0.870	0.665	0.204	0.920	0.804	0.783	0.819	0.653	0.772	0.692
SPL * ADI	0.003[1]	0.009[1]	0.002[1]	0.002[1]	0.009[1]	0.005[1]	0.238	0.006[1]	0.004[1]	0.002[1]	0.001[1]	0.005[1]	0.000[1]
PMP * CV^2	0.775	0.284	0.538	0.382	0.650	0.697	0.080	0.452	0.090	0.277	0.606	0.400	0.752
PMP * ADI	0.527	0.319	0.395	0.389	0.499	0.198	0.008[1]	0.317	0.789	0.448	0.485	0.528	0.736
CV^2 * ADI	0.256	0.175	0.438	0.354	0.312	0.114	0.075	0.380	0.808	0.436	0.356	0.309	0.659

Superscript [1] indicates significance at the 0.01 level.

Superscript [5] indicates significance at the 0.05 level.

No superscript denotes a lack of significance at both levels (at 0.01 and 0.05 level).

8.7.3.1 The effect of seasonal period length

The coefficients of *SPL* increase with seasonal period length (quarterly, monthly and weekly respectively) as expected. Quarterly *SPL* reduces the forecasting error on average for all methods, compared with a monthly *SPL* (Table 8.23a). This can be explained by the fact that most forecasting methods will perform well for a quarterly *SPL* but as a monthly and weekly *SPL* were selected, the method's performance will have less effect on reducing the forecasting error; in particular with the MW method. The interaction of $SPL \times PMP$ is found to be only significant with the DES, TAES and WRDF methods. Table 8.23b shows that for a quarterly *SPL* the effect of primary maintenance processes *PMP* on accuracy measurement will be reduced for the hard-time and increased by condition-monitoring components, similarly for DES and TAES methods on a monthly *SPL* basis, conversely, for WRDF method the effect of *PMP* on accuracy measuring will be increased for the hard-time and reduced by condition-monitoring components. Finally for a weekly *SPL* the effect of *PMP* on accuracy measuring will be increased for the hard-time and reduced by condition-monitoring components for these methods.

8.7.3.2 The effect of primary maintenance processes

Primary maintenance processes, *PMP*, show that hard-time *HT* components have more effect in increasing the forecasting error measuring MAPE, compared with condition-monitoring *CM* (Table 8.23a). The interaction of *PMP* with both CV^2 and *ADI* was found to be significant for most methods, Table 8.23c indicating that as CV^2 increases the effect of *PMP* on MAPE will be reduced for the hard-time and increased by condition-monitoring components for all methods. And it is a similar story for *ADI* as the average inter-demand interval increases the effect of *PMP* on MAPE will be reduced with *HT* and increased for *CM* components for all methods except for the AW, Holt and MW methods.

8.7.3.3 The effect of squared coefficient of variation on demand

From Table 8.23a the coefficient of CV^2 is positive and similar for all methods. However, Table 8.23c shows that for the DES method this positive coefficient is augmented by a positive coefficient of $CV^2 \times ADI$, i.e. as *ADI* increases this effect increases, while for the MW method this positive coefficient is offset by a negative coefficient of $CV^2 \times ADI$, i.e. as *ADI* increases this effect reduces.

8.7.3.4 The effect of average inter-demand interval

In this study the coefficient of *ADI* is positive, i.e. as *ADI* increases the impact of reducing the forecasting method performance will be higher (higher MAPE). Table 8.23a shows the coefficient effect to be much higher for the MW (3.08) while on average (0.50) for the rest of the methods. The interaction of $SPL \times ADI$, shows that the coefficient of *ADI* decreases as *SPL* increases (Table 8.23c), but the benefit is usually less as *ADI* increases, indicating that for very lumpy demand, the advantage of a quarterly *SPL* is reduced, i.e. with weekly *SPL*, the *ADI* improves the forecasting method's performance. On the other hand, with a quarterly *SPL*, the *ADI* displays a minor impact on the forecasting performance. Hence the relevance of *ADI* depends on the seasonal period length selected.

Table 8.23a Coefficients of fitted models: main effect measured by MAPE technique.

Methods	CV^2 coefficient	ADI coefficient	Seasonal period length coefficient levels SPL = 4	SPL = 12	SPL = 52	PMP coefficients HT	CM
ARRSES	0.7459	**0.56057**	**-1.1206**	**0.0162**	**1.1044**	**0.5024**	**-0.5024**
AW	**1.4153**	**0.53050**	**-1.0565**	**-0.0370**	**1.0935**	**0.4721**	**-0.4721**
Croston	**0.7087**	**0.57775**	**-1.1567**	**-0.0080**	**1.1647**	**0.5454**	**-0.5454**
DES	**0.9346**	**0.54884**	**-1.1020**	**0.0823**	**1.0197**	**0.6264**	**-0.6264**
Holt	0.6743	**0.46677**	**-1.0382**	**-0.0935**	**1.1317**	**0.4431**	**-0.4431**
MTBR	**0.9144**	**0.41238**	**-0.8178**	**0.0282**	**0.7896**	**0.7171**	**-0.7171**
MW	**5.8040**	**3.08110**	**-2.9568**	**-0.8741**	**3.8309**	0.7837	-0.7837
SES	**0.9258**	**0.52308**	**-0.9888**	**-0.0656**	**1.0544**	**0.5763**	**-0.5763**
SRM	1.1008	**0.24350**	**-0.6740**	**-0.0609**	**0.7349**	**0.5535**	**-0.5535**
TAES	**0.9665**	**0.60377**	**-1.1090**	**0.0097**	**1.0993**	**0.6476**	**-0.6476**
WCDR	0.7345	**0.55559**	**-1.1078**	**0.0239**	**1.0839**	**0.6445**	**-0.6445**
WMA	**1.2576**	**0.43977**	**-1.2226**	**0.1537**	**1.0689**	**0.4444**	**-0.4444**
WRDF	**0.9907**	**0.57909**	**-1.0286**	**0.0467**	**0.9819**	**0.5858**	**-0.5858**

Significant factors shown in bold.

Table 8.23b Coefficients of the fitted models MAPE - continued.

Methods	SPL * PMP						SPL * CV^2		
	SPL = 4		SPL = 12		SPL = 52				
	HT	CM	HT	CM	HT	CM	SPL = 4	SPL = 12	SPL = 52
ARRSES	-0.09472	0.09472	-0.01096	0.01096	0.10568	-0.10568	0.4447	0.2449	-0.6896
AW	-0.02867	0.02867	-0.06592	0.06592	0.09459	-0.09459	0.2345	0.3191	-0.5536
Croston	-0.11346	0.11346	-0.01245	0.01245	0.12591	-0.12591	0.5553	0.3522	-0.9075
DES	**-0.12285**	**0.12285**	**-0.04211**	**0.04211**	**0.16496**	**-0.16496**	0.3558	0.2938	-0.6496
Holt	-0.06814	0.06814	-0.04321	0.04321	0.11135	-0.11135	0.5189	0.4330	-0.9519
MTBR	-0.08958	0.08958	-0.00487	0.00487	0.09445	-0.09445	0.5423	0.2007	-0.7430
MW	-0.03050	0.03050	-0.03360	0.03360	0.06410	-0.06410	0.9360	0.9800	-1.9160
SES	-0.11804	0.11804	-0.03021	0.03021	0.14825	-0.14825	0.4762	0.3767	-0.8529
SRM	-0.11628	0.11628	0.01389	-0.01389	0.10239	-0.10239	0.5260	0.2184	-0.7444
TAES	**-0.16313**	**0.16313**	**-0.00152**	**0.00152**	**0.16465**	**-0.16465**	0.5664	0.3498	-0.9162
WCDR	-0.04181	0.04181	-0.05031	0.05031	0.09212	-0.09212	0.5115	0.3283	-0.8398
WMA	-0.08706	0.08706	-0.02345	0.02345	0.11051	-0.11051	0.2965	0.3788	-0.6753
WRDF	**-0.16215**	**0.16215**	**0.00564**	**-0.00564**	**0.15651**	**-0.15651**	0.4699	0.1540	-0.6239

Significant interactions shown in bold.

Table 8.23c Coefficients of the fitted models MAPE - continued.

Methods	SPL * ADI			PMP * CV^2		PMP * ADI		CV^2 * ADI
	SPL = 4	SPL = 12	SPL = 52	HT	CM	HT	CM	
ARRSES	**0.5570**	**-0.14659**	**-0.41041**	**-0.7191**	**0.7191**	**-0.13735**	**0.13735**	0.12300
AW	**0.5929**	**-0.12110**	**-0.47180**	**-0.8247**	**0.8247**	-0.05192	0.05192	-0.16590
Croston	**0.5998**	**-0.16728**	**-0.43252**	**-0.8967**	**0.8967**	**-0.13635**	**0.13635**	0.16576
DES	**0.6248**	**-0.21030**	**-0.41450**	**-0.9427**	**0.9427**	**-0.18090**	**0.18090**	**0.20820**
Holt	**0.4685**	**-0.09842**	**-0.37008**	**-0.7066**	**0.7066**	-0.08697	0.08697	0.13504
MTBR	**0.3807**	**-0.10488**	**-0.27582**	**-1.4015**	**1.4015**	**-0.13481**	**0.13481**	0.17340
MW	**2.1575**	**0.42260**	**-2.58010**	**-0.9702**	**0.9702**	-0.49100	0.49100	**-4.03490**
SES	**0.4440**	**-0.08377**	**-0.36023**	**-0.9353**	**0.9353**	**-0.15025**	**0.15025**	0.14544
SRM	**0.3139**	**-0.08784**	**-0.22606**	**-0.9347**	**0.9347**	**-0.12494**	**0.12494**	0.14760
TAES	**0.6169**	**-0.18018**	**-0.43672**	**-1.1749**	**1.1749**	**-0.15855**	**0.15855**	0.17320
WCDR	**0.5394**	**-0.14253**	**-0.39687**	**-1.0067**	**1.0067**	**-0.15086**	**0.15086**	0.18040
WMA	**0.7095**	**-0.27225**	**-0.43725**	**-0.7667**	**0.7667**	**-0.10272**	**0.10272**	-0.04670
WRDF	**0.5519**	**-0.14560**	**-0.4063**	**-0.9377**	**0.9377**	**-0.15726**	**0.15726**	0.11480

Significant interactions shown in bold.

Table 8.24a Coefficients of fitted models: main effect measured by MAD technique.

Methods	CV^2 coefficient	ADI coefficient	Seasonal period length coefficient levels SPL = 4	SPL = 12	SPL = 52	PMP coefficients HT	CM
ARRSES	0.9322	**-0.5705**	**1.0882**	**0.0237**	**-1.1119**	-0.2522	0.2522
AW	-0.5427	**-1.0378**	0.9990	-0.2463	-0.7527	-0.1268	0.1268
Croston	0.9823	**-0.5896**	**1.2910**	**-0.0043**	**-1.2867**	-0.1912	0.1912
DES	1.1419	**-0.5400**	**1.2301**	**-0.0410**	**-1.1891**	-0.1715	0.1715
Holt	0.9550	**-0.5154**	**1.1744**	**-0.0311**	**-1.1433**	-0.2627	0.2627
MTBR	2.0340	-0.3980	**1.7673**	**0.4131**	**-2.1804**	0.2398	-0.2398
MW	-1.3240	**-2.6769**	0.2827	0.5587	-0.8414	**-1.4755**	**1.4755**
SES	1.0200	**-0.5300**	**1.1121**	**-0.0374**	**-1.0747**	-0.2332	0.2332
SRM	1.0740	**-0.8186**	**1.5820**	**-0.1334**	**-1.4486**	0.0626	-0.0626
TAES	1.1652	**-0.5139**	**1.2127**	**0.0118**	**-1.2245**	-0.1245	0.1245
WCDR	0.9052	**-0.6698**	**1.3183**	**-0.0157**	**-1.3026**	-0.0957	0.0957
WMA	1.2018	**-0.5475**	**1.1412**	**0.0152**	**-1.1564**	-0.2220	0.2220
WRDF	1.0637	**-0.4940**	**1.0898**	**0.0400**	**-1.1298**	-0.1516	0.1516

Significant factors shown in bold.

Table 8.24b Coefficients of the fitted models MAD - continued.

Methods	SPL * PMP SPL = 4 HT	SPL = 4 CM	SPL = 12 HT	SPL = 12 CM	SPL = 52 HT	SPL = 52 CM	SPL * CV^2 SPL = 4	SPL = 12	SPL = 52
ARRSES	-0.04783	0.04783	0.03520	-0.03520	0.01263	-0.01263	-0.1955	-0.1318	0.3273
AW	-0.03162	0.03162	0.03360	-0.03360	-0.00198	0.00198	0.7627	0.4721	-1.2348
Croston	-0.05611	0.05611	0.02501	-0.02501	0.03110	-0.03110	-0.3377	-0.2389	0.5766
DES	-0.06983	0.06983	0.02357	-0.02357	0.04626	-0.04626	-0.2320	-0.1349	0.3669
Holt	-0.00674	0.00674	0.00050	-0.00050	0.00624	-0.00624	-0.3708	-0.1122	0.4830
MTBR	-0.03310	0.03310	-0.01840	0.01840	0.05150	-0.05150	-1.2955	-1.0462	2.3417
MW	0.13230	-0.13230	0.13360	-0.13360	-0.26590	0.2659	0.7240	0.1970	-0.9210
SES	-0.03847	0.03847	0.03069	-0.03069	0.00778	-0.00778	-0.2353	-0.0684	0.3037
SRM	-0.13440	0.13440	0.13050	-0.13050	0.00390	-0.00390	0.0546	-0.4326	0.3780
TAES	-0.08927	0.08927	0.02476	-0.02476	0.06451	-0.06451	-0.2293	-0.1942	0.4235
WCDR	0.05291	-0.05291	-0.02580	0.02580	-0.02711	0.02711	-0.3427	-0.1561	0.4988
WMA	-0.05950	0.05950	0.02342	-0.02342	0.03608	-0.03608	-0.2442	-0.2084	0.4526
WRDF	-0.08565	0.08565	0.03766	-0.03766	0.04799	-0.04799	-0.1999	-0.1548	0.3547

Significant interactions shown in bold.

Table 8.24c Coefficients of the fitted models MAD - continued.

Methods	SPL * ADI			PMP * CV^2		PMP * ADI		CV^2 * ADI
	SPL = 4	SPL = 12	SPL = 52	HT	CM	HT	CM	
ARRSES	**-0.4103**	**0.0384**	**0.3719**	-0.1587	0.1587	0.07728	-0.07728	-0.1689
AW	**-0.6796**	**0.0793**	**0.6003**	-0.4513	0.4513	0.11055	-0.11055	0.4007
Croston	**-0.5092**	**0.0938**	**0.4154**	-0.2754	0.2754	0.05805	-0.05805	-0.0866
DES	**-0.4688**	**0.1043**	**0.3645**	-0.3625	0.3625	0.06582	-0.06582	-0.1595
Holt	**-0.4081**	**0.0719**	**0.3362**	-0.1100	0.1100	0.06865	-0.06865	-0.1891
MTBR	**-0.6529**	**0.0694**	**0.5835**	-0.4133	0.4133	-0.18310	0.18310	-0.4422
MW	-0.1722	-0.6405	0.8127	-0.9298	0.9298	**1.3854**	**-1.3854**	1.2680
SES	**-0.4126**	**0.0742**	**0.3384**	-0.2813	0.2813	0.07625	-0.07625	-0.1754
SRM	**-0.7493**	**0.1958**	**0.5535**	-1.0851	1.0851	0.03259	-0.03259	0.1697
TAES	**-0.4077**	**0.0601**	**0.3476**	-0.5297	0.5297	0.05454	-0.05454	-0.1428
WCDR	**-0.5993**	**0.1192**	**0.4801**	-0.2640	0.2640	0.05600	-0.05600	-0.1158
WMA	**-0.4504**	**0.0911**	**0.3593**	-0.3087	0.3087	0.07167	-0.07167	-0.2204
WRDF	**-0.3501**	**0.0299**	**0.3202**	-0.3952	0.3952	0.04480	-0.04480	-0.1304

Significant interactions shown in bold.

Table 8.25a Coefficients of fitted models: main effect measured by ME technique.

Methods	CV^2 coefficient	ADI coefficient	Seasonal period length coefficient levels SPL = 4	SPL = 12	SPL = 52	PMP coefficients HT	CM
ARRSES	-1.191	0.3882	-1.6239	0.6083	1.0156	-0.8364	0.8364
AW	1.509	**2.5980**	**-4.7190**	**2.5300**	**2.1890**	-0.5295	0.5295
Croston	-1.402	0.5800	**-2.2020**	**0.8152**	**1.3868**	-0.9000	0.9000
DES	-1.564	0.5776	-1.8634	0.4973	1.3661	-0.8934	0.8934
Holt	0.497	**0.7174**	**-2.0116**	**0.9198**	**1.0918**	0.0977	-0.0977
MTBR	16.15	3.2870	-7.3150	0.7490	6.5660	6.2510	-6.2510
MW	10.29	-1.0440	-12.669	2.0660	10.603	-2.6780	2.6780
SES	-0.676	0.6326	-1.7354	0.6618	1.0736	-0.7076	0.7076
SRM	-12.00	0.6170	-4.5950	2.3230	2.2720	**-8.4090**	**8.4090**
TAES	-0.748	0.6710	**-2.3318**	**1.0178**	**1.3140**	-0.6478	0.6478
WCDR	2.393	0.9844	-1.9640	0.6910	1.2730	0.1277	-0.1277
WMA	-1.499	0.5254	**-2.0094**	**0.8688**	**1.1406**	**-1.2370**	**1.2370**
WRDF	**-5.912**	0.3832	-2.5790	0.8670	1.7120	**-3.1767**	**3.1767**

Significant factors shown in bold.

Table 8.25b Coefficients of the fitted models ME - continued.

Methods	SPL * PMP						SPL * CV^2		
	SPL = 4		SPL = 12		SPL = 52				
	HT	CM	HT	CM	HT	CM	SPL = 4	SPL = 12	SPL = 52
ARRSES	0.5838	-0.5838	-0.2229	0.2229	-0.3609	0.3609	-0.312	-0.347	0.659
AW	0.4478	-0.4478	-0.2301	0.2301	-0.2177	0.2177	-1.732	-0.388	2.120
Croston	0.2939	-0.2939	-0.0277	0.0277	-0.2662	0.2662	0.677	-0.495	-0.182
DES	**0.8105**	**-0.8105**	**-0.3272**	**0.3272**	**-0.4833**	**0.4833**	-1.007	0.250	0.757
Holt	0.3193	-0.3193	-0.2116	0.2116	-0.1077	0.1077	-0.195	-0.221	0.416
MTBR	-2.9710	2.9710	0.7060	-0.7060	2.2650	-2.2650	9.561	1.737	-11.298
MW	0.1990	-0.1990	0.4440	-0.4440	-0.6430	0.6430	4.980	14.68	-19.66
SES	0.3424	-0.3424	-0.1977	0.1977	-0.1447	0.1447	-0.594	-0.178	0.772
SRM	**4.5180**	**-4.5180**	**-1.6880**	**1.6880**	**-2.8300**	**2.8300**	-6.341	-1.037	7.378
TAES	0.1980	-0.1980	-0.0352	0.0352	-0.1628	0.1628	0.787	-0.617	-0.170
WCDR	-0.3850	0.3850	-0.0549	0.0549	0.4399	-0.4399	0.815	-0.100	-0.715
WMA	0.3546	-0.3546	-0.1465	0.1465	-0.2081	0.2081	-0.430	-0.410	0.840
WRDF	**1.4582**	**-1.4582**	**-0.4206**	**0.4206**	**-1.0376**	**1.0376**	-2.051	-0.378	2.429

Significant interactions shown in bold.

Table 8.25c Coefficients of the fitted models ME - continued.

Methods	SPL * ADI			PMP * CV^2		PMP * ADI		CV^2 * ADI
	SPL = 4	SPL = 12	SPL = 52	HT	CM	HT	CM	
ARRSES	0.7182	-0.2549	-0.4633	**2.761**	**-2.761**	0.1224	-0.1224	-0.2377
AW	**4.1130**	**-1.8743**	**-2.2387**	1.993	-1.993	0.0580	-0.0580	-1.2440
Croston	1.2388	-0.5454	-0.6934	**2.585**	**-2.585**	0.1376	-0.1376	-0.1500
DES	1.0000	-0.3662	-0.6338	**3.340**	**-3.340**	0.1070	-0.1070	-0.2774
Holt	1.1366	-0.4974	-0.6392	0.687	-0.687	-0.0505	0.0505	-0.1941
MTBR	4.1530	-1.5420	-2.6110	-16.775	16.775	-0.8310	0.8310	0.8470
MW	9.9350	-6.6720	-3.2630	**-9.837**	**9.837**	3.7320	-3.7320	-3.9750
SES	1.0550	-0.4143	-0.6407	2.362	-2.362	0.0587	-0.0587	-0.2698
SRM	1.6150	-0.6620	-0.9530	**26.181**	**-26.181**	1.3471	-1.3471	-3.8020
TAES	1.3494	-0.6150	-0.7344	1.848	-1.848	0.0825	-0.0825	-0.0840
WCDR	1.3374	-0.5177	-0.8197	-0.825	0.825	-0.1340	0.1340	-0.1272
WMA	1.0584	-0.4465	-0.6119	**3.457**	**-3.457**	0.1375	-0.1375	-0.3342
WRDF	1.0943	-0.3783	-0.7160	**9.646**	**-9.646**	0.4558	-0.4558	-0.6497

Significant interactions shown in bold.

Table 8.26a Coefficients of fitted models: main effect measured by MPE technique.

Methods	CV^2 coefficient	ADI coefficient	Seasonal period length coefficient levels			PMP coefficients	
			SPL = 4	SPL = 12	SPL = 52	HT	CM
ARRSES	30.93	**-27.946**	**32.61**	**16.66**	**-49.27**	**-23.17**	**23.17**
AW	35.95	37.860	-23.39	29.41	-6.02	-13.62	13.62
Croston	15.86	**-25.270**	13.14	10.55	-23.69	-14.69	14.69
DES	27.97	**-21.799**	**36.20**	**-2.30**	**-33.90**	**-23.967**	**23.967**
Holt	**89.09**	3.706	**15.60**	**41.85**	**-57.45**	8.76	-8.76
MTBR	14.96	**-28.740**	26.74	5.95	-32.69	-10.15	10.15
MW	243.30	145.10	**-292.8**	**43.40**	**249.4**	0.31	-0.31
SES	50.75	-5.568	**8.03**	**35.01**	**-43.04**	-13.261	13.261
SRM	-42.30	-4.880	6.09	-1.58	-4.51	-35.08	35.08
TAES	44.30	**-17.129**	**19.73**	**34.41**	**-54.14**	-10.36	10.36
WCDR	56.70	**-22.550**	**40.87**	**19.85**	**-60.72**	-10.31	10.31
WMA	-12.75	-6.098	16.03	6.775	-22.805	-6.583	6.583
WRDF	-6.45	**-27.517**	**26.22**	**17.89**	**-44.11**	**-23.10**	**23.10**

Significant factors shown in bold.

Table 8.26b Coefficients of the fitted models MPE - continued.

Methods	SPL * PMP						SPL * CV^2		
	SPL = 4		SPL = 12		SPL = 52				
	HT	CM	HT	CM	HT	CM	SPL = 4	SPL = 12	SPL = 52
ARRSES	8.628	-8.628	1.737	-1.737	-10.365	10.365	-7.37	-23.31	30.68
AW	7.966	-7.966	0.936	-0.936	-8.902	8.902	-28.53	-10.77	39.30
Croston	0.560	-0.560	-1.873	1.873	1.313	-1.313	11.08	-6.84	-4.24
DES	**10.743**	**-10.743**	**3.321**	**-3.321**	**-14.064**	**14.064**	-9.66	14.14	-4.48
Holt	-0.622	0.622	-1.148	1.148	1.770	-1.770	**-61.75**	**-21.38**	**83.13**
MTBR	-6.111	6.111	3.900	-3.900	2.211	-2.211	66.52	3.33	-69.85
MW	2.690	-2.690	-1.590	1.590	-1.100	1.100	-57.90	186.8	-128.9
SES	4.069	-4.069	-0.804	0.804	-3.265	3.265	-47.67	-8.57	56.24
SRM	18.83	-18.83	-3.803	3.803	-15.027	15.027	13.52	3.87	-17.39
TAES	4.141	-4.141	-0.039	0.039	-4.102	4.102	-11.27	-30.86	42.13
WCDR	1.627	-1.627	-0.558	0.558	-1.069	1.069	-14.05	-18.67	32.72
WMA	2.900	-2.900	-0.939	0.939	-1.961	1.961	3.18	-24.00	20.82
WRDF	6.498	-6.498	4.395	-4.395	-10.893	10.893	-7.70	-10.55	18.25

Significant interactions shown in bold.

Table 8.26c Coefficients of the fitted models MPE - continued.

Methods	SPL * ADI			PMP * CV^2		PMP * ADI		CV^2 * ADI
	SPL = 4	SPL = 12	SPL = 52	HT	CM	HT	CM	
ARRSES	**-12.67**	**-2.477**	**15.147**	30.47	-30.47	**8.377**	**-8.377**	**-22.513**
AW	43.62	-19.12	-24.50	30.71	-30.71	0.730	-0.730	-45.35
Croston	-2.66	-6.93	9.59	12.15	-12.15	8.345	-8.345	-22.12
DES	-16.77	4.560	12.21	15.92	-15.92	**11.951**	**-11.951**	**-27.032**
Holt	**23.77**	**-21.149**	**-2.621**	-12.68	12.68	-4.815	4.815	**-27.557**
MTBR	-9.35	-2.93	12.28	-30.48	30.48	9.857	-9.857	-3.69
MW	**266.56**	**-117.9**	**-148.66**	-72.53	72.53	2.710	-2.710	-116.2
SES	**25.26**	**-21.222**	**-4.038**	7.96	-7.96	5.600	-5.600	**-24.096**
SRM	-4.05	5.13	-1.08	86.56	-86.56	11.202	-11.202	-19.34
TAES	**4.86**	**-12.135**	**7.275**	-2.42	2.42	5.170	-5.170	**-19.732**
WCDR	**-8.17**	**-4.711**	**12.881**	-16.70	16.70	5.144	-5.144	**-17.511**
WMA	-11.362	4.462	6.90	14.62	-14.62	0.924	-0.924	-0.525
WRDF	**-6.97**	**-6.730**	**13.70**	27.40	-27.40	**9.319**	**-9.319**	-12.584

Significant interactions shown in bold.

Table 8.27a Coefficients of fitted models: main effect measured by MSE technique.

Methods	CV^2 coefficient	ADI coefficient	Seasonal period length coefficient levels SPL = 4	SPL = 12	SPL = 52	PMP coefficients HT	CM
ARRSES	2.431	**-0.9987**	**2.4812**	**-0.1406**	**-2.3406**	-0.4509	0.4509
AW	-1.104	**-1.9108**	2.0823	-0.3770	-1.7053	-0.1879	0.1879
Croston	**2.453**	**-1.0228**	**2.6515**	**-0.0993**	**-2.5522**	-0.4094	0.4094
DES	**2.590**	**-1.0053**	**2.6220**	**-0.2161**	**-2.4059**	-0.3378	0.3378
Holt	**2.535**	**-0.9133**	**2.5539**	**-0.1373**	**-2.4166**	-0.4485	0.4485
MTBR	**3.931**	-0.7360	**3.4357**	**0.5869**	**-4.0226**	0.2951	-0.2951
MW	-2.815	**-5.6370**	0.9870	0.9330	-1.9200	**-2.993**	**2.993**
SES	**2.462**	**-0.9484**	**2.4293**	**-0.1605**	**-2.2688**	-0.4114	0.4114
SRM	2.816	**-1.3854**	**3.0804**	**-0.3747**	**-2.7057**	0.1216	-0.1216
TAES	**2.565**	**-0.9467**	**2.5186**	**-0.0200**	**-2.4986**	-0.3017	0.3017
WCDR	2.268	**-1.0489**	**2.6014**	**-0.0659**	**-2.5355**	-0.2337	0.2337
WMA	**2.686**	**-0.9538**	**2.3612**	**-0.0191**	**-2.3421**	-0.3230	0.3230
WRDF	**2.448**	**-0.9465**	**2.3490**	**0.0608**	**-2.4098**	-0.3135	0.3135

Significant factors shown in bold.

Table 8.27b Coefficients of the fitted models MSE - continued.

Methods	SPL * PMP						SPL * CV^2		
	SPL = 4		SPL = 12		SPL = 52		SPL = 4	SPL = 12	SPL = 52
	HT	CM	HT	CM	HT	CM			
ARRSES	-0.1111	0.1111	0.0296	-0.0296	0.0815	-0.0815	-0.3801	-0.3914	0.7715
AW	-0.1201	0.1201	0.1004	-0.1004	0.0197	-0.0197	1.5840	0.5050	-2.0890
Croston	-0.1069	0.1069	0.0219	-0.0219	0.0850	-0.0850	-0.6892	-0.4463	1.1355
DES	-0.1235	0.1235	0.0302	-0.0302	0.0933	-0.0933	-0.4803	-0.1101	0.5904
Holt	-0.0822	0.0822	-0.0029	0.0029	0.0851	-0.0851	-0.8596	-0.2280	1.0876
MTBR	-0.0231	0.0231	-0.0308	0.0308	0.0539	-0.0539	-2.2330	-1.8760	4.1090
MW	0.2410	-0.2410	0.2452	-0.2452	-0.4862	0.4862	1.1460	0.7140	-1.8600
SES	-0.0937	0.0937	0.0412	-0.0412	0.0525	-0.0525	-0.5973	-0.0722	0.6695
SRM	-0.2838	0.2838	0.2593	-0.2593	0.0245	-0.0245	0.0450	-0.7480	0.7030
TAES	-0.1500	0.1500	0.0116	-0.0116	0.1384	-0.1384	-0.4760	-0.3607	0.8367
WCDR	0.0990	-0.0990	-0.0488	0.0488	-0.0502	0.0502	-0.8155	-0.3768	1.1923
WMA	-0.1382	0.1382	0.0286	-0.0286	0.1096	-0.1096	-0.4891	-0.4947	0.9838
WRDF	-0.1483	0.1483	0.0809	-0.0809	0.0674	-0.0674	-0.4268	-0.3555	0.7823

Significant interactions shown in bold.

Table 8.27c Coefficients of the fitted models MSE - continued.

Methods	SPL * ADI			PMP * CV^2		PMP * ADI		CV^2 * ADI
	SPL = 4	SPL = 12	SPL = 52	HT	CM	HT	CM	
ARRSES	**-1.0349**	**0.2777**	**0.7572**	-0.2745	0.2745	0.0992	-0.0992	-0.3634
AW	**-1.4244**	**0.2304**	**1.1940**	-0.9307	0.9307	0.1605	-0.1605	1.0301
Croston	**-1.0196**	**0.2582**	**0.7614**	-0.5491	0.5491	0.1239	-0.1239	-0.2511
DES	**-1.0527**	**0.3061**	**0.7466**	-0.7704	0.7704	0.1268	-0.1268	-0.3015
Holt	**-0.9091**	**0.2374**	**0.6717**	-0.4153	0.4153	0.1056	-0.1056	-0.3430
MTBR	**-1.3212**	**0.2547**	**1.0665**	-0.5470	0.5470	-0.3130	0.3130	-0.8117
MW	-0.7070	-1.2570	1.9640	-1.8840	1.8840	**2.8420**	**-2.8420**	3.2440
SES	**-0.8883**	**0.2276**	**0.6607**	-0.6919	0.6919	0.1430	-0.1430	-0.2856
SRM	**-1.4550**	**0.4399**	**1.0151**	-2.1300	2.1300	0.0540	-0.0540	0.2168
TAES	**-0.8758**	**0.1794**	**0.6964**	-0.9551	0.9551	0.1103	-0.1103	-0.2382
WCDR	**-1.0801**	**0.2772**	**0.8029**	-0.4636	0.4636	0.1063	-0.1063	-0.3052
WMA	**-0.9712**	**0.2561**	**0.7151**	-0.7760	0.7760	0.0965	-0.0965	-0.3283
WRDF	**-0.8268**	**0.1356**	**0.6912**	-0.7667	0.7667	0.1097	-0.1097	-0.2611

Significant interactions shown in bold.

Table 8.28a Coefficients of fitted models: main effect measured by RMSE technique.

Methods	CV^2 coefficient	ADI coefficient	Seasonal period length coefficient levels SPL = 4	SPL = 12	SPL = 52	PMP coefficients HT	CM
ARRSES	**1.2349**	**-0.4958**	**1.2478**	**-0.0639**	**-1.1839**	-0.2263	0.2263
AW	-0.5497	**-0.9545**	1.0424	-0.1875	-0.8549	-0.0916	0.0916
Croston	**1.2240**	**-0.5129**	**1.3241**	**-0.0494**	**-1.2747**	-0.2062	0.2062
DES	**1.2865**	**-0.5043**	**1.3108**	**-0.1096**	**-1.2012**	-0.1684	0.1684
Holt	**1.2602**	**-0.4573**	**1.2763**	**-0.0685**	**-1.2078**	-0.2226	0.2226
MTBR	**1.9360**	-0.3697	**1.6899**	**0.2653**	**-1.9552**	0.1547	-0.1547
MW	-1.4070	**-2.8183**	0.4919	0.4642	-0.9561	**-1.4995**	**1.4995**
SES	**1.2030**	**-0.4775**	**1.2101**	**-0.0760**	**-1.1341**	-0.2141	0.2141
SRM	1.4090	**-0.6926**	**1.5398**	**-0.1884**	**-1.3514**	0.0614	-0.0614
TAES	**1.2879**	**-0.4725**	**1.2600**	**-0.0098**	**-1.2502**	-0.1511	0.1511
WCDR	1.1325	**-0.5249**	**1.3026**	**-0.0322**	**-1.2704**	-0.1157	0.1157
WMA	**1.3496**	**-0.4757**	**1.1829**	**-0.0095**	**-1.1734**	-0.1620	0.1620
WRDF	0.1650	**-0.4500**	**1.1335**	**0.0710**	**-1.2045**	-0.1444	0.1444

Significant factors shown in bold.

Table 8.28b Coefficients of the fitted models RMSE - continued.

Methods	SPL * PMP						SPL * CV^2		
	SPL = 4		SPL = 12		SPL = 52				
	HT	CM	HT	CM	HT	CM	SPL = 4	SPL = 12	SPL = 52
ARRSES	-0.05446	0.05446	0.01459	-0.01459	0.03987	-0.03987	-0.2084	-0.2072	0.4156
AW	-0.06063	0.06063	0.04985	-0.04985	0.01078	-0.01078	0.7886	0.2484	-1.0370
Croston	-0.05339	0.05339	0.01161	-0.01161	0.04178	-0.04178	-0.3429	-0.2250	0.5679
DES	-0.06172	0.06172	0.01520	-0.01520	0.04652	-0.04652	-0.2346	-0.0533	0.2879
Holt	-0.04162	0.04162	-0.00130	0.00130	0.04292	-0.04292	-0.4249	-0.1145	0.5394
MTBR	-0.01850	0.01850	-0.02190	0.02190	0.04040	-0.04040	-1.0747	-0.8921	1.9668
MW	0.12100	-0.12100	0.12310	-0.12310	-0.24410	0.24410	0.5760	0.3580	-0.9340
SES	-0.04365	0.04365	0.01895	-0.01895	0.02470	-0.02470	-0.2910	-0.0415	0.3325
SRM	-0.14200	0.14200	0.12940	-0.12940	0.01260	-0.01260	0.0239	-0.3705	0.3466
TAES	-0.07507	0.07507	0.00509	-0.00509	0.06998	-0.06998	-0.2402	-0.1780	0.4182
WCDR	0.04936	-0.04936	-0.02429	0.02429	-0.02507	0.02507	-0.4069	-0.1931	0.6000
WMA	-0.06889	0.06889	0.01389	-0.01389	0.05500	-0.05500	-0.2483	-0.2491	0.4974
WRDF	-0.10731	0.10731	-0.01640	0.01640	0.12371	-0.12371	0.3345	0.1860	-0.5205

Significant interactions shown in bold.

Table 8.28c Coefficients of the fitted models RMSE - continued.

Methods	SPL * ADI			PMP * CV^2		PMP * ADI		CV^2 * ADI
	SPL = 4	SPL = 12	SPL = 52	HT	CM	HT	CM	
ARRSES	**-0.5170**	**0.1380**	**0.3790**	-0.1312	0.1312	0.04829	-0.04829	-0.1867
AW	**-0.7124**	**0.1155**	**0.5969**	-0.4644	0.4644	0.07838	-0.07838	0.5156
Croston	**-0.5092**	**0.1293**	**0.3799**	-0.2756	0.2756	0.06336	-0.06336	-0.1242
DES	**-0.5276**	**0.1537**	**0.3739**	-0.3874	0.3874	0.06341	-0.06341	-0.1467
Holt	**-0.4553**	**0.1191**	**0.3362**	-0.2101	0.2101	0.05220	-0.05220	-0.1678
MTBR	**-0.6570**	**0.1290**	**0.5280**	-0.2808	0.2808	-0.15520	0.15520	-0.4103
MW	-0.3529	-0.6268	0.9797	-0.9422	0.9422	**1.42300**	**-1.42300**	1.6199
SES	**-0.4452**	**0.1140**	**0.3312**	-0.3302	0.3302	0.07314	-0.07314	-0.1377
SRM	**-0.7276**	**0.2198**	**0.5078**	-1.0652	1.0652	0.02646	-0.02646	0.1069
TAES	**-0.4378**	**0.0891**	**0.3487**	-0.4774	0.4774	0.05531	-0.05531	-0.1219
WCDR	**-0.5415**	**0.1400**	**0.4015**	-0.2345	0.2345	0.05287	-0.05287	-0.1503
WMA	**-0.4864**	**0.1288**	**0.3576**	-0.3865	0.3865	0.04815	-0.04815	-0.1671
WRDF	**-0.4522**	**0.0337**	**0.4185**	-0.1304	0.1304	0.02323	-0.02323	0.0651

Significant interactions shown in bold.

Table 8.29a Coefficients of fitted models: main effect measured by SSE technique.

Methods	CV^2 coefficient	ADI coefficient	Seasonal period length coefficient levels			PMP coefficients	
			SPL = 4	SPL = 12	SPL = 52	HT	CM
ARRSES	2.417	**-1.3050**	1.6300	-0.3600	-1.2700	-0.8609	0.8609
AW	1.445	**-1.5153**	1.5010	-0.1908	-1.3102	-0.6737	0.6737
Croston	2.438	**-1.3325**	**1.7923**	**-0.3264**	**-1.4659**	-0.8194	0.8194
DES	2.532	**-1.3207**	**1.7570**	**-0.4488**	**-1.3082**	-0.7463	0.7463
Holt	2.499	**-1.2232**	**1.6950**	**-0.3664**	**-1.3286**	-0.8561	0.8561
MTBR	3.829	**-1.0523**	**2.5184**	**0.2952**	**-2.8136**	-0.1000	0.1000
MW	-0.907	**-6.0160**	0.3200	1.3360	-1.6560	**-4.3830**	**4.3830**
SES	2.396	**-1.2608**	1.5623	-0.3807	-1.1816	-0.8356	0.8356
SRM	3.866	**-1.5747**	**2.4244**	**-0.5902**	**-1.8342**	-0.3837	0.3837
TAES	2.540	**-1.2543**	**1.6596**	**-0.2518**	**-1.4078**	-0.7104	0.7104
WCDR	2.226	**-1.3613**	**1.7410**	**-0.2967**	**-1.4443**	-0.6426	0.6426
WMA	2.676	**-1.2612**	1.5034	-0.2502	-1.2532	-0.7347	0.7347
WRDF	2.400	**-1.2602**	1.4839	-0.1719	-1.3120	-0.7239	0.7239

Significant factors shown in bold.

Table 8.29b Coefficients of the fitted models SSE - continued.

Methods	SPL * PMP						SPL * CV^2		
	SPL = 4		SPL = 12		SPL = 52				
	HT	CM	HT	CM	HT	CM	SPL = 4	SPL = 12	SPL = 52
ARRSES	-0.0163	0.0163	0.0142	-0.0142	0.0021	-0.0021	-0.521	-0.4508	0.9718
AW	-0.0338	0.0338	0.0005	-0.0005	0.0333	-0.0333	-0.363	-0.6170	0.9800
Croston	-0.0138	0.0138	0.0049	-0.0049	0.0089	-0.0089	-0.822	-0.4906	1.3126
DES	-0.0300	0.0300	0.0142	-0.0142	0.0158	-0.0158	-0.587	-0.1458	0.7328
Holt	0.0109	-0.0109	-0.0196	0.0196	0.0087	-0.0087	-0.979	-0.2700	1.2490
MTBR	0.0564	-0.0564	-0.0602	0.0602	0.0038	-0.0038	-2.260	-1.8160	4.0760
MW	0.6386	-0.6386	0.0994	-0.0994	-0.7380	0.7380	-1.290	-0.3800	1.6700
SES	0.0056	-0.0056	0.0202	-0.0202	-0.0258	0.0258	-0.714	-0.1241	0.8381
SRM	-0.1583	0.1583	0.2368	-0.2368	-0.0785	0.0785	-0.556	-0.8570	1.4130
TAES	-0.0566	0.0566	-0.0054	0.0054	0.0620	-0.0620	-0.598	-0.3967	0.9947
WCDR	0.1925	-0.1925	-0.0652	0.0652	-0.1273	0.1273	-0.930	-0.4155	1.3455
WMA	-0.0445	0.0445	0.0115	-0.0115	0.0330	-0.0330	-0.620	-0.5340	1.1540
WRDF	-0.0547	0.0547	0.0648	-0.0648	-0.0101	0.0101	-0.536	-0.3893	0.9253

Significant interactions shown in bold.

Table 8.29c Coefficients of the fitted models SSE - continued.

Methods	SPL * ADI			PMP * CV^2		PMP * ADI		CV^2 * ADI
	SPL = 4	SPL = 12	SPL = 52	HT	CM	HT	CM	
ARRSES	**-1.3731**	**0.3859**	**0.9872**	0.630	-0.630	0.1549	-0.1549	-0.1985
AW	-1.4000	0.3070	1.0930	0.517	-0.517	0.1577	-0.1577	0.1585
Croston	**-1.3559**	**0.3661**	**0.9898**	0.353	-0.353	0.1820	-0.1820	-0.0891
DES	**-1.3916**	**0.4157**	**0.9759**	0.122	-0.122	0.1854	-0.1854	-0.1218
Holt	**-1.2487**	**0.3465**	**0.9022**	0.483	-0.483	0.1622	-0.1622	-0.1725
MTBR	**-1.6554**	**0.3690**	**1.2864**	0.335	-0.335	-0.2519	0.2519	-0.6510
MW	-0.7800	-1.4510	2.2310	0.975	-0.975	**3.2920**	**-3.2920**	2.2670
SES	**-1.2276**	**0.3365**	**0.8911**	0.241	-0.241	0.2022	-0.2022	-0.1175
SRM	**-1.8428**	**0.5513**	**1.2915**	-0.933	0.933	0.1084	-0.1084	-0.1339
TAES	**-1.2149**	**0.2889**	**0.9260**	-0.055	0.055	0.1671	-0.1671	-0.0754
WCDR	**-1.4199**	**0.3870**	**1.0329**	0.431	-0.431	0.1646	-0.1646	-0.1326
WMA	**-1.3093**	**0.3656**	**0.9437**	0.129	-0.129	0.1549	-0.1549	-0.1726
WRDF	**-1.1648**	**0.2447**	**0.9201**	0.127	-0.127	0.1695	-0.1695	-0.0874

Significant interactions shown in bold.

8.8 Predictive error-forecasting model, *PEFM*

In trying to establish which forecast method is best in any particular situation, it is necessary to have statistical information available, particularly with regard to the size of the forecasting errors. The predictive error forecasting model, as its name suggests, is thus a model whereby the forecast error predicted for any component selected together with its most efficient parameters is found. By entering in the prepared dialog-box, the forecasting factors of a specific item [e.g. *SPL*, *PMP*, $CV^2$and *ADI*, (see Figure 8.10)], the adapted Visual Basic for Applications, VBA, runs through a series of complex calculations of prepared coefficients. The linear statistical procedure GLM is fitted to the data for each method, allowing estimation of any forecasting accuracy measurement for any given set of factors and covariates included. The coefficients used are slightly different to those given in Table 8.23 to 8.29 as non-significant terms are eliminated one by one. These coefficients are presented in tabular form for each of the thirteen forecasting methods. The predictive model then selects the most appropriate forecasting method based on the lowest forecast errors (e.g. measured in terms of MAPE selected). The whole process takes less than a second. This process may be demonstrated by the following example:

8.8.1 Illustrative example

For this example, the DES method is selected, and assumes factor values of: *SPL* = 12 (monthly), *PMP* = *HT*, $CV^2 = 0.39$, *ADI* = 2.76 and in addition to those factors we select the MAPE technique as a forecast accuracy measurement.

Table 8.16 reminds us that the DES method has five significant interactions which are then reduced to four after non-significant terms are eliminated: *PMP* and CV^2, all interact with *SPL*. This means that *PMP* and CV^2 factors will all depend on the level of the *SPL* (quarterly, monthly or weekly). *PMP* interacts with both CV^2 and *ADI* and both factors will also depend on the level of *PMP* (*HT* or *CM*). The constant term in the fitted GLM is 3.0789 . The other estimated coefficients follow.

Effect of *SPL* = 12 is given by 0.1671

Effect of *PMP* = *HT* is given by 0.6458

Coefficient of CV^2 is 1.5031

Coefficient of *ADI* is 0.62223

Coefficient for *SPL* interacts with *PMP* combination = -0.07015

Additional coefficient of *ADI* for *SPL* of 12 = -0.20068

Additional coefficient of CV^2 for *PMP* of *HT* = -0.7919

Additional coefficient of *ADI* for *PMP* of *HT* = -0.21538

The estimated forecast error measured in terms of MAPE is then given as:

log MAPE = 3.0789 + (0.1671) + (0.6458) + (1.5031 × 0.39) + (0.62223 × 2.76) + (-0.07015) + (-0.20068 × 2.76) + (-0.7919 × 0.39) + (-0.21538 × 2.76) = 4.67 by taking the natural logarithm. Hence MAPE is equal to 106.49

The MAPE estimated in this way for these input variables are displayed in ascending order, as shown in Figure 8.10 (for consecutive running of model see Appendix E, and for detailed function descriptions see Appendix D).

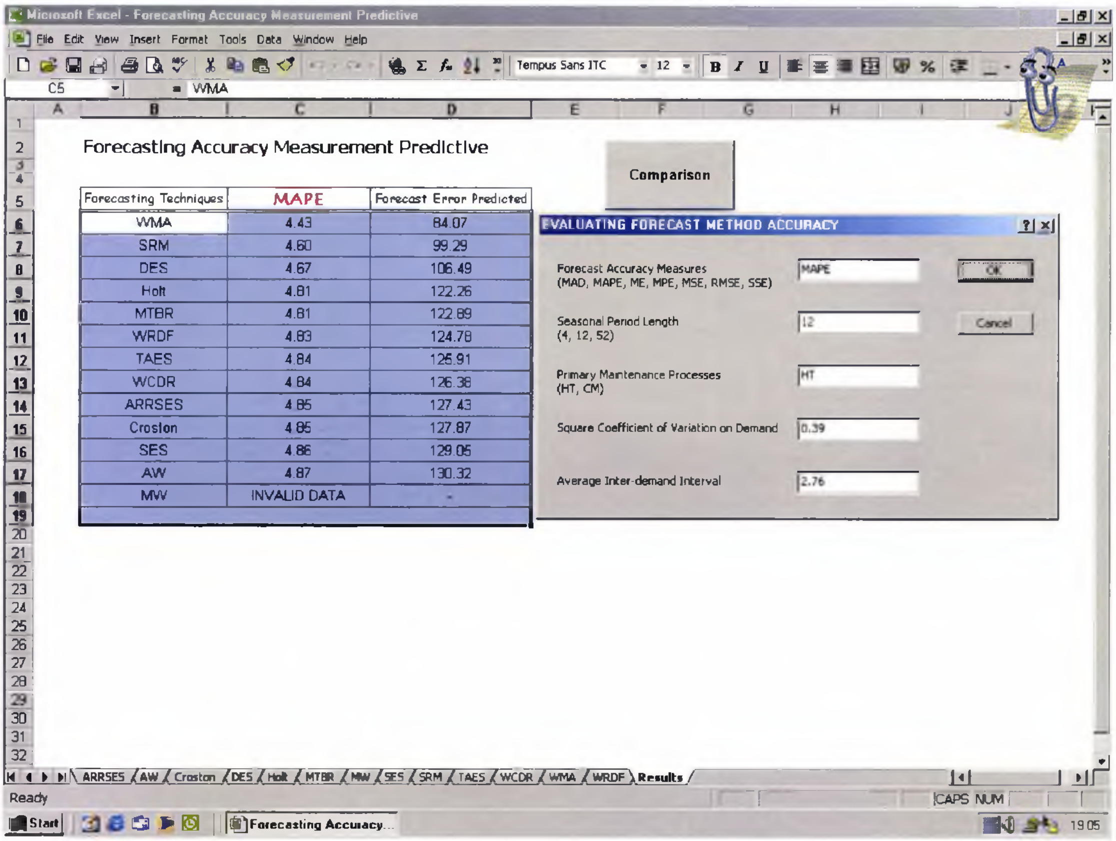


Figure 8.10 - Proposed predictive error forecasting model, dialog box.

8.9 Discussion and conclusions

The results of this investigation lead us to several important conclusions. Given the focus of this investigation, it is important to note first the significant impact of the sources of demand lumpiness on airline operations. We do believe, however, that our conclusions will assist in the selection of the proper forecasting method and factors for time-series likely to be encountered in practice. These experimental results have three important implications:

8.9.1 Sources of lumpiness

The actual demand tested in this study demonstrates that managing uncertain lumpy demand entails dealing with a multidimensional problem. Hence airline operators facing lumpy demand should carefully identify which drivers actually induce lumpiness in the demand. In particular, this study shows how lumpiness may be generated from three different sources of airline operations. Understanding the sources of lumpiness is essential for many reasons. Firstly, management may try to act, directly or indirectly, on the above sources to reduce the level of lumpiness of the demand. In this study, we demonstrate how the square coefficient of variation CV^2, and the average inter-demand interval *ADI* can be highly affected by the factors *AUR*, *COL* and *PMP* and in particular CV^2. They are shown to be the major source in increasing the demand size. This can give a clearer picture to material managers and could also yield substantial benefits, e.g. by reducing or increasing the MTBO, and focusing on components with high failure rates such as *CM* components. This may generate a smoother, albeit still uncertain, demand. Secondly, understanding the source of lumpiness is necessary in order to choose the proper forecasting method and its reduction. The results indicate that the variability in the data increases with the level of aircraft utilisation and flying hours. This means that as the aircraft utilization rate is increased, this of course increases wear and tear on the components, which therefore increases the demand rate.

8.9.2 Methods evaluation

The results comparison, displayed in Tables 8.6 to 8.14, were then simplified by Table 8.15 in order to indicate overall theoretical superiority. These theoretical conditions are based on the squared coefficient of variation and the average inter-demand interval of demand pattern for both hard-time and condition-monitored components. An appraisal of the forecasting accuracy results presented in Table 8.15 taking account of both demand pattern and forecasting error clearly indicated the general superiority of the WMA method. This is closely followed by the Holt and then Croston methods. Those were also found to be much more appropriate methods to apply, rather than that of traditional single exponential smoothing, for items with low and intermittent demands.

Thus the forecasting methods can be affected by the estimates of the mean and variance of demand size, and the average inter-demand interval.

In addition, we also observed that forecasting accuracy measurements differ. This can be explained mostly in terms of the variability of the demand rather than the biased or unbiased nature of the estimation method under consideration.

8.9.3 Statistical analysis and predictive error forecasting model

Accurate forecasting is critical for the airline operators as the price of not having the right part available at the right time in the right place is steep. An aircraft operator can incur costs of more than $50,000 for each hour a plane is on the ground. However, it was recognized from the start that demands for aircraft spares exhibited unexpectedly high variation and a large number of airline companies still used earlier methods [52, 55] specifically SES and MTBR, with little or no appreciation of the other forecasting methods used in this study. The results of this study show the use of the SES and MTBR methods to be questionable as those methods consistently create poor forecasting performance, with their performance remaining poor as the demand variability increases. Accordingly, it is recommended that companies reconsider using these methods.

The evaluations made in the study were made for aircraft parts which had previously received little attention. They clearly show that traditional forecasting techniques mentioned above are based on assumptions that are inappropriate for parts with sporadic demand. Croston [37] demonstrated that using simple exponential smoothing forecast methods to set inventory levels can lead to excessive stock levels. The results analysis of this study concludes that the forecasting demand methods are clearly dominated by the weighted moving average and its superiority increases with the increase of *SPL*. WMA is much superior to exponential smoothing and could provide tangible benefits to *airline operators* and *maintenance service organisations* forecasting intermittent demand. The highest forecasting error occurs when Winter's method forecasts demand with high variation. This conclusion contradicts previous research of forecasting intermittent demand, particularly [136] and [107]. The results shown in Table 8.15 reinforced, once again, the continued superiority of the WMA, Holt and Croston methods.

This research has shown that the level of appropriate factors has an effect on the forecasting performance. The results indicate that the impact of demand variability, such as CV^2 and *ADI*, on forecast errors (measured in terms of MAPE) is significant, that as demand variability (CV^2 and *ADI*) increases, so the MAPE increases. *ADI* has more effect on a quarterly *SPL* than with a monthly and weekly *SPL*. This was observed in most methods except for the MW. Further, to determine if there are isolatable conditions or characteristics according to aircraft component type or their associated parts which may cause certain forecasting methods to predict more accurately, *PMP* was tested, and was shown to have a significant effect in terms of forecasting performance. Again this was for most methods except for the MW. Generally, hard-time *HT* components have more effect in increasing accuracy measuring MAPE, compared with condition-monitoring *CM*.

Owing to the sporadic nature of demand for aircraft maintenance repair parts, airline operators are still looking for superior forecasting that can provide more economical and smoother planning procurement. In an effort to achieve this the study has presented a model that could be of great benefit to airline operators and other maintenance service organisations. It will enable them to select in advance the appropriate forecasting method that better meets their cyclical demand for parts. This approach is consistent with the purpose of this study, which aims to compare different forecasting methods when faced with intermittent demand.

Finally, given the consistent results obtained (e.g., Tables 8.4 to 8.29), it is believed these results are robust, especially in the light of their congruence with theoretical arguments appearing in the literature. This study has taken a step in the direction of defining the relationship between the accuracy of forecasting measurement and their factors. Although we have used data from one particular airline operator, it is suggested that these findings may be applicable elsewhere as other industrial sectors have similar demand patterns as airlines.

The adaptability of the model to variations of factor input, for example in the case of fleet or product change, is assured. One direction of further research however would be the inclusion of a *smoothing constant parameters* factor and an examination of the impact of this additional parameter on forecasting method performance. Such a study could enhance the model presented here.

9. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

As we stated in our introduction we aimed to develop the argument that MRP is better suited to handling intermittent demand patterns typical of aircraft parts inventory. This was as a response to the problems indicated by respondents to our initial aviation survey. This was further developed in an authentic case study of an airline company's parts inventory system (Chapter 6-8) with the consequent production of a usable small scale MRP-spreadsheet focussed on lot-size methodology. In this Chapter we will present a brief summary of the work done in this thesis followed by two sections; the first addressing issues of MRP implementation and the second presenting indications for further research in the area of MRP application to aircraft parts inventory.

9.1 Concluding remarks

Over the past decades, industrial producers have learned how to take strategic advantage of the MRP system. With the ability to quote, schedule production, control inventory and manage on-time delivery, MRP has added significantly to the productivity of thousands of companies in the manufacturing sector. However, can MRP systems, appropriate for manufacturing, be adapted to aircraft parts inventory overhaul and repair? Is the benefit worth the effort and cost?

We believe so, and have elaborated the need for MRP through a discussion of the traditional ROP system. In this research, the task of adapting MRP to aircraft parts inventory has been discussed and a framework for other MRP input has been proposed with the help of a case study application from KLM-uk's components overhaul workshop. The main focus of this study has been to resolve the problems raised by aviation companies in response to our survey.

- We have been able to show that the traditional independent demand based ROP approach to spare parts inventory is not a viable answer to aircraft maintenance.

Greater benefits come to companies that are able to implement an MRP system which on the contrary calculates item needs through a parent-component dependent relationship. *Airline operators* and *maintenance service organisations* that persist in using ROP may on the one hand feel that they can live with the cost of carrying excess inventory, but stockouts, on the other hand, may not be so easily ignored, as they delay the component overhaul process entailing further loss of revenue. We have shown that in practice component inventory in overhaul workshops is based on dependent demand and better ensures that parts arrive in time to meet order due dates.

- We found a small range of companies using MRP with significant benefits. There were still, however, some problems involved with the effective running of MRP and a general lack of confidence in the system was frequently reported.

- Our earlier survey showed that 21% of MO and 15% of AO believed the system was more appropriate to manufacturing industry outside of aviation. We want to emphasise though that both environments are comparable in regard to planning, execution, and operational characteristics. This study has shown that MRP can be an effective scheduling method under intermittent demand conditions within a variety of operating environments.

However, in order to have MRP perform well, it is necessary to ascertain lot-size parameters in addition to establishing accurate demand forecasting. Despite the importance of these MRP input parameters, the effects are not well understood and few prescriptive methods of setting them exist. This research has taken a preliminary look at the effect lot-sizing methods have on MRP performance. We find that intermittent demand has no detrimental effect on MRP performance unless used in conjunction with lot-sizing methods such as EOQ, LFL and FOQ, the ones ironically most commonly used by aviation companies. Our experimental results indicate that lot-sizing methods such as WWA and MSM2 appear to be the most appropriate under almost all operating conditions tested.

The survey repeatedly found that the main concern of most of the companies was the unpredictability of parts (intermittent). This study has attempted to penetrate the main

sources of lumpiness, concluding that the square coefficient of variation CV^2, and the average inter-demand interval *ADI*, can be highly affected by the factors *AUR*, *COL* and *PMP* (but more particularly CV^2) which are shown to be the major sources of increasing the demand size. Accounting for these factors could improve methodology.
The results of this research clearly indicate the general superiority of the WMA method in forecasting intermittent demand. This is closely followed by the Holt and the Croston methods which were also found to be much more appropriate methods to apply to items with low and intermittent demands rather than traditional single exponential smoothing.

Because of the high cost of the MRP system, many companies found standard MRP systems impossible to implement, both financially and environmentally. As a consequence of this, we have developed an MRP-spreadsheet which could work as an alternative for a small business unable to incorporate a larger and more comprehensive MRP system. Our proposed MRP-spreadsheet could provide companies with a good foundation, which could later, with growth and greater resources, be adapted to larger and more comprehensive systems. A few companies have already shown a great interest in this mini MRP-spreadsheet (e.g. RDC Communications, Inc., DORMA Architectural Hardware, DuPont Consulting Solutions, and General Electric USA).

Owing to the sporadic nature of demand for aircraft maintenance repair parts, airline operators are still looking for superior methods of lot-sizing and forecasting that can provide more economical and smoother procurement. Many aviation companies were dissatisfied with their current use of lot-size and forecasting methods. We have taken a step in the direction of defining the relationship between the methods and their factors in order to enable the management practitioners to select the method that suits their particular demand fluctuations. As such, two models we have named as the Lot-size predictive cost model, *LPCM* and the Predictive error-forecasting model, *PEFM*, have been presented in this thesis which will better enable aviation companies to select in advance the appropriate lot-size and forecasting method that best meets their cyclical demand for parts. We have used data from one particular airline operator, KLM-uk, but suggest that the findings may be applicable elsewhere where manufacturers and others have similar demand patterns to those of airlines.

In addition to the above technical issues, notwithstanding the great benefits gained from implementing an MRP system, *airline operators* and *maintenance service organisation* companies still report some lack of system use. To overcome these problems, we confirm that credibility in the MRP system can only be achieved with a high level of visible management commitment, continuous monitoring and consistently accurate data. A key factor to its success lies in a comprehensive MRP education and training program prior to and during implementation.

9.2 Summary of limitations and recommendations for further research

The results and associated conclusions of this study must be viewed in the light of the assumptions made and the context of the study itself. These are:

- We used both *PH* and *OC* as categorical variables rather than covariates.
- There is no discount for quantity taken into account.
- The safety stock level was assumed to be zero.
- Exclusion of any operating impact of component part commonality.
- The study is not concerned with multilevel lot-size situations. A single-level lot-size only was used.

The recommendations for further research emanate from these aforementioned points.

A materials manager may be offered discounted prices for parts ordered in larger quantities. Effective decision making concerning the acceptance or rejection of these purchase *quantity discounts* can inevitably lead to significant cost savings. One direction of further research would be an examination of the effect of this additional parameter on various lot-sizing methods' performance. There are no known studies examining such interactions within the aviation context.

Our survey showed that companies apply different levels of safety stock. We have proposed that the best treatment for safety stock in an MRP environment is to completely eliminate it, as the MRP system works on the philosophy of reducing inventories and determining true need dates while a safety stock works against both objectives. However, as the nature of airline operations differs, certain safety stocks may be kept, in response to MEL and/or criticality, to minimize the aircraft-on-ground time. The experimental design for a further study could evaluate the differences in the average safety stock needed to achieve various service level policies with a variety of demand patterns, and secondly, the interaction of different service levels with experimental factors such as *CVD* and various lot-size methods.

Another related issue is component part commonality which has been viewed as a means of cost reduction. It is frequently practiced, particularly at lower levels of BOM (e.g. Main and Nose Undercarriage Units). Commonality provides for the minimisation of the problem of handling multiple-part demands while maintaining a desired service level. The degree of commonality may have a significant effect on MRP system performance in the area of lot-size method and safety stock in terms of total cost. This needs to be proven.

Taking into account the above mentioned limitations and other previously mentioned factors, further experimental study is needed for both single and multilevel lot-size methods. Due to the interdependencies of lot-sizes at different levels of the BOM, multilevel lot-sizing is an important technical issue in MRP systems where a change in order size or timing at one level can result in changes at other levels. We need to know how significant the interaction is between single-stage lot size methods, when applied to different levels of the BOM structure, and how such factors affect lot size performance and interaction.

Regarding the forecasting of intermittent demand, research shows that combining forecasts (averages of forecasts) from two or more techniques can dramatically improve forecast accuracy. In this study, we have mainly investigated the performance of individual forecasting methods with regard to an intermittent demand pattern. A further study is also needed to investigate if such combinations could improve forecasting accuracy and whether the variation of accuracy among different combinations decreases as the number of methods on average increases. So too, research including the *smoothing constant parameters* $(\alpha, \beta \text{ and } \gamma)$ factor together with an examination of its impact on forecasting method performance would be appropriate.

Taking the above limitations into account and following the leads towards further research, we believe that the models presented herein could be considerably enhanced.

Finally, after this discussion of the possibilities of adopting the MRP system into aircraft parts inventory, it remains only to improve our MRP system through an integration with a pull system, such as JIT, which in the survey, some aviation companies identified as being the only system they used. Many studies have compared the two tools, and have attested to their being totally compatible once certain philosophical and technical issues had been accommodated. Many researchers believe that the relationship of MRP and JIT is not only possible but that it should be absolutely mandatory. Together they may form the planning and control backbone for the future of the industry. The fact that MRP performs better than JIT when there is intermittent demand and that JIT cannot be used effectively when there are lead-time variations, are matters that further research will have to address.

This thesis is complete in as much as all aspects for adapting MRP into the aircraft parts inventory systems have been discussed and explained. We firmly believe that more airline operators and maintenance service organisations can and should enjoy the benefits of this system. We urge them to consider the advantages set out herein.

APPENDICES

Appendix A:

The implementation of the survey, obstacles encountered and methods arrived at for overcoming them.

I originally addressed my questionnaires to the aviation companies, but I did not have a contact name. As a result delays occurred as it took some time for the questionnaire to reach the right department. Replies might have been more forthcoming had I addressed my survey directly to an individual employee of the company.

In order to prompt the companies to respond to my questionnaires I sent reminder letters, but these did not prove to be very successful. Only approximately four to five percent of replies resulted from reminder letters which was rather disappointing.

The next stage in my research was direct telephone communication with the aviation companies. It was often a problem explaining to the receptionist whom I needed to speak to. In many cases I had to speak to three or four people before I was put through to the person who was going to complete the questionnaire.

I was surprised to discover that only 10% of the companies that I telephoned had actually received my survey. Often the questionnaires were 'lost' amongst the internal mailing system within the company. In these cases I sent further copies of the questionnaire directly to the materials manager that I had spoken to. I soon discovered that it is very important to find out the precise job title of the person in the company knowledgeable about materials management. The titles for those managers varied and some are listed below:

Aeronautical Material Purchasing Manager
Commercial Manager
Engineering Inventory Controller
Fleet Materials Manager
Inventory Administration Director
Inventory Manager
Chief Storekeeper
Engineering Director
Engineering Materials and Logistics Manager
Inventory Administrator
Inventory Control Manager
Inventory Planning Manager

Logistics Manager
Material Control Manager
Material Management Manager
Materials Planning Superintendent
Material Sales Manager
Material Requirements Director
Procurements Director
Provisioning Manager
Purchasing and Materials Director
Spare Parts Planning Manager
Strategic Planning Manager
Supply Manager
Technical Planning and Materials Manager
Technical Supplies Manager
Materials Aerocomponents Director
Materials Manager
Material Planning Manager
Materials and Purchasing Director
Material Support Manager
Production Services Manager
Provisioning Group Leader
Purchasing Manager
Purchasing and Logistics Manager
Store Manager
Supervisor Material Control
Technical Planning & Cost Control Director
Technical Purchasing Manager
Warranty Claims Manager

Through my conversations with the store managers I found the majority of airline companies were very interested in my research and wanted me to send them the results once I had completed my research. They agreed to complete the questionnaires provided they received the results of this survey. By telephoning the airlines to remind them about my questionnaire I received a better response - on average about eight to ten replies per week.

Some replies were still outstanding after several months. I realised that these airline companies were very busy and did not, therefore, have the spare time available to complete the survey. Some companies asked for extra time to complete the questionnaire, but I found on several occasions during this period the managers had either retired or left the company and, although I received letters of apology for this, I still had to spend unnecessary time explaining once again the purpose of my survey. I also discovered that one of the companies I had originally approached was no longer in operation, although it had been willing to participate with my project.

Finally, I had several replies from companies who had genuinely confirmed completion of the survey and posted them back, but these seem to have got mislaid in the internal / external mailing system at the university as I did not receive them.

It is by no means assured that any given questionnaire will produce a good quantity of responses. I found the following things helpful. First, to telephone the company to establish whether or not they are willing to help with the survey. It is imperative that to explain that the information acquired will be treated as confidential and is for university research purposes only and will not be passed on to any other companies. It is then very important to find out who to send the questionnaire to, which department they are in and the full mailing address. This ensures that the survey reaches the correct individual and should then be returned promptly. The companies listings indicate their primary area of business such as: airframe work, engine overhaul, avionics repair, landing gear overhaul, major systems and components work, completions of corporate aircraft and interior refurbishments all under regulatory approvals of CAA, FAA and JAA, the listings appear alphabetically:

Survey respondents (airline operator and maintenance service organizations)

A.1 Responses received

1. Aero Corp.
2. Aerolineas Argentinas
3. Aeromexico
4. Aero Union Corp.
5. Agusta Gruppo
6. Air 2000
7. Air Asia
8. Aircraft Maintenance & Engineering Co.
9. Air France (Orly)
10. Air France (Toulouse)
11. Air India
12. Air Inter
13. Air Lanka
14. Air Malta
15. Air Mauritius
16. Air New Zealand (Auckland)
17. Air New Zealand (Christchurch)
18. Airod
19. Air-Tech Malaysia
20. Air UK (KLM-uk).
21. Air Wisconsin Inc.
22. Airwork Corp.
23. Air Zimbabwe
24. A J Walter International
25. Alaska Airlines Inc.
26. Alitalia - Linee Aeree Italiane
27. All Nippon Airways
28. America West Airlines Inc.
29. American Airlines
30. Anglo American Airmotive Ltd.
31. Ansett Australia
32. Arkansas Aerospace Inc.
33. ASTA Aircraft Services Pty Ltd.
34. Avianca Airlines Colombia
35. Boeing Commercial Airplane Group
36. Braathens SAFE
37. Bristol Aerospace Ltd.
38. British Aerospace Aviation Services
39. British Aerospace (Jet stream Aircraft)
40. British Airways
41. British Airways Engine Overhaul
42. British Midland Airways
43. Canadian Airlines International
44. Canadian Commercial Aircraft Overhaul
45. Cargolux Airlines International
46. Cathay Pacific Airways Ltd.

47. China Airlines (Taiwan)
48. Clay Lacy Aviation
49. Comtran International
50. Crossair
51. The Dee Howard Company
52. Delta Airlines Inc.
53. Deutsche Lufthansa
54. Dowty Aerospace Aviation Services
55. Egypt Air
56. EL AL Israel Airlines
57. Emirates International Airlines
58. Ethiopian Airlines Corp.
59. Eva Air
60. Federal Express
61. FFV Aerotech (USA)
62. Finnair
63. First Air Maintenance Services
64. FLS Aerospace Support Ltd.
65. Fokker Aircraft Services
66. FR Aviation Ltd.
67. Garuda Indonesia
68. General Electric Co.
69. Gulf Air
70. Gulf Aircraft Maintenance Company
71. Hapag-Lloyd Fluggesellschaft
72. Hawaiian Airlines Inc.
73. Hawker de Havilland - Perth
74. HeavyLift Aircraft Engineering
75. Hong Kong Aircraft Engineering
76. Hunting Aircraft (UK)
77. Hunting Aviation Accessories
78. Hunting Avionics
79. Hunting Cargo Airlines
80. IBERIA
81. Icelandair
82. Innotech Aviation Ltd.
83. Israel Aircraft Industrial - IAI
84. Japan Airlines Co. Ltd. - JAL
85. Japan Air System - JAS
86. JEA Engineering
87. Karair
88. K-C Aviation
89. Kearsley Airways Ltd.
90. Kenya Airways
91. KLM - Royal Dutch Airlines
92. Korean Airlines Co. Ltd.
93. Kuwait Airways Corp.
94. LAB
95. LanChile
96. Lineas Aereas Aviaco
97. Lockheed Aeromod Center Greenville
98. Lockheed Aircraft Service Co.
99. Lockheed Commercial Aircraft Center
100. LOT - Polish Airlines
101. LTU - International Airways
102. Luxair
103. Maersk Air
104. Malaysia Airlines
105. Marshall of Cambridge (Aerospace)
106. Meridiana
107. Mexicana Airlines
108. Middle East Airlines Airliban - MEA
109. Monarch Airlines
110. MTU Maintenance GmbH
111. National Airmotive Corp.
112. Nayak Aircraft Services GmbH
113. NORDAM Repair Division
114. Normalair-Garrett Ltd.
115. Northwest Airlines Inc.
116. Officine Aeronavali Venezia
117. Oficinas Gerais de Material Aeronautico
118. Olympic Airways
119. Oman Aviation Services
120. Pakistan International Airlines - PIA
121. Parker Bertea Aerospace
122. Pemco Air Support Services
123. Philippine Airlines Inc.
124. Pratt & Whitney (Germany)
125. Pratt & Whitney (UK)
126. Qantas Airways (Melbourne)
127. Qantas Airways (Sydney)
128. Rolls-Royce Aero Engine Service

129. Rolls-Royce (Canada)
130. Rolls Wood Group (Repair / Overhauls)
131. Royal Air Force - RAF
132. Royal Air Maroc
133. Royal Jordanian Airlines
134. Royal Navy Aircraft Yard - RNAY
135. Ryder Airlines Services Accessories
136. Ryder Airline Service Caledonian
137. Ryder Aviall (Dallas)
138. Sabena Belgian World Airlines
139. Safair Freighters
140. Saudia - Saudi Arabian Airlines
141. Scandinavian Aero Engine Services
142. Scandinavian Airlines System-Denmark
143. Scandinavian Airlines System-Norway
144. Scandinavian Airlines System-Sweden
145. Serv-Air Inc.
146. Shannon Aerospace Ltd.
147. Simera Division of Denel
148. Singapore Aerospace Supplies
149. Singapore Airlines Ltd.
150. Smith's (Harlow) Aerospace Ltd.
151. Southern Air Transport
152. SRS Aviation (Ireland)
153. Standard Aero Ltd.
154. Staravia Ltd.
155. Sudan Airways
156. Sundstrand Aerospace Corp.
157. Swissair
158. Syrianair
159. TAESA Airlines
160. TACA International Airlines
161. Team Aer Lingus
162. Thai Airways International
163. Transbrasil SA-Linas Aereas
164. Trans European Airways Maintenance
165. Trans Mediterranean Airways - TMA
166. Trans World Airlines - TWA
167. Tunis Air
168. Turborreactores
169. Turkish Airlines
170. United Airlines
171. USAir
172. VARIG Brazilian Airlines
173. Wideroe Flyveselskap
174. World Aviation Support Ltd.
175. Yemen Airways

A.2 Apologies received: Company unable to complete survey

1. Aeroflot
2. Aero Systems Aviation Corp.
3. Aerotest
4. Accessory Overhaul Group
5. Air Canada
6. Air Creebec
7. Air Jamaica Ltd.
8. Airkaman of Jacksonville
9. Air Littoral
10. American Trans Air
11. Associated Air Center
12. Austrian Airlines
13. Banyan Air Service
14. BF Goodrich Component Services
15. Britannia Airways
16. British Aerospace (Military Aircraft)
17. CAE Aviation Ltd. (Canada)
18. Caledonian Airborne Engineering
19. Carnival Airlines
20. Chrysler Technologies A/B Systems
21. Commodore Aviation
22. Continental Airlines Inc.
23. CUK Ltd.
24. Cyprus Airways Ltd.
25. Dalfort Aviation
26. Deutsche Aerospace Airbus
27. Dunlop Aviation Services
28. DynAir Tech of Texas
29. Field Aviation West
30. GB Aircraft Maintenance

31. Greenwich Aero Services
32. Grumman St Augustine
33. Guangzhou Aircraft Maintenance Eng.
34. Hamilton Aviation
35. H+S Aviation Ltd.
36. Hughes Aviation Services
37. Hunting Airmotive Ltd.
38. JAMCO (Japan)
39. Jet Aviation (Basel)
40. JJ & W Aircraft Services
41. Kelowna Flight craft
42. Martinair Holland
43. RAS Maintenance
44. Rich International Airways
45. Royal Brunei Airlines
46. South Centre Maintenance
47. Southwest Airlines Co.
48. Triad International Maintenance Co.
49. Tramco
50. Virgin Atlantic Airways
51. West Virginia Air Center

A.3 No correspondence received

1. Appalachian Flying Services
2. Aviation Spares Ltd. (Maintenance)
3. Cameroon Airlines
4. De Bery Aviation
5. Deutsche Aerospace
6. Euravia Engineering & Supply Ltd.
7. Europe Aero Service
8. FFV Aerotech (Sweden)
9. Field Aviation East
10. General Air Services
11. Ghana Airways
12. Hellenic Aerospace Industry
13. Iran Air
14. King Aerospace
15. Lineas Aereas de Espana
16. Malev - Hungarian Airlines
17. MBB Aircraft Service Centre
18. Narcam Aircraft
19. Nigeria Airways Ltd.
20. Pacific Aircraft Maintenance
21. Rio-Sul Airlines

A.4 Companies no longer in operation

1. Australian Airlines
2. Canadian Arrowspace Inc.
3. Cross-Continent Aircraft Services
4. Lucas Aviation
5. Satolas Maintenance Service
6. Sterling Airways Technical Services
7. UTA - Union de Transport

A.5 Companies willing to co-operate but replies not yet received

1. AAR Oklahoma
2. Aeroplex of Central Europe
3. Air Algerie
4. Alenia (IRI Finmeccanica Group)
5. Aloha Airlines Inc.
6. Avensa - Aerovias Venezolanas
7. Chem Tronics
8. DynAir Tech of Arizona
9. DynAir Tech of Florida
10. Evergreen Air Center
11. Hunting Aircraft (USA)
12. Linjeflyg
13. Matrix Aeronautica
14. Mesaba Airlines
15. Mobile Aerospace Engineering Inc.
16. Northrop Worldwide Aircraft Service
17. Page Avjet
18. Professional Modification Services

19. Ryan Aviation
20. Ryder Aviall (Burbank)
21. SECA Groupe Aerospatiale
22. Schreiner Aircraft Maintenance
23. Sogerma-Socea
24. South African Airways
25. TAP - Air Portugal
26. Transair
27. Transportes Aeromar
28. USAir Shuttle
29. VASP Brazilian Airlines

A.6 Companies eager to receive conclusions of survey

1. Aerolineas Argentinas
2. Air Asia
3. Air France (Orly)
4. Air Inter
5. Air New Zealand (Christchurch)
6. Airod
7. American Airlines
8. Ansett Australia
9. Bristol Aerospace Ltd.
10. Canadian Airlines International
11. Crossair
12. Deutsche Lufthansa
13. Emirates International Airlines
14. Gulf Air
15. Hawker de Havilland - Perth
16. Korean Airlines Co. Ltd.
17. Lockheed Aeromod Center Greenville
18. Lockheed Commercial Aircraft Center
19. Middle East Airlines Airliban - MEA
20. Northwest Airlines Inc.
21. Officine Aeronavali Venezia
22. Oficinas Gerais de Material Aeronautico
23. Pakistan International Airlines - PIA
24. Pratt & Whitney (UK)
25. Rolls-Royce Aero Engine Service
26. Ryder Airlines Services Accessories
27. Ryder Airline Service Caledonian
28. Ryder Aviall (Dallas)
29. Safair Freighters
30. Simera Division of Denel
31. Sudan Airways
32. TACA International Airlines
33. Team Aer Lingus
34. Transbrasil SA-Linas Aereas
35. Trans Mediterranean Airways - TMA
36. VARIG Brazilian Airlines

A.7 Survey questionnaires

The following are the questions, which comprised the survey that was sent out. Although the respondents were people dealing with the area of spare parts management, nevertheless some of the terms, for example regarding lot-sizing methods, would have been unfamiliar. Therefore I enclosed attached sheets of definitions and explanations along with the questionnaire. In addition there was an illustrated example of an MRP calculation because I expected that only a few would have previous experience of this system. Further to this, several respondents commented that after reviewing this they realised that there own system used the same logic as MRP but that they simply called it by another name.

1. Do you know of MRP?
If YES please answer questions (Q.13 to Q.35), or
If NO please answer questions (Q.2 to Q.12)

2. If you know of MRP but have not used it, could you please tell us why not?

3. Do you use a computer to keep records (inventory control system), so that you can find out what is in stock?

4. What action do you take when you run out of stock of something? Do you prefer to expedite, borrow or use loan stock or buy?

5. How do you plan for orders? Do you usually order at regular intervals for each item?

6. Managers closely monitor inventories to keep them at acceptably low levels. Inventories are normally reported to them in three basic ways:
- Average aggregate inventory value.
- Weeks of supply.
- Inventory turnover.

If you use any of these types of inventory measuring, please tell us which one and how you calculate the inventory value.

7. How much is done purely automatically and how much is still done manually?

8. How do you work out your capacity requirements plan (e.g. by man hours per flying hours or by monthly budget)?

9. Do you think your inventory system is appropriate for your company? If NO why not?

10. Companies sometimes classify components according to their importance by, for instance, their price, so the very expensive receive more urgent attention than the less expensive ones. The total cost expenditure is thus reduced. How do you classify components other than by the normal division into repairable and rotable?

11. Once the spare parts have been sent for repair to a contractor (workshop), if it is not in your control you have no idea once it leaves your company how much progress has been made and how long it will take. Normally there is a time agreed in the contract for how long the repair will take. Do you work to an agreed time or do you rely on the contractor?

12. What happens when you change the fleet size or bring a new type of aircraft into service; i.e. what happens when you do not have historical data? How do you get the new data, and do you have to ask the manufacturer?

13. Which MRP software does your company use?

14. MRP inventory records are:

- Planning factors (lead-time, lot-sizing, safety stock)
- Gross requirements
- Scheduled receipts
- Projected on-hand inventory
- Planned order receipts
- Planned order release

Does your company use the same inventory records (procedures)? If not please tell us which you use?

15. If you use the MRP system, could you please tell us how you work out your MRP system? Do you do the calculations, or do you accept the computer statement?

16. Lead times for purchased items are usually determined following discussions and negotiation between the purchasing personnel within the respective company and suppliers. In your case how do you calculate your purchase lead-time (e.g. by agreement or from past data)?

17. MRP's time bucket is usually represented in days, weeks or months.
In which time bucket do you represent your planning horizon?

18. The MRP planning horizon varies from between **10** weeks to **52** weeks. It depends upon the type of firm and the products involved. What is the duration of your MRP planning horizon, either in days, weeks or months?

19. What type of lot-size method do you use from the following lot-size methods for ordering the appropriate quantities, and have you found it reliable for controlling your spare parts stock and why?

- The lot for lot (LFL) method
- The fixed order quantity method
- The economic order quantity method
- The fixed order periods method
- The periodic order quantity method
- The fixed period requirements method
- The part period balancing method
- The Wagner-Whitin algorithm
- The least unit cost
- The least total cost
- The part-period algorithm:

20. Are you satisfied with the selected method of lot-size calculations?

21. Safety stocks are planned to protect against unexpected fluctuations in demand or supply. Do you think safety stock should be used? If yes, do you use safety stock at: all levels; low levels; or to end-item (finished goods levels)?

22. How do you calculate the safety stock quantities? Is it by practice (experience), estimation, or taking the average?

23. Do you use BOM processor (software package)?

24. A good BOM format can be useful in engineering, accounting, and maintenance, as well as in production planning and control. The BOM has two methods for specifying component requirements by:

- Using single-level BOMs with reference pointers.
- Using indented BOM file.

Which of the these methods do you apply? Which do you find better and why?

25. There are two basic approaches to re-planning within MRP systems:

I. Top-down planning.

- Regenerative planning
- Net change

II. Bottom-up re-planning.

- Pegged requirements
- Firm planned orders

If you use one of these systems please answer (Q.26 & Q.27)

If you do not use either of these, which system do you use?

26. Once the MRP is "run" (on the computer), orders are released, and goods are produced. As time passes, the status of orders changes and the MRP system must be updated. With a regenerative MRP system, re-planning is usually done on a weekly basis. Do you use the Regenerative MRP system and how often do you re-plan your MRP system? If more than once a week, what has been the effect on your system?

27. Do you use a Net change MRP system? If not, what type of system do you use if items change or items are not previously planned?

28. The MRP system has evolved into MRPII. Which one of the systems do you use at the present time?

29. How much is done purely automatically and how much is still done manually?

30. Companies sometimes classify components according to their importance by, for instance, their price, so the very expensive receive more urgent attention than the less expensive ones. The total cost expenditure is thus reduced. How do you classify components other than the normal division of repairable and rotable?

31. Once the spare parts have been sent for repair to a contractor (workshop), if it is not in your control you have no idea once it leaves your company how much progress has been made and how long it will take. Normally there is a time agreed in the contract for how long the repair will take. Do you work to an agreed time or do you rely on the contractor?

32. What happens when you change the fleet size or bring a new type of aircraft into service; i.e. what happens when you do not have historical data? How do you get the new data, and do you have to ask the manufacturer?

33. Having implemented an MRP system:

- Does the system work? Is the company reaping any benefits?

34. The benefits of successful installations are often remarkable as a result of their:

- Reducing inventory costs.
- Improving scheduling effectiveness.
- Responding more quickly to market demands.
- Increasing on-time customer deliveries.
- Cutting over-time.
- Reducing component shortages.
- Lowering indirect labour.
- Reducing direct labour.

Has your company enjoyed any of these benefits?

If YES please tell us which of the benefits your company enjoys.

35. If you have been using MRP and for some reason it has failed or it was unsuccessful, would you please tell us if it was for one of the following reasons:

- Lack of top management commitment to the project.
- Lack of education in MRP for those who have to use the system.
- Unrealistic master schedule MS.
- Inaccurate data, particularly BOM data and inventory data.

Appendix B.

Visual Basic Module for MRP-Spreadsheet Calculations

B.1 Table of routines contained in VBA functions module

Key:

EF Excel Function
FN Excel Visual Basic for Applications Function
OB Excel VBA Object
P Procedure
R Remark
V Variable

Function name	Type	Description
Abs	FN	Takes the absolute value of a number.
Activate	FN	Activates an object - often a sheet or cell.
Activesheet	FN	The active worksheet.
Activeworkbook	FN	The active workbook when several are open.
Application.min	EF	Returns the minimum value from a range.
Application.round	EF	Rounds a number to the nearest whole number.
Array	OB	A one or two dimensional matrix/array of values.
Asheet	V	Variable name used to store the activesheet's name.
Auto_open	P	A procedure which is automatically run when the sheet is opened.
Average_inv	V	Calculates/holds average inventory value in total cost procedure.
Bestj	V	Stores Best j value in the MSM1/MSM2 methods.
Boolean	EF	A variable type which can be True or False.
Caption	EF	Many objects have a caption property e.g. a dialog box.
Cellpos	V	Used to store a cell position.
Cells-moved	V	Counts the number of cells moved in the POQ method.
Cellvalue	V	Accumulates value to write into the 'triangle of cells' in the WWA method
ClearContents	EF	Removes contents from the selected range of cells.
ClearPlan	P	Clears planned order receipts and order releases.
Cleartriangle	P	Clears triangle in the WWA method.
Colidx	V	Column index - another counter.
Colind	V	Another column index.
Columnindex	V	Column index.
Countback	V	Counts backwards, used in the WWA method.
Counter	V	A variable used to count.
Ctr	V	A variable used to count.
Cum_demand	V	Used to accumulate the demand.
Cum-oc	V	Used to accumulate the order cost.
Cum-pp	V	Used to accumulate the part-period.
Curr-period	V	The current period number.
Dialogscreen2	P	Displays a dialog sheet to prompt for run time variables.
Dialogsheets	EF	Displays or tests for the active display of a dialog sheet.
EditBoxes	EF	Edit boxes are used on dialog sheets to allow users to enter values.
Ending-inv	V	Calculates ending inventory in the FOQ method.
Errflag	V	Used to indicate an error condition.
F-curr	V	Used in the BTH2 Method to store current F value.
F-Prev	V	Used in the BTH2 Method to store previous F value.
Firstsetup	V	A flag used to test/detect for the first set-up in a method.
Flag	V	Used in method PPB to indicate a set of conditions being met.

Gofwd	V	A column index indicator going forwards.
Gross-total	V	Accumulates demand.
Int	EF	Returns the integer value of a number.
Loop-inc	V	Loop incremented in WWA method.
Looptimes	V	Counts the number of times round a loop.
Majorloop	TEXT	Annotation indicating major loop(s) within a procedure.
Maxchange	EF	Maximum change value when switching recalculation on or off.
Maxqty	V	Maximum quantity.
Maxvalue	V	Maximum value.
MenuBars	EF	Function used to control Excel menu bars.
Menuitems	EF	Used to add/delete items to a custom menu bar.
Minvalue	V	Minimum value.
Modificationflag	V	Used in the MSM1 method to indicate whether the modification test has been passed and made.
Modstart	V	Used in MSM1/MSM2 to record starting column positions.
Movedemand	P	Moves demand values along one or more periods.
Netreqs	V	Net requirements in the FOQ Method.
Newcol	V	New column.
Newt	V	New *t* value in BTH1.
Nobest	V	Flag to indicate whether a 'best' find has been made in MSM1.
Nofinds	V	Counts no of finds (demand / max qty) in WWA method.
No-weeks	V	Counts no of weeks in POQ.
Numweeks	V	Calculates number of weeks to move demands by.
Offset	EF	Used to offset the active cell to cells before/after rows or columns.
Oldt	V	Old *t* Value.
OnAction	EF	Used with custom menu items to determine the procedure to run.
P	V	Value read from spreadsheet labelled T_{EOQ}
Periods	V	The number of periods or planning horizon.
PP	V	The variable part-period (*PP*) in the PPA/PPB methods.
PrecisonAsdisplayed	EF	Property associated with switching recalculation on/off.
Prev-period	V	Stores previous period number (SM Method).
Propcounter	V	Property counter used in WWA.
Property2	V	Flag used to indicate whether property 2 condition has been met.
Re-calcs	R	Re-calculates.
Replen1	V	Replenishment 1 in MSM2.
Replen2	V	Replenishment 2 in MSM2.
Reset	EF	Resets the Excel menu bars.
Rowindex	V	Tracks the row number in the WWA method (in the triangle).
ScreenUpdating	EF	Switches screen updating to on or off.
Searchrow	V	The current search row in the WWA method.
Startpoint	V	Stores the starting point e.g. ICA method.
Temp	V	Used to temporarily store a value.
Teoq	V	Read the T_{EOQ} value from the spreadsheet for use by Excel VBA.
Titletext	V	Title Text for a Selected MRP Lot-size Method.
Totalcost	P	Calculates the total cost of the calling procedure's method.
Val1	V	Used as part of the MSM1 / MSM2 calculations.
Xlautomatic	EF	Switches spreadsheet recalculation to automatic.
Xlmanual	EF	Switches spreadsheet recalculation to manual.
Xlworksheet	EF	Part of the syntax for menu bars.

B.2 VBA running tips

1. To stop the VBA running, press Esc key then select End.
2. If you experience some problems with Microsoft Application, such as being unable to quit the programme, you may have to turn off the Microsoft Office Manager Extensions File.
3. Once the spreadsheet is open, make sure the following functions are selected: Go to Tools Add-Ins then click:
    - Analysis ToolPak
    - Analysis ToolPak - VBA
    - Crosstab sheet function
    - Update Add-in Links

B.3 Rate of exchange, 13.07.1996, Financial Times

£1.00 = 1.60 US$

Appendix C.

Visual Basic Module for Lot-size Predictive Cost Model, *LPCM*

Table of routines contained in VBA functions module

Key:

EF Excel Function
FN Excel Visual Basic for Applications Function
OB Excel VBA Object
P Procedure
R Remark
V Variable

Function name	Type	Description
a, b, c	OB	Cell Objects used in moving around the worksheets.
Asheet	OB	Worksheet object used to move from one sheet to the next.
ActiveCell	FN	Returns the location (address) of the active cell.
Asheet.Name	FN	Returns the name of the active worksheet.
Auv	V	Annual usage value.
Auvmoq	V	*AUV* * *MOQ*
Coeffauvcvd	V	Coefficient of *AUV* * *CVD*
Coeffcvd	V	Coefficient of *CVD*
Coeffcvdph	V	Coefficient of *CVD* * *PH*
Coefficoc	V	Coefficient of *OC*
Coefficph	V	Coefficient of *PH*
Coeffmoq	V	Coefficient of *MOQ*
Coeffmoqph	V	Coefficient of *MOQ* * *PH*
Coeffoc	V	Coefficient of *OC* for varying order costs (an array).

Coeffocauv	V	Coefficient of *OC* * *AUV*
Coeffoccvd	V	Coefficient of *OC* * *CVD*
Coeffocph	V	Coefficient of *OC* * *PH*
Coeffphauv	V	Coefficient of *PH* * *AUV*
Coeffphcvd	V	Coefficient of *PH* * *CVD*
Coeffphmoq	V	Coefficient of *PH* * *MOQ*
Const_val	V	Constant value.
Ctr2	V	Counter used in reading a 2 dimensional array
Cvd	V	Coefficient of variation in demand.
Cvdmoq	V	*CVD* * *MOQ*
Dim	FN	Declares variables used within the routine.
Double	FN	Variable type of double numerical precision.
False	FN	Object property evaluating to false.
Icphbit	V	Coefficient of *IC* * *PH* determined for the final formula.
Integer	FN	Variable type of integer values only.
IsEmpty	FN	Object contents are empty.
Key1	FN	Part of the sort function denoting which column to sort in.
Len	FN	Length of a text or string variable.
Ln	EF	Returns the natural logarithm of a number.
Logauv	V	Log of *AUV* coefficient (Logauvcoeff).
Logauvcoeff	V	Coefficient of log *AUV* Coefficient.
MatchCase	FN	Part of sort function determining whether to match case or not.
Moq	V	*MOQ*
Object	V	Denotes an Excel VBA object e.g. cell, worksheet etc.
Oc	V	*OC*
Ocauvbit	V	Coefficient of *OC* * *AUV* determined for the final formula.
Ocbit	V	Coefficient of *OC* determined for the final formula.
Occvdbit	V	Coefficient of *OC* * *CVD* determined for the final formula.
Ocphbit	V	Coefficient of *OC* * *PH* determined for the final formula.
Order1	FN	Part of the sort function – specifies sort order (ascending/descending).
Orientation	FN	Part of the sort function determining the data orientation.
Ph	V	*PH*
Phcvdbit	V	Coefficient of *PH* * *CVD* determined for the final formula.
Phmoqbit	V	Coefficient of *PH* * *MOQ* determined for the final formula.
Range	FN	Specifies a range of cells.
TC	V	Total cost (final formula).
Text	FN	Denotes a text variable type.
Trim	FN	Removes spaces from a text variable.
Val	FN	Returns a number from a text variable.
Value	FN	Returns the value of an object.
Variant	V	Variable type which assumes the variable type of the data read.
XlAscending	FN	Part of the sort function specifying the sort order.
XlGuess	FN	Part of the sort function (specifies data heading guess).
XlTopToBottom	FN	Part of the sort function used with the orientation parameter.

Appendix D.

Visual Basic Module for Predictive Error-Forecasting Model, *PEFM*

Table of routines contained in VBA functions module

Key:

EF Excel Function
FN Excel Visual Basic for Applications Function
OB Excel VBA Object
P Procedure
R Remark
V Variable

Function name	Type	Description
Adi	V	Average inter-demand interval.
Adicoeff	V	*ADI* Coefficient.
Bitonpmp	V	Coefficient of *PMP* determined for the final formula.
Bitonpmparray	V	Coefficient of *PMP* array read from the worksheet.
Bitonspl	V	Coefficient of *SPL* determined for the final formula.
Bitonsplarray	V	Coefficient of *SPL* array read from the worksheet.
Case	FN	Used in the construct 'SELECT CASE'.
ColorIndex	FN	A property of the font to specify the colour used.
Constant	V	The formula constant factor.
Cv2	V	Coefficient of variation on demand.
Cv2adi	V	Coefficient of $CV^2 * ADI$
Cv2coeff	V	Coefficient of CV^2
Cv2spl	V	Coefficient of $CV^2 * SPL$
Cv2splarray	V	Coefficient of $CV^2 * SPL$ array read from the worksheet.
Extraspl	V	Coefficient of *SPL* * *PMP* determined for the final formula.
Extrasplarray	V	Coefficient of *SPL* * *PMP* array read from the worksheet.
Fe	V	Final formula result.
Font	V	Object property – the font.
Foremeasure	V	Forecast accuracy measure to be used (MAD, MAPE etc).
Operation	FN	Part of the 'Paste Special' function.
Paste	FN	Pastes clipboard contents to the worksheet.
PasteSpecial	FN	Identical to the Excel function paste special.
Pmp	V	Primary maintenance processes.
Pmpadi	V	Coefficient of *PMP* * *ADI* for the final formula.
Pmpadiarray	V	Coefficient of *PMP* * *ADI* read into this array.
Pmpcv2	V	Coefficient of $PMP * CV^2$ for the final formula.
Pmpcv2array	V	Coefficient of $PMP * CV^2$ read into this array.
SkipBlanks	FN	Part of the 'Paste Special' function.
Spl	V	Seasonal period length.
Spladi	V	Coefficient of *SPL* * *ADI* for the final formula.
Spladiarray	V	Coefficient of *SPL* * *ADI* read into this array.
String	FN	Denotes a string variable type.
Transpose	FN	Part of the 'Paste Special' function.
TRUE	FN	Object evaluation or attribute – e.g. boolean variable can be True or False.
XlNone	FN	Part of the 'Paste Special' function.

Appendix E.

Compact Disk Contents

The attached CD at the back of the thesis has the following folders which contain;

1. MRP-Spreadsheet Calculations
   - MRP spreadsheet-monthly periods
   - MRP spreadsheet-weekly periods

2. MRP Lot-sizing Methods
   - General linear model results
   - Main factors' coefficients
   - Method's-main results
   - Minitab worksheet data
   - Lot-size predictive cost model, *LPCM*

3. Spare Parts Forecasting
   - Flight hours and landings
   - Forecasting spreadsheet calculations
   - Method's-main results
   - Minitab worksheet data
   - Parts demand
   - Predictive error-forecasting model, *PEFM*

PUBLICATIONS

Below is a list of published papers extracted from the present work. The papers were published either in the journals referred to or presented to established international conferences and appeared in their proceedings.

Publications in journals

1. Ghobbar, A. A., and Friend, C. H., 1996, "Aircraft Maintenance and Inventory Control Using the Reorder Point System", *International Journal of Production Research*, vol. 34, no. 10, pp. 2863-2878.

2. Friend, C. H., and Ghobbar, A. A., 1999, "Extending Visual Basic for Applications to MRP: Low Budget Spreadsheet Alternatives in Aircraft Maintenance", *Production and Inventory Management Journal*, vol. 40, no. 4, pp. 9-20.

3. Friend, C. H., Swift, A. L., and Ghobbar, A. A., 2001, "A Predictive Cost Model in Lot-Sizing Methodology, With Specific Reference to Aircraft Parts Inventory: An Appraisal", *Production and Inventory Management Journal*, vol. 42, no. 3 & 4, pp. 24-33.

4. Friend, C. H., Swift, A. L., and Ghobbar, A. A., 2002, "A Comparison of Lot-Sizing Methods in Aircraft Repairable Component Inventory Systems", *Journal of Aircraft*, vol. 40, no. 8, pp.

5. Ghobbar, A. A., and Friend, C. H., 2002, "Forecasting Intermittent Demand for Aircraft Spare Parts: A Comparative Evaluation of Methods", *Computers and Operations Research*, vol. 29, no. 9, pp.

6. Ghobbar, A. A., and Friend, C. H., 2002, "An Evaluation of Forecasting Methods for Intermittent Parts Demand in the Aviation Field: A Predictive Model", *Computers and Operations Research*, vol. 29, no. 10, pp.

7. Ghobbar, A. A., and Friend, C. H., 2002, "Sources of Intermittent Demand for Aircraft Spare Parts in Airline Operations", *Journal of Air Transport Management*, vol. 8, no. 4, pp. 23-33.

Presented papers and conference proceedings

8. Friend, C. H., and Ghobbar, A. A., 1996, "Aircraft Maintenance and Inventory Control: Using the Material Requirements Planning System–Can It Reduce Costs and Increase Efficiency?", *Airframe Finishing Maintenance and Repair, Conference and Exposition, SAE,* Jacksonville, Florida, USA, April 29th - May 1st, paper no. 961253.

9. Ghobbar, A. A., 1996, "Aircraft Maintenance and Inventory Control: Applications of ROP and MRP Systems", *Civil Spares Group of the Society of British Aerospace Companies (SBAC) Autumn Meeting*, Dunlop Aviation, Coventry, UK, 8th October.

10. Friend, C. H., Swift, A. L., and Ghobbar, A. A., 2001, "Establishing a Predictive Cost Model for Lot-Sizing Methodology in Aircraft Component Inventories: Comparative Approach", *43rd Annual Conference Proceedings of Operational Research Society*, The University of Bath, UK, 4th-6th September, paper no. 70.

11. Ghobbar, A. A., and Friend, C. H., 2001, "Forecasting Intermittent Demand in the Airline Industry: A Comparative Evaluation of Various Methods", *43rd Annual Conference Proceedings of Operational Research Society*, The University of Bath, UK, 4th-6th September, paper no. 69.

REFERENCES

1. Adams, J. L., Abell, J. B., and Isaacson, K. E., 1993, "Modelling and Forecasting the Demand for Aircraft Recoverable Spare Parts", *RAND*, Santa Monica, CA, USA.

2. Anderson, J., Schroeder, R., Tupy, S., and White, E., 1982, "Materials requirements planning systems: the state-of-the-art", *Production and Inventory Management Journal*, vol. 23, no. 4, pp. 51-67.

3. Aull, R. L., and LaForge, R. L., 1989, "Using the incremental part-period algorithm to compute allowable limits on MRP system nervousness", *Production and Inventory Management Journal*, vol. 30, no. 4, pp. 28-31.

4. Barrett, R. T., and LaForge, R. L., 1991, "A study of replanning frequencies in a MRP system", *Computer Operation Research*, vol. 18, no. 6, pp. 569-578.

5. Bartezzaghi, E., Verganti, R., and Zotteri, G., 1999, "A simulation framework for forecasting uncertain lumpy demand", *International Journal of Production Economics*, vol. 59, no. 1-3, pp. 499-510.

6. Benton, W. C., and Srivastava, R., 1985, "Product structure complexity and multi level lot sizing using alternative costing policies", *Decision Sciences,* vol.16, no.4, pp. 357-369.

7. Berry, W. L., 1972, "Lot sizing procedures for requirements planning systems: a framework for analysis", *Production and Inventory Management Journal*, vol. 13, no. 2, pp. 19-34.

8. Beversluis, W. S., and Jordan, H. H., 1995, "Using a spreadsheet for capacity planning and scheduling", *Production and Inventory Management Journal,* vol. 36, no. 2, pp. 12-15.

9. Bitran, G. R., Magnanti, T. L., and Yanasse, H. H., 1984, "Approximation methods for the uncapacitated dynamic lot-size problem", *Management Science*, vol. 30, no. 9, pp. 1121-1140.

10. Blackburn, J. D., Kropp, D. H., and Millen, R. A., 1986, "A comparison of strategies to dampen nervousness in MRP systems", *Management Sciences,* vol. 32, no. 4, pp. 413-429.

11. Blackburn, J. D., and Millen, R. A., 1979, "Selecting a lot-sizing technique for a single-level assembly process", *school of management, Boston University*, USA, paper no. 1.

12. Blackburn, J. D., and Millen, R. A., 1980, "Heuristic lot-sizing performance in a rolling-schedule environment", *Decision Sciences*, vol. 11, no. 3, pp. 691-701.

13. Blackstone, J. H., 1986, "Rough/cut capacity planning using spreadsheets", *29th Annual International Conference Proceedings, APICS,* USA, pp. 190-191.

14. Blood, B. E., 1993, "How to raise the performance level of your MRP II system", *Aerospace & Defense Symposium Proceedings*, *APICS*, paper C8, Washington, DC, USA.

15. Bobko, P. B., and Whybark, D. C., 1985, "The coefficient of variation as a factor in MRP research", *Decision Sciences,* vol.16, no. 4, pp. 420-427.

16. Boe, W. J., and Yilmaz, C., 1983, "The incremental order quantity", *Production and Inventory Management Journal*, vol. 24, no. 2, pp. 94-100.

17. Bookbinder, J. H., and H'ng, B., 1986, "Production lot sizing for deterministic rolling schedules", *Production and Inventory Management Journal*, vol. 6, no.3, pp. 349-362.

18. Bookbinder, J. H., and Tan, J. Y., 1985, "Two lot-sizing heuristics for the case of

deterministic time-varying demands", *International Journal of Operations And Production Management*, vol. 5, no. 4, pp. 30-42.

19. Bowser, K., 1994, "Design a math model to provision spare part requirements", *Remanufacturing Seminar Proceedings, APICS,* USA, pp. 22-23.

20. Brandewie, T. J., 1988, "DoD production contracts: incentives based on inventory turnover calculated from progress payment request forms", *Aerospace & Defense Integrated Planning & Control Conference Proceedings, APICS,* Los Angeles, CA, USA, pp. 509-521.

21. Bregman, R. L., 1991, "Selecting among MRP lot-sizing methods for purchased components when the planning horizon is limited", *Production and Inventory Management Journal*, vol. 32, no. 2, pp. 32-39.

22. Bregman, R. L., 1994, "An analytical framework for comparing material requirements planning to reorder point systems", *European Journal of Operational Research*, vol. 75, no. 1, pp. 74-88.

23. Brett, L. F., 1984, "Integration of MSG-3 into airline operation", *Aerospace congress and exposition*, *SAE*, Long Beach, CA, USA, paper no. 841483.

24. Brown, R. G., and Meyer, R. F., 1961, "The fundamental theorem of exponential smoothing", *Operational Research Quarterly*, vol. 9, no. 5, pp. 673-685.

25. Browne, J., Harhen, J., and Shivnan, J., 1990, "Production Management Systems: A CIM Perspective", *Addison-Wesley*, Cheltenham, UK.

26. Campbell, H. S., 1963, "The Relationship of Resource Demands to Air Base Operations", *RAND*, Santa Monica, CA, USA.

27. Choi, H. G., Malstrom, E. M., and Classen, R. J., 1984, "Computer simulation of lot-sizing algorithms in three-stage multi-echelon inventory systems", *Journal of*

Operation Management, vol. 4, no. 3, pp. 259-277.

28. Chong, P. S., 1987, "A dispute on James R. Evans' an efficient implementation of the wagner-whitin algorithm for dynamic lot sizing", *Journal of Operation Management*, vol. 7, no. 1 & 2, pp. 27-29.

29. Christer, A. H., and Wang, W., 1995, "A simple condition monitoring model for a direct monitoring process", *European Journal of Operational Research*, vol. 82, no. 2, pp. 258-269.

30. Civil Aviation Authority, 1990, "Condition Monitored Maintenance: an Explanatory Handbook", *CAA*, CAP 418, London, UK.

31. Civil Aviation Authority, 1990, "Master Minimum Equipment Lists, MMEL, and Minimum Equipment Lists, MEL", *CAA*, CAP 549, London, UK.

32. Civil Aviation Authority, 1992, "Air Operators' Certificates: Part Two Arrangements for Maintenance Support", *CAA*, CAP 360, London, UK.

33. Clarke, M. D., 1998, "Irregular airline operations: A review of the state-of-the-practice in airline operations control centres", *Journal of Air Transport Management*, vol. 4, no. 2, pp. 67-76.

34. Clode, D. M., 1993, "A survey of UK manufacturer control over the past ten years", *Production and Inventory Management Journal*, vol. 34, no. 2, pp. 53-56.

35. Coleman, B. J., 1992, "A further analysis of variable demand lot-sizing techniques", *Production and Inventory Management Journal*, vol. 33, no. 3, pp. 19-24.

36. Cornwell, L. W., and Modianos, D. T., 1990, "Management tool: using spreadsheets for simulation models", *Production and Inventory Management Journal*, vol. 31, no. 3, pp. 8-17.

37. Croston, J. D., 1972, "Forecasting and stock control for intermittent demands", *Operational Research Quarterly*, vol. 23, no. 3, pp. 289-303.

38. De Matteis, J. J., 1968, "An economic lot-sizing technique: I the part-period algorithm", *IBM Systems Journal*, vol. 7, no. 1, pp. 30-38.

39. Estep, J. A., 1996, "Tailoring your MRP system to meet your needs", *Institute of Industrial Engineers, IIE Solutions*, vol. 28, no. 9, pp. 36-39.

40. Evans, J. R., 1985, "An efficient implementation of the wagner-whitin algorithm for dynamic lot-sizing", *Journal of Operations Management*, vol. 5, no. 2, pp. 229-235.

41. Fildes, R., and Beard, C., 1992, "Forecasting systems for production and inventory control", *International Journal of Operations and Production Management*, vol. 12, no. 5, pp. 4-27.

42. Fliedner, G., 1999, "An investigation of aggregate variable time series forecast strategies with specific subaggregate time series statistical correlation", *Computers & Operations Research*, vol. 26, no. 10&11, pp. 1133-1149.

43. Flores, B. E., and Whybark, D. C., 1986, "Multiple criteria ABC analysis", *International Journal of Operations and Production Management*, vol. 6, no. 3, pp. 38-46.

44. Flores, B. E., and Whybark, D. C., 1988, "Implementing multiple criteria ABC analysis", *Engineering Costs and Production Economics*, vol. 15, no. 1, pp. 191-195.

45. Fordyce, J. M., and Webster, F. M., 1984, "The wagner-whitin algorithm made simple", *Production and Inventory Management Journal*, vol. 25, no. 2, pp. 21-30.

46. Fourcaud, R., 1993, "Is repair/remanufacturing really different", *Remanufacturing Seminar Proceedings*, *APICS*, Oklahoma City, OK, USA, pp. 4-9.

47. Frazer, J. D., and Nakhai, B., 1992, "The problems with MRP on microcomputer spreadsheets", *Production and Inventory Management Journal,* vol. 33, no. 3, pp. 1-5.

48. Freeland, J. R., and Colley, J. L., 1982, "A simple heuristic method for lot sizing in a time-phased reorder system", *Production and Inventory Management Journal*, vol. 23, no. 1, pp. 15-22.

49. Freeman, J., 1993, "Spreadsheet gaming and management skills development", *Operation Research Insight,* vol. 6, no. 1, pp. 9-13.

50. Freund, R. J., and Wilson, W. J., 1998, "Regression Analysis: Statistical Modelling of a Response Variable", *Academic Press*, San Diego, CA, USA.

51. Friend, C. H., 1992, "Aircraft Maintenance Management", *Longman Scientific & Technical*, Harlow, UK.

52. Friend, C. H., and Ghobbar, A. A., 1996, "Aircraft maintenance and inventory control: using the material requirements planning system–can it reduce costs and increase efficiency?", *Airframe Finishing Maintenance and Repair Conference and Exposition*, *SAE,* Jacksonville, FL, USA, paper no. 961253.

53. Friend, C. H., and Ghobbar, A. A., 1999, "Extending visual basic for applications to MRP: low budget spreadsheet alternatives in aircraft maintenance", *Production and Inventory Management Journal*, vol. 40, no. 4, pp. 9-20.

54. Gaither, N., 1983, "An improved lot-sizing model for MRP systems", *Production and Inventory Management Journal*, vol. 24, no. 3, pp.10-19.

55. Ghobbar, A. A., and Friend, C. H., 1996, "Aircraft maintenance and inventory

control using the reorder point system", *International Journal of Production Research*, vol. 34, no. 10, pp. 2863-2878.

56. Gorham, T., 1968, "Dynamic order quantities", *Production and Inventory Management Journal*, vol. 9, no. 1, pp. 75-79.

57. Grommesh, B., 1990, "MRP II will work in a defence repair/remanufacturing environment", *33rd International Conference Proceedings*, *APICS,* Orlando, FL, USA, pp. 575-578.

58. Gupta, Y. P., Keung, Y. K., and Gupta, M. C., 1992, "Comparative analysis of lot-sizing models for multi-stage systems: a simulation study", *International Journal of Production Research*, vol. 30, no. 10, pp. 695-716.

59. Haddock, J., and Hubicki, D. E., 1989, "Which lot-sizing techniques are used in material requirements planning", *Production and Inventory Management Journal*, vol. 30, no. 3, pp. 53-56.

60. Hamid, A. A., Agus, A., and Hassan, M. E., 1991, "Computerised materials requirements planning in manufacturing companies in Malaysia", *International Journal of Production Economics*, vol. 51, no., pp. 73-79.

61. Harold, J. E., 1997, "Evaluating and implementing EDI at a small electronics manufacturer", *Production and Inventory Management Journal*, vol. 38, no. 3, pp. 1-5.

62. Haupt, M., 1992, "MRP II in aerospace and defence: are we ready for the challenges of the 1990s?", *Aerospace and Defense Symposium Proceedings*, *APICS,* Los Angeles, CA, USA, pp. 114-117.

63. Herbig, P., Milewicz, J., and Golden, J. E., 1994, "Differences in forecasting behaviour between industrial product firms and consumer product firms." *Journal of Business and Industrial Marketing*, vol.9, no. 1, pp. 60-69.

64. Ho, C. J., 1995, "Examining the impact of demand lumpiness on the lot-sizing performance in MRP systems", *International Journal of Production Research,* vol. 33, no. 9, pp. 2579-2599.

65. Holt, C. C., 1957, "Forecasting seasonal and trends by exponentially weighted moving averages", *Office of naval research*, Carnegie institute of technology, Pittsburgh, PA, research memorandum no. 52.

66. Jeunet, J., and Jonard, N., 2000, "Measuring the performance of lot-sizing techniques in uncertain environments", *International Journal of Production Economics,* vol. 64, no. 1&3, pp. 197-208.

67. Johnston, F. R., and Boylan, J. E., 1996, "Forecasting for items with intermittent demand", *Journal of the Operational Research Society*, vol. 47, no. 1, pp. 113-121.

68. Joint Aviation Authorities, 1991, "Joint Aviation Requirements: Approved Maintenance Organisations", *CAA*, JAR-145, London, UK.

69. Kaimann, R. A., 1969, "EOQ vs. dynamic programming–which one to use for inventory ordering", *Production and Inventory Management Journal,* vol. 10, no. 4, pp. 66-74.

70. Kalman, R. E., and Bucy, R. S., 1961, "New results in linear filtering and prediction theory", *Journal of Basic Engineering*, vol. 83, no., pp. 95-108.

71. Kanet, J. J., 1984, "Inventory planning at black and decker", *Production and Inventory Management Journal*, vol. 25, no. 3, pp. 9-22.

72. Kelleher, J. P., 1989, "Achieving flexibility and meeting inventory record accuracy requirements by ABC analysis", *LA-ADSIG Conference Proceedings, APICS,* Los Angeles, CA, USA, pp. 8-13.

73. Kerber, W. M., 1990, "Structuring and managing the bill of material under changing company conditions", *33rd International* Conference Proceedings, *APICS,* Orlando, FL, USA, pp.421-424.

74. Kharab, A., 2000, "An advanced macro spreadsheet program for the simplex method", *Computers & Operations Research*, vol. 27, no. 3, pp. 233-243.

75. King, F. H., 1985, "Aviation Maintenance Management", *Southern Illinois University Press*, Carbondale, USA.

76. Krueger, R. A., 1990, "Master planning in textile and apparel and other flow shop", *33rd International* Conference Proceedings, *APICS,* Orlando, FL, USA, pp. 401-404.

77. Krupp, J. A., 1994, "Measuring inventory management performance", *Production and Inventory Management Journal*, vol. 35, no. 4, pp. 1-5.

78. LaForge, R. L., 1982, "MRP and the part-period algorithm", *Journal of Purchasing and Materials Management*, vol. 18, no. 4, pp. 21-26.

79. LaForge, R. L., and Sturr, V., 1986, "MRP practices in a random sample of manufacturing firms", *Production and Inventory Management Journal*, vol. 28, no. 3, pp.129-137.

80. Lee, T. S., and Adam, E. E., 1986, "Forecasting error evaluation in material requirements planning (MRP) production-inventory systems", *Management Science*, vol. 32, no. 9, pp. 1186-1205.

81. Lengyel, A. and Mackay, D. W., 1993, "Unlocking the benefits of your enterprise system: the new information plan", *Aerospace & Defense Symposium Proceedings*, Washington DC, USA, paper F8.

82. Leon, L., Przasnyski, Z., and Seal, K. C., 1996, "Spreadsheets and OR/MS

models: an end-user perspective", *Interfaces*, vol. 26, no. 2, pp. 92-104.

83. Lunn, T., and Neff, S. A., 1992, "MRP Integrating Material Requirements Planning and Modern Business", *IRWIN*, APICS, Homewood, Illinois, USA.

84. Makridakis, S., 1993, "Accuracy measures: theoretical and practical concerns", *International Journal of Forecasting*, vol. 9, no. 4, pp. 527-529.

85. Makridakis, S., and Hibon, M., 1979, "Accuracy of forecasting: an empirical investigation", *Journal of Royal Statistic Society*, vol. A142, pp. 97-145.

86. Makridakis, S., Wheelwright, S. C., and Hyndman, R. J., 1998, "Forecasting: Methods and Applications", 3rd edition, *John Wiley*, New York, USA.

87. Marcontell, D. A., Hesse, R., and Grum, A. F., 1993, "Center wing life extension for the C-130", *Production and Inventory Management Journal,* vol. 34, no. 3, pp. 36-38.

88. Markland, R. E., 1970, "A comparative study of demand forecasting techniques for military helicopter spare parts", *Naval Research Logistics Quarterly*, vol. 17, no. 1, pp. 103-119.

89. Martin, A., 2000, "An integrated introduction to spreadsheet and programming skills for operational research students", *Journal of the Operational Research Society*, vol. 51, no. 12, pp. 1399-1408.

90. Martin, R. L., 1989, "Paperless purchasing in the aerospace and defence environment", *Aerospace and Defense Symposium Proceedings*, *APICS,* New Orleans, Louisiana, USA, pp. 401-407.

91. McDonald, M., 2000, "Goodbye EDI, hello internet", *Air Transport World*, vol. 37, no. 10, pp. 84-87.

92. Mitra, A., Cox, J. F., Blackstone, J. H., and Jesse, R. R., 1983, "A re-examination of lot sizing procedures for requirements planning systems: some modified rules", *International Journal of Production Research*, vol. 21, no. 4, pp. 471-478.

93. Nakata, D., 1984, "An introduction to MSG-3", *Aerospace congress and exposition, SAE*. Long Beach, CA, USA, paper no. 841481.

94. Nelms, D. W., 1995, "Inventory managers not parts salesman", *Air Transport World*, vol.32, no. 3, pp.78-79.

95. Nydick, R. L., and Weiss, H. J., 1989, "An evaluation of variable-demand lot-sizing techniques", *Production and Inventory Management Journal*, vol. 30, no. 4, pp. 41-44.

96. Patterson, J. W., and LaForge, R. L., 1985, "The incremental part-period algorithm: an alternative to EOQ", *Journal of Purchasing and Materials Management*, vol. 21, no. 2, pp. 28-33.

97. Pfunder, K. R., 1986, "Selecting the right approach to establish MRO stocking levels", *APICS-Fall Seminar Proceedings*, Orlando, FL, USA, pp. 103-111.

98. Plossl, G. W., 1995, "Orlicky's Material Requirements Planning", *McGraw-Hill*, 2nd Edition, New York, USA.

99. Ragsdale, C. T., and Plane, D. R., 2000, "On modelling time series data using spreadsheets", *Omega*, vol. 28, no. 2, pp. 215-221.

100. Ramani, S., and Krishnan Kutty, K. V., 1985, "Management of multi-item, multi-group inventories with multiple criteria under service level constraints", *Engineering Costs and Production Economics*, vol. 9, no. 1, pp. 59-64.

101. Rao, A. V., 1973, "A comment on: forecasting and stock control for intermittent demands", *Operational Research Quarterly*, vol. 24, no. 4, pp. 639-640.

102. Ritchie, E., and Tsado, A. K., 1986, "A review of lot-sizing techniques for deterministic time-varying demand", *Production and Inventory Management Journal*, vol. 27, no. 3, pp. 65-79.

103. Ritzman, L. P., Krajewski, L. J., and Bragg, D., 1983, "Performance comparison between MRP and ROP systems", *Simulation and Inventory Control, Society for Computer Simulation*, pp. 47-54.

104. Rodenrys, J., 1995, "Running MRP in a windows environment", *The Performance Advantage, APICS,* vol. 5, no. 1, pp. 40-42.

105. Rosenberg, B., 1998, "Business jet operators adopt MSG-3 philosophy", *Overhaul and Maintenance*, vol. 4, no. 3, pp. 39-42.

106. Sanders, N. R., 1997, "Measuring forecast accuracy: some practical suggestions", *Production and Inventory Management Journal*, vol. 38, no. 1, pp. 43-46.

107. Sani, B., and Kingsman, B. G., 1997, "Selecting the best periodic inventory control and demand forecasting methods for low demand items", *Journal of the Operational Research Society*, vol. 48, no. 7, pp. 700-713.

108. Saydam, C., and Mcknew, M., 1987, "A fast microcomputer program for ordering using the wagner-whitin algorithm", *Production and Inventory Management Journal*, vol. 28, no. 4, pp. 15-19.

109. Schmahl, K. E., and Anand, S., 1994, "Impact of a decision support and finite scheduling system on a large machine shop", *Production and Inventory Management Journal*, vol. 35, no. 4, pp. 54-58.

110. Schonberger, R. J., 1980, "The ROP/shortage list system", *Production and Inventory Management Journal*, vol. 21, no. 4, pp. 106-117.

111. Schroeder, R. G., Anderson, J. C., Tupy, S. E., and White, E. M., 1981, "A study

of MRP benefits and costs", *Journal of Operations Management,* vol. 2, no. 1, pp. 1-9.

112. Schuster, E. W., and Finch, B. J., 1990, "A deterministic spreadsheet simulation model for production scheduling in a lumpy demand environment", *Production and Inventory Management Journal,* vol. 31, no. 1, pp. 39-43.

113. Silver, E. A., and Meal, H. C., 1969, "A simple modification of the EOQ for the case of A varying demand rate", *Production and Inventory Management Journal*, vol. 10, no. 4, pp. 52-65.

114. Silver, E. A., and Meal, H. C., 1973, "A heuristic for selecting lot size quantities for the case of a deterministic time-varying demand rate and discrete opportunities for replenishment", *Production and Inventory Management Journal*, vol. 14, no. 2, pp. 64-74.

115. Silver, E. A., and Miltenburg, J., 1984, "Two modifications of the silver-meal lot sizing heuristic", *INFOR*, vol. 22, no. 1, pp. 56-69.

116. Silver, E. A., and Peterson, R., 1985, "Decision Systems for Inventory Management and Production Planning", *John Wiley*, 2nd Edition, New York, USA.

117. Smith, J. R., and Golden, P. A., 1991, "Airline: A Strategic Management Simulation", *Prentice-Hall*, Englewood Cliffs, NJ, USA.

118. Sounderpandian, J., 1989, "MRP on spreadsheets: a do-it-yourself alternative for small firms", *Production and Inventory Management Journal,* vol. 30, no. 2, pp. 6-11.

119. Sounderpandian, J., 1994, "MRP on spreadsheets: an update", *Production and Inventory Management Journal,* vol. 35, no. 3, pp. 60-64.

120. Sponseller, E. A., 1992, "Overlapped scheduling of flow-shop production using a spreadsheet model", *Production and Inventory Management Journal*, vol. 33, no. 2, pp. 74-79.

121. Sridharan, S. V., and Berry, W. L., 1990, "Freezing the master production schedule under demand uncertainty", *Decision Sciences*, vol. 21, no. 1, pp. 97-120.

122. Syntetos, A. A., 2001, "Forecasting of intermittent demand", *Unpublished PhD thesis*, Buckinghamshire Business School, Brunel University, UK.

123. Theise, E. S., 1990, "A spreadsheet for preparing forecasts with winters' method", *Production and Inventory Management Journal*, vol. 31, no. 2, pp. 3-9.

124. Toelle, R. A., 1996, "How not to lot size", *Production and Inventory Management Journal*, vol. 37, no. 2, pp. 8-10.

125. Udo, G. J., and Grant, T., 1993, "Making EDI pay off: the averitt express experience", *Production and Inventory Management Journal*, vol. 34, no. 4, pp. 6-11.

126. Veral, E. A., and LaForge, R. L., 1985, "The performance of a simple incremental lot-sizing rule in a multilevel inventory environment", *Decision Sciences*, vol. 16, no. 1, pp. 57-72.

127. Wagner, H. M., and Whitin, T. M., 1958, "Dynamic version of the economic lot size model", *Management Science*, vol. 5, no. 1, pp. 89-96.

128. Watson, R. B., 1987, "The effects of demand-forecast fluctuations on customer service and inventory cost when demand is lumpy", *Journal of the Operational Research Society*, vol. 38, no. 1, pp. 75-82.

129. Wemmerlov, U., 1979, "Design factors in MRP systems: a limited survey",

Production and Inventory Management Journal, vol. 20, no. 4, pp. 15-34.

130. Wemmerlov, U., 1981, "The ubiquitous EOQ its relation to discrete lot sizing heuristics", *International Journal of Operations and Production Management*, vol. 1, no. 3, pp. 161-179.

131. Wemmerlov, U., 1982, "Statistical aspects of the evaluation of lot-sizing techniques by the use of simulation", *International Journal of Production Research*, vol. 20, no. 4, pp. 461-473.

132. Wemmerlov, U., 1989, "The behaviour of lot-sizing procedures in the presence of forecast errors", *Journal of Operations Management*, vol. 8, no. 1, pp. 37-47.

133. White, E. M., Anderson, J. C., and Schroeder, R. G., 1982, "A study of the MRP implementation process", *Journal of Operations Management*, vol. 2, no. 3, pp. 145-153.

134. Wilcox, J. E., 1970, "How to forecast lumpy items", *Production and Inventory Management Journal*, vol. 11, no. 1, pp. 51-54.

135. Willemain, T. R., Ratti, E. W. L., and Smart, C. N., 1994, "Forecasting intermittent demand using a cox process model", *INFORMS Meetings*, Boston, USA, pp. 1-14.

136. Willemain, T. R., Smart, C. N., Shockor, J. H., and DeSautels, P. A., 1994, "Forecasting intermittent demand in manufacturing: a comparative evaluation of Croston's method", *International Journal of Forecasting*, vol. 10, no. 4, pp. 529-538.

137. Williams, T. M., 1984, "Stock control with sporadic and slow-moving demand", *Journal of the Operational Research Society*, vol. 35, no. 10, pp. 939-948.

138. Wilson, J. R., 1997, "All together, now", *Air Transport World*, vol. 34, no. 6, pp.

97-98.

139. Wilson, L. W., 1994, "High performance cycle counting", *37th International Conference Proceedings*, *APICS*, USA, pp. 354-357.

140. Winters, P. R., 1960, "Forecasting sales by exponentially weighted moving averages", *Management Science*, vol. 6, no. 3, pp. 324-342.

141. Zhao, X., and Lee, T. S., 1993, "Freezing the master production schedule for material requirements planning systems under demand uncertainty", *Journal of Operations Management*, vol. 11, no. 2, pp. 185-205.