Maintenance Scheduling and Inventory Control Policy in Aviation Industry an-Integrated Framework

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Abstract

Airlines seek to minimise operating costs, in all aspect of business areas. Some of these areas are the aircraft maintenance and inventory control policies associated.

Maintenance is one of the essential operations in aviation industry. Any shortcoming in maintenance causes reducing in the income rate.

In addition, there is a direct relationship between maintenance and inventory department in any company is a vital to guarantee the availability of spare parts to carry out the required maintenance.

Therefore, this research presents an integrated framework for maintenance scheduling and inventory control policies in aviation industry, aiming to minimise the maintenance cost by addressing a models for determining the optimum maintenance scheduling for aircraft components and its inventory control policy. The interval between maintenance for the components is optimised by minimising the total cost. This consists of labour cost, spare parts cost and delay cost etc.

A decision to replace a component must also be taken when a component cannot attain the minimum reliability.

Mathematical models are developed to calculate the expected costs based on the cost of corrective, preventive maintenance and the probability of failure. The maintenance scheduling mathematical model is developed to act as a maintenance decision making model to determine the optimum preventive maintenance interval of the expensive aircraft components. A decision making inventory control model to balance the cost of repair and purchase cost is developed and will be integrated with the scheduling maintenance to guarantee the availability of the required components and act as an integrated framework, this would facilitate the decision making process in aviation industry in relation to scheduling and inventory policies.

Glossary

A C	Airworthiness Certificate
AMM	Airplane Maintenance Manual
AOG	Aircraft On Ground
APU	Auxiliary Power Unit
ATA	Air Transport Association of America
CM	Condition Monitoring
DMI	Deferred Maintenance Item
FAA	U.S Federal Aviation Administration
FH	Flight Hours
GMM	General Maintenance Manual
GSE	Ground Support Equipment
HMV	Heavy Maintenance Visit
HT	Hard Time
IATA	International Air Transport Association
MCC	Maintenance Control Centre
MEL	Maintenance Equipment List
MPD	Maintenance Planning Data document
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
NFF	No Fault Found
OC	On Condition
QA	Quality Assurance
QC	Quality Control
R&I	Removal and Installation
R	Reliability
SB	Service Bulletin
SD	Standard Deviation

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Chapter One

Introduction and Problem Definition

This chapter is divided into six sections. The first section presents an introduction to the thesis, the second section deals with the historical background on aviation industry, the third section presents the problem definition, the fourth gives thesis aims and objectives, and the fifth section indicates the structure of the thesis, and sixth section summarises the conclusion.

1.1 Introduction

The goal of maintenance in the aviation industry is to provide a serviceable aircraft for airline companies at minimum cost with a safety guarantee. There are many different problems encounter the airline companies such as environmental, economical, political and operational problems. The environment problem relates to aircraft pollutions of CO_2 emission and level of noise. The economical problem is when the air lines are affected by economic recession such as what is happening now days. The politic problems as embargo that imposed on Libya between 1990 and 2000. The operation problems include airline companies' competitions, weather conditions, management, and one important issue represented by the aircraft maintenance, and because the author has more than ten years experience working in Libyan Arab Airlines Company in technical management. The author focused on how to minimise the high maintenance costs considering to maintenance scheduling and inventory control policy associated to guarantee effective operational environment for the aircrafts.

Moreover, modern aircraft consist of many integrated systems, and every system includes many expensive components costing many thousands of pounds. Early detection of failure and replacement or repair of a failed component will help to prevent further deterioration which could become much more costly or even result in catastrophic failure. Often the system returns into operation during repair of a failed component by a used but operative one. Such maintenance actions do not renew the system completely but enable the system to continue to operate. However, over time, the system will deteriorate with normal wear and tear; therefore a major maintenance overhaul will be required.

The maintenance management for airline companies attempts to keep the aircraft serviceable by maintaining all systems and components in good working condition.

Aircraft components can be classified into two types, repairable and consumable (not repairable); the life-time of most repairable components is determined by flying-hours. The repairable components are very expensive, and need an appropriate follow-up by scheduling maintenance to determine the optimum life-time and its technical condition. Meanwhile, the availability of existing alternative spare-parts in stock is important, because when the operating parts on the aircraft fail or reach their life-span and is replaced or repaired, a successful inventory-control policy is essential.

In order to identify a suitable spare-part, the maintenance management have to take an economic decision through their maintenance schedule and inventory-control policy, taking into consideration the optimal time to perform a repair or replace the components to minimise the excessive costs and guarantee safety.

1.2 Historical Background on Aviation Industry & Maintenance

1.2.1 Aviation Industry

Aviation industry requires Federal Aviation Administration (FAA) regulations to lay down maintenance requirements all of which must be met before releasing an aircraft into service. This is not the case with other commercial transport modes. In aviation we have a relationship with gravity, and temperature problems (e.g., very hot engines and very cold air at high altitude). Aviation industry has an interactive group of people determined to make aviation a safe, efficient, and pleasurable activity. Airline-operators, industry trade-associations, regulatory authorities, flight-crews, and maintenance-personnel all work together to ensure aviation safety from the design of aircraft and its systems, through the development of maintenance-programs and modifications, and continuing throughout the lifetime of the aircraft.

1.2.2 Aviation Maintenance

In the early days of aviation, maintenance was performed "as necessary" and the aircraft often required maintenance several times for every hour of flying-time. Major maintenance activities consisted of overhauling nearly everything on the aircraft. Even though the airplanes and their systems were quite simple at first, maintenance carried out became quite expensive with the increasing complexity of the aircraft and their systems over the following years.

The modern approach to maintenance is more sophisticated. The aircraft are designed for safety, airworthiness, and maintainability, and a detailed maintenance-program is developed along with very new aircraft or a derivative of an existing model. A sophisticated approach to maintenance requires sophisticated management both at the manufacturers in development of the initial maintenance-program and at the airlines to accomplish all that is necessary to maintain the superior record of safety already mentioned.

Concerning the technical management, it takes discipline to properly conduct the maintenance activities in the airline companies. There is a need to define some terms:

Maintenance: the tools, equipment, spare-parts, and labour needed to accomplish the actual work.

Engineering: the design, analysis, and technical assistance required to support maintenance work.

Management: the organization, control, and administration of the many facets of the maintenance operation.

1.3 Problem Definition

To perform the different maintenance-programs for an aircraft such as preventive or corrective maintenance, it needs careful consideration from the maintenance management team and good coordination between maintenance and inventory departments to guarantee the availability of parts needed to complete maintenance tasks on time.

The maintenance schedule is the process of identifying the optimum/near-optimum time at which the component/part should be maintained. In the aviation industry, safety will take priority over other issues such as time, cost and resources etc. However, balanced decisions need to be made in order to avoid costly maintenance-schedules. This is one of the problems that will be addressed in this project.

Furthermore, many repairable components are very expensive. When the item fails, a decision has to be made whether it is economical to repair or replace the failed item with a new item from the cost point of view. This is also another problem for consideration in this research work.

Solving the above two problems in an integrated environment is very important to ensure a successful cooperation between the maintenance and inventory departments which is a real challenge in the aviation industry. This represents the main aim of this research which is the development of an integrated framework for these two problems.

1.4 Aims and Objectives

1.4.1 Aim

To develop an integrated framework to combine maintenance-scheduling and inventory-control policy in aviation industry to minimise the maintenance cost without compromising the safety.

1.4.2 Objectives

The objectives of this thesis are:

1. To develop a maintenance decision-making model to determine the optimum preventive-maintenance interval for expensive aircraft components.
2. To develop an inventory decision-making model to balance the cost of repair and purchase-cost for expensive components.
3. To integrate the maintenance-scheduling and the inventory-control models to act as an integrated framework to guarantee the availability of the required components to accomplish maintenance activities on time.
4. To implement the proposed framework.

1.5 Structure of the Thesis

The first chapter gave a brief overview of the research objectives and the problem. The second chapter contains a literature review of the research work performed in the areas of maintenance-scheduling and inventory-control in aviation industry. The third chapter deals with the thesis-framework and methodology. The fourth chapter presents the maintenance-scheduling mathematical-model. The fifth chapter presents the inventory mathematical-model. The sixth chapter provides the integration between the two mathematical-models that concern maintenance-scheduling and inventory; and the seventh chapter summarises the conclusion and recommendation for future work.

1.6 Conclusion

In this chapter, the author introduced a historical background on aviation industry covering majority of the problems associated with this industry and maintenance and inventory were drawn to be the main problems covered in this research work. Problem definition, aims and objectives of the thesis were stated and clearly the focus will be on maintenance and inventory of aviation industry.

A literature review and the latest developments in the field of this thesis will be presented in the next chapter.

Chapter Two

Literature Review

2.1 Introduction

The aim of this chapter is to present a concise review of the mathematical models that are used in maintenance-management in aviation industry. This will include the topics of:

- Aircraft-maintenance.
- Maintenance-scheduling.
- Inventory-control policy.
- Reliability.

2.2 Aircraft-maintenance

Gupta et al. (2003) asserted that in the airline industry, the role of aircraft-maintenance is to provide safe, airworthy, on-time aircraft, every day. Aircraft-maintenance must be planned and performed according to prescribed procedures and standards. An airline generally has a diverse fleet of aircraft. Each fleet-type has a predetermined maintenance-programme established by the manufacturer. Based on an airline's experience and mode of operation, an original programme is adapted to meet Federal Aviation Administration (FAA) approval. Maintenance-task standards specify when each task is scheduled and how much time is spent on each task. The author in this topic will delineate the different definitions and introduce the basic principles related to aircraft-maintenance in the aviation environment in order to let the reader know and understand the aircraft-maintenance management background. This includes the definition of aircraft-maintenance, the kind of maintenance, the aircraft-maintenance programmes, the aircraft-maintenance process, aircraft-maintenance costs, aircraft-maintenance documentation, the aircraft-maintenance organization, aircraft-maintenance activities and aircraft-components. In addition, the different mathematical models will be described that are used to meet and accomplish the purpose of aircraft-maintenance management. The latter is aimed at decreasing the adverse effects of breakdown and increasing facility and availability at minimum cost.

Samaranayake et al. (2002) reported that the aircraft-maintenance is a high cost activity, in terms of both capital equipment, down-time and spare-parts inventory. The airlines have divided the aircraft maintenance-process into distinct stages:

1. Inspection.
2. Disconnection and removal.
3. Rectification.
4. Component change.
5. Servicing, reconnection and reinstallation.

They affirmed that general commercial aircraft-maintenance consists of a number of problem-areas, such as: the hangar, scheduling, heavy-maintenance scheduling, maintenance-planning at various levels and engine maintenance.

2.2.1 Maintenance Resources and Demands

Al-Sultan and Duffuaa (1995) indicated that the maintenance-resources are:

1. Personnel, which are classified according to the skills available.
2. Materials, which include spare-parts.
3. Tools and equipment, which are necessary to perform various maintenance-functions.
4. Facilities, which are needed to perform the maintenance-tasks.

Moreover, in maintenance-systems, demands can be classified into four categories:

1. Emergency repairs, which are the types of repairs that are not known with certainty in advance.
2. General repairs, overhauls, and replacement.
3. Preventive Maintenance.
4. Routine maintenance, which includes those maintenance-operations which are routine in nature, such as inspection, lubrication, etc.

They proposed quantitative approaches based on mathematical-programming for the framework that will make it implemental, extended some of the ideas on maintenance control and defined requirements for a maintenance-control information-system (MCIS) to be used for maintenance-control purposes.

Goh and Lim (1996) mentioned that an aircraft has an economic life of about 25 years and to keep it in serviceable condition, regular checks and repairs are conducted. Some of the repair and overhaul work involves parts and components that can be removed from the plane. The frequency of such repair activities depends on the manufacturer's specification. For example, the Boeing 737 aircraft requires maintenance every 40,000 to 45,000 hours of flight-time. They also developed the Total Quality Management (TQM) approach and applied it to improve the re-work rate and repair turn-time of the blade section of the engine-turbine.

There is a need to develop new techniques for maintaining the airworthiness of aging aircraft and for improving methods for the accurate prediction of the residual life of repaired structures. Shhyur et al. (1996) have used an artificial neural-network model to develop meaningful indicators that establish national air-operator profiles for comparison purposes.

These provide guidelines for the efficient scheduling of FAA safety inspectors and identify national service difficulties. The major objectives of this article are:

1. To provide guidelines for the efficient scheduling of FAA safety inspectors.
2. To develop meaningful indicators which establish national air-operator profiles for comparison purposes.
3. To identify national Service Difficulty Reporting (SDR) trends and inputs to improve the Federal Aviation Administration (FAA) surveillance-system.

How to operate the aging aircraft safely and economically? Suyitno and Sutarmadji (1997) recommended that a better maintenance-quality could be achieved by implementing a Corrosion Prevention and Control Programme (CPCP) earlier and more frequently to detect the corrosion problems. Corrosion is related to exposure time and the environment is the electrochemical deterioration of a metal because of its chemical reaction with the surrounding corrosive environment. The industry has classified the conventional corrosion condition into three levels. Level 1 corrosion, level 2 corrosion, and level 3 corrosion. Level 1, 2 discovered on initial inspection, or occurring between successive inspections, level 3 corrosion found during first or subsequent inspections. In addition, they asserted that because aircraft corrosion is unavoidable, a balanced, effective and efficient CPCP must planned and worked out from the initial design until the aircraft is out of service. In the case of CPCP the following aspects should be taken into consideration: design, manufacturing, operation and maintenance.

Fatigue tests of components or the entire airframe are extremely valuable in the early life of an aircraft. Goranson (1997) provided fundamental principles data behind the durability and damage-tolerance technology standards and gave some examples of a more rational approach to the development of flexible maintenance-programs without compromising safety, which permit efficient maintenance-planning to achieve the required fatigue-damage detection reliability-levels on aircraft.

Reliability-centred Maintenance (RCM) is a method for maintenance-planning developed within the aircraft industry to reduce the maintenance-cost. Rausand (1998) presented a structured approach to Reliability-centred Maintenance (RCM), and discussed the various steps in the approach. The RCM method provides a framework for utilizing operating experience in a more systematic way. The main objective of RCM is to reduce the maintenance-cost, by focusing on the most important functions of the system, and avoiding or removing maintenance-actions that are not strictly necessary.

Labib et al (1998) developed a model of maintenance decision-making using an Analytic Hierarchy Process (AHP) mathematical model. The proposed model serves as an approach to monitor performance, and to provide focused feedback to the pilot. A proposed model can be described as a feedback mechanism which can be compared with aeroplane panel-indicators that give the pilot a feedback on performance, location, altitude, pressure, and others.
The authors in this article mentioned that the mathematical models as simulation, heuristic (genetic algorithm), and inventory control model have been formulated for many typical situations. These models can be useful in answering questions such as: how much maintenance should be done on the machine? How frequently should the part be replaced? How many spares should be kept in stock and how should the shutdown be scheduled?

Peck, JR et al. (1998) analysed the discretionary managerial strategies undertaken by airlines with regard to aircraft maintenance and utilised the normative procedure of Data Envelopment Analysis (DEA) to assess which of these strategies were relatively efficient.

Federal aviation regulations require that all aircraft undergo maintenance after flying a certain number of hours. Airlines usually schedule routine-maintenance only at night to avoid cutting into aircraft utilisation, and most major U.S. airlines observe the maintenance-regulations by requiring that aircraft spend a night at a maintenance-station after at most three or four days of flying. Talluri (1998) modelled the maintenance-routing problem as one of generating an appropriately-directed graph (called a line-of-flight graph) and finding the k-days of flying before an overnight stop at a maintenance-station and an opportunity for a balance-check. Moreover, the Federal Aviation Administration (FAA) requires several types of aircraft maintenance-checks, which are called A, B, C, and D and vary in their scope, duration, and frequency.

It is difficult to predict the progress in future in improving the levels of maintenance-free operating period (MFOP) achievement. Cini and Griffith (1999) described how BAe Airbus is approaching the challenge of understanding the repercussions of the application of the MFOP philosophy to Airbus aircraft that addresses the need for supportability as an integrated solution through the life cycle of the product. Supportability enables flexibility in scheduled maintenance by increasing maintenance-check intervals through improved design processes.

Addressing the effectiveness of maintenance, Crocker (1999) paid particular attention to three areas for aircraft-safety: inspection-effectiveness, repair-effectiveness and maintenance-induced failures. He tried to understand how they may affect the overall operational-effectiveness of a system, and what steps can be taken to avoid the failures. An example was giving to support the study.

Mckone et al. (1999) proposed a theoretical framework for understanding the use of Total Productive Maintenance (TPM) and how it depends on managerial factors such as Just in Time, Total Quality Management (TQM) and Employee Environment (EE) as well as environmental and organizational factors such as country, industry and company characteristics. They tested this framework using data from 97 plants in three different countries to determine what types of companies are most likely to aggressively pursue TPM practices.

2.2.2 Types of Aircraft-maintenance

Every system and associated component has a function to perform. The primary objective of maintenance is to keep the system serviceable and available to perform that function. When the system fails, the maintenance-technician has to diagnose the fault and rectify the failure as quickly as possible to return it to a serviceable condition. Knotts (1999) and Wu el al. (2004) affirmed that the objective of aircraft-maintenance, civil or military, is to provide a fully-serviceable aircraft when it is required by the operator at minimum cost; and they added that maintenance is those actions required for restoring an item to a serviceable condition, including servicing, repair, modification, overhaul, inspection and determination of condition. They divided the maintenance into two categories:

2.2.2.1 Corrective Maintenance

These are all actions performed as a result of failure to restore an item to a satisfactory condition by providing correction of a known or suspected malfunction. Corrective maintenance can include any of the following steps: defect-location, defect-isolation, disassembly, replacement, reassembly, adjustment and testing. This type of maintenance is known as unscheduled-maintenance.

2.2.2.2 Preventive Maintenance

These are all actions performed at defined intervals to retain an item in a serviceable condition by systematic inspection, detection, replacement, adjustment, calibration, and cleaning. This type of maintenance is carried out at prescribed points in an aircraft's and equipment's life and is termed scheduled-maintenance.

2.2.3 Aircraft-maintenance Process

Furthermore, Knotts (1999) and Kinnison (2004) reported that there are three primary maintenance-processes to accomplish the scheduled-maintenance actions. These processes are called Hard Time (HT), On-condition (OC), and Condition Monitoring (CM) as described in the following section:

2.2.3.1 The Hard Time (HT) process

Hard Time is a failure-prevention process which requires that the item be removed from the aircraft and either completely overhauled, partially overhauled (restored), or discarded before exceeding the specified interval. The Hard Time interval may be specified by calendar-time, engine or airplane check-interval (engine-change , "C" check), landing- or operating-cycles, flight hours, block hours, specified flights (over water , terminating), or in conjunction with another process (OC).

When HT is specified, the component will be removed from the aircraft and overhauled, restored, or discarded, whichever is appropriate. This will be done before the component has exceeded the specified time-interval. Kinnison (2004) reported that the component overhaul or restoration will restore the component to a condition that will give reasonable assurance of satisfactory operation until the next scheduled removal. Ideally, Hard Time would be applied to a component that always fails at x hours of operation. This component would then be replaced at the last scheduled maintenance-period prior to the accumulation of x hours; thus the operator would get maximum hours out of the component and the component would never fail in service (ideally).

Hard Time is also applied to items having a direct adverse effect on safety and items subject to reliability-degradation with age but having no possible maintenance-check for that condition. The former components are not eligible for condition-monitoring because of the safety issue. For some components, such as rubber products, it is impossible to determine how much serviceability is remaining..

The structural-inspection, landing-gear overhaul, and replacement of life-limited engine parts are all controlled by Hard Time. Frequently, checking mechanical linkages and actuators, hydraulic pumps and motors, electric motors and generators, and similar items subject to a definite wear-out cycle will also be identified as Hard Time. For items having clearly-defined wear-out periods, Hard Time is probably the most economical process.

2.2.3.2 The On-condition (OC) Process

On-condition is a failure-prevention process that requires that the item be periodically inspected or tested against some appropriate physical standard (wear- or deterioration-limits) to determine whether or not the item can continue in service. After failing an OC check, the component must be overhauled or restored to the extent of at least replacing out-of tolerance parts. Overhaul or repair must restore the unit to a condition that will give comprehensible assurance of satisfactory operation for at least one additional OC check-interval. If the item cannot be overhauled or restored, or if it cannot be restored to a condition where it can operate for one more OC check period, then it must be discarded. On-condition must be restricted to components, equipment, or systems on which a determination of continued airworthiness may be made by measurements, tests, or other means without doing a tear-down inspection. These On-condition checks are to be performed within the time-limits (intervals) prescribed for each OC check. Examples of components susceptible to the On-condition process are as follows: Brake indicator pins, control cables, linkages, control robs, pulleys, rollers, tracks, jack screws.

2.2.3.3 The Condition-monitoring (CM) process

The Condition-monitoring process is applied when neither the Hard Time nor the On-condition process can be applied. The CM process involves the monitoring of the failure-rates and removals of individual components or systems that do not have a definite lifetime or a visible wear-out period. CM is not a failure-prevention process as are HT and OC. There are no maintenance-tasks suitable for evaluating the life expectancy of the CM item and there is no requirement to replace the item before it fails. Neither time nor condition standards can be used to control CM items because these components do not have such attributes. Therefore, CM components are operated until failure occurs and replacements of CM items are operated to failure.

The ATA states that these items must comply with the following conditions:

- A CM item has no direct adverse effect on safety when it fails: i.e. the aircraft continues to fly to a safe landing.
- A CM item must not have any "hidden function" (i.e., a malfunction that is not evident to the crew) whose failure may have a direct adverse effect on safety.
- A CM item must be included in the operator's condition-monitoring or reliability programme: that is, there must be some sort of data-collection and analysis for those items for maintenance to get a better understanding of the nature of failure for those components or systems. The maintenance-processes are summarised in Figure 2.1:-

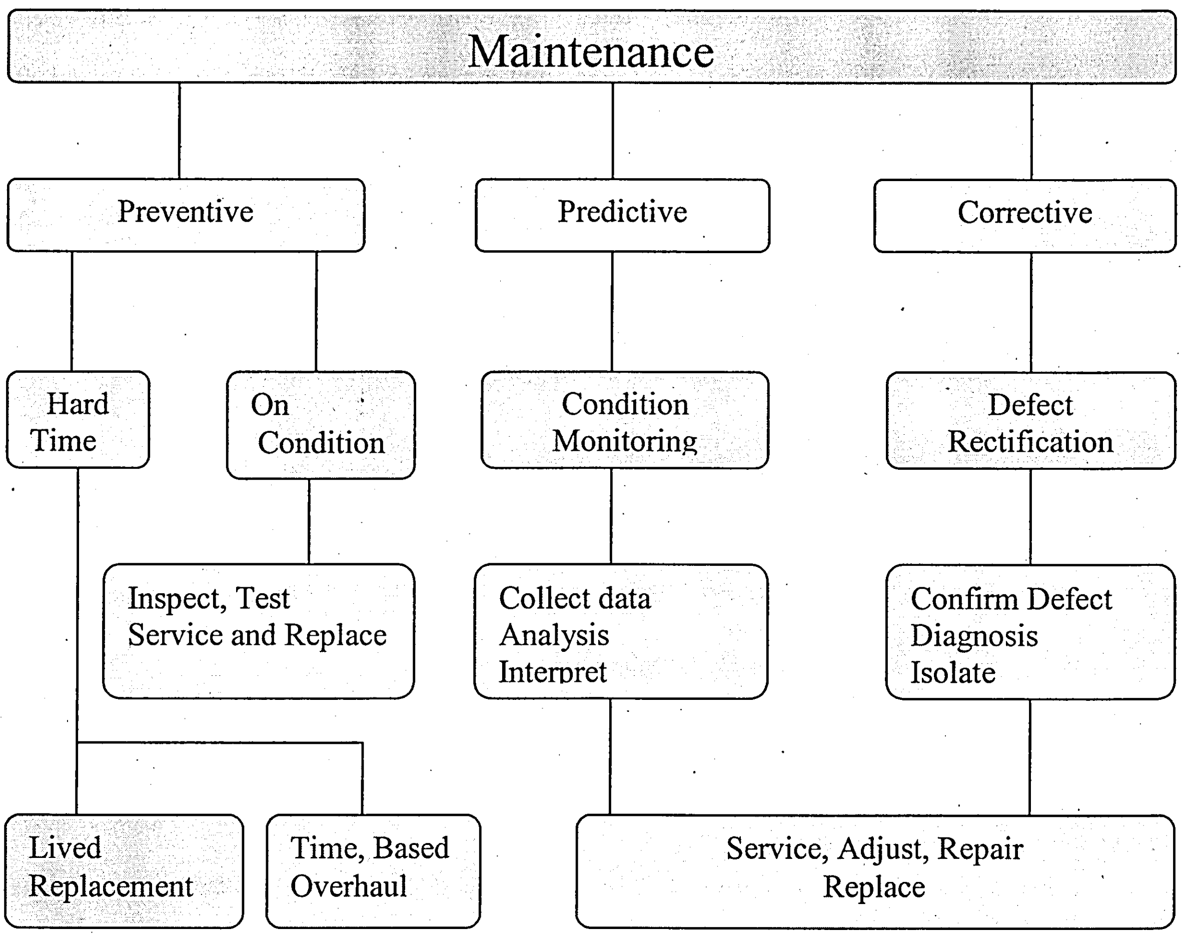

Figure 2.1 Maintenance Process. Knotts (1999).

Alfares (1999) reported that the information on aircraft maintenance-processes and policies was obtained by:

1. Weekly flight-schedules.
2. Weekly maintenance-planning schedules.
3. Weekend-work schedules.
4. Yearly maintenance-projections.
5. Employee time-sheets.
6. Maintenance-work log-books.
7. Company manuals on work-schedules.

2.2.4 Aircraft-maintenance Intervals (Checks)

Kinnison (2004) indicated that various maintenance-checks have been named and can identify their own named intervals as long as they maintain the integrity of the original maintenance-task requirements or receive approval for deviations. The standard intervals are as follows:

2.2.4.1 Transit Checks

A transit check is performed after landing and before the next take-off: that is, while the airplane is in transit at the airport. It is also performed before the first flight of the day. The transit checks consists of oil-level check and fill actions and a general visual inspection, called a walk-around, to check for any fluid leaks, open or loose panels, and damage to the flight-control services. Although the oil check and fill requires the opening of the engine cowling, the remainder of the transit check is usually done with the minimum of stands or other tools and equipment. If a problem is found, however, the resulting action will be unscheduled maintenance. This check is often done jointly by maintenance and flight-crew personnel. At stations where no maintenance is available, the flight-crew will do a walk-around inspection: i.e. they will do everything except open cowling and check oil-levels.

2.2.4.2 48-hour Check

The 48-hour Check is performed once every 48 hours. This check includes tasks that are more detailed than the transit checks, for example checking items such as wheels and brakes as well as certain fluids such as oil-levels for the auxiliary-power unit (APU), the integrated-drive generator (IDG), and the aircraft hydraulic-fluid level.

2.2.4.3 Hourly-limit Checks

Certain checks are determined by the number of hours the unit or system has been operating: 100, 200, 250, and 300 hours, etc. This approach is used for engines, airplane flight-controls, and numerous other systems that are operating on a continual basis during the flight or on the ground.

2.2.4.4 Operating-cycle-limit Checks

Other airplane systems are maintained on a schedule determined by the number of operating-cycles they have endured. Items such as tyres, brakes, and landing-gear, for instance, are used only during take-offs and landings.

2.2.5 Aircraft-maintenance Regular Checks

Clarke et al. (1996), Talluri (1998), Alfares (1999), and Kinnison (2004) introduced the idea that the periodic checks that have to be done on all aircraft after a certain period of time or usage are usually referred to by the airlines as one of the following: A Check, B

Check, C Check, or D Check. A and B checks are lighter checks, while C and D are considered heavier checks. The Federal Aviation Administration mandated that each aircraft has to undergo these four major types of checks, and they vary in scope, duration and frequency as in the following section:

2.2.5.1 Type A Check

The first major check (denoted as Type A) actually mandated by the FAA occurs at every 65 flight-hours, or about once a week. Type A checks involve inspection of all major systems such as landing-gear, engine and control-surfaces.

2.2.5.2 Type B Check

Clarke et al. (1996), and Alfares (1999) reported that the second major check (designated as Type B) is performed every 300-600 flight-hours, and entails a thorough visual inspection plus lubrication of all moving parts such as the horizontal stabilizer and ailerons.

2.2.5.3 Type C Check

This is performed approximately every 12-18 months. This maintenance-check takes the aircraft out of service and requires plenty of space, usually in a hangar at a maintenance-base.

2.2.5.4 Type D Check

This is the heaviest check for the airplane, which occurs approximately every 4-5 years. This requires even more space and time than all other checks, and must be performed at a maintenance-base.

The major checks, designated as Type C and D, require taking the aircraft out of service for up to a month at a time. The principle concern of the airlines is in meeting the type A and B checks' requirements through their self-imposed 4-day inspection and maintenance-policy. Unless there are exceptional circumstances the repairs take place at night. The frequency of these checks for an aircraft depends on the combination of:

1. Flight-hours.
2. Number of take-offs.
3. Landing-cycles.

Knotts (1999) developed an expert-system to evaluate all maintenance-activity times, which estimates fault-diagnosis activity times using knowledge-based systems and offered a vision for applying the technology and techniques to provide cost-effective and timely-fault diagnosis.

Moreover, he reported that scheduled flights are delayed mainly due to the following factors with percentages:-

1. 33% air-traffic congestion.
2. 13% weather and flight-crew problems.
3. 17% passenger-problems.
4. 17% ramp-handling problems.
5. 20% technical problems.

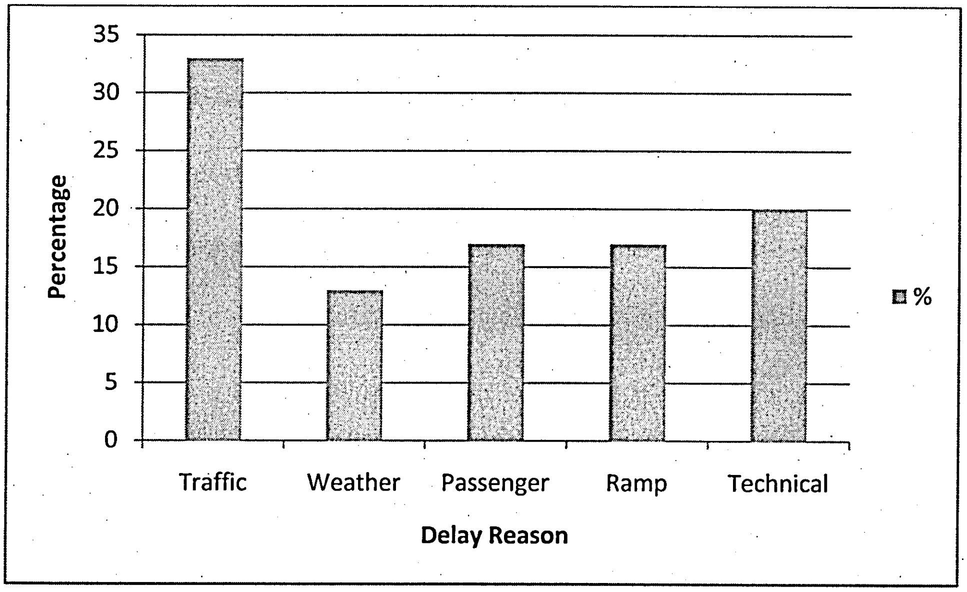

Figure 2.2 Aircraft-delay Factors. Knots (1999).

As regards human factors in aviation safety, Mcfadden and Towell (1999) presented a survey of the literature on human factors in airline-safety and built a conceptual framework for designing future safety studies. They included recommendations for how data should be collected and stored in order for researchers to analyze flight safety-data more effectively.

What is the best method to present team skills-training? An answer was provided by Kraus and Gramopadhye (1999) who developed a computer-based multimedia tool, the Aircraft Maintenance Team Training (AMTT) software. This aimed to determine and examine the effectiveness and applicability of computer-based multimedia team-training for aircraft-maintenance technicians; and also to evaluate the use of computers in acquiring knowledge on team-skills. The general objective of the study was to demonstrate the effectiveness of advanced technology for team-training.

2.2.6 Maintenance Costs

Anderson and Rasumussen (1999) presented a modelling approach for maintenance-decision support based on information about the technical condition of the items which includes cost of the spare-parts, material, labour and the cost of downtime. They classified the costs into three main categories: operation-costs, planned-maintenance costs and corrective-maintenance costs. Figure 2.2 provides a maintenance-costs structure in which at a lower level of detail they listed the maintenance-costs as energy costs, cost-efficiency loss, minor-maintenance costs, down-time costs, person-hours costs and spare-parts costs.

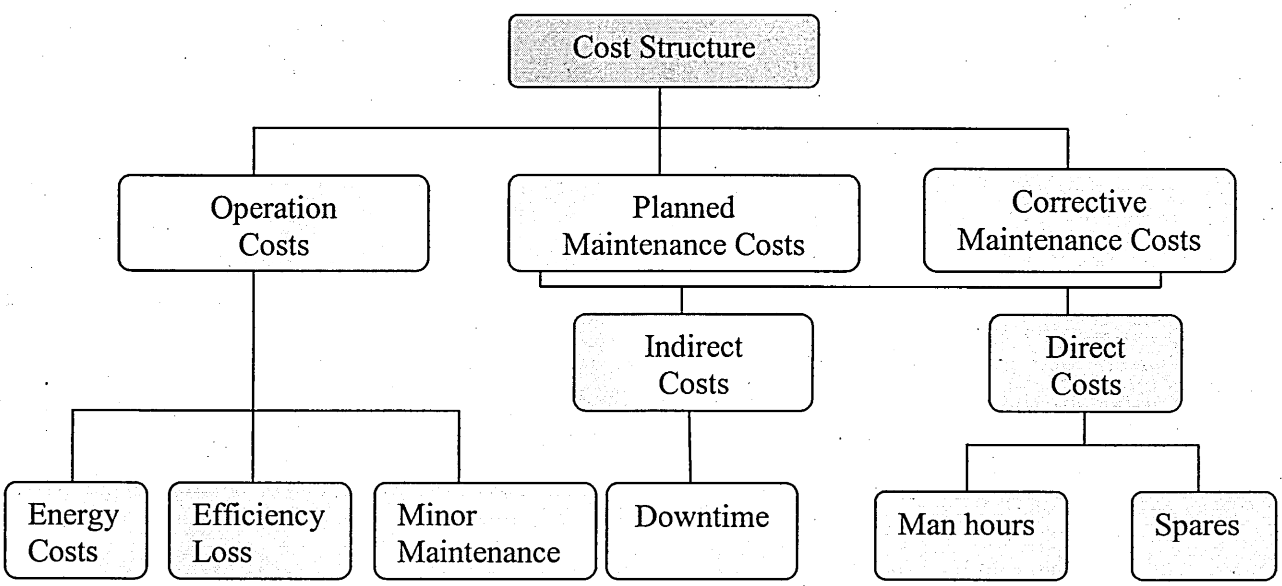

Figure 2.3 Cost breakdown structure, Anderson and Rasmussen (1999).

An opportunistic k-out-of n: G system with imperfect Preventive Maintenance (PM) is studied by Pham and Wang (2000). They proposed two new opportunistic maintenance models (τ,T) with the consideration of reliability requirements. In those two models, only minimal repairs are performed on failed components before time τ and the corrective maintenance (CM) of all failed components is combined with PM of all functioning but deteriorated components after this. If the system survives to time T without perfect maintenance, it will be subject to PM at time T.

Maintenance Resource Management (MRM) is the part of human maintenance-factors which addresses the issues of management, organisation, communication, problem-solving, and decision-making. Taylor (2000a) defined Maintenance Resource Management as a collaboration and communication for maintenance-safety which evolved from Aviation Maintenance Technician (AMT) participation in safety improvement. Two case-studies were reviewed and assessed in terms of degree of top-management support, the quality of intervention, and the extent of measurement and feedback.

Many airlines use surveys to understand the attitudes, opinions and perceptions of their employees. It is important that surveys are scientifically "good" measures. Taylor (2000b) described and developed a test of the effectiveness of the Maintenance Resource Management - Technical Operation Questionnaire MRM/TOQ. The MRM/TOQ includes attitude measures related to the reliability which were modified and developed technical operations and has become widely used for assessing communication and management improvement programs specifically for use in aviation maintenance.

In a review of human error in aviation maintenance and inspection, Latorella and Prabhu (2000) mentioned that a major airline showed the distribution of 122 maintenance errors over a period of three years to be: omission (56%), incorrect installations (30%), wrong parts (8%), others (6%). The author reviewed reactive and pro-active methods of error-detection and several intervention strategies for identifying, reporting, and managing human-error in aviation maintenance and inspection. The major categories of human-error in maintenance and inspection tasks are: defective component, missing component, wrong component, incorrect configuration, incorrect assembly, functional defects, tactile defects, and procedural defects.

In an application of the Analytic Hierarchy Process (AHP) for selecting the best maintenance- strategy, Bevilacqua and Braglia (2000) described an application of this process for selecting the best maintenance-strategy for an important Italian oil-refinery.

In an attempt to understand the human contribution to major accidents and disasters through organisational and management factors, McDonald et al. (2000) proposed a self-regulatory model to examine how different organisations manage safety, with particular emphasis on the human and organisational aspects. The model was effective in analysing the salient features of each organisation's safety-management system, though it underestimated the roles of planning and change.

To investigate the relationship between flight-schedule punctuality and aircraft turn-around efficiency at airports, Wu and Caves (2000) applied a mathematical model to simulate aircraft turn-around operations by considering the stochastic effects of schedule-punctuality as well as aircraft turn-around performance, in order to minimise system operational-costs and to maintain a required level of schedule-punctuality. The aim was to investigate how the trade-off situation between the ground-time of a turn-around aircraft and schedule- punctuality performance varies with the buffer-time allocated to the schedule.

In an investigation of the effect of team-training on aircraft maintenance technicians, Kraus and Gramopadhye (2001) used the Aircraft Maintenance Team Training (AMTT) software to examine the role of advanced technology, specifically computer-based multimedia presentations, in adding team skills-training to aircraft maintenance techniques; and to evaluate the transfer-effects of the computer-based training delivery-system to the operational environment.

Sandoh and Igaki (2001) proposed two types of model-inspection policies for a scale which weighs products in the final stage of manufacturing some specific products, such as chemical products. Under model I, an inspection includes an adjustment activity. Under model II, the inspection can only detect a scale malfunction.

Nakagawa and Hua (2002) asserted that the reliability of a series parallel system with the same number of series and parallels tends to one as its number goes to infinity, and also is an increasing function of its number if the failure-probability of a unit is lower than the golden ratio. They mentioned that the system-reliability can be improved by redundancy of units.

In strategic maintenance-management, Murthy et al. (2002) discussed the Strategic Maintenance Management (SMM) approach developed by the Reliability Engineering and Risk Management Group (RERMG) at the University of Queensland. It involved linking the technical, operational and commercial issues in an integrated framework. The key features of the approach are:

1. An understanding of the science of degradation.
2. The need for proper data-collection and analysis.
3. The use of mathematical models for evaluating alternate maintenance-strategies and for selecting the optimal maintenance-strategy.
4. Continuous improvement in business-performance.

The activities at the RERMG to help industry implement the SMM approach were briefly discussed and illustrated through three case-studies. They discussed the idea of reliability that conveys the concept of dependability, successful operation or performance and absence of failures.

Hobbs and Williamson (2002) examined whether the three-way distinction (violations, skill-based errors and mistakes) of unsafe acts is applicable in the context of aircraft-maintenance, and whether involvement in maintenance safety-occurrences can be predicted on the basis of self-reported unsafe acts. A Maintenance Behaviour Questionnaire (MBQ) was developed to explore patterns of unsafe acts committed by aircraft mechanics.

Davidson and Labib (2003) proposed a new concept of decision-analysis based on a Multiple Criteria Decision-making (MCDM) process. The proposed model uses the Analytic Hierarchy Process (AHP) mathematical model as a backbone and integrates elements of a modified Failure Model and Effects Analysis (FMEA). A case-study described the Concord aircraft accident supported with figures to show the best decision-making.

With reference to the new tools for aircraft-maintenance, Komorowski (2003) presented an overview of the advances in understanding the impact of corrosion on structural-integrity and the associated tools available for inspection, assessment and repair. A comprehensive set of tools includes: inspection-systems and methods, structural-integrity assessment codes, repair technologies and equipment, and maintenance-scheduling and risk-assessment codes.

Tsai et al (2004) presented a method of periodical Preventive Maintenance (PM) policy based on availability consideration of multi-component systems. They gave an example and sets of figures following the proposed model of reliability, to show the relationship between the time and the reliability for different time subsystems.

2.2.7 Goals and Objectives of the Aircraft-maintenance Programme

Kinnison (2004) summarized the goals and objectives in the following steps:

2.2.7.1 Goals of an Airline-maintenance Programme

1. To deliver airworthy aircraft to the flight-department in time to meet the flight-schedule.
2. To deliver aircraft with all necessary maintenance actions completed or properly deferred.

2.2.7.2 Aircraft-maintenance Programme Objectives

1. To ensure the realization of the inherent safety- and reliability-levels of the equipment.
2. To restore safety and reliability to their inherent-levels when deterioration has occurred.
3. To obtain the information necessary for adjustment and optimisation of the maintenance-programme when these inherent levels are not met.
4. To obtain the information necessary for design-improvement of those items whose inherent reliability proves inadequate.
5. To accomplish these objectives at a minimum total cost including the costs of maintenance and cost of residual-failures.

2.2.8 Aircraft-maintenance Documentation

Documentation identifies the aircraft, its systems, and the work to be done on them. Some documents will be made-to-order for the operator by the supplier, others will be generic. Most of these documents have standard revision-cycles and changes are distributed on a regular basis by the airframe manufacturer. Kinnison (2004) mentioned that some documents are designated as "controlled" and some "none-controlled" documents. A controlled document is one that is used for operation and /or maintenance of the aircraft in accordance with FAA regulations. Such documents have limited distribution within the airline and require regular revision-cycles with a list of revisions, active and rescinded page-numbers recorded in the document. The operator is required to use only up-to-date documents.

2.2.8.1 Types of Documentation

There are three main types of documentation; each of them includes many documents illustrated in the following points:

1. Manufacturer Documentation
    a. Airplane maintenance manual (AMM).
    b. Component and vendor manuals.
    c. Fault isolation manual (FIM).
    d. Fault reporting manual (FRM).
    e. Illustrated parts catalogue (IPC).
    f. Storage and recovery document (SRD).
    g. Structural repair manual (SRM).
    h. Maintenance planning data document (MPD).
    i. Schematic diagram manual (SDM).

j. Wiring diagram manual (WDM).

k. Master minimum equipment list (MMEL).

l. Dispatch deviation guide (DDG).

m. Configuration deviation list (CDL).

n. Task cards (TC).

o. Service bulletins, service letters, and maintenance tips.

2. Regulatory Documentation

   a. Federal aviation regulations (FARs).

   b. Advisory circulars (ACs).

   c. Airworthiness directives (Ads).

   d. Notice of proposed rulemaking (NPR).

3. Airline Generating Documentation

   a. Operation specifications.

   b. Technical policies and procedures manual.

   c. Inspection manual.

   d. Quality assurance manual.

   e. Reliability program manual.

   f. Minimum equipment list.

   g. Task cards.

   h. Engineering orders (EO).

2.2.8.2 ATA Document standards

Each system or system-type was assigned a chapter-number. For example, hydraulic systems are in ATA Chapter 29 for all manufacturers, which is illustrated in Figure 2.4.

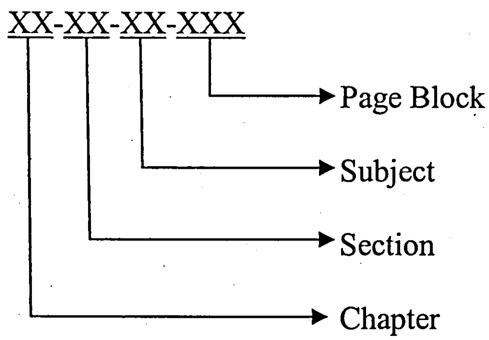

Figure 2.4 Document Standards.

Example:

52	Doors.
52-11	Passenger Doors.
52-11-02	Passenger Door Handle.
52-11-02-401	Rear Passenger Door Handle.

To reduce the confusion in maintenance, the Air Transport Association of America (ATA) stepped in and standardized the overall format of the maintenance-manuals so that all manufactures' documents would be more compatible. Each system was assigned a chapter number; in the following Tables 2.1 and 2.2, Kinnison (2004) showed that the ATA Standard Chapter-numbers and the Aircraft Maintenance-manual Page-block assignment are:

Table 2.1 ATA Standard Chapter-numbers. (Kinnison, 2004).

ATA	Subject	ATA	Subject
5	Time-limits, Maintenance-checks	37	Vacuum
6	Dimensions and Access-panel	38	Water/Waste
7	Lifting and Shoring	45	Central Maintenance-centre
8	Levelling and Shoring	49	Airborne Auxiliary-power
9	Towing and Taxi-ing	51	Standard Practices
10	Parking, Storage, and Return-to-service	52	Doors
11	Placards and Markings	53	Fuselage
12	Servicing	54	Nacelles/Pylon
20	Standard Practices (Airframe)	55	Stabiliser
21	Air-conditioning	56	Windows
22	Auto-flight	57	Wings
23	Communications	70	Engine
24	Electrical-power	71	Power-plant
25	Equipment/Furnishing	72	Engine (Internals)
26	Fire-protection	73	Engine Fuel-control
27	Flight-controls	74	Ignition
28	Fuel	75	Air
29	Hydraulic-power	76	Engine-controls
30	Ice and Rain-protection	77	Engine-indicating
31	Indicating/Recording System	78	Exhaust
32	Landing-gear	79	Oil
33	Lights	80	Starting
34	Navigation	82	Water-injection
35	Oxygen	91	Charts (Miscellaneous)
36	Pneumatic		

Table 2.2 Airplane Maintenance-manual Page-block Assignments. Kinnison (2004).

Block	Title	Description
001-099	Description and Operation	Identifies the various operational modes of the system and describes how the system and its essential components work.
101-199	Fault Isolation	Fault trees used to perform fault-isolation for various problems occurring within a system.
201-299	Maintenance-practices	An R/I procedure followed by a BITE test, a functional test, an adjustment procedure, or servicing instructions
301-399	Servicing	All servicing-tasks: checks fill and replacement of oil, hydraulic fluid, water, fuel.
401-499	Removal/Installation	Detailed, step-by-step instructions on how to remove a Line Replaceable Unit (LRU) and replace it with a like item.
501-599	Adjustment/Test	Procedures for making adjustments or performing tests to the systems whenever a component or system has been replaced and such adjustments or tests are required.
601-699	Inspection/Checks	Zone inspections of aircraft.
701-799	Cleaning/Painting	Procedures for cleaning and painting of the aircraft.
801-899	Approved Repairs	Repairs to structure and aircraft-skin approved by FAA for airline-maintenance organizations.

2.2.9 The Aircraft-maintenance Organisation

The structure for an effective maintenance organization will vary with the size and type of organization. It also varies with the management philosophy of the company. But one thing must be kept in mind: the organization-structure must allow the company to meet its goals and objectives, and each unit within the company must be capable with sufficient personnel and authority to carry out the objectives and meet the goals. Figure 2.5 illustrates the structure of the maintenance-organization:-

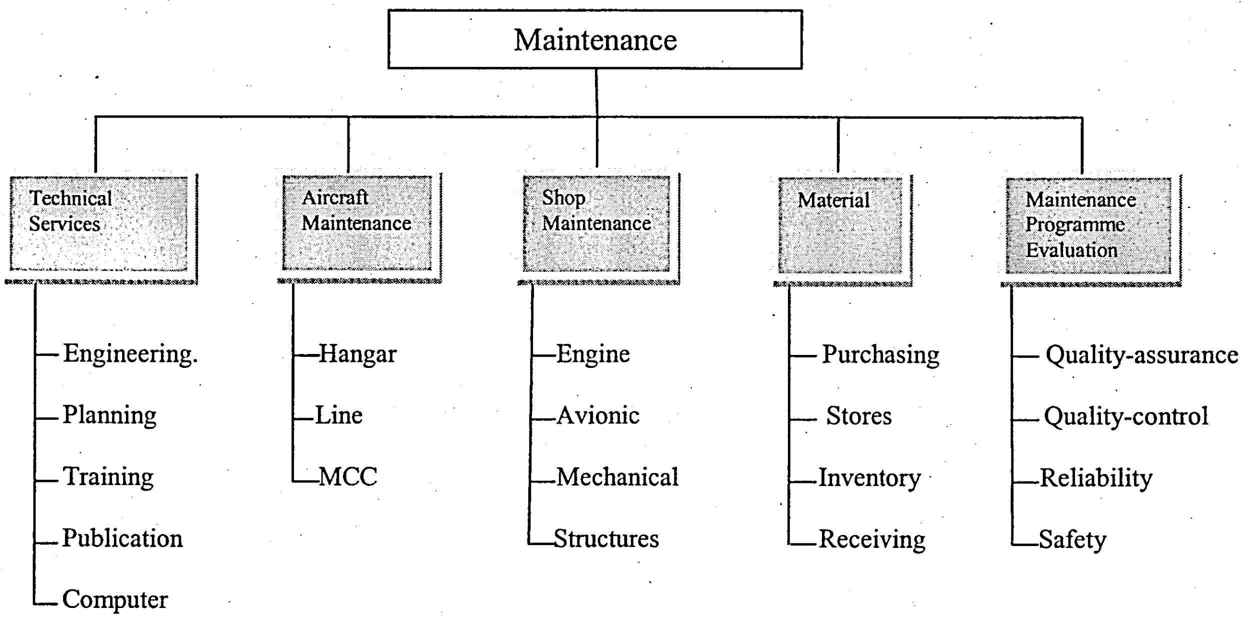

Figure (2.5) The Structure of a Typical Aircraft-maintenance Organization. Kinnison (2004).

2.2.10 Aircraft-maintenance Activities

There are two types of maintenance: scheduled and un-scheduled maintenance. Kinnison (2004) reported that the working maintenance- organization, however, is not divided in that manner. For operational reasons, maintenance-activities are divided into the categories of on-aircraft maintenance and off-aircraft maintenance.

On-aircraft maintenance is future divided into line and hangar-maintenance activities, and the off-aircraft maintenance into maintenance overhaul-shops.

2.2.10.1 Line-maintenance

Depending on the size of the airline, the line maintenance organisation may take on different structures. The kind of work done by line-maintenance is any maintenance that can be done on the aircraft in service without taking it out of service; i.e., without removing it from the flight-schedule. This includes everything from daily checks and transit checks to the longer-term checks. The Maintenance Control Centre (MCC) is the heart of line- maintenance, which coordinates all maintenance activity, scheduled or unscheduled, for the aircraft in service. Alfares (1999) indicated that the workload of line- maintenance workers includes the following duties: pre-flight, through-flight, post-flight checks, calendar and 50-hour inspection, A-checks, time-limited component changes, supporting special flights, fixing pilot-reported problems and maintenance discrepancies, and on-the-job training.

Gupta et al. (2003) reported that line-maintenance is called short routine-maintenance and includes regular short inspections of an aircraft between arrival and departure at an airport. Line-maintenance has the greatest effect on flight-schedules and maintenance-delay rates.

2.2.10.2 Hangar Maintenance

This is the maintenance which is done on out-of-service aircraft. It includes any major maintenance or modification on aircraft that have been temporarily removed from the flight-schedule. Hobbs and Williamson (2003) mentioned that an aircraft hangar is a highly-regulated workplace and mechanics are expected to carry out their duties while observing legal requirements, manufacturer's maintenance-manuals, company-procedures and unwritten norms of safe behaviour.

The hangar building also provides space for numerous support-shops, overhaul-shops and ground-support equipment as well as office-space for the hangar maintenance-staff. A dock-area should be provided to serve as the control-centre of the hangar maintenance check-in process.

2.2.10.3 Maintenance Overhaul-shops

There are two types of shop-maintenance activities in an airline maintenance-organization. The support-shops include such special skills and activities as welding, sheet-metal working, composite-materials working, and aircraft-interior maintenance. These shops are usually part of the hangar maintenance-organization. The work they do is primarily in support of out-of-service aircraft, although some support is given to line-maintenance as needed.

The other type of maintenance-shops at an airline, the overhaul-shops, involves support for the specialized equipment on the aircraft such as engines, avionics, hydraulic, and pneumatic-systems.

In the industry of aircraft-maintenance, the maintenance-personnel allocation is a complicated and important issue. How to select a suitable staff to perform a particular maintenance-task at the right time is a critical factor for the success of a Maintenance Service Company. Cheung et al. (2005) proposed and developed a method of a fuzzy Analytical Hierarchy Process (AHP) approach to improve staff allocation and to support of decision-making process within the maintenance industry.

A case-study was used to illustrate the selection of the most suitable engineer for a particular maintenance-task using a fuzzy-judgement matrix. The purpose of this study in general was to propose an approach to facilitate the allocation of labour- resources.

Chan et al. (2005) studied the effectiveness and implementation of the Total Productive Maintenance (TPM) programme for an electronic manufacturing-company. The goal of TPM is to maximise equipment-effectiveness by making the estimation of the maintenance-cost of airframes easier and considering the need for reliability, using commercial software.

How to make easier the estimation of maintenance-cost of airframes, Salamanca and Quiroz (2005) proposed a new method using commercial reliability-software to evaluate the economic life of aircraft-structures. The calculated optimal stress-distribution function can be used with commercial reliability-software to estimate the crack-size population. They used an example illustrated with a figure to show maintenance-cost variation with the interval inspections.

Bertolini and Bevilacqua (2006) proposed a goal-programming approach to the selection of maintenance-strategies for the centrifugal pumps of oil-refinery plants, and evaluated the quality control system selection, information system project evaluation, and facility allocation problems through an adequate application of the Analytic Hierarchy Process (AHP). A Goal Programming approach is proposed to minimise maintenance-costs and allows considering multiple criteria to measure performance, multi-objectives/goals and constraints. The aim of the analysis was to identify the optimal maintenance policy for each failure-type, taking into account the feasibility of the different alternatives. To accomplish the aim, a case-study was introduced.

In relation to maintenance-management, there was an important research paper issued by Garg and Deshmukh (2006) that introduced and reviewed the literature on maintenance-management. Their objectives were to: suggest a classification of available literature in the field of maintenance-management; identify emerging trends in the field of maintenance management; identify critical observations on each classification; and consolidate all available literature in the field. A total of 142 papers were collected and analysed. They made a broad classification of the literature into six areas: 27 papers on maintenance optimisation models, 58 papers on maintenance techniques, 9 papers on maintenance-scheduling, 23 papers on maintenance-performance measurements, 6 papers on maintenance information-systems and 19 papers on maintenance policies.

In general, maintenance-optimisation models cover four aspects: a description of a technical system, its function and importance; a modelling of the deterioration of the system in time and possible consequences for this system; a description of the available information about the system and actions open to management; and an objective function and an optimisation technique which helps in finding the best balance. The models have been classified according to the modelling of the deterioration as deterministic or stochastic models. A sub-classification of this area in to 12 sub-areas is as follows: Bayesian Approach; Mixed-integer Linear-programming formulation; Areas 3 to 6: Maintenance-approaches using fuzzy multiple-criteria decision-making and linguistic approaches; Areas 7 to 8: simulation and Markovian probabilistic models; Areas 9 to 11: Analytic Hierarchy Process (AHP); and Area 12: Miscellaneous.

Maintenance-techniques: these techniques have been further sub-classified into ten areas as: Preventive Maintenance (PM); Condition-based maintenance; Total Productive Maintenance (TPM); Computerized Maintenance Management Systems (CMMS); Reliability Centred

Maintenance (RCM); Predictive Maintenance; Maintenance-outsourcing; Effectiveness-centred Maintenance; Strategic Maintenance-management; and Risk-based Maintenance.

Maintenance scheduling means bringing together with precise timing the six elements of the successful maintenance-job such as tools, materials/parts, and the availability of the unit to be serviced, the information needed to complete the job, and the necessary permissions.

Maintenance-performance measurement: this includes measurement-techniques and criteria, e.g.: Overall Equipment/craft Effectiveness (OEE); Performance-measurement relationship with maintenance-strategy; the effect of maintenance-induced failures on operational effectiveness; and other miscellaneous measures.

Maintenance information-systems: these focus on information technology (IT) which can help to improve maintenance-practices and create better competitiveness.

Maintenance policies: Thousands of maintenance and replacement models have been created which can fall in to some categories of maintenance and replacement policies like age-replacement, random-age replacement policy, block-replacement policy, periodic PM policy, failure-limit policy, etc. Each kind of policy has different characteristics, advantages and disadvantages. Bertolini and Bevilacqua have summarized, classified and compared various existing maintenance-policies for both single-unit and multi-unit systems with emphasis on single-unit systems; and optimal policies on imperfect maintenance with a few important results like maintenance-integration and emerging maintenance-concepts such as: Economic-manufacturing Quantity-determination in an imperfect PM, Simulation in Maintenance, Customized Maintenance and Object- oriented Maintenance Management.

Finally, a large number of papers in this field suggesting a classification into various areas and sub-areas in the field of Maintenance-management were identified to help researchers specify gaps in the literature and direct research-efforts suitably. These will be useful to researchers, maintenance-professionals and others concerned with maintenance to help them understand the importance of maintenance-management.

A component with deterioration and random failure is modelled by Jayakumar and Asgarpoor (2006), using Markov processes while incorporating the concept of minor and major Preventive Maintenance.

The service life of critical aerospace components is governed by the modes of degradation and failure such as: fatigue, fracture, corrosion and wear. Gas-turbine discs are usually the most critical engine-components, which must endure substantial mechanical and thermal loading. Witek (2006) performed a fracture analysis to investigate the damage-mechanism of the turbine-disc by using a geometrically-complicated Finite Element (FE) model with some nonlinearity as contact and elastic plastic material was created.

2.3 Maintenance-scheduling

Scheduling plays a significant role in the field of aviation and it is considered a key function, which influences the utilization of aircraft-operation and maintenance.

Some of the complex issues affecting operations-management are: people, luggage, freight and aircraft having to be moved over vast distances. Flights, crews, maintenance, cargo and even meals have to be scheduled. Fuel, spares, tools, training and publications have to be provisioned. All of these factors have to be considered against a background of timetables coupled with operating and maintenance costs: that is, time and money.

The author will be focus in this study on maintenance, which will try to determine the optimum interval for doing the Preventive Maintenance that minimises the total maintenance cost by developing and utilising a mathematical model.

The fleet-assignment problem is to determine which aircraft-type should fly each flight segment. Clarke et al. (1996) provided modelling-devices for including maintenance and crew considerations into the basic model, while retaining its solvability to maximize revenue minus operating costs. They aimed to minimize the number of crews used in the airline subject to crew-rest requirements and the completion of all missions within the specified time-frame.

Rishel and Christy (1996) mentioned that the purpose of performing scheduled maintenance is to reduce the number of failures and they evaluated the impact of incorporating scheduled-maintenance policies in the production-environment and predicted emergency activities into the Material-Requirement Planning system (MRP) to minimize downtime during a failure, and reduce disruptions to the production-process. The operation-research community has developed a number of computer-models to aid in the solution of airline-scheduling problems.

Mathaisel (1996) provided reports on the application of the integration of computer-science and operation-research in a decision-support system for airline-system operation-control. The application integrates real-time, flight-following, aircraft-routing, maintenance, crew-management and flight-planning with dynamic aircraft-rescheduling and fleet-rerouting algorithms for irregular operations.

Susova and Petrov (1997) used the analytical model (Markov Model-Based Reliability and Safety Evaluation for aircraft maintenance-system optimization) for solving a number of practical tasks: redundancy optimization, determining check-intervals, optimizing aircraft minimum-equipment list in order to minimize operation-costs and ensure flight safety. Fleet assignment determines the type of aircraft to operate each flight in a given schedule, subject to a variety of side-constraints, due to marketing and operational-, maintenance- and crew-restrictions.

Rushmeier and Kontogiorgis (1997) presented an advanced model for the formulation and solution of large-scale fleet-assignment problems that arise in the scheduling of air-transportation. Computational results on actual schedules showed that high quality assignments for one-day problems can be obtained within an hour of computation. The use of the model at Unedited State Air results in an annual benefit of at least $15 million.

2.3.1 The Objectives of Maintenance-scheduling and Its Constraints

Dufuaa and Al-Sultan (1997) reported that the purpose of performing scheduled maintenance is to reduce the number of failures and the objective of maintenance-scheduling could be one of the following:

1. To minimize equipment and personnel idle-time.
2. To minimize total scheduling-time.
3. To minimize delay of certain jobs.
4. To minimize the shut-down costs.
5. To minimize plant shut-down time.
6. To maximize equipment-availability.

However, in maintenance-scheduling, constraints usually impose limits on:

1. The availability of various types of skills.
2. Equipment and tool availability.
3. The availability of spare-parts.
4. Arrival times and job-requirements of all incoming jobs.
5. The sequence of job-operations.

Furthermore, Dufuaa and Al-Sultan discussed the problem of the scheduling and planning of maintenance, and two relevant mathematical-programming approaches to this problem were presented. An expansion to the state-of the-art maintenance-management information-system has been proposed in order to utilize the mathematical-programming approach and to have effective control of the maintenance-scheduling problem. For many companies the scheduling of job-shops proves very difficult.

Gatland et al. (1997) developed a simulation model to provide a better understanding of the available capacity of the engine-maintenance facility versus the current realized capacity. The model clearly demonstrates that the loading of engines into the repair-cycle has a great effect on the capacity of the facility.

Keskinocak and Tayur (1998) developed the integer-programming formulation, provided the problem description and computational complexity, discussed special cases and described a heuristic approach and the computational results.

Usher et al. (1998) presented a method for predicting a cost-optimal Preventive Maintenance policy for a repairable system with an increasing Rate of Occurrence of Failure (ROCOF). A numerical example was illustrated and computational results were offered so that a comparison could be made between three different approaches, namely, a genetic algorithm, a branch and bound approach and a random search.

Knapp and Mahajan (1998) developed a mathematical-model for optimizing manpower-allocation by maintenance-area, craft-type, training-level, and in-house versus sub-contracted employees, as well as selecting between a centralized versus decentralized organizational structure. The system was designed to undergo the balance-check every day, and to solve the fleet-assignment and aircraft-routing problems. The objective of the developed model was to reduce the cost of the resources used in the maintenance-department. Maintenance-costs include the cost of the spare parts, material, workers, and the cost of down-time.

Barnhart et al. (1998) used a string-based model and a branch-and-price solution approach and provided computational results for the combined fleet-assignment and aircraft- routing problems, both without equal utilization requirement and for aircraft-routing problems requiring equal aircraft-utilization. They presented the optional maintenance-strategies and their relationship to aircraft-reliability, as measured by the percentage of scheduled flights delayed because of mathematical problems. The objective was to solve the fleet-assignment and aircraft-routing problems at the same time.

Wessels (1998) defined scheduled maintenance as a formal set of maintenance-activities performed at regularly-scheduled intervals that diagnose and repair all degraded modes such that the system is restored to full capacity. The intervals can take the form of scheduled cycles (e.g. at every 100 hours), or times (e.g. at every week, month of operation). Because the critical parameter of scheduled maintenance is the interval, if the interval is correctly calculated, then no repair-breakdowns will occur during the interval. He also offered an analytical approach which enables a particular organization to evaluate the impact of scheduled maintenance-intervals on the system-reliability model and maintainability-parameters for machinery and equipment.

To help with aircraft-maintenance workforce-scheduling, Alfares (1999) presented a new integer programming-formulation to obtain an optimum seven-day work-schedule with no increase in workforce-size. The main recommendation of the study was to change from a five-day to a seven-day workforce for aircraft-maintenance workers. A real case-study was applied at Saudi Aramco in Saudi Arabia, which in 1997 included 13 fixed-wing aircraft and 19 helicopters. The study objective was to determine the optimum maintenance-workforce schedule to satisfy growing labour-requirements with minimum cost.

Duffuaa and Al-Sultan (1999) reviewed and developed a stochastic programming model; the model integrated the deterministic and the stochastic components of the scheduling problem. An example illustrating the model has been given to demonstrate the utility of the model and the value of the stochastic solution. They analyzed maintenance-scheduling problems such as:

1. Job-completion times or job-standard times.
2. Availability of equipment for performing maintenance-jobs.
3. Spare-parts delivery-times at job-sites.

Kumar et al. (1999) developed a procedure for adjusting Preventive Maintenance intervals after each inspection and maintenance activity; they considered either residual-life or the required reliability of the engine after every inspection and maintenance task and used these two measures to adjust the scheduled-maintenance frequency and hard time.

Lofsten (1999) developed a non-linear programming model to determine whether to schedule Preventive Maintenance and the model trades off the capital costs of Preventive Maintenance and the sum of Corrective Maintenance and down-time costs based on the production-line's state. The model considers maintenance policies and determines economic values of maintenance policies based on their Net-Present-Values. It is used to calculate the expected costs when postponing Preventive Maintenance for an item that is soon to fail based on the cost of Corrective and Preventive Maintenance and the probability of failure.

Airline-coordinators have to find a minimal-cost reassignment of aircraft and crews that satisfies all required safety-rules, has little impact on passengers, and minimizes operational difficulties for the airline. Lettovesky (2000) developed a new solution-framework, which he implemented, and tested. This provides, in almost real-time, a recovery-plan for reassignment-crews to restore a disrupted crew-schedule. He supported this with a case-study and the computational results demonstrate that the application of optimization-based solution-techniques to crew-rescheduling is possible and the medium-sized disruptions to the crew-schedule can be handled within an acceptable running-time.

Addressing the fleet-assignment problem, Akdeniz (2001) introduced and discussed a Corrosion Prevention and Control Program (CPCP) process for upgrading structural-inspection programs for older airplanes and investigated sub-surface corrosion on principal airplane-structures and its effects on airplane-safety.

Cordeau et al. (2001) proposed a solution-approach based on Bender's decomposition methodology for the simultaneous routing of aircraft and scheduling of crew to determine a minimum-cost set of aircraft routes and crew-pairings such that each flight-leg is covered by one aircraft and one crew, and side constraints are satisfied. The objective of the crew-scheduling problem is to determine a minimum-cost set of pairings. The cost of pairing depends not only on the total flight-time but also on the waiting-time during connections as well related to accommodation-expenses.

The successful completion of a manufacturing or maintenance project depends on the availability of an accurate and reliable schedule of activities and a list of expected material- and resource-demands. Samaranayake et al. (2002) developed a unitary structuring approach, composed of the Critical Path Method (CPM), Materials Requirement Planning (MRP) and Production Activity Control (PAC) techniques, for assembly-scheduling to enable the development of a methodology for comprehensive management of projects and materials for the purpose of aircraft-maintenance. Airlines plan aircraft-routes and crew-schedules in advance and disruptions occur every day. As a result, flight-schedules may become unfeasible and will need to be updated. The results from the example used indicated potential benefits in terms of improved forward-planning capability and the potential for spare-parts-inventory reduction.

Stojkovic et al. (2002) presented a model that attempts to reinstate planned airline-services following an unexpected disruption in airline operations without changes to aircraft-itineraries and crew-rotations. The model extends prior time-based models by considering not only activity start-time variables, but also activity-duration variables. The model re-optimizes departure-times to take into account the sequences of activities that have to be carried out within all aircraft-routes and crew-rotations. The new schedule was obtained by reducing flying, ground-service, maintenance, or passenger-transfer time. The costs of time-reduction, elements of the crew-costs and passenger-inconvenience were included in the objective function.

Artana and Ishida (2002) developed a method for determining the maintenance-intervals for components of a liquid-ring primer of a ship's bilge-system in the wear-out phase. A spreadsheet technique was used for the model optimisation, and Microsoft Excel Solver was applied to solve for the optimal schedule with respect to minimum total cost. This method demonstrates spreadsheet-modelling as one option which is easy to use and is readily available.

Gupta et al. (2003) developed a computerized simulation-model for the aircraft line-maintenance department in Continental Airlines. The model gave objective justification for simple solutions like staggered shifts and part-time labour, which can meet resistance in a workforce.

Yan et al. (2004) developed the maintenance-manpower supply-planning model and flexible strategic models that can help an airline to find an effective maintenance-manpower supply-plan (manpower-scheduling), which aimed to minimise the total maintenance-manpower supply. A case-study was applied on six different types of aircraft, 51 aircraft in total.

To help with airline-schedule planning, Lohatepanont and Barnhart (2004) presented integrated models and solution algorithms that simultaneously optimize the selection of flight-legs and the assignment of aircraft-types to the selected flight-legs to maximize revenue and minimise operating-costs.

Wu et al. (2004) discovered and developed a new method based on a Maintenance-free Operating Period (MFOP) in order to reduce the Direct Maintenance Costs (DMC). They illustrated the formula for DMC, and introduced and defined the factors which affect it. Furthermore, they indicated the process of fault-diagnosis. Their ideas are being developed for the A340-600, and a fault-diagnosis expert system has been incorporated in the central maintenance computer-system of the Boeing 777. Moreover, they defined the direct maintenance cost (DMC) as the labour and material costs directly expended in performing the maintenance of an aircraft or related equipment. The factors which have an effect on DMC can be categorized as follows: design-factors, fault-diagnosis efficiency, organization-related variables and environmental-factors.

To optimize the utilization of ground-support vehicles and enhance the logistics of aircraft-maintenance activities, Cheung et al. (2005) proposed a mathematical-model using Generic Algorithms (GA). A generator provides an effective and efficient schedule for the aircraft-maintenance services industry. The model was illustrated with a numerical case-study. The aim of this study was to optimize the utilization of ground-support vehicles; to enhance the logistics of aircraft-maintenance activities; and to solve the scheduling-problem for aircraft-engine maintenance.

Kleeman and Lamont (2005) introduced a Multi-objective Genetic Algorithm (MOGA) for solving the problem of minimizing the time needed to return engines to mission-capable status, and to minimize the associated cost by limiting the number of times an engine has to be taken from the active-inventory for maintenance.

Solving the fleet-assignment problem has always been a challenging task for the airlines. Sherali et al. (2006) presented a tutorial on the basic and enhanced models and approaches that have been developed for the fleet-assignment problem, including their integration with other airline-decision processes such as schedule-design, aircraft-maintenance routing, and crew-scheduling. They proposed solution-techniques that include additional considerations in the traditional fleeting-models. These could consider itinerary-based demand-forecasts and the recapture-effect, as well as investigating the effectiveness of alternative approaches such as randomized search-procedures and studying dynamic fleeting-mechanisms that update the initial fleeting-solutions. Departures-approach and more information regarding demand-patterns are gathered, thus providing a more effective way to match the airline's supply with demand.

Tam et al. (2006) proposed simple models to assist managers of small to medium production-plants to determine the optimal maintenance-intervals for a multi-component system with different managerial requirements, namely maximum reliability, maintenance-budget constraint, and the minimum total cost. The proposed models only required very few input-parameters which can be obtained or estimated easily.

Heavy industry maintenance-facilities at aircraft service-centres or railroad-yards must contend with scheduling Preventive Maintenance tasks to ensure critical equipment remains available. Quan et al. (2007) presented a novel evolutionary algorithm to solve the Preventive Maintenance scheduling-problem, which formulated as a multiple-objective problem.

Addressing the minimisation of total maintenance-cost for a set of identical machines, Khalil et al. (2009) developed a mathematical-model as a combination of Corrective and Preventive Maintenance for scheduling maintenance by optimising the interval between Preventive Maintenance.

2.4 Inventory-control Policy

To keep the aircraft in a serviceable condition, regular checks and repairs are necessary. Some of the repairs and overhaul-work involve parts and components that need to be removed from the plane. This needs accurate inventory-control policy. The repair and replace policy is important to reduce the aircraft-maintenance costs by applying a mathematical-model which helps in making decisions.

Al-Garni (1996) presented two policies for tyre-replacement and evaluated them by using reliability- and cost-parameters in Saudi Arabia. He compared them to the international standard using a reliability-model and cost-data.

2.4.1 Types of Inventory

Ghobbar and Friend (1996) mentioned that there are several types of inventory such as:-

1. Cycle.
2. Safety.
3. Stock.
4. Anticipation.
5. Pipeline.

There are three types of inventory-measures represented by the average of supply, weeks of supply, and inventory-turnover. The authors introduced the results of a simple survey of the Re-order Point System (ROP) in airline-operators and maintenance-service organizations. The survey covered 283 aviation companies, 62% of whom replied and it was supported with tables and figures.

Considering the maintenance of aircraft engine components, Hopp and Kuo (1998) analyzed the multi-component joint-replacement problem for systems with multiple non-safety-critical components, and systems with one safety-critical component and multiple non-safety-critical components. They proposed three heuristic approaches to find a good practical policy.

Numerical tests indicated that the base-interval approach almost always yields the smallest average system maintenance-cost among the three.

Winter et al. (1998) discussed and described a system aimed at enabling British Aerospace Airbus Limited (BAAL) to reduce their fastener-inventory. Constraint satisfaction techniques were used to determine which fasteners are suitable for a particular application, given a body of design-knowledge and an inventory of fasteners. In addition, knowledge-refinement techniques are used to refine the design-knowledge if the domain-expert disagrees with the retrieved-fasteners.

Armstrong and Atkins (1998) introduced the note on joint-optimisation of maintenance and inventory to devise a coordinated age-replacement and spare-ordering policy to operate the system at the lowest possible long-run average-cost rate.

Das and Sarkar (1999) developed a mathematical-model for a discrete production-inventory system with fairly general characteristic. The primary objective of the study was to determine when to perform Preventive Maintenance. The mathematical-model of the system provided a useful tool for deriving the expressions for system performance-measures.

Francis et al. (1999) examined the use of best-practice benchmarking as an approach to performance-improvement in the airline-industry. The case-study draws upon phenomenological evidence from the aircraft-maintenance section of Britannia Airways.

Nechval and Nechval (1999) investigated the effect of risk-estimation on the simplest of inventory-problems. It was shown that when risk-estimation is ignored, stock-levels may be incorrectly compiled and service-levels may be inadequate.

Xie and Ho (1999) showed that time-series models are very suitable for repairable-system analysis for engineering decision-making as illustrated by examples and a comparative study.

Bahrami-G. et al (2000) developed methods and models for determining an optimal replacement-time for equipment that deteriorates with time. The methods and models developed contributed to maintenance decision-making. Results were shown for a case where the equipment time-to-failure has a normal distribution. These results also hold for a Weibull distribution with known shape- and scale-parameters.

Xie et al. (2000) studied the calculation, and investigated the use, of average failure-rate for maintained Weibull-distributed components. The average failure-rate was used as the failure-rate of the exponential model. Tables

Love et al. (2000) proposed the use of a discrete Semi-Markov Decision Process (SMDP) to determine optimal policies. The structure of the decision-model utilized two state-variables (real age, number of failures incurred to date).

Tongshui et al. (2000) presented a control-model of a demand-pulled spare-parts inventory, and conducted a case-study to support the model, which relied on maintenance-information and reliability analysis. The philosophy of the model is to probe into the demand for parts at instalment-status and maintenance-status in order to control parts.

Van Noortwijk (2000) proposed and illustrated a maintenance-model to determine optimal age-replacement repair- and lifecycle-costing policies, which optimally balance both the failure-cost against the preventive-repair cost, and the initial cost against the future cost. The model can be applied to solve decision-problems in maintenance-optimisation and life-cycle costing.

Cassady et al (2001) developed a selective maintenance model for component life length, repair, and replacement decision making by using the Weibull distribution to identify maintenance activities that optimise system reliability while considering operational requirements.

Feng and Xiao (2001) presented a stochastic control-model, illustrated by a numerical example with related figures to show how their analysis works under the stated assumptions, and developed optimal control-rules. The basic model was subsequently extended to consider multiple-fares on each route, time-dependent demands, and booking-control on an extended network.

Jiang et al. (2001) studied a maintenance-model with general repairs and two types of replacement: failure and preventive replacement. The objective was to find the repair/replacement policy minimising the long-run expected average cost per unit time.

Salameh and Ghattas (2001) provided and presented a modification to the traditional lot-size square formulas by incorporating the time required to conduct Preventive Maintenance as a parameter in the solution. This was by using a mathematical-model heuristic solution-procedure supported with a numerical example. The optimum just-in-time inventory buffer level is found by trading off the holding-cost and the shortage-cost such that their sum is the minimum.

Beltran and Krass (2002) presented and analysed the Dynamic Lot Sizing (DLS) version of the inventory-control problem with saleable-returns and concave ordering, holding and disposal costs where demands can be positive and negative and disposal of excess inventory is allowed. The proposed methodology appears to be quite adequate for dealing with realistically-sized problems.

Farrero et al (2002) studied the distribution of failure in a manufacturing system, and then examined the application of an appropriate maintenance-program to increase the reliability of component equipment.

General discussions on maintenance-inventories have been presented by Kennedy et al. (2002). They updated the discussion of maintenance-inventories and a discussion of the future research needed, and gave a method for calculating the optimum re-order point and re-order quantities for maintenance-stores. They suggest using a re-order point equal to the lead-time demand where the cumulative-distribution function is almost nearly. They also studied the impact of aircraft-spares provisioning-decisions on the availability of aircraft.

Cochran and Lewis (2002) developed tools and methods to assess the impact of logistics-support on combat-capability, which was concerned with the impact of aircraft-spares provisioning-decisions on the availability of aircraft. In addition, they confirmed that decisions concerning aircraft-spares support require a rapid response for safety reasons.

Analytical models have proven to provide a quicker response-time than corresponding simulation-models. A case-study demonstrated the improvement in computational accuracy that is achieved by reflecting the impact of small numbers of aircraft on availability-projections.

Mabini and Christer (2002) presented a model for determining stock-levels of repairable items supporting a fleet of commercial aircraft operated by a transportation-company in the Philippines. The items are characterised by infrequent demand, high cost and a hierarchical (or indenture) structure. The system has three re-supply sources of serviceable parts, namely; the in-house repair-shop, the out-house repair-shops, and the suppliers. Non-repairable items are scrapped and replaced with new items on a one-for one basis. The model considers two levels of indenture presented by modules and components. The objective is to minimise the total expected steady-state annual cost of holding inventories and of aircraft delays.

Batchoun et al. (2003) attempted to determine the optimal allocation of aircraft-parts used as spares for the replacement of detective parts on board a departing flight. In order to minimise the cost of delay caused by unexpected failure, Generic Algorithms (GAs) are used to allocate the initial quantity of parts among the airports. The results were very encouraging, showing the good performance of the Generic Algorithms in solving the spares problem and dealing with techniques applicable to predicting spare-parts demand for airline-fleets.

Ghobbar and Friend (2003b) presented a model to airline-operators and other maintenance-service organisations to select the appropriate forecasting method to meet their cyclic demand for parts. The main objectives were to develop a predictive model and analyse the behaviour of different forecasting-methods when dealing with lumpy and uncertain demand. They used a Microsoft Excel spreadsheet as a practical and efficient tool.

Mathew and Kennedy (2003) developed a Net Present Value (NPV) model for the optimal replacement-policy of the entire equipment; the model accommodates a large number of factors such as increasing maintenance-costs due to the aging of equipment, technological change, and inflation.

Lin et al. (2003) integrated the Economic Production Quality (EPQ) models with the joint effects of maintenance policy by inspection and the production system, including raw materials and the cost of operating a single facility in order to minimize the expected total cost for the system. Numerical examples were considered with the relevant data to support the study.

Qian et al. (2003) proposed the extended cumulative-damage model with maintenance at each shock and minimal repair at failure, and replacement at scheduled time T or at N^{th} failure, whichever occurs first. They derived the expected cost, and then discussed the optimal replacement-policy which minimizes it.

Shankar and Sahani (2003) studied the maintenance-float problem as a model to describe both the catastrophic and/or wear-out failures. They made an attempt to study, through some numerical calculations, the effect of wear-out preventive maintenance and repair on the float-factor evaluation.

Braglia et al. (2004) presented and developed a new multi-attribute technique decision-support tool followed by a case-study to define the best strategies for spare-parts inventory management. This could be used by maintenance-managers or staff as an internal structural procedure of the company and adopted as a basic approach to revise and validate the inventory policy used for each type of spare-part in an easy and fast way.

Castro and Alfa (2004) presented two different models of replacement-policy based on the lifetime of the unit. The first approach, named Model I, is to replace the unit by a new one when the unit attains a predetermined lifetime. The other approach, named Model II, is to close the repair-facility when the lifetime of the unit attains a predetermined quantity.

Ghobbar (2004) conducted a study at one of the largest U.K. airline-operators in their component-overhaul workshop to find the best and most accurate forecasting-method on the basis of demand-pattern fluctuation. The experimental results of 13 forecasting-methods, including those used by aviation-companies, were examined and analysed in terms of average mean absolute-percentage error to enable airline inventory-management practitioners to choose a forecasting-method for particular operating-factors.

Juang and Anderson (2004) considered a Bayesian theoretic approach to determine an optimal adaptive Preventive Maintenance policy with minimal repair. By incorporating minimal repair, major repair, planned replacement, un-replacement and periodic scheduled maintenance in the model, the mathematical formulas of the expected cost per unit time are obtained.

Saranga (2004) attempted to use Generic Algorithms for opportunistic maintenance in complex systems. A simple generic algorithm was applied to hypothetical data to test the validity of the model. This paper tries to address the questions of how to decide whether a particular item needs opportunistic maintenance, and if so, how cost-effective the opportunistic maintenance is in comparison to a later grounding. These questions play an important role; especially in the case of complex-systems containing expensive items with hard lives and condition-monitoring maintenance-strategies. Examples with two case-studies were included to support the study.

Sheu and Chien (2004) developed a general model for the average cost per unit time and this is based on the stochastic behaviour of the assumed system and reflects the cost of storing a spare as well as the cost of system-downtime by considering a generalized age-replacement policy of a system subject to shocks with random lead-time.

Zequeira et al. (2004) presented and examined a model to determine the optimal length of continuous production-periods between maintenance-actions, and the buffer-inventories to satisfy demand during Preventive Maintenance or repair manufacturing facility. They analysed the joint-determination by introducing numerical examples with illustrations of different figures such as the relation between the cost-rate and operational time in days as a function of the buffer-inventory in units, the optimal operational-time as a function of the failure-rate, and the optimal buffer-inventory as a function of the failure-rate. As a result they considered that the time to shift to imperfect production has an exponential distribution.

Chelbi and Ait-Kadi (2004) described a joint-strategy of buffer-stock production and preventive maintenance for a randomly-failing production-unit, operating in an environment where repair and preventive maintenance duration are random. The objective is to determine simultaneously the optimal preventive maintenance period T and the size of the buffer-stock S which minimize the total average cost per unit time unit. A mathematical-model has been developed for this strategy. It takes into account the probability-distributions associated with lifetime, repair-time, preventive maintenance duration, as well as the renewal-process associated with the operation repair-cycles of the production unit.

Park and Yoo (2004) compared three types of replacement policy for a group of identical units under minimal repair. The units and group replacement-interval are divided into repair- and waiting-intervals and each unit undergoes minimal repair at failure during the repair-interval. The expected cost-rate expressions under each policy are derived and numerical examples are given to demonstrate the results.

Lee (2005) mentioned that the inventory can be used to protect the manufacturer against the randomness in production, to respond to variable customer-demand, and to keep higher availability of goods to maintain high-quality customer-service. The amount of inventory needed should depend on the safety-stock to protect against the demand-uncertainty and to achieve a high service-level for satisfying customers demand. The inventory problem determines the inventory-level that balances the two extreme cases. Lee developed an analytical cost/benefit model to quantify the effects of investment in preventive maintenance and inventory projects on tangible performance-measures. The model can be solved by an interactive process using the Sequential Quadratic Programming Method.

Voordijk and Meijboom (2005) answered the question as to what the dominant supply-chain co-ordination strategies are in the Dutch aerospace industry, given the market environment of this industry by combining data from case-studies with the four co-ordination strategies proposed by Galbraith: i.e. slack, self-contained tasks, lateral-relations, and number of hierarchical levels. The case-studies show that lateral-relations and information-systems are clearly present.

Destombes et al. (2006) introduced component wear-out in a model for the trade-off between spare-part inventories, repair-capacity, and maintenance policy by using two methods and numerical examples to analyse the relationship between these control-variables and the system-availability.

Kovalyov et al (2006) studied the problem of optimal testing and repairing a failed-series system comprising of n components. The problem is to find a sequence of testing and repairing operations for the components such that the system is always repaired and the total expected cost of testing and repairing the components is minimized. The objective was to minimise the total expected cost of testing and repairing the system.

Ho and Silva (2006) presented the bootstrap to correct biases in a maximum-likelihood estimator of Mean Time to Failure (MTTF) and percentiles in a Weibull regression-model; and introduced a simulation-study to compare and to compute the biases of estimators for MTTF.

Lai and Chen (2006) developed an optimal periodic-replacement policy for a two-unit system, subject to failure-rate interaction between units, by incorporating costs with respect to replacement and minimal repair to minimize expected cost rate per unit time. A numerical example was giving to illustrate the method.

P.Ji and Tsang (2006) developed a preventive replacement model to help maintenance engineers to know whether a system is aged or not, so that they can make a decision on replacement.

2.4.2 Inventory Classification

Ramanathan (2006) asserted that inventory-classification using ABC analysis is one of the most widely-employed techniques in organizations. Normally, the items are classified based on the annual use-value, which is the product of annual-demand and average unit-price:

1. Class A items are relatively few in number and constitute a relatively small use-value.
2. Class C items are relatively large in number but constitute a relatively small amount of annual use-value.
3. Items between the above two classes constitute Class B.

ABC analysis is successful only when the inventory being classified contains items more or less all the same and the main difference among the items is in its annual use-value (computed from unit-price and demand-volume). In practice, an organization of even moderate size has to control thousands of inventory-items and they need not be very homogeneous. As more and more customers demand a wide-range of products, the need to increase the variety of inventory items is also increasing.

Thus, it has been generally recognized that the traditional ABC analysis may not be able to provide a good classification of inventory-items in practice.

Ramanathan proposed and illustrated a weighted linear optimization model for classifying inventory-items in the presence of multiple criteria. The model was similar to linear-programming models employed in data-envelopment analysis. The methodologies were illustrated using an example.

Deshpande and Lyer (2006) used an application of operations-research techniques at the United States Coast Guard (USCG) to improve the performance of its aircraft-service parts supply-chain. They developed a part age-dependent supply-replenishment policy for managing the service-parts supply-chain at the USCG. The impact of this policy was evaluated based on actual-demand data for 41 critical parts over a five-year period.

Saranga and Kumar (2006) developed a mathematical-model for Level of Repair Analysis (LORA), which is an approach used during the design-stage of complex equipment for analysis of the cost-effectiveness of computing maintenance-strategies, and proposed a solution methodology based on Generic Algorithms. The concept was illustrated using a hypothetical aircraft-engine case-study.

Dimitrakos and Kyriakidis (2007) developed an efficient special-purpose policy iteration algorithm that generates a sequence of improving control-limit policies. The study was supported with numerical examples.

Leung et al. (2007) introduced the Carrol-Hung (CH) method, an innovative reliability analysis tool for bridging the industrial practice of Condition Monitoring (CM) alerts and the process of identifying candidates for reliability improvement.

MacDonnell and Clegg (2007) mentioned that there are three major changes which should be taken into account when considering how to manage an airline-fleet: business models, aircraft technology, and supporting information-processing technology to develop a system-strategy for supply-chain management in aerospace maintenance, repair and overhaul (MRO). In general their purpose is to promote the increased use of computer-based systems to automate, communicate, and optimise the business information process in the aircraft-maintenance industry.

Sun and Mathew (2007) developed a new Split-system Model (SSM) using probability theory based on the concept of separating repaired and unrepaired components within a system virtually when modelling the reliability of the system after repairs. A case-study was introduced to show the changes in reliability with preventive maintenance actions, and to quantify preventive maintenance intervals after imperfect repairs.

Lee et al. (2008) presented a multi-objective simulation optimization framework for the aircraft spare-parts allocation problem to provide a non-dominated Pareto set of solutions to the decision-makers. Computational results showed that, for the aircraft spare-parts allocation problem, the framework is capable of finding those non-dominated inventory and replacement policies with low average-cost and high service-levels.

2.4.3 Material Support

Kinninson (2004) wrote that materials are one of the key units within an airline's maintenance-organization that spends the most money. The materials directorate has four management-positions:

2.4.3.1 Inventory Control

Inventory Control is responsible for ensuring that all necessary spare-parts and supplies are available to maintenance facilities throughout the organization. Its purpose is to support all maintenance activities through the maintenance of stock-levels in the right stores and to respond to demand in a timely manner. It is also responsible for the adaptation of the stock-levels as changes in fleet make-up dictate.

2.4.3.2 Stores

Stores are responsible for issuing and exchanging parts with the engineers. Stores are also responsible for the delivery of parts to the work-centres, and where appropriate, to ensure that supplies of any spare-parts which require special storage and handling are properly managed. The unit also stores the details of the appropriate methods of replacing parts for the maintenance-shop.

2.4.3.3 Purchasing

Purchasing/Procurement is responsible for the purchase of all spare-parts and supplies used by maintenance. Its main duty is to deal with suppliers and manufacturers, attending to matters such as specifications, cost and delivery. It purchases materials and exercises major control over the financial budget.

2.4.3.4 Shipping and Receiving

Shipping and Receiving will handle all packing and unpacking of parts and supplies being shipped into and out of the airline.

2.4.4 The Inventory-support Functions

The inventory-support functions can be stated briefly as:

2.4.4.1 Ordering

The initial role of ordering includes the provision of new equipment, when the systems become part of the fleet. It also includes re-ordering of supplies on hand whenever they drop below a certain level. It has to provide the equipment on the recommended spare-parts list prepared by the aircraft-manufacturer. This list is based on the manufacturer's recommendations and the vast experience of the fleet of airlines that are already using such equipment in similar operations. The quantity necessary for day-to-day operations is determined by a number of variables, and these vary from one process to another. For example, the schedule of flights and number of hours has flown the length of the journeys and the environment, as well as the number of aircraft in the fleet, the rate of use of components, and therefore the number of parts necessary for the support and maintenance of operations.

2.4.4.2 Storing

The storing of parts is the next materials function to consider. There are two categories:

i. putting every part where it can be readily located and issued when needed.

ii. Storing certain parts under specified conditions. The latter category includes proper storage of fuels, lubricants, paints, oils, and other flammable or perishable items. Oxygen-bottles and the tools used on oxygen-systems require special handling and storage.

2.4.4.3 Issuing

Items such as screws, nuts, and other regularly-used parts and equipment are best stored in the open, and should be stored near the work-sites for the engineers to access them easily. It would be better for all parties involved to be able to request the physical and mechanical parts, as needed, and to attend to, and deal with, the proper parts and other important milestones such as the computer- and paper-work.

2.4.4.4 Controlling

Control of the parts covers a variety of activities which are required to follow up the flying-hours, flight-cycles and calendar. There are a number of systems which require the removal of parts of the service before a specified interval has elapsed.

2.4.4.5 Handling of Parts and supplies

Dealing with parts and supplies is sometimes referred to as "shipping and receiving". Dealing with the receipt of parts and supplies involves, in some cases, incoming inspection and quality-control to ensure that it is correct, allocating a serial number if necessary, recording the situation and the service and the expiration date. After receipt and inspection of incoming supplies, they are distributed to stores around the hangar to the right place, e.g. the maintenance-line and work-shops, and computer records are updated accordingly.

2.5 Reliability

Cini and Griffith (1999) reported that reliability provides source-data for systems safety-analysis. Nakagawa and Hua (2002) mentioned that the system-reliability can be improved by redundancy of units. Kinnison (2004) reported that there are two approaches to the concept of reliability in the aviation industry:

1. The first approach is to look at the overall airline-reliability. This is measured essentially by dispatch-reliability: that is, by how often the airline achieves an on-time departure of its scheduled flights.
2. The second approach is to consider reliability as a program specifically designed to address the problems of maintenance, which provides analysis of, and corrective actions for, items to improve the overall reliability of the equipment.

Xie and Ho (1999) indicated that repairable-system reliability analysis enables us to obtain information such as whether to continue the test-modify cycle, terminate the operation, or replace the system. The objective of repairable-system failure data-analysis is to describe the failure phenomenon. This is usually done by fitting the failure data with an appropriate model such as the Duane model.

A non-repairable system can only fail once, and a lifetime model such as the Weibull distribution can be used to predict the time at which such a system fails. On the other hand, since, for a repairable system, the failed items are repaired and placed back in service, which is the case of maintenance engineering, the model chosen must allow for a sequence of repeated failures, and it must be capable of reflecting changes in reliability as the system ages.

A repairable system can be characterized in two ways, either by a counting process or in terms of successive failure-times of the items.

2.5.1 Types of Reliability

Kinnison (2004) reported that there are four types of reliability related to maintenance activity:

1. Statistical reliability.
2. Historical reliability.
3. Event-oriented reliability.
4. Dispatch reliability.

2.5.2 Elements of a Reliability Program

Kinnison (2004) mentioned that a good reliability programme consists of seven elements:

1. Data-collection.
2. Problem-area alerting.
3. Data-display.
4. Data-analysis.
5. Corrective actions.
6. Follow-up analysis.
7. Monthly report.

Xie and Goh (2000), and Tam et al. (2006) mentioned that the Weibull distribution was invented by Waloddi Weibull in 1937, and the reliability function is given by:

$$R(t)=\exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]$$

Where:

t is the time.

β Is the shape-parameter.

η Is the characteristic life.

Crocker (1999) mentioned that if failures are age–related, usually as a result of wear or accumulated stress, then the Mean Time between Failures (MTBF) for the component will decrease as the number of times the component is repaired increases. Many components subject to wear show that their times-to-failure can be described by a Weibull Distribution. Ho and Silva (2006) indicated that the Weibull distribution is often used to model failure-times in engineering. Its hazard function can assume different shapes and this property makes this probabilistic distribution attractive to be employed to model failure-times of equipment. Furthermore, Kong and Goh (2000) showed that the Weibull distribution is usually a better model for component life-time.

Rishel and Christy (1996) mentioned that the shape-parameter for the Weibull distribution indicates the type of failure-rate characterizing each machine. A shape-parameter equal to 1.0 indicates that the machine experiences a constant-rate failure. If the Weibull distribution is characterized by a shape-parameter less than 1.0, the machine experiences a declining rate of failures with the highest probability for failure occurring early in the machine's life. This probability of failure declines as the machine ages. Alternatively, a shape-parameter greater than 1.0 indicates that the machine has an increasing failure-rate.

2.6 Key finding summary and Conclusions

Table 2.3 shows the key findings in the previous literature review stating the problem(s) covered as well as the methods employed to solve the problem in the mentioned references.

Table 2.3 Literature review key findings for aircraft maintenance.

No.	Author	Year	Issue or Problem	Method
Aircraft Maintenance				
1	Al-Sultan and Duffuaa	1995	Maintenance control.	Artificial neural-network model.
2	Goh and Lim	1996	Re-work rate and repair turn-time.	Total Quality Management approach.
3	Shhyur et al	1996	Prediction of the residual life.	Artificial neural-network model.
4	Suyitno and Sutarmadji	1997	How to operate the aging aircraft safely.	Corrosion Prevention and control programme.
5	Goranson	1997	Fatigue-damage detection.	Damage-tolerance technology.
6	Rausand	1998	Reduce the maintenance cost.	Reliability-centred maintenance.
7	Labib et al.	1998	Maintenance decision making.	Analytic hierarchy process.
8	Peck et al.	1998	Aircraft maintenance.	Data envelopment analysis.
9	Talluri	1998	Maintenance –routing problem.	Line-of-flight graph.
10	Mckone et al	1999	The use of total productive maintenance.	Proposed a theoretical framework.
11	Knots	1999	Evaluate the maintenance-activity times.	Expert-system.
12	Mcfadden and Towell	1999	Human factors in aviation safety.	Survey.
13	Kraus and Gramopadhye	1999	Team skills-training.	Computer-based multimedia tool.
14	Anderson and Rasumussen	1999	Maintenance-decision support.	Modelling approach.
15	Bevilacqua and Braglia	2000	Selecting the best maintenance-strategy.	Analytic Hierarchy Process.
16	Daviston and Labib	2003	The best decision-making.	Analytic Hierarchy Process.
17	Salamanca and Quiroz	2005	Evaluate the economic life aircraft-structure.	Commercial reliability-software.
18	Jayakumar and Asgarpoor	2006	Concept of minor and major preventive maintenance.	Markov processes.
19	Bertolini and Bevlacqua	2006	The selection of maintenance-strategies.	Goal-programming approach.
20	Witek	2006	Investigate the damage-mechanism of the turbine-disk.	Geometrically-complicated finite element model.

No.	Author	Year	Issue or Problem	Method
Maintenance Scheduling				
21	Clarke	1996	Fleet-assignment problem.	Modelling-devices.
22	Susova and Petrov	1997	Minimise operating-costs.	Markov model-based reliability.
23	Gatland et al	1997	Availability capacity of the engine-maintenance facility.	Simulation model.
24	Knapp and Mahajan	1998	Optimising manpower-allocation.	Mathematical model.
25	Alfares	1999	Aircraft-maintenance workforce-scheduling.	Integer programming-formulation.
26	Lofsten	1999	Preventive maintenance scheduling.	Non-linear programming model.
27	Lettovesky	2000	Find a minimal-cost reassignment of aircraft and crews.	New solution-framework.
28	Gupta et al	2003	Aircraft line-maintenance.	Computerised simulation-model.
29	Lohatepanont and Barnhart	2004	Airline-schedule planning	Integrated and algorithms models
30	Wu et al.	2004	Reduce the direct maintenance costs.	Maintenance-free operating period.
31	Cheung et al.	2005	Optimize the utilization of ground-support	Mathematical-model using Generic Algorithms (GA).
32	Kleeman and Lamont	2005	Aircraft engine maintenance scheduling.	Multi objective evolutionary algorithm.
33	Quant et al.	2007	Preventive maintenance scheduling.	Novel evolutionary algorithm
34	Khalil et al.	2009	Minimisation of the total maintenance-cost	Mathematical-model
Inventory control policy				
35	Das and Sarkar	1999	Discrete production-inventory.	Mathematical-model.
36	Love et al.	2000	Determine optimal policies.	Semi-Markov Decision Process.
37	Van Noortwijk	2000	Determine optimal age=replacement repair.	Maintenance-model.
38	Mabini and Christer	2002	Determine stock-levels of repairable items.	Mathematical-model.
39	Batchoun et al	2003	Determine the optimal allocation of aircraft-parts.	Generic Algorithms (Gas).
40	Mathew and Kennedy	2003	Optimal replacement-policy.	Net Present Value (NPV) model.
41	p.Ji and Tsang	2006	A system is aged or not	Preventive replacement model.
42	Lee et al.	2008	Aircraft spare-parts allocation.	A multi-objective simulation.

Based on the literature review and above mentioned literature review analysis. The following facts can be drawn:

1. In aviation industry, there is a need for a maintenance-management system that can be used to provide the optimum interval at which maintenance should be carried out.
2. Also, it was very unusual to find an inventory policy that balanced the cost of repair and purchase in making decisions, in particular for expensive components.
3. Moreover, the literature review provided no availability of an integrated framework to integrate the above two problems in an aircraft environment. It is expected that this will provide a decision-making tool by which the cost incurred in maintenance and inventory, as well as the time needed for maintenance, will be reduced. Therefore, the above three points represent the main aim and objectives of this thesis.

In this chapter, the researcher introduced the literature review which included three sections as follows:

- Aircraft maintenance.
- Scheduling maintenance.
- Inventory.

The literature review in this chapter provided and introduced different models such as simulation, linear-programming, integer-programming, mathematical-programming, heuristics and algorithms-programming to solve different problems related to the subject of the thesis. In the next chapter, the proposed methodologies to be used in this research will be discussed and introduced.

Chapter Three

Research Methodologies and Proposed Integrated Framework

3.1 Introduction

The problems associated with maintenance and inventory control policy in the aviation industry were introduced in the literature review in Chapter Two. Many approaches are available for maintenance-scheduling and inventory control policy problems. Most of these approaches are operation-research management-science techniques. The choice of which approach to use depends on the scope of the problem, i.e. the objectives, constraints and type of data available.

Duffuaa and Al-Sultan **(1997)** summarized these approaches as: Deterministic Optimization Techniques, Markov Decision Theory, PERT, Game Theory, Queuing, Simulation, Inventory Models, Reliability Theory and Decision Theory, Work Study and Analytical Hierarchy Process. They have added stochastic programming with a certain objective in mind, and when a set of constraints are given.

In brief, some approaches introduced in this field exist in the literature review in Chapter Two such as: Susova and Petrove (1997) used Markov model-based reliability and safety evaluation for aircraft-maintenance system-optimisation. Gupta et al. (1997) used computerised-simulation maintenance for aircraft line-maintenance planning in Continental Airlines. Gatland et al. (1997) solved engine-maintenance capacity problems with simulation. Labib et al. (1998) used an Analytical Hierarchy Process (AHP) model as a maintenance decision-making tool. Alfares (1999) used integer program formulation to obtain an optimum seven-day work-schedule with no increase in workforce-size. Artana and Ishida (2002) used spreadsheet-modelling of optimal maintenance-scheduling for components in the wear-out phase.

Lohatepanont and Barnhart (2004) used integrated and algorithms models for schedule-design and fleet-assignment. Cheang et al. (2005) developed an aircraft-service scheduling model by using generic algorithms to maximise the utilisation of ground-support vehicles and enhance the logistics of aircraft-maintenance activities. Jayakumar and Asgarpoor (2006) used linear-programming for maintenance-optimisation of equipment. Bertolini and Bevilacqua (2006) used a combined goal-programming - AHP approach to the maintenance selection problem. Linear-programming deals with only one single objective to be minimized or maximized, and subject to some constraint; it, therefore, has limitations in solving a problem with multiple-objectives. Goal-programming, instead, can be used as an effective approach to handle a decision concerning multiple and conflicting goals.

The life-limit of all aircraft components follows the manufacturer's recommendation, and because there are different operating conditions in different countries, this may lead to a change in the life-limit for different reasons such as:

The weather: for example (Libya) is a desert country, that means the aircraft and its systems and components are subject to high temperature. Also there are the effects of dust on the oil and fuel systems and components like engines, pumps and joints which use lubrication for their movement. Another airport is near to the Mediterranean Sea where an aircraft and its systems and components are subject to high humidity and salinity or brininess. This causes corrosion and has a big impact on the life of an aircraft and its systems and components. From the author's experience of more ten years in Libyan Arab Airlines in technical management, there were a percentage of repairable components which failed earlier or technical problems happening before parts reached the end of their expected life-time.

For the reasons explained previously, the author focuses on how to calculate and minimise the maintenance-cost by using a mathematical-model to determine the new life-limit that helps to avoid technical problems and early failure by optimising the interval for maintaining the different components in the aircraft.

The components may difficult to repair in-house out-house or its high cost, which may lead to purchasing a new components. This situation is not considered at the moment in Libyan Arab Airlines. Also, the repair-price was high and greater than the cost of purchasing new components. For this reason the author focuses on how to solve that problem in this study. Table 3.1 shows the comparison between the component-price and the real repair-cost data taken from Libyan Arab Airlines.

Table 3.1 Real Purchase and Repair-costs for Some Components (Libyan Arab Airlines C.).

Component Name	Part Number	Purchase Cost (£)	Repair Cost (£)	Year
Fuel Pump	24361	16120	18500.8	2004
Pressurising and Pump Valve	714810	1860	1968.5	2004
Fuel Heater	522649	3100	900.24	2001
Fuel Control Unit (FCU)	720050	15500	16740	2003
Ignition Unit	42074	2480	2449	2004
Starter Valve	979078	1860	4299.7	2000
Starter	383152-16-1	6820	11780	2003
Refuelling Isolation Valve	6562	4340	5115	2004

In this study two mathematical-programming approaches are utilised to determine the optimal solution for maintenance-scheduling and inventory-control policy in the aviation industry.

The models will be developed on the principle that the objective of any maintenance and inventory problem is to balance the cost with an optimal time to perform a repair or replace the components, to minimise the excessive costs and guarantee safety.

This Chapter will introduce and explain the two main subjects related to study, which are optimisation and mathematical models, and proposed operational framework.

3.2 Optimization

In mathematics, the term optimization, or mathematical-programming, refers to the study of problems which seeks to minimize or maximize a real function by systematically choosing the values of real or integer variables from within an allowed set.

Optimisation problems consist of the following three basic components:

1. An objective function to maximize or to minimize. For example, in the manufacturing process, we might want to maximize the profit or reduce cost. The installation of empirical data to the user-defined model may reduce the total deviations of the observed data from the model predictions.
2. The variables could include using different amounts of resources or time spent on each activity. In the installation of data problems, unknowns are determined by the parameters of the model. Working on the design problem, variables are used to determine the form and dimensions of the design-team.
3. A set of restrictions that will allow for unknowns to take certain values, but excluding others. Working on the design-problem, we would probably limit the weight of the product and this constitutes a form of constraint.

Thus, the optimisation problem is to find the values of the variables to minimize or maximize the objective function with the fulfilment of the restrictions.

3.2.1 Objective Function

Almost all optimization problems have one objective, which is to function.

- The goal. In some cases, for example in the graphic design of integrated circuits, the goal is to find a set of variables that satisfy the constraints of the model. This type of problem is usually called the feasibility of the problem.
- Multiple-objective tasks. In many cases, it would be helpful to use the maximum number of different objectives at the same time. For example, in the aircraft-design problem, it would be nice to reduce weight and achieve maximum power at the same time. Usually, different objectives are not compatible; variables to achieve the optimum goal may be far from optimal for other objectives. In practice, problems with multiple-objectives may require the reformulation or replacement of some goals before deciding on any of a range of different objectives.

3.2.2 Variables

These are essential. If there are no changes we cannot determine the purpose and function of the problem and constraints.

3.2.3 Constraints

In fact, the field of unrestricted improvement is a large and important one for many of the algorithms and software available. In practice, the logical answers in terms of the underlying physical or economic problem can often be obtained without restrictions on the variables.

Here are some examples of using optimisation. Rushmeier and Kontogiorgis (1997) presented an advanced model in the optimisation of airline-fleet assignment. Knapp and Mahajan (1998) developed a model for optimising labour-allocation by maintenance-area, craft-type, training-level and in-house versus sub-contracted employees. Stojkovic et al. (2002) proposed an optimisation model for a real-time flight-scheduling problem.

3.3 Mathematical Models

Al-sultan and Duffuaa (1997) used mathematical-programming models to develop a plan while considering the objective and constraints at the same time. Kraus and Gramopadhye (1999) asserted that the decision-making sub-module has three main topic areas: The first area is problem-identification, the second area is the generation of ideas, and the third area is decision-making tools. Labib et al. (1998) mentioned that mathematical-models have been formulated for many typical situations. These models can be useful in answering questions such as:

- How much maintenance should be done on the item?
- How frequently should this item be replaced?
- How many spares should be scheduled?

Taha (2003) showed that a cornerstone of operation research (OR) is the mathematical model, which provides a basis for making decisions (MD) and indicated that to solve the decision making problem we have to identify the following three steps:

1. **Definition of the Problem**

This involves defining the scope of the problem under investigation. The end-result of the investigation is to identify three principal elements of the decision problem namely:

- Description of the decision-alternatives.
- Determination of the objective of the study.

- Specification of the limitations under which the modelled system operates.

2. Construction of the Model

This entails translating the problem-definition into mathematical relationships.

3. Solution of the Model

An important aspect of the model-solution is sensitivity-analysis. This deals with obtaining additional information about the behaviour of the optimum solution when the model undergoes some parameter-changes. Sensitivity-analysis is particularly needed when the parameters of the model cannot be estimated.

4. Validation of the Model

This checks whether or not the proposed model does what it is supposed to do, that is:

- Does the model predict adequately the behaviour of the system under study?
- Dose the solution make sense?
- Are the results acceptable?

A common method for checking the validity of model is to compare its output with the historical data.

The model is valid if, under similar input-conditions, it reproduces past performance.

5. Implementation of the Solution

The implementation of a validated model involves the translation of the results into an operating construction.

In maintenance-optimization, a huge number of maintenance-optimization models have been published and many of the articles were written by statisticians and scientists in operation-research. A general problem with most of the models is that the necessary input-data is not often available or not in the format required by the models.

Many authors reported that different mathematical-programming were used in maintenance-modelling such as: Linear-programming, Integer-programming, Quadratic-programming, Non-linear- programming, and Stochastic-programming.

Al-Sultan and Duffuaa (1995) considered the maintenance-control system proposed by mathematical-programming; and Duffuaa and Al-sultan (1997) discussed the problem of scheduling and planning maintenance.

3.4 The proposed methodologies:-

It has been found that mathematical-programming is the most suitable tool to model and solve the problems under investigation due to its ability to provide the optimum solution not like heuristics which may provide near optimum solution or not like simulation which offers alternative solutions to choose from. In addition, mathematical programming was chosen due to the nature of the problems under investigation which are most suits to the use of mathematics in terms of obvious objectives and clear variables and constraints with less complexity problems than those required simulation tool as a method to handle not only the complexity involved but also the interaction between variables. The problems considered to be solved in this thesis are maintenance-scheduling and inventory-control policies as well as their integration.

3.4.1 Maintenance-scheduling

A mathematical model for maintenance-scheduling tasks will be developed. The total maintenance-cost is based on a balance between the costs of failure of a component (corrective maintenance) during operation and the cost of planned maintenance (preventive maintenance). This can be considered as a distinctive feature of an optimal replacement-policy. The proposed model will provide an optimum interval at which the preventive maintenance should be carried out.

3.4.2 Inventory

A decision-making process represented by a mathematical-model of an inventory will be developed, which strives for the best balance between the cost of repair and the cost of replacing a new item on an aircraft. The objective is to minimise the total expected maintenance-cost.

3.5 Proposed Integrated Framework

Khalil et al. (2009) mentioned that a key question for researchers and practitioners concerned about preventive maintenance is what is the optimum preventive maintenance interval? In reality, many parameters affect the intervals, such as correction and prevention costs. In fact, intervals that are too long or too short, or include no preventive maintenance, would all be costly.

- Intervals which are too long would result in both inconveniences, as they will involve preventive maintenance actions and lead to uncontrolled breakdowns.
- Intervals which are too short would lead to greater prevention costs than needed

- No preventive maintenance would lead to breakdown, which would affect the operation of the aircraft and might lead to a tragedy.

3.5.1 Information

There are five kinds of information which should be combined in the Technical Planning Department to determine and prepare the list of all items or components that should be removed from the aircraft in the next maintenance-check. The sources of this information are:

1. The Logbook: this is the crew-book on the aircraft that follows the flying hours and the technical problems which occurred during the flight and is completed by the aircraft crew.
2. MCC is the Maintenance Control Centre that coordinates all maintenance-work with other departments such as engineering, planning, warehouse and maintenance.
3. COASL means Component Operating and Storage Limit, which is issued by the aircraft-manufacturer and gives information relating to repairable components such as: part number, denomination, the repair-intervals and storage limit.
4. The warehouse is responsible for the availability of all kinds of repairable and consumable parts and items for all the aircraft fleet.
5. The Hangar provides the information about the available space, personnel, facilities and tools.

In addition, the technical planning deals with the day-to-day activities of maintenance, which involves daily, 48-hours, and transit checks. The technical planning deals with the latter checks and modifications due to airworthiness-directives, service-bulletins, and engineering-orders; it also involves the planning and scheduling of all aspects of these checks including labour, parts, and facilities. Coordination with the warehouse is an important task to provide all that the aircraft need for different checks and services by following and determining the life-limit for the repairable components.

The decision to remove any component on the aircraft for the maintenance process is usually made by the Planning Department.

The movement of components has four main activity-locations:

1. The Planning Department follows all repairable components on the aircraft by using the COASL; all the life-limits of the components are checked by flying-hours and cycles. The team of engineers in the Technical Planning Department prepare the list including any repairable component which is due for a coming maintenance check according to its life-limit. The list moves to the store before the check-time to provide the hangar with the spare-parts on check-time.
2. The removal from an aircraft of failed components or the components which have reached their life-limit occurs at the hangar during any regular maintenance-check or sometimes during the line-maintenance.
3. A defective component that has been removed from an aircraft in the hangar will be sent to the in-house repair shop e.g. engine-shop, sheet-metal shop, cable-shop, or avionic-shop for inspection and possible repair. Some components may require special repair-services beyond the capability of in-house repair. They will be sent to the appropriate out-house repair-shop. A failed component is found to be in one of three states:
    - In-house repairable.
    - Out-house repairable or
    - Non-repairable.

Non-repairable components will be scrapped.

4. The warehouse (store) is responsible for the availability and supply of what the aircraft-maintenance needs in terms of different equipment and parts and components. The part is back-ordered if not available. Mabini and Christer, (2002) reported that any aviation company requires at least a 96% service-level on requisition at the store: this means that the probability that a component can be supplied on demand must not be lower than 0.96. The repair or purchase of a new item will be decided after the removal inspection and the condition of any repairable item has been tested.

3.5.2. Components-list Preparation

This section introduces the components that must be removed from the aircraft when they arrive at their life-limit for maintenance, and may be need to be replaced or repaired for a continuing life-cycle on the aircraft.

3.5.3 Mathematical-models

In this section, the author will present and develop the two mathematical models for maintenance-scheduling and inventory-control policy which deal with the different components that will be valid for any system on the aircraft.

3.5.4 Integration

The two mathematical-models concerning the maintenance-scheduling and inventory will be combined and integrated. Because of the complex and very long calculation for both models and to give the reader information easily, the author will develop the software programme by using the Visual Basic 6.0 version that includes many facilities. It is considered a positive and constructive tool for calculating and it has an excellent output-show.

3.5.5 Output

The output and integration results will be obtained from implementation of the Visual Basic software program directly or as reports issued by an integrated-database program.

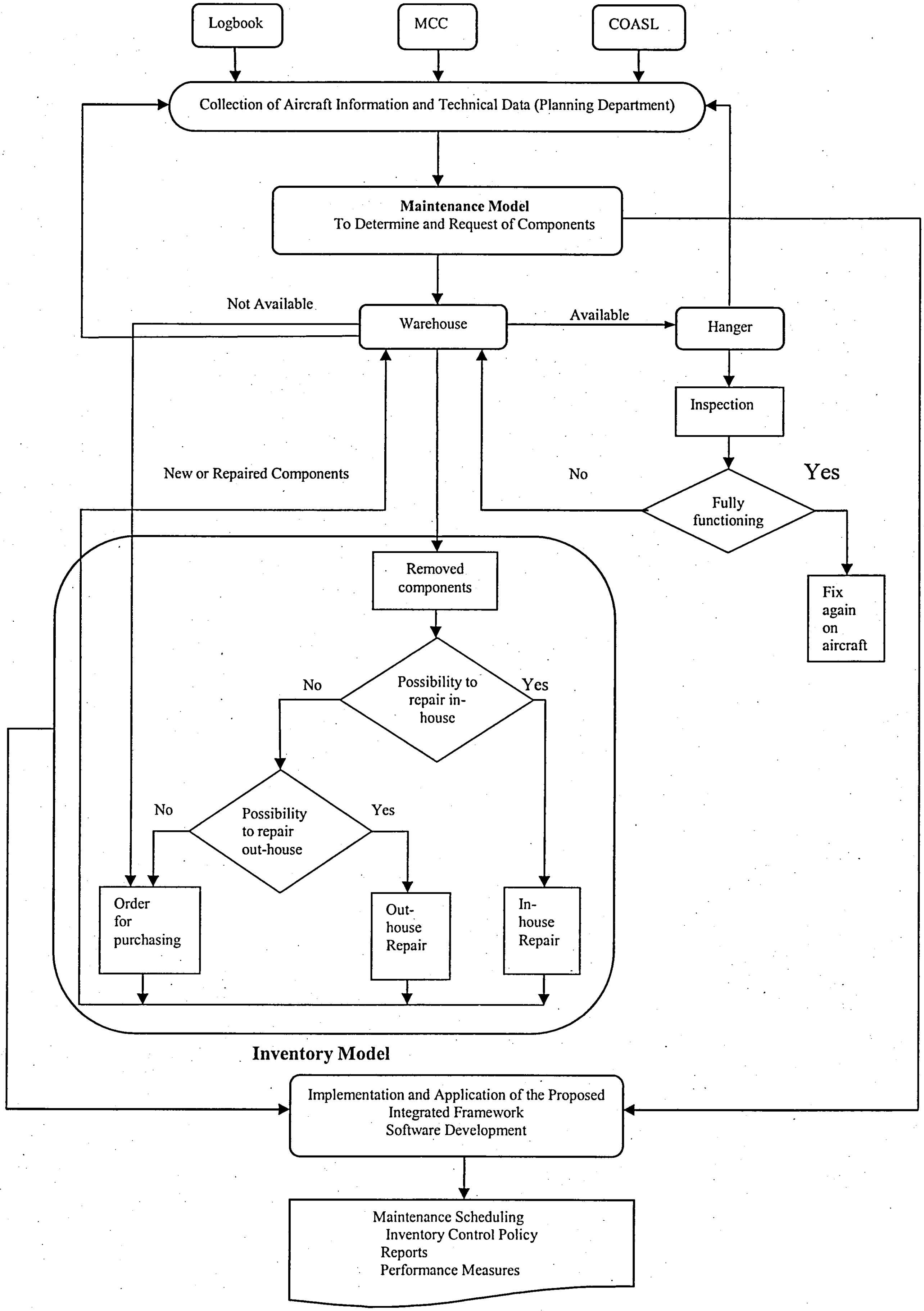

Figure 3.1 Operational framework

3.6 Conclusions

The methodology is based on two instruments. Firstly, the nature of the problems under investigation proved that mathematical-programming is a suitable application. Secondly, it was decided to utilise optimization in order to calculate the optimum interval or range within which the maintenance-task should be carried out to minimize the maintenance-cost. Furthermore, these instruments were used to solve the decision on inventory-control policy for determining the balance point to repair or replace any item on the aircraft in order to minimize the total maintenance cost.

In the next two Chapters, Four and Five, the two decision-making models related to the maintenance scheduling and inventory control policy will be developed. The two proposed mathematical models will be applied and calculations will be carried out manually to demonstrate the application of the models.

Chapter Four

Development of the Proposed Mathematical Model for Decision-making in Maintenance-scheduling

4.1 Introduction

Chapter Three discussed the methodology and the framework of the thesis, which focuses on the use of mathematical models in aircraft-maintenance management. In the literature review in Chapter Two, it was stated that Khalil et al. (2009) developed a mathematical model of maintenance-scheduling as a decision-support model to minimise maintenance-costs in industry. They emphasised the interval of preventive maintenance as being the focus of attention for the maintenance-modeller. The critical parameter of scheduled maintenance is the interval. The application of scheduled maintenance-intervals should serve to minimise the occurrence of repair-breakdowns between intervals. Therefore, the need is for an optimisation technique which identifies the optimum time-interval of preventive actions in respect of the safety of the aircraft; but the level of fault-prevention is also a critical point to consider before the development of a preventive maintenance system.

In this chapter the mathematical model mentioned in the previous chapter will be used and applied in the aviation industry instead of industry field without compromising the safety. The mathematical model will be developed to identify the optimum interval at which a part should be maintained. The balance of the costs of failure of the component for aircraft-operation, taking into consideration safety as the highest priority, versus the cost of planned maintenance is the main feature of the proposed model. This chapter will be divided into two parts:

- Proposed mathematical model for maintenance-scheduling.
- Case-studies and manual calculation.

4.2 Proposed Decision-making Model for Maintenance

Khalil et al. (2009) mentioned that the cost of different types of maintenance can be evaluated by considering changes in the value of the actuation-time. If the actuation-time is increased, preventive tasks are carried out with less frequency and the level of preventive maintenance is lower. As a result the costs associated with preventive maintenance (PM) and actuation-time will decrease as the intervals between scheduled PM increases. However, the increase in the actuation-time also increases the probability of failure in a component and therefore the relative level of corrective maintenance will grow.

Therefore, the costs associated with corrective maintenance increases with the increasing actuation time, while the costs associated with preventive maintenance decrease with the increasing actuation-time. There should be an optimum value for the time of actuation, that is, a combination of preventive maintenance and corrective maintenance, at which the total cost of maintenance, has a minimum value. Within the following section the development of the proposed cost function will be discussed.

4.2.1 Objective Function

The objective function is a formula that expresses exactly what the optimization is. In this part of study the total maintenance cost of an aircraft will be optimized. Then, the objective function is to minimize the total maintenance cost.

$$\text{Min.} \sum_{i=1}^{n} T_{mc}$$

Where

n Number of aircraft repairable-components

4.2.2 Variables

Variables are called decisions and through the study of the available literature that discusses maintenance-optimisation models, a list of the most relevant variables that affect the total maintenance operation cost were identified and the different maintenance-parameters were reviewed. A key point for the success of any mathematical model in reflecting reality is its validity. The validity of a model consists of its accuracy in reflecting reality. The model presented in this research is composed of time, probabilities of failure and survival, and costs of correction and prevention.

The variables in the first model that concerned maintenance-scheduling are presented in table 4.1, where three groups of factors are identified.

1. The probabilities of failure and survival of the component at a given point in time.
2. The time spent by maintenance personnel in carrying out corrective and preventive actions.
3. The absolute costs of carrying out corrective and preventive actions for the same component.

Table 4.1 Maintenance-scheduling Variables

Notation	Description	Unit
	Probability	
P_f	The probability of failure.	
P_s	The probability of survival.	
	Time	
C_t	The time spent by maintenance personnel in carrying out a corrective action.	Flying hour
P_t	The time spent by maintenance personnel in carrying out a preventive action.	Flying hour
T	Time (Interval by flying hours).	Flying hour
	Cost	
S_c	Spare-part cost.	£
C_f	Cost of failure.	£
C_p	Cost of failure-prevention.	£
I_{lc}	The maintenance (in-house labour) cost.	£/h
D_c	Delay cost.	£/h
C_{mc}	Corrective Maintenance Cost.	£/h
P_{mc}	Preventive Maintenance Cost.	£/h
T_{mc}	Total Maintenance Cost.	£/h

4.2.3 Cost-variables Identification

To calculate the total maintenance cost, there is a group of factors to be considered in the calculation. The key factors are identified as follows:

4.2.3.1 The Identification of the Intervals of Major Aircraft Maintenance-checks (T)

The time-interval depends on the type of maintenance-checks (A, B, C, and D) as mentioned in Chapter Two, Section 2.2.4. Let us consider that we carry out the type 'B' check. Kimonos (2004) reported that an airline takes on average 300 flying hours before entering an aircraft to the hangar and this is considered as a removal time for components. This is considered because, once the optimal time-interval for carrying out the maintenance of a particular part is identified, a group of such similar parts which need maintenance at similar intervals are identified and, depending on those intervals, the maintenance scheduling of those parts would be economical.

T Optimum is $\in$ {300, 600, 900, 1200, 1500, 1800 ...}........................ (4.1)

Where 300 flying-hours is the average for doing the B maintenance regular check or once every month whichever comes first. This is the recommendation from ATA.

4.2.3.2 The Identification of the Distribution of the Probability of Failure against Time

In order to calculate the probability of a failure before a certain time using statistical tables, the distribution must first be converted to the standard normal distribution. The formula for conversion of any normal distribution to the standard distribution is as follows:

$$Z = \frac{T-\mu}{\sigma} \quad \text{...} (4.2)$$

Where:

Z	Is the parameter of the standard normal distribution.
T	Is the parameter at which the probability is aimed to be calculated.
μ	Is the distribution mean.
σ	Is the distribution standard deviation.

All the Normal Distribution Functions are dependent mainly on:

1. The Mean of the Distribution represented by the component life-time (μ).
2. The Standard Deviation of the Distribution (σ).
3. The real parameter at which the probability is aimed to be calculated (T).

In order to predict the failure of the component, probability will be used in these cases and there are many available probability-distributions. The normal distribution is the most commonly used. The principle reasons are:

1. Normality is important in statistical implication.
2. Normality arises naturally in many physical, biological and social measurement situations.

The actual normal probability distribution $f(x)$ is given by the formula:

$$f(x) = \frac{1}{\sigma .\sqrt{2.\pi}} .e^{-\frac{(1-\mu)^2}{2\sigma^2}} \quad \text{...} (4.3)$$

Where the value of $\sigma = 1$, and $f(x)$ represent the probability of failure P_f

4.2.3.3 The Corrective Maintenance Cost

The cost of corrective action involves finding the defect location, disassembly, replacement, reassembly, alignment/adjustment, and testing. In this case, the only costs that should be considered are the cost of spare parts and the delay costs, i.e.:

1. Cost of spare parts (S_c).
2. Delay costs (D_c), because the aircraft does not operate while the problem is being corrected (C_t).

Then, the total cost of corrective action is:-

$$C_f = S_c + (D_c \times C_t) \quad (4.4)$$

Then the cost of corrective maintenance will be calculated as a result of multiplying the cost of failure by the probability of failure as in the following equation:

$$C_{mc} = C_f \times P_f \quad (4.5)$$

4.2.3.4 The Preventive Maintenance Cost

As mentioned in the earlier chapters, preventive maintenance in an aircraft environment is carried out at regular intervals by doing the systematic inspection, detection and replacement of worn-out items, adjustment, calibration and cleaning as the major tasks.

Hence the cost of this type of maintenance involves the cost of the spare parts and the cost of the maintenance labour involved i.e.:

1. Cost of spare parts (S_c).

2. The maintenance in-house labour cost per hour (I_{lc}) during the time to carry out a preventive task (P_t).

Then, the total cost of preventive action is:-

$$C_p = S_c + (I_{lc} \times P_t) \quad \text{.......... (4.6)}$$

Then the cost of preventive maintenance will be calculated as a result of multiplying the cost of failure-prevention by the probability of survival as in the following equation:

$$P_{mc} = C_p \times P_s \quad \text{.......... (4.7)}$$

4.2.3.5 Total Maintenance Cost

The mathematical formulation that continuously calculates the total cost of maintenance for a system component at successive intervals of time is Khalil et al (2009):-

$$T_{mc} = \frac{C_f \times P_f + C_p \times (1 - P_f)}{T \times (1 - P_f)} \quad \text{.......... (4.8)}$$

The numerator consists of:

The first term is the risk of failure, and the cost of failure is constant, but the whole risk increases with time, as the probability of failure increases.

The second term is a financial expression of prevention, which is the product of the cost of prevention by the probability of a non-failure (probability of survival of the component). Again, the cost of prevention is constant, but the term decreases with time, as an early prevention costs more than a late check, (if the cost of the risk of failure is ignored). The summation of both terms in the numerator gives a full financial expression of the maintenance cost of component at a given point of time.

The denominator consists of:

1. The lifetime of which the probabilities are calculated.
2. The probability of survival at the given lifetime.

The division by the lifetime returns an output per unit of time (hour), while the division by the probability of survival is the total cost of maintenance, which is inversely proportional to the probability of survival. This division adds a reliability parameter to the cost-function, which is boosted at low survival-probabilities. Otherwise, it might mislead the decision-maker, as a lower cost would have appeared to occur at extremely long lifetime. However, in reality, there is a very low chance that the part would survive this long. Therefore, the multiplication of the lifetime at which the model is worked by the probability of survival in the denominator, returns the realistic lifetime by which the numerator should be divided.

4.3 Case-studies and Manual Calculation

In order to illustrate the applicability of the proposed model, three real case-studies from the aviation environment will be discussed. The three cases under consideration are shown in Table 4.2. These cases focus on the fuel-system components in the jet aircraft, type Boeing 737.

4.3.1 Case-studies

Gatland et al. (1997) indicated that engine-removals occur for a variety of reasons. First, the engine has parts that are time-restricted either by the manufacturer or the

FAA. These parts must be removed, inspected, and repaired before their time expires. Second, the engine is boroscope-inspected (a tube is inserted into the engine for viewing its inner parts by either video or eye) on given-intervals to determine wear. If the wear of particular parts is beyond limits, the engine is removed and overhauled to prevent a failure. The goal is to remove the engine before a failure. Engine-removals are classified by the amount of hours or cycles the engine has flown. The engine-maintenance goal is to meet the flying needs of the airline and have a replacement engine available at the time of removal.

In order to illustrate the content of this work, three case-studies from the aviation environment will be discussed. These case-studies represent three real items in the fuel-system in the aircraft jet-engine as below:

Table 4.2 Case-studies

Case-study	**Description**	**Part No.**	**Life-limit (Flying Hours)**	**Spare-part Cost (£)**
Case One	Starter	383152-16	6000	7700
Case Two	Fuel Heater	522649	7500	3500
Case Three	Fuel Pump	24361	11000	18200

Assumptions

In order to adopt a mathematical-model a set of assumptions is proposed in order to determine the problem within boundaries as follows:

1. The kind of aircraft is Boeing 737.
2. The prices are considered in sterling (£).
3. Maintenance-personnel are well-qualified and capable of carrying out any sort of maintenance actions.

4. Resources, tools and spare parts are always available and adequate to carry out any recommended job.
5. The Mathematical-model's calculation will be considered as hourly rate per person.
6. The distribution of the probability of failure against time is normal distribution.
7. The components probability of survival is an important issue that affects aircraft safety. Because it is difficult to find historical data to calculate the standard deviation value for the aircraft engine-components, the standard deviation is assumed and equals 11% of life-limit, which was found to be appropriate, since, when the standard deviation increase beyond this level, the probability of survival decrease.

4.3.2 Manual Calculation

The manual calculation will be related to the three case-studies mentioned above, and will use the previous equations from (4.1) to (4.8) in Section 4.2.3. In the following section, the manual calculation will be applied on the single first interval only: that equals 300 flying-hours. The rest of the intervals will be calculated by implementing the Visual Basic program in Chapter Six.

4.3.2.1 The Calculation of the Standard Normal Distribution (Z)

To calculate the probability of failure, we should firstly find out the standard normal distribution, as in the following equation:

$$Z = \frac{T - \mu}{\sigma}$$

Where:

T Is the real parameter at which the probability is aimed to be calculated, which refers to the regular aircraft maintenance-checks every 300 flying-hours.

μ Is the distribution mean, which represents the engine-components' life-time in flying-hours.

σ Is the distribution standard deviation, and because the data relating to repair times between two preventive maintenance times from the Libyan Arab Airlines Company were not available, the distribution standard deviation will be assumed to be 11% of the engine-components' life-time by flying hours. This is because, at this percentage and from the calculation, the component probability of survival was high and the component probability of failure was very low where σ is equivalent to 1200 flying-hours for Case One, 820 flying-hours for Case Two and 660 flying-hours for Case Three. The following calculation will deal with Case One and the remaining cases will be calculated by the software programme.

Therefore the value of Z from the formula $Z = \frac{T-\mu}{\sigma}$ is obtained as:

Case One:

$$Z = \frac{300-6000}{660}$$

$$Z = -8.64$$

Case Two:

$$Z = \frac{300-7500}{820}$$

$$Z = -8.78$$

Case Three:

$$Z = \frac{300 - 11000}{1200}$$

$$Z = -8.916$$

4.3.2.2 The Calculation of the Probability of Component Failure Using the Standard Normal Distribution Function:

The actual normal probability distribution $f(x)$ is given by the formula:

$$f(x) = \frac{1}{\sigma .\sqrt{2.\pi}}.e^{-\frac{(1-\mu)^2}{2\sigma^2}}$$

Applying the above equation to find out the failure-probability in all cases:

$$P_f = 0$$

Therefore, the probability of the module not failing is obtained for all cases:

$$1 - P_f \sim 1$$

4.3.2.3The Cost of Failure (C_f) of the Component:

This is obtained as:

C_f = Spare part cost + (Delay-cost × Corrective Time)

$$C_f = S_c + (D_c \times C_t)$$

Knotts (1999) reported that the delay-cost for aircraft B737 is about £150/minute, and because technical delays represent 20% of the total delay-cost, the delay-cost will be multiplied by 0.2.

Case One:

$C_f = 7700 + (150 \times 0.2 \times 60 \times 1)$

$C_f = 9500$ £/h

Case Two:

$C_f = 3500 + (150 \times 0.2 \times 60 \times 1)$

$C_f = 5300$ £/h

Case Three:

$C_f = 18200 + (150 \times 0.2 \times 60 \times 1)$

$C_f = 20000$ £/h

4.3.2.4 The Cost of Preventive Maintenance of the Above Component According to the Formula:

This is obtained as:

$C_p = S_c + (I_{lc} \times P_t)$

Case One:

$C_p = 7700 + (2.5 \times 1)$

$C_p = 7702.5$ £/h

Case Two:

$C_p = 3500 + (2.5 \times 1)$

$C_p = 3502.5$ £/h

Case Three:

$C_p = 18200 + (2.5 \times 1)$

C_p=18002.5 £/h

4.3.2.5 The Corrective Maintenance Cost Calculation

$C_{mc} = C_f \times P_f$

Case One:

$C_{mc} = 9500 \times 0$

C_{mc}=0 £/h

Case Two:

$C_{mc} = 5300 \times 0$

C_{mc}=0 £/h

Case Three:

$C_{mc} = 20000 \times 0$

C_{mc}=0 £/h

4.3.2.6 The Preventive Maintenance Cost Calculation

$P_{mc} = C_p \times P_s$

Case One:

P_{mc}= 7702.5 × (1-0)

P_{mc} =7702.5£/h

Case Two:

$P_{mc} = 3502.5 \times (1\text{-}0)$

P_{mc} =3502.5£/h

Case Three:

$P_{mc} = 18002.5 \times (1\text{-}0)$

P_{mc} =18002.5 £/h

4.3.2.7 Total Maintenance Cost Calculation

$$T_{mc} = \frac{C_f \times P_f + C_p \times (1 - P_f)}{T \times (1 - P_f)}$$

Case One:

$$T_{mc} = \frac{9500 \times 0 + 7702.5 \times (1 - 0)}{300 \times (1 - 0)}$$

T_{mc} =25.68 £/h

Case Two:

$$T_{mc} = \frac{5300 \times 0 + 3502.5 \times (1 - 0)}{300 \times (1 - 0)}$$

T_{mc} =11.68 £/h

Case Three:

$$T_{mc} = \frac{20000 \times 0 + 18002.5 \times (1 - 0)}{300 \times (1 - 0)}$$

T_{mc} =60.68 £/h

Table 4.3 shows the manually-calculated results for the first interval that is represented by 300 flying-hours for Case One that include the entry-data such as: service-interval, life-limit, and standard deviation; and the outputs such as: probability of failure, probability of survival, failure-cost, corrective-maintenance cost, preventive-maintenance cost, and total maintenance cost.

Table 4.3 Total Maintenance Cost at 300 Flying-hours for Case-studies 1, 2, and 3

Case	T (f-h)	μ (f-h)	σ	Z	p_f	$1-p_f$	C_f (£/h)	C_P (£/h)	C_{mc} (£/h)	C_{mp} (£/h)	T_{mc} (£/h)
One	300	6000	660	-8.64	0.0	1.0	9500	7702.5	0	7702.5	25.68
Two	300	7500	820	-8.78	0.0	1.0	5300	3502.5	0	3502.5	11.68
Three	300	11000	1200	-8.912	0.0	1.0	20000	18002.5	0	18002.5	60.68

The rest of the calculation will be repeated with the remaining intervals, i.e.

T Optimum is $\in$ {300, 600, 900, 1200, 1500, 1800 ...} flying-hours;

and this will be validated by using the Visual Basic Microsoft in Chapter Six.

4.4 Conclusion

A mathematical model for maintenance-scheduling activities was developed. The total cost was calculated using the proposed model and based on a balance between the cost of failure of an item during operation and the cost of planned maintenance to determine the optimum interval at which preventive-maintenance should be carried out. Three case-studies were provided to facilitate understanding the applicability of the proposed scheduling model.

In the next chapter, a mathematical-model for inventory-control policy will be illustrated and developed.

Chapter Five

Development of the Proposed Inventory Decision-making Mathematical Model

5.1 Introduction

Inventory is primarily concerned with the problem of controlling the repairable components supporting a fleet of commercial aircraft. The scheduled-maintenance decision-making model was developing in Chapter Four and applied to different components that are characterised by their low demand, high cost in the jet-engine unit.

The purpose of the inventory model is to determine the balance-decision between the repair and purchase of components, which leads to minimizing the total expected annual cost of inventory.

This chapter will be divided into two sections:

- The proposed Inventory Mathematical Model
- Case-studies and Manual Calculation

5.2 The Proposed Inventory Mathematical Model

Mabini and Christer (2002) developed and presented a model for determining stock-levels of repairable items supporting a fleet of commercial aircraft that minimizes the total expected annual cost. In this regard, there will be four cost-factors to be considered: the cost of holding serviceable and non-serviceable components; the purchase-cost; the repair-cost and the aircraft-delay cost due to shortage of components. The model strove for the best balance between the cost of holding inventories and that of aircraft service delays. The author will apply the model here to determine the decision-making concerning the balance between the repair and purchase of a new component to minimize the total inventory cost.

5.2.1 The Inventory Objective Function

The objective function is to minimise the total inventory cost (Tic) which leads to minimizing the technical administration costs Mabini and Christer (2002).

Minimize $Tic = Dc + Hc + Pc + Rc$

Subject to:

- Probability of components availability ≥ 0.96

Where:

Dc is the delay-cost.

$Dc = 365(F_c.\tau.\lambda)$

Hc is the holding-cost.

$$Hc = H\left[\sum_{x=0}^{S_l}(S_l - x).p(x,\lambda T_r) + (1-p_n).\lambda T_r\right]$$

Pc is the purchase-cost.

$Pc = 365(\lambda.p_n.S_c)$

Rc is the repair-cost.

$Rc = 365(\mu_i C_i + \mu_o C_o)$

All symbols will be illustrated in the following section.

5.2.2 Inventory Variables

In Table 5.1 the inventory variables will be illustrated and ordered as: demand, probability, costs, and time, delay and Weibull distribution parameters to enable the reader to know easily all the related variables.

Table 5.1 Inventory Variables Definition

Notation	Description	Unit
Demand		
λ	Average number of components demanded per day for the fleet.	
μ_i	Average number of components repaired in-house per day.	
μ_o	Average number of components repaired out-house per day.	
Probability		
p_i	Probability that component is in-house repairable.	
p_o	Probability that component is out-house repairable.	
p_n	Probability that component is non-repairable.	
Time		
T_i	Total in-house repair-time.	Day
T_r	Expected re-supply-time.	Day
T_o	Out-house repair-time.	Day
T_p	Purchase lead-time.	Day
S_l	Stock-level.	
Delay		
τ	Expected amount of aircraft-delay time due to component failure.	Day
Weibull distribution parameters		
$P(w,z)$	Poisson probability that w units are demanded within a given period when the average demand within the same period is z.	
$F(x)$	Cumulative Density Function (CDF) for the Weibull distribution.	

R	Reliability.	
α	Scale parameter of the Weibull distribution.	
β	Shape parameter of the Weibull distribution.	
	Cost	
F_c	Fine (Penalty) cost per non-operational aircraft.	£/day
C_i	In-house repair cost.	£/day
C_o	Out-house repair cost.	£/day
H	Inventory holding cost per unit time.	£/year
S_c	Spare cost.	£
Hc	Holding cost of serviceable and non-serviceable components.	£/year
Dc	Delay cost.	£/year
Pc	Purchase cost.	£/year
Rc	Repair cost.	£/year
L_i	In-house labour cost.	£/hour
L_o	Out-house labour cost.	£/hour
Tic	Total inventory cost.	£/year

To find the optimum-time for the replacement of the components, this model is applied where the repair-cost is very high. The mathematical expression could be represented as:

$$\frac{PurchaseCost}{Reliability} V/S \frac{RepairCost}{Reliability} \quad \text{...} (5.1)$$

The numerator on the left-hand side i.e. total purchase-cost includes purchase-cost, holding-cost and delay-cost; whereas the right-hand side i.e. total repair-cost includes repair-cost, holding-cost of the serviceable item and delay-cost due to item-unavailability in stock.

The decision should be made on the basis that:

If

$$\frac{PurchaseCost}{Reliability} \leq \frac{RepairCost}{Reliability}$$

Replace it.

If

$$\frac{PurchaseCost}{Reliability} \geq \frac{RepairCost}{Reliability}$$

Repair it.

5.2.3 Variable Relationships

To calculate the expected annual cost of the inventory-system, there are a set of factors to be considered in the calculation. The key factors are identified as follows: -

5.2.3.1 The Re-supply Time:

This is calculated as the purchase lead-time of the new component. In all those cases mentioned above, the re-supply time is calculated as Mabini and Christer (2002):

$$T_r = p_i T_i + p_o T_o + p_n T_p \quad \text{(5.2)}$$

More-over, the component back-order due to out of stock is related to components required to repair the failed component. The expected re-supply depends on the type of failure, which determines whether the component is repaired in-house or out-house. If the component completely failed or, in other words, cannot be repaired to work at the desired level of reliability, those components are scrapped.

For the component calculation:

$p_i + p_o + p_n = 1$

5.2.3.2 Holding-cost

The holding-cost relates to both the warehouse and the repair-shop. Taking into consideration the warehouse capacity and the capital investment, the holding-cost also includes the components which are sent for out-house repair.

$$Hc = H\left[\sum_{x=0}^{S_l}(S_l - x).p(x,\lambda T_r) + (1-p_n).\lambda T_r\right] \quad \text{.................................... (5.3)}$$

5.2.3.3 Purchase-cost

Purchase-cost is calculated per year and includes variables like demand for the components, the probability that it is non-repairable and the purchase-price Mabini and Christer (2002).

$$Pc = 365(\lambda.p_n S_c) \quad \text{.. (5.4)}$$

5.2.3.4 Repair-cost

Repair-cost is the sum of the in-house repair-cost multiplied by the average number of components required in-house per day, and the out-house repair-cost multiplied by the average number of components required out-house per day Mabini and Christer (2002).

$$Rc = 365(\mu_i C_i + \mu_o C_o) \quad \text{.. (5.5)}$$

5.2.3.5 Delay-cost

Delay-cost is calculated with the following formula. Delay-cost is directly related to the number and duration of components' back-orders Mabini and Christer (2002).

$$Dc = 365(F_c.\tau.\lambda) \quad (5.6)$$

5.2.3.6 Reliability

Reliability of the component at any given time is calculated using Weibull Distribution, which is widely-used to present the life-time of a device. Tobias and David (1995) reported that the Weibull distribution has proved to be successful for many product-failure mechanisms because it is a flexible distribution with a wide variety of possible failure-rate curves. In addition, the Weibull distribution also has a derivation as a so-called "extreme value" distribution, which suggests its theoretical applicability when failure is due to a "weakest link" of may possible failure-points. The Cumulative Density Function (CDF) of the Weibull distribution is given by the equation:

$$F(x) = 1 - e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \quad (5.7)$$

Where α and β are scale and shape parameter of the Weibull distribution respectively.

5.2.3.7 Estimation of Weibull parameters

Tobias and Trindade (1995) and Rausand (1998) mentioned that both scale and shape parameters are dependent on two constraints. The first constraint is the Removal Time or Failure Time (RT) and the second constraint is the Cumulative Failure Rate (CFR).

The Removal Time or Failure Time of any aircraft component is dependent on the preventive maintenance period, which is either specified by the manufacturer or identified by specific checks. The different checks and the maintenance-schedules are specified in the literature review in Chapter 2. These identify the intervals of major aircraft maintenance-checks.

The time-interval depends on the type of maintenance-checks (A, B, C or D) as mentioned above.

Let us consider that we carry out the type 'B' check; an aircraft takes 300 flying-hours before getting to the hangar.

T Optimum is $\in$ {300, 600, 900, 1200, 1500, 1800, 2100 ...}, where 300 flying-hours is the average for doing the (B) regular maintenance check or once every month whichever comes first. These removal times or intervals are considered as the RT or Failure Time.

The Cumulative Failure Rate is obtained from the different checks performed on the components. For calculation purposes, the Cumulative Failure Rate is assumed to be constant. But in a real aircraft-environment the maintenance-engineers provide these data.

For a new component the Cumulative Failure Rate is assumed as 0.0001 and for a repaired component is assumed as 0.001. From these data we are now able to estimate the Weibull parameters by the method of least square or regression analysis.

Regression analysis can be used to find the best-fitting curve for given variables Mabini and Christer (2002).

$$\hat{H}(t) = (\alpha t)^{\beta} \quad \text{.......... (5.8)}$$

Where:

$\hat{H}(t)$ is the Cumulative Failure Rate (regression equation).

$(\alpha t)^{\beta}$ is the exponential constant failure rate.

We arrive at the following equation to get the regression line (Lawrence L. Lapin, 1990):

$$\ln\left[\hat{H}(t)\right] = \beta \ln(\alpha) + \beta \ln(t) \quad \text{.......... (5.9)}$$

5.3 Case-studies

The same three case-studies introduced in Chapter Four, section 4.3, will be used here to demonstrate the application of the proposed inventory-model. The case-studies and entry-data are illustrated in table 5.2:

Table 5.2 Case-studies and the Entry-data

Case-studies	Entry-data								
	Life-time (Flying-hours)	Price (£)	Demand (Per day)	Probability			Time (days)		
	μ	S_c	λ	p_i	p_o	p_n	T_i	T_o	T_p
C_1	6000	7700	0.00164	0.75	0.20	0.05	7	35	45
C_2	7500	3500	0.001315	0.75	0.20	0.05	6	30	45
C_3	11000	18200	0.0009	0.70	0.25	0.05	8	50	40

5.3.1 Assumptions

To apply a mathematical-model, a set of assumptions is necessary in order to determine the problem within boundaries, as follows:

- Fine (Penalty) cost per non-operational aircraft per day is £2500 and the prices are considered in Stirling (£).
- The mathematical-model repair-cost calculation will be considered per person per hour.
- Demand for components is calculated using a Poisson process.
- The average rate of demand relates to a component's life-time.
- Non-repairable components are scrapped and replenished through purchases.
- There is sufficient in-house repair capacity for components for in-house repair to commence immediately subject to spares-availability.
- Components sent to out-house repair-shops are repaired and returned to the company warehouse in a serviceable state.
- A one-for-one inventory-policy is applied for purchases. This is appropriate for high-cost, low-demand.
- The holding-cost is the same for both serviceable and non-serviceable components.
- The average number of serviceable components delivered to the warehouse per unit-time is fixed.
- The majority of components are repaired in-house with relatively short repair-periods compared to out-house and new-purchase lead-times.
- The demand-rates and the stock-levels for these components are low.

5.3.2 Manual Calculation

Case-study One will be illustrated manually in this section to show how to accomplish the calculation. Table 5.2 includes the entry-data and, using the equations (5.1) to (5.9), are as shown in the following steps:

5.3.2.1 The Delay-cost will be calculated from the following equation:

$$Dc = 365(F_c.\tau.\lambda)$$

Where:

F_c = £2500 per day

λ =0.001641843

τ Is the expected amount of aircraft-delay time due to component-failure and, from the author's experience, the average is 2 days.

Then:

Dc =365(2500 x 2 x 0.001641843)

Thus Dc=3000 £/day

The rest of the calculations will be repeated with the remaining intervals: 900, 1200, 1500..., and will be calculated by using the Visual Basic Microsoft in the next chapter.

5.3.2.2 The Holding-cost Calculation

To calculate the holding-cost, the expected re-supply time for component T_i should be calculated first.

Where:

$$T_r = p_i T_i + p_o T_o + p_n T_p$$

The sum of the component probability is:

$$p_i + p_o + p_n = 1$$

0.75 + 0.2 + 0.05 = 1

$T_r =$ 0.75 x 7 + 0.2 x 30 + 0.05 x 45

Thus T_r = 14.5 days

$$Hc = H\left[\sum_{x=0}^{S_l}(S_l - x).p(x,\lambda T_r) + (1-p_n).\lambda T_r\right]$$

Where:

H is the annual holding-cost per unit and equal to 25% of the unit price

$$H = 0.25 S_C$$

H = 0.25 x 7700

H = £1925

$S_l = 2$

$x_0 = 0$

$x_1 = 1$

λT_r = 0.00164 x 14.5

λT_r = 0.0238 day

$$p(x_0, \lambda T_r) = \frac{(\lambda T_r)^{x_0} \times \exp(-\lambda T_r)}{Fact(x_0)}$$

$$p(0,0.0238) = \frac{(0.0238)^0 \times \exp(-0.0238)}{Fact(0)}$$

Then, $p(0,0.0238) = 0.9764$

$$p(x_1, \lambda T_r) = \frac{(\lambda T_r)^{x_1} \times \exp(-\lambda T_r)}{Fact(x_1)}$$

$$p(1{,}0.0238) = \frac{(0.0238)^1 \times \exp(-0.0238)}{Fact(1)}$$

Then, $p(1{,}0.0238) = 0.02327$

$(S_i - x_0) \times p(x_0, \lambda T_r) =$ (2-0) * (0.9764) = 1.9528924

$(S_i - x_1) \times p(x_1, \lambda T_r) =$ (2-1) * (0.02327) = 0.0232742

By applying equation 5.3

$Hc =$ 1925[(1.9528 + 0.023227) + (1-0.05) * 0.0238]

$Hc =$ £3847.71

5.3.2.3 Purchase-cost Calculation

$$Pc = 365(\lambda . p_n . S_c)$$

$Pc =$ 365(0.00164 x 0.05 x 7700)

$Pc =$ £231

Total purchase-cost = purchase-cost + holding-cost + delay-cost

Total purchase-cost = 231 + 3847.6 + 3000

Total purchase-cost = £7078.6

5.3.2.4 Repair-cost Calculation

$$Rc = 365(\mu_i C_i + \mu_o C_o)$$

Assumptions:

Table 5.3 Repair-cost Assumptions

In-house average hourly rate	2.5 £/h
Out-house average hourly rate	10 £/h
One shift per day in hours in-house	8 h
One shift per day in hours out-house	8 h
Total in-house salary for one worker per day	40 £/h
Total out-house salary for one worker per day	200 £/h
μ_i is the average number of components repaired in-house per day	0.0001 λ
μ_o is the average number of components repaired out-house per day	0.0001 λ

The component in-house repair-cost:

Where:

C_i = Spare Cost + (Salary/day x no. of workers x no. of days required to repair component in-house)

$C_i = S_C + (L_i T_i)$

C_i=7700 + (20 x 7)

C_i = £7840

The component out-house repair-cost:

C_o = Spare Cost + (Salary/day x no. of workers x no. of days required to repair component out-house)

$C_o = S_C + (L_o T_o)$

C_o=7700 + (80 x 35)

C_o= £10500

By applying the equation

$$Rc = 365(\mu_i C_i + \mu_o C_o)$$

Rc= 365 x [0.012887 + .017260]

Rc=£11.004

Total repair cost = repair cost + holding cost +delay cost

Total repair cost = 11.004 + 3847.6 + 3000

Total repair cost = £6858.604

5.3.2.5 Reliability Calculation and Estimation of Weibull Parameters

Cumulative Density Function (CDF) of the Weibull distribution is given by the equation:

$$F(t) = 1 - e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$$

The reliability is:

$$R = 1 - F(t)$$

Where α and β are scale and shape parameters of the Weibull distribution respectively, which can be calculated by using the method of least square or regression analysis. In regression analysis we find the best-fitting curve for given variables. If we take the natural logarithm of Weibull failure-time Distribution:

$$\hat{H}(t) = (\alpha t)^{\beta}$$

We get the following equation:

$$\ln\left[\hat{H}(t)\right] = \beta \ln(\alpha) + \beta \ln(t)$$

The following Table shows intervals (T), (CFR) and the natural logarithm of the assumed data.

Table 5.4 Natural Logarithm

T	CFR 1	CFR 2	Ln(CFR 1)	Ln(CFR 2)
300	0.0001	0.001	-9.21034	-6.90776
600	0.0002	0.002	-8.51719	-6.21461
900	0.0003	0.003	-8.11173	-5.80914
1200	0.0004	0.004	-7.82405	-5.52146
1500	0.0005	0.005	-7.6009	-5.29832
1800	0.0006	0.006	-7.41858	-5.116
2100	0.0007	0.007	-7.26443	-4.96185
2400	0.0008	0.008	-7.1309	-4.82831
2700	0.0009	0.009	-7.01312	-4.71053
3000	0.001	0.01	-6.90776	-4.60517
3300	0.0011	0.011	-6.81245	-4.50986
3600	0.0012	0.012	-6.72543	-4.42285
3900	0.0013	0.013	-6.64539	-4.34281
4200	0.0014	0.014	-6.57128	-4.2687
4500	0.0015	0.015	-6.50229	-4.19971
4800	0.0016	0.016	-6.43775	-4.13517
5100	0.0017	0.017	-6.37713	-4.07454
5400	0.0018	0.018	-6.31997	-4.01738
5700	0.0019	0.019	-6.2659	-3.96332
6000	0.002	0.02	-6.21461	-3.91202
6300	0.0021	0.021	-6.16582	-3.86323
6600	0.0022	0.022	-6.1193	-3.81671
6900	0.0023	0.023	-6.07485	-3.77226
7200	0.0024	0.024	-6.03229	-3.7297
7500	0.0025	0.025	-5.99146	-3.68888
7800	0.0026	0.026	-5.95224	-3.64966
8100	0.0027	0.027	-5.9145	-3.61192
8400	0.0028	0.028	-5.87814	-3.57555
8700	0.0029	0.029	-5.84304	-3.54046
9000	0.003	0.03	-5.80914	-3.50656
9300	0.0031	0.031	-5.77635	-3.47377
9600	0.0032	0.032	-5.7446	-3.44202
9900	0.0033	0.033	-5.71383	-3.41125
10200	0.0034	0.034	-5.68398	-3.38139
10500	0.0035	0.035	-5.65499	-3.35241
10800	0.0036	0.036	-5.62682	-3.32424
11100	0.0037	0.037	-5.59942	-3.29684

The regression equation is calculated by using the statistical package mistakes Minitab 15.

Two regression equations are obtained, one for ln RT vs. ln CFR 0.0001, and another one for ln RT vs. CFR with 0.001.

By applying the Minitab software that is showed in Appendix A, the following equations will be obtained:-

- When the Cumulative Failure Repair (CFR1) is 0.001, the regression equation is:

C1=12.6 + 1.00C2

$\beta = 1$ (shape parameter)

$$\alpha = \exp\left(\frac{12.6}{1}\right)$$

$\alpha = 296558$ (Scale parameter)

- When the Cumulative Failure Repair (CFR2) is 0.0001, the regression equation is:

C1=14.9 + 1.00C2

$\beta = 1$ (shape parameter)

$$\alpha = \exp\left(\frac{14.9}{1}\right)$$

$\alpha = 2957929$ (scale parameter)

Substituting these values in the Weibull CDF, we get the probability of failure at any given point of time. The reliability of the module at any given point of time is:

$$\mathrm{Re}\,liability = 1 - F(t).$$

Therefore the proposed expression to calculate the optimal replacement-time will be:

$$\frac{Pc + Dc + Hc}{1 - F(x)} \geq \frac{Rc + Dc + Hc}{1 - F(x)}$$

Where the left-hand side denominator represents the reliability of the new component; and the right-hand side denominator represents the reliability of the repaired component. (Lapin, 1990)

For the positive values of the expression, which means purchase-cost is more than the repair-cost, the repair option is best. When the expression turns from a positive value to negative, it suggests that the repair-cost is higher than the purchase-cost; the failed component is replaced with new component.

5.4 Conclusion

A Mathematical model for the inventory was developed in this chapter, where the total cost of repair or replacement of a component was based on a balance between the costs of repair and purchasing components. In the next chapter the framework for integrating maintenance-scheduling and inventory-control using the Visual Basic programme will be explored and used to facilitate the long and complicated calculations. In addition, the results will be discussed and analysed to take the best decision concerning the repair or purchase of a new component.

Chapter Six

Implementation and Application of the Proposed Integrated Framework

6.1 Introduction

The proposed mathematical models concerning the maintenance-scheduling and inventory were applied manually and separately. In this chapter, Visual Basic 6.0 (VB) programming language is used to develop and implement the proposed integrated framework. The program will be established and validated using the three case-studies introduced in chapters 4 and 5. The software development and application of the proposed integrated framework will be illustrated in appendix A. This chapter includes:

- Implementation of the proposed integrated framework
- Analysis of the Visual Basic 6.0 (VB) programme results
- Conclusion

6.2 Implementation of the proposed integrated framework

Figure 6.1 illustrated bellow shows the proposed integrated framework, which made of five components:

1. Source Data represented by logbook, MCC, COASL, Hanger, and Warehouse.
2. Input Data that includes Spare part costs, Interval, Component Live limit, Standard.
3. Maintenance Model.
4. Inventory Model.
5. Output Data concerning maintenance scheduling and inventory control policy.

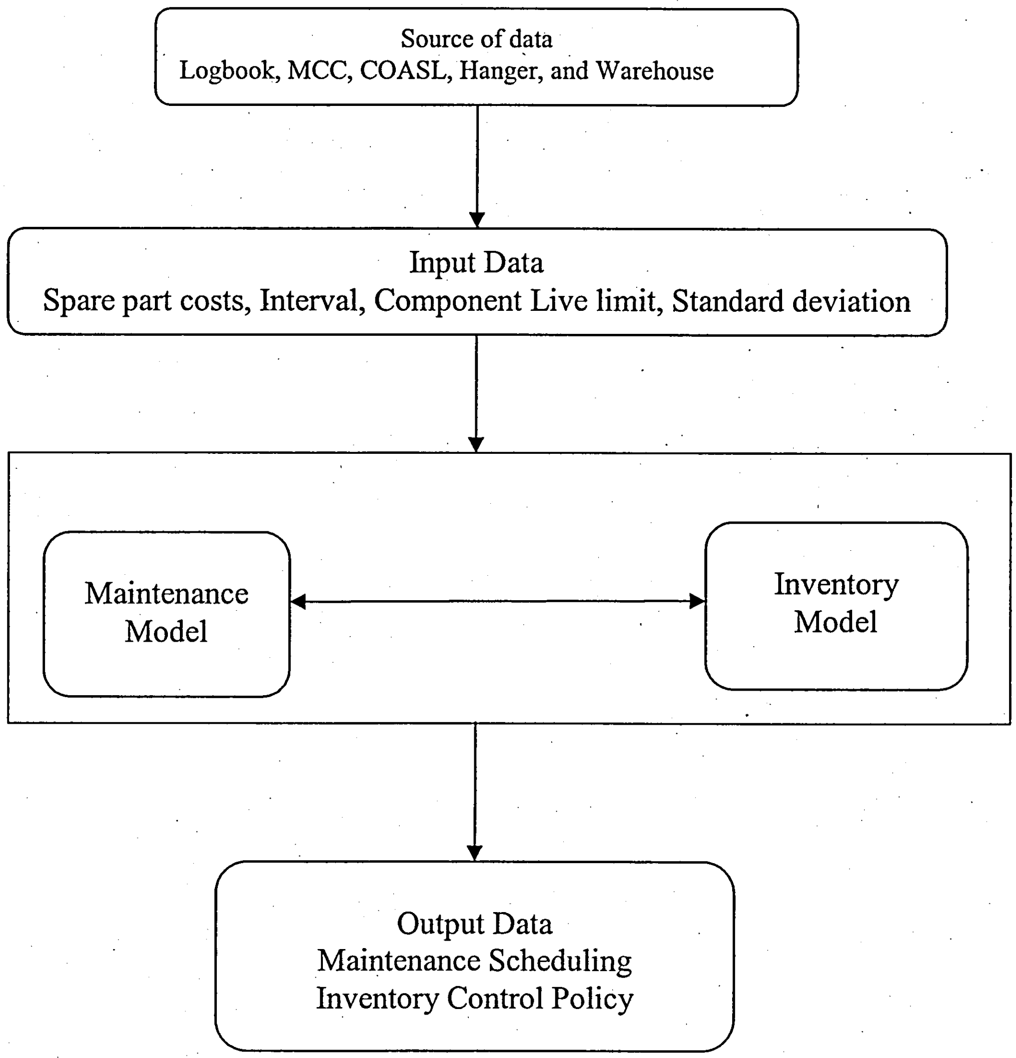

Figure 6.1 Proposed Integrated Framework

6.3 Analysis of the Visual Basic (VB) Program Results

The output results are presented by:

- Output tables created by linking database software
- Excel software graphs

In the following sections the above outputs will be analysed separately:

6.3.1 Output Tables Issued by Linked Database Software

The three tables 6.1, 6.2, and 6.3 present the results from the three case-studies that are covered in this research. They are issued and printed as a report by database software linked with the Visual Basic 6.0 software. These tables indicate and introduce the integration results that were obtained when the mathematical-models were applied. They combine the maintenance-scheduling outputs and the inventory outputs in one table. The results include the important results such as: Probability of Survival (PS), Repair Reliability (RR), New Reliability (RN), Corrective Maintenance Cost (CMC), Preventive Maintenance Cost (PMC), Total Maintenance Cost (TMC), and Total Repair Cost (TRC) And Total Purchase Cost (TPC).

From the Tables of output-results in general we notice in all three case-studies:

- The intervals (I) present the regular (B) maintenance checks and they were started from 300 fh and raised by 300 fh. That mean the intervals are 300, 600, 900, 1200, 1500 …
- Both Cost of Failure (CF) and Cost of Failure-prevention (CP) are constant in all different intervals, because the Spares-cost, Labour-cost, Corrective Time and Preventive Time are constant for each case-study.
- Standard Normal Distribution (Z) was increasing with the rising of the intervals.

- Corrective Maintenance Cost (CMC) started very small and equalled zero, because the Probability of Failure equalled zero in the first few intervals, which means the component was still new or was repaired as a new.
- Preventive Maintenance Cost (PMC) decreased inversely with the rising intervals, because the Probability of Survival equalled one in the first few intervals.
- Total Maintenance Cost (TMC) was decreasing with the increasing intervals, and then at a unique interval it begins increasing again.
- Total Repair Cost (TRC) and Total Purchase Cost (TPC) both increase as the intervals increase, but at a unique interval the Total Repair Cost was less than the Total Purchase Cost until at a unique interval the Total Repair Cost (TRC) becomes greater than the Total Purchase Cost.

The following section will explain and analyse each case-study individually:

6.3.1.1 Case One Integration-output Table

Table 6.1 is related to Case One (a starter for the B737 aircraft jet-engine). The manufacturer's life-time for this component was 6000fh and the spares-cost is £3500, which was obtained from using the Visual Basic 6.0 and linked database software.

The table mentioned above contains information about the interval at which the maintenance-task should be carried out. In addition, the probability associated with this interval and the expected Preventive, Corrective and Total Costs are shown. For example, the optimum interval for preventive maintenance should be at 4800 flying hours at which the expected maintenance cost is £ 1.77/h.

The minimum Total Maintenance Cost was £1.7684/h at the interval 4800fh instead of 6000fh and at this interval the Total Repair Cost was £6970.63, less than the Total Purchase Cost (£7090.21); and that means it is better to repair this component if it was damaged at this interval than to purchase a new component.

In addition, at this interval the probability of survival and reliability were high: the probability of survival was 0.924; and the reliability was 0.98 for repairing and 0.998 for a new component.

Furthermore, the decision-model gave us a range of intervals at which to do the maintenance at a minimum maintenance-cost: the intervals were 4200fh, 4500fh and 4800fh. This enabled the practitioners to choose the first available chance to do the maintenance at minimum cost.

Table 6.1 Case One Integration Results

I	PS	RR	RN	CMC	PMC	TMC	TRC	TPC
300	1.000	0.999	1.000	£0.00	£7,702.50	£25.67	£6,865.66	£7,079.4
600	1.000	0.998	1.000	£0.00	£7,702.50	£12.84	£6,872.60	£7,080.1
900	1.000	0.997	1.000	£0.00	£7,702.50	£8.56	£6,879.56	£7,080.9
1200	1.000	0.996	1.000	£0.00	£7,702.50	£6.42	£6,886.52	£7,081.6
1500	1.000	0.995	0.999	£0.00	£7,702.50	£5.14	£6,893.49	£7,082.3
1800	1.000	0.994	0.999	£0.00	£7,702.50	£4.28	£6,900.47	£7,083.0
2100	1.000	0.993	0.999	£0.00	£7,702.50	£3.67	£6,907.45	£7,083.7
2400	1.000	0.992	0.999	£0.00	£7,702.50	£3.21	£6,914.45	£7,084.5
2700	1.000	0.991	0.999	£0.01	£7,702.49	£2.85	£6,921.44	£7,085.2
3000	1.000	0.990	0.999	£0.12	£7,702.40	£2.57	£6,928.45	£7,085.9
3300	1.000	0.989	0.999	£0.88	£7,701.79	£2.33	£6,935.46	£7,086.6
3600	0.999	0.988	0.999	£5.10	£7,698.37	£2.14	£6,942.48	£7,087.3
3900	0.997	0.987	0.999	£24.00	£7,683.04	£1.98	£6,949.51	£7,088.0
4200	0.990	0.986	0.999	£91.94	£7,627.96	£1.86	£6,956.54	£7,088.8
4500	0.970	0.985	0.998	£286.42	£7,470.27	£1.78	£6,963.58	£7,089.5
4800	0.924	0.984	0.998	£725.76	£7,114.06	£1.77	£6,970.63	£7,090.2
5100	0.843	0.983	0.998	£1,495.71	£6,489.79	£1.86	£6,977.69	£7,090.9
5400	0.736	0.982	0.998	£2,507.11	£5,669.76	£2.06	£6,984.75	£7,091.6
5700	0.640	0.981	0.998	£3,417.97	£4,931.24	£2.29	£6,991.82	£7,092.4
6000	0.601	0.980	0.998	£3,789.95	£4,629.65	£2.33	£6,998.89	£7,093.1
6300	0.640	0.979	0.998	£3,417.97	£4,931.24	£2.07	£7,005.98	£7,093.8
6600	0.736	0.978	0.998	£2,507.11	£5,669.76	£1.68	£7,013.07	£7,094.5
6900	0.843	0.977	0.998	£1,495.71	£6,489.79	£1.37	£7,020.17	£7,095.2
7200	0.924	0.976	0.998	£725.76	£7,114.06	£1.18	£7,027.27	£7,096.0
7500	0.970	0.975	0.997	£286.42	£7,470.27	£1.07	£7,034.38	£7,096.7
7800	0.990	0.974	0.997	£91.94	£7,627.96	£1.00	£7,041.50	£7,097.4
8100	0.997	0.973	0.997	£24.00	£7,683.04	£0.95	£7,048.63	£7,098.1
8400	0.999	0.972	0.997	£5.10	£7,698.37	£0.92	£7,055.76	£7,098.8
8700	1.000	0.971	0.997	£0.88	£7,701.79	£0.89	£7,062.91	£7,099.6
9000	1.000	0.970	0.997	£0.12	£7,702.40	£0.86	£7,070.05	£7,100.3
9300	1.000	0.969	0.997	£0.01	£7,702.49	£0.83	£7,077.21	£7,101.0
9600	1.000	0.968	0.997	£0.00	£7,702.50	£0.80	£7,084.37	£7,101.7
9900	1.000	0.967	0.997	£0.00	£7,702.50	£0.78	£7,091.54	£7,102.4
10200	1.000	0.966	0.997	£0.00	£7,702.50	£0.76	£7,098.72	£7,103.2
10500	1.000	0.965	0.996	£0.00	£7,702.50	£0.73	£7,105.91	£7,103.9
10800	1.000	0.964	0.996	£0.00	£7,702.50	£0.71	£7,113.10	£7,104.6
11100	1.000	0.963	0.996	£0.00	£7,702.50	£0.69	£7,120.30	£7,105.3

6.3.1.2 Case Two Integration Table Results

Table 6.2 shows Case 2 results for a fuel pump for the same kind of aircraft. The life-time given by the manufacturer was 7500fh and the spares-cost is £7700. Moreover, and from Table 6.7, the minimum Total Maintenance Cost is £0.650 at the interval 5700f; the Total Repair Cost at this interval is £4230.2 and the Total Purchase Cost at this interval is £4241.4. The Repair Cost is less than the Total Purchase Cost. That means that in this case also it is better to repair the component than to purchase a new one if the component has failed. The Probability of Survival is 0.963 and the Repair Reliability is 0.981 and the reliability of a new one is 0.998. In addition, the mathematical-model gave us a range of best intervals to do the maintenance: at 5400fh, 5700fh and 6000fh. At these intervals the total maintenance costs were the minimum values: respectively, £0.664, £0.65 and £0.657.

Table 6.2 Case Two Integration Results

I	PS	RR	RN	CMC	PMC	TMC	TRC	TPC
300	1.000	0.999	1.000	£0.00	£3,502.50	£11.68	£4,158.04	£4,233.7
600	1.000	0.998	1.000	£0.00	£3,502.50	£5.84	£4,162.25	£4,234.1
900	1.000	0.997	1.000	£0.00	£3,502.50	£3.89	£4,166.46	£4,234.6
1200	1.000	0.996	1.000	£0.00	£3,502.50	£2.92	£4,170.68	£4,235.0
1500	1.000	0.995	0.999	£0.00	£3,502.50	£2.34	£4,174.90	£4,235.4
1800	1.000	0.994	0.999	£0.00	£3,502.50	£1.95	£4,179.13	£4,235.8
2100	1.000	0.993	0.999	£0.00	£3,502.50	£1.67	£4,183.36	£4,236.3
2400	1.000	0.992	0.999	£0.00	£3,502.50	£1.46	£4,187.59	£4,236.7
2700	1.000	0.991	0.999	£0.00	£3,502.50	£1.30	£4,191.83	£4,237.1
3000	1.000	0.990	0.999	£0.00	£3,502.50	£1.17	£4,196.07	£4,237.6
3300	1.000	0.989	0.999	£0.00	£3,502.50	£1.06	£4,200.32	£4,238.0
3600	1.000	0.988	0.999	£0.03	£3,502.48	£0.97	£4,204.57	£4,238.4
3900	1.000	0.987	0.999	£0.16	£3,502.40	£0.90	£4,208.82	£4,238.9
4200	1.000	0.986	0.999	£0.71	£3,502.03	£0.83	£4,213.08	£4,239.3
4500	0.999	0.985	0.998	£2.84	£3,500.62	£0.78	£4,217.35	£4,239.7
4800	0.998	0.984	0.998	£9.99	£3,495.90	£0.73	£4,221.62	£4,240.1
5100	0.994	0.983	0.998	£30.73	£3,482.19	£0.69	£4,225.89	£4,240.6
5400	0.984	0.982	0.998	£82.84	£3,447.76	£0.66	£4,230.17	£4,241.0
5700	0.963	0.981	0.998	£195.66	£3,373.20	£0.65	£4,234.45	£4,241.4
6000	0.924	0.980	0.998	£404.90	£3,234.92	£0.66	£4,238.73	£4,241.9
6300	0.861	0.979	0.998	£734.12	£3,017.36	£0.69	£4,243.02	£4,242.3
6600	0.780	0.978	0.998	£1,166.17	£2,731.84	£0.76	£4,247.32	£4,242.7
6900	0.694	0.977	0.998	£1,623.05	£2,429.91	£0.85	£4,251.62	£4,243.2
7200	0.627	0.976	0.998	£1,979.12	£2,194.60	£0.93	£4,255.92	£4,243.6
7500	0.601	0.975	0.997	£2,114.40	£2,105.20	£0.94	£4,260.23	£4,244.0
7800	0.627	0.974	0.997	£1,979.12	£2,194.60	£0.85	£4,264.54	£4,244.4
8100	0.694	0.973	0.997	£1,623.05	£2,429.91	£0.72	£4,268.86	£4,244.9
8400	0.780	0.972	0.997	£1,166.17	£2,731.84	£0.59	£4,273.18	£4,245.3
8700	0.861	0.971	0.997	£734.12	£3,017.36	£0.50	£4,277.50	£4,245.7
9000	0.924	0.970	0.997	£404.90	£3,234.92	£0.44	£4,281.83	£4,246.2
9300	0.963	0.969	0.997	£195.66	£3,373.20	£0.40	£4,286.16	£4,246.6
9600	0.984	0.968	0.997	£82.84	£3,447.76	£0.37	£4,290.50	£4,247.0
9900	0.994	0.967	0.997	£30.73	£3,482.19	£0.36	£4,294.84	£4,247.5
10200	0.998	0.966	0.997	£9.99	£3,495.90	£0.34	£4,299.19	£4,247.9
10500	0.999	0.965	0.996	£2.84	£3,500.62	£0.33	£4,303.54	£4,248.3
10800	1.000	0.964	0.996	£0.71	£3,502.03	£0.32	£4,307.90	£4,248.8
11100	1.000	0.963	0.996	£0.16	£3,502.40	£0.32	£4,312.26	£4,249.2

6.3.1.3 Case Three Integration Table Results

Table 6.3 displays Case Three results for the jet-engine of the B737 aircraft. The manufacturer's life-time till removal and maintenance of this component was 11000fh. The spares-cost is £18200 and the minimum Total Maintenance Cost was £2.2534 at the interval 8700fh. The Total Repair Cost is £11065.3 and the Total Purchase Cost is £11062.6. At this interval the Total Repair Cost is greater than the Total Purchase Cost. That means that it is better to purchase a new component than to repair the failed one; the Probability of Survival is 0.96, Repair Reliability is 0.972 and New Reliability Is 0.9972. All these values are high. Moreover, the model gave us the range of best intervals to do the maintenance; these intervals are: 8400fh, 8700fh and 9000fh. But at 9000fh the Probability of Survival is less than 0.9 and at this interval the Probability of Survival is 0.89.

Table 6.3 Case Three integration results

I	PS	RR	RN	CMC	PMC	TMC	TRC	TPC
300	1.000	0.999	1.000	£0.00	£18,202.50	£60.67	£10,756.42	£11,031.2
600	1.000	0.998	1.000	£0.00	£18,202.50	£30.34	£10,767.30	£11,032.3
900	1.000	0.997	1.000	£0.00	£18,202.50	£20.23	£10,778.20	£11,033.4
1200	1.000	0.996	1.000	£0.00	£18,202.50	£15.17	£10,789.11	£11,034.6
1500	1.000	0.995	0.999	£0.00	£18,202.50	£12.14	£10,800.03	£11,035.7
1800	1.000	0.994	0.999	£0.00	£18,202.50	£10.11	£10,810.96	£11,036.8
2100	1.000	0.993	0.999	£0.00	£18,202.50	£8.67	£10,821.90	£11,037.9
2400	1.000	0.992	0.999	£0.00	£18,202.50	£7.58	£10,832.86	£11,039.0
2700	1.000	0.991	0.999	£0.00	£18,202.50	£6.74	£10,843.82	£11,040.2
3000	1.000	0.990	0.999	£0.00	£18,202.50	£6.07	£10,854.80	£11,041.3
3300	1.000	0.989	0.999	£0.00	£18,202.50	£5.52	£10,865.78	£11,042.4
3600	1.000	0.988	0.999	£0.00	£18,202.50	£5.06	£10,876.78	£11,043.5
3900	1.000	0.987	0.999	£0.00	£18,202.50	£4.67	£10,887.79	£11,044.6
4200	1.000	0.986	0.999	£0.00	£18,202.50	£4.33	£10,898.81	£11,045.8
4500	1.000	0.985	0.998	£0.00	£18,202.50	£4.05	£10,909.84	£11,046.9
4800	1.000	0.984	0.998	£0.02	£18,202.49	£3.79	£10,920.88	£11,048.0
5100	1.000	0.983	0.998	£0.05	£18,202.45	£3.57	£10,931.93	£11,049.1
5400	1.000	0.982	0.998	£0.18	£18,202.34	£3.37	£10,943.00	£11,050.2
5700	1.000	0.981	0.998	£0.54	£18,202.00	£3.19	£10,954.07	£11,051.4
6000	1.000	0.980	0.998	£1.56	£18,201.08	£3.03	£10,965.16	£11,052.5
6300	1.000	0.979	0.998	£4.22	£18,198.66	£2.89	£10,976.26	£11,053.6
6600	0.999	0.978	0.998	£10.73	£18,192.73	£2.76	£10,987.37	£11,054.7
6900	0.999	0.977	0.998	£25.63	£18,179.17	£2.64	£10,998.49	£11,055.8
7200	0.997	0.976	0.998	£57.58	£18,150.09	£2.54	£11,009.62	£11,057.0
7500	0.994	0.975	0.997	£121.64	£18,091.79	£2.44	£11,020.76	£11,058.1
7800	0.988	0.974	0.997	£241.66	£17,982.56	£2.37	£11,031.92	£11,059.2
8100	0.977	0.973	0.997	£451.46	£17,791.62	£2.30	£11,043.08	£11,060.3
8400	0.960	0.972	0.997	£793.11	£17,480.67	£2.27	£11,054.26	£11,061.5
8700	0.934	0.971	0.997	£1,310.26	£17,010.00	£2.25	£11,065.45	£11,062.6
9000	0.898	0.970	0.997	£2,035.55	£16,349.89	£2.27	£11,076.65	£11,063.7
9300	0.851	0.969	0.997	£2,973.80	£15,495.97	£2.33	£11,087.86	£11,064.8
9600	0.796	0.968	0.997	£4,085.49	£14,484.20	£2.43	£11,099.08	£11,065.9
9900	0.736	0.967	0.997	£5,278.13	£13,398.75	£2.56	£11,110.31	£11,067.1
10200	0.679	0.966	0.997	£6,412.38	£12,366.44	£2.71	£11,121.56	£11,068.2
10500	0.634	0.965	0.996	£7,325.91	£11,535.01	£2.83	£11,132.82	£11,069.3
10800	0.606	0.964	0.996	£7,870.60	£11,039.27	£2.89	£11,144.08	£11,070.4
11100	0.602	0.963	0.996	£7,951.65	£10,965.51	£2.83	£11,155.36	£11,071.6

6.3.2 Graphical Presentation of the Results

The outputs and results in the tables 6.4, 6.5, and 6.6 were provided in a form of figures; and to make the results clearer they are graphically presented to help the reader understand them easily and quickly.

6.3.2.1 Maintenance- scheduling Graphs

Figures 6.2, 6.3, and 6.4 present the relationship between the Total Maintenance Cost (£) in the vertical axis and the intervals (flying hours) in the horizontal axis. The curves in all cases were approximately the same in shape; that means the curves were decreasing and dropping gradually near the horizontal axis to reach the minimum Total Maintenance Cost point. From the curves in all the case-studies we notice the range of lowest points near to the minimum point and after then the points rise gradually again.

Figure 6.2 presents the relationship between the Total Maintenance Costs and time (intervals by flying hours) for Case One. As can be seen, this curve decreases and droops sharply at the first few intervals; and after that, it droops steadily until it reaches the lowest point which represents the minimum Total Maintenance Cost. After this point the curve starts rising steadily again. In Case One the lowest point was at the interval 4800fh with a cost of £1.76/h. Beside this point there is a range of points on the curve which are nearly the same in terms of cost, but different in the time-interval. This is an important benefit and one of the great advantages of the proposed model which will provide flexibility in carrying out preventive-maintenance.

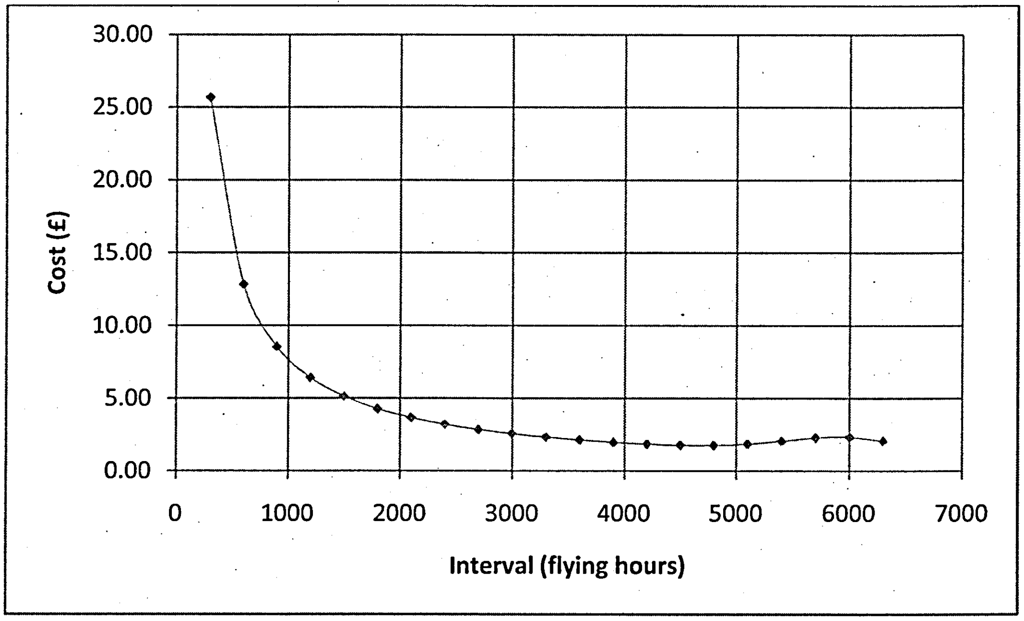

Figure 6.2 Total Maintenance Cost against Time for Case One

Cases Two and Three have different amounts in the costs and different intervals. In Figure 6.3 which represents Case Two, the lowest point on the curve, which shows the minimum Total Cost, was at 5700fh with £0.65/h .

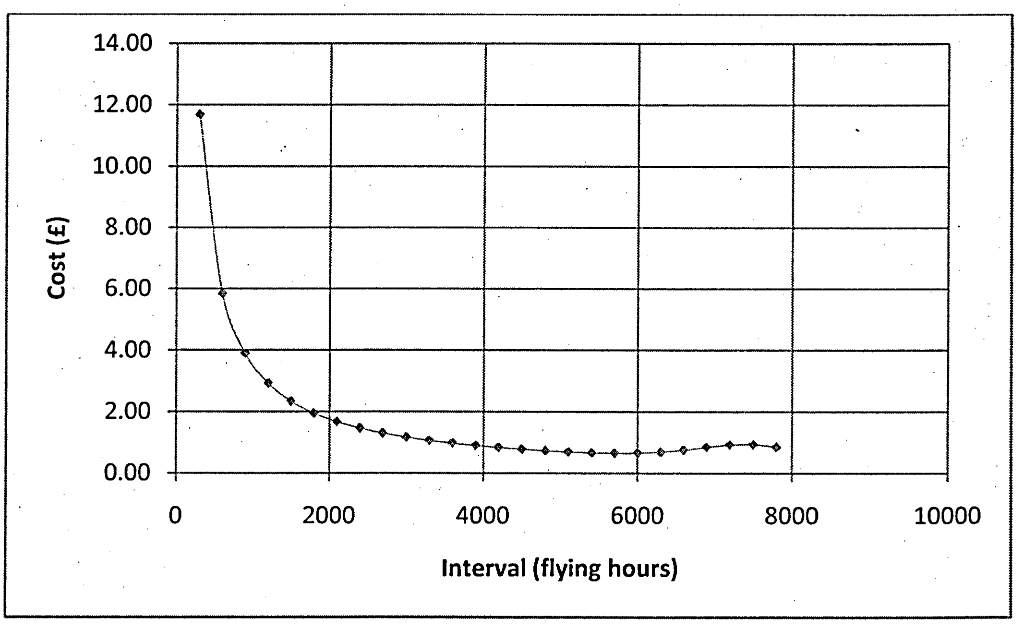

Figure 6.3 Total Maintenance Cost against Time for Case Two

In Figure 6.4 which represents Case Three, the minimum Total Maintenance Cost represented by the lowest point on the curve was at 8400fh with £2.26/h.

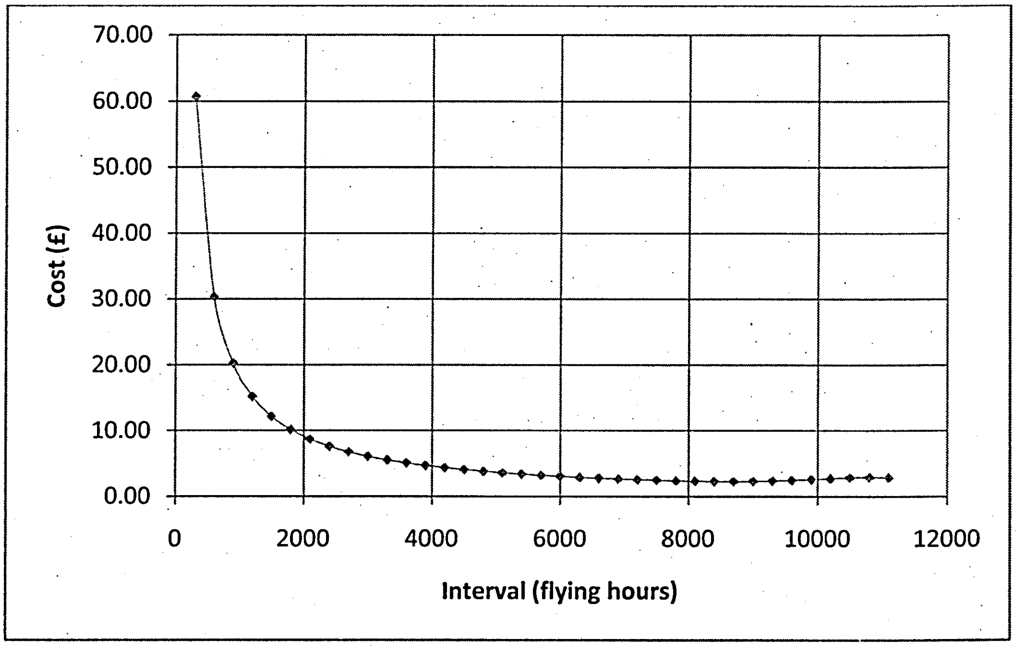

Figure 6.4 Total Maintenance Cost against Time for Case Three

The above graphs displayed the interval with the minimum cost. However, the graphs show the flexibility that can be provided by using the proposed model, as it gives a range rather than exact point to carry out the maintenance task. For example, for these particular components, the maintenance can in fact be carried out at a range of intervals measured by flying hours and the cost is still at an acceptable level. This model was applied to the other components under investigation.

6.3.2.2 Inventory Graphs

The Inventory Output Graphs present the relationship between the Total Repair Cost and the Total Purchase Cost. The horizontal axis represents the intervals in flying hours; and the vertical axis represents the cost of the total repair and total purchase. The relationship between the Total Repair Cost and Total Purchase Cost are represented by two crossing lines and the lines are nearly straight. The two lines are rising with the increasing number of intervals; the purchase line increases steadily and the repair line increases sharply. The three case-studies' inventory graphs are nearly the same in shape as well. The crossing-point between two lines is the decision-point for repairing or purchasing the component: that means that, before the crossing-point, the Total Repair Cost is less than the Total Purchase Cost. In this case the decision-maker will decide to repair the failed component; and after this point the decision is to change or replace the component with a used or new component because of the difference in the cost. The following section includes in brief the analysis of the three case- studies relating to the above figures.

Figures 6.5, 6.6, and 6.7 in the following section show and illustrate the crossing-point between the Total Repair Cost and Total Purchase Cost. In Case One, the crossing-point was at 10200 flying-hours; in Case Two it was at 6300 flying-hours; and, in Case Three, it was at 8700 flying-hours. That means before these points, the Total Repair Cost in the three case-studies was lower than the Total Purchase Cost. Then, in these conditions the decision is to

Repair the components rather than purchase new ones, because the cost is lower.

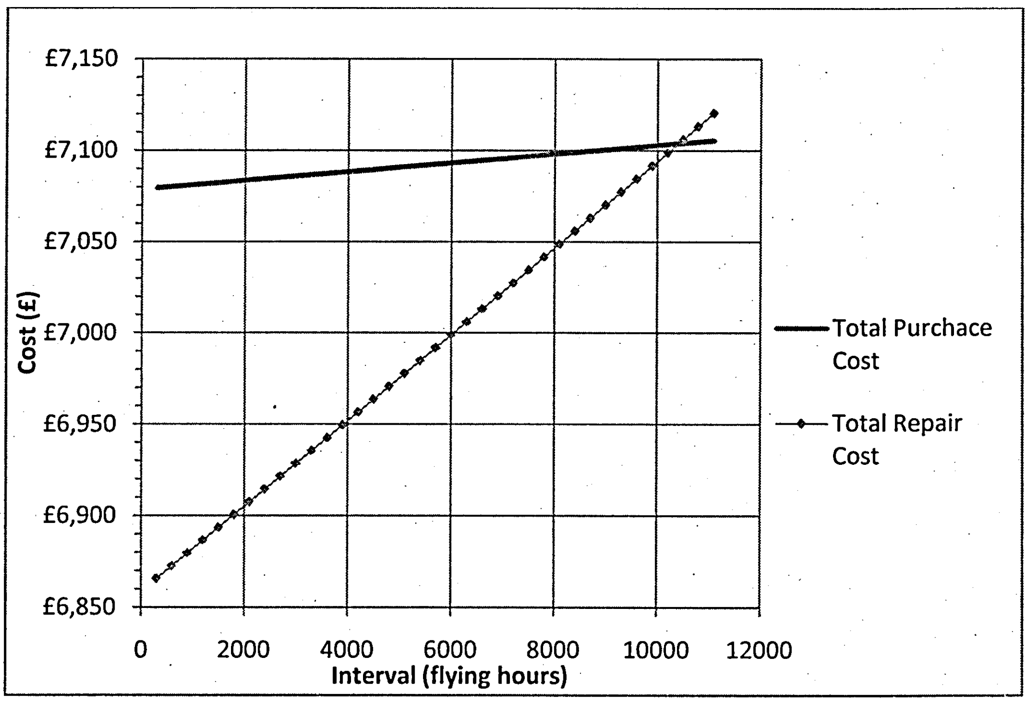

Figure 6.5 Relationship between the Total Repair Cost and the Total Purchase Cost for Case1.

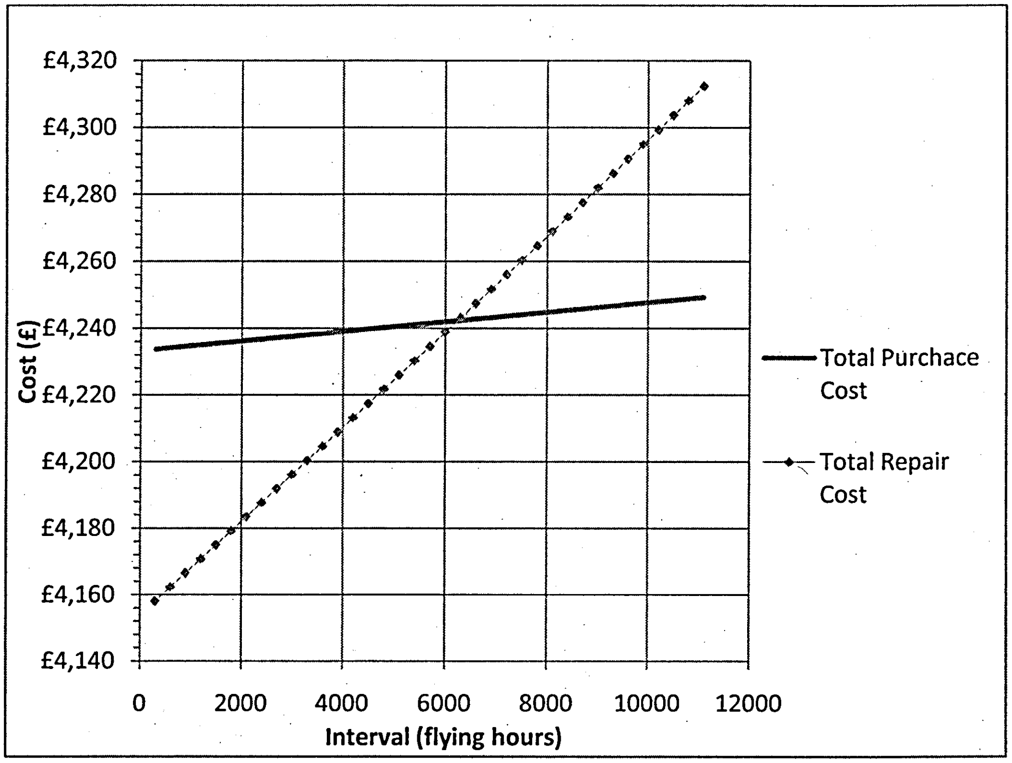

Figure 6.6 Relationship between the Total Repair Cost and the Total Purchase Cost for Case 2.

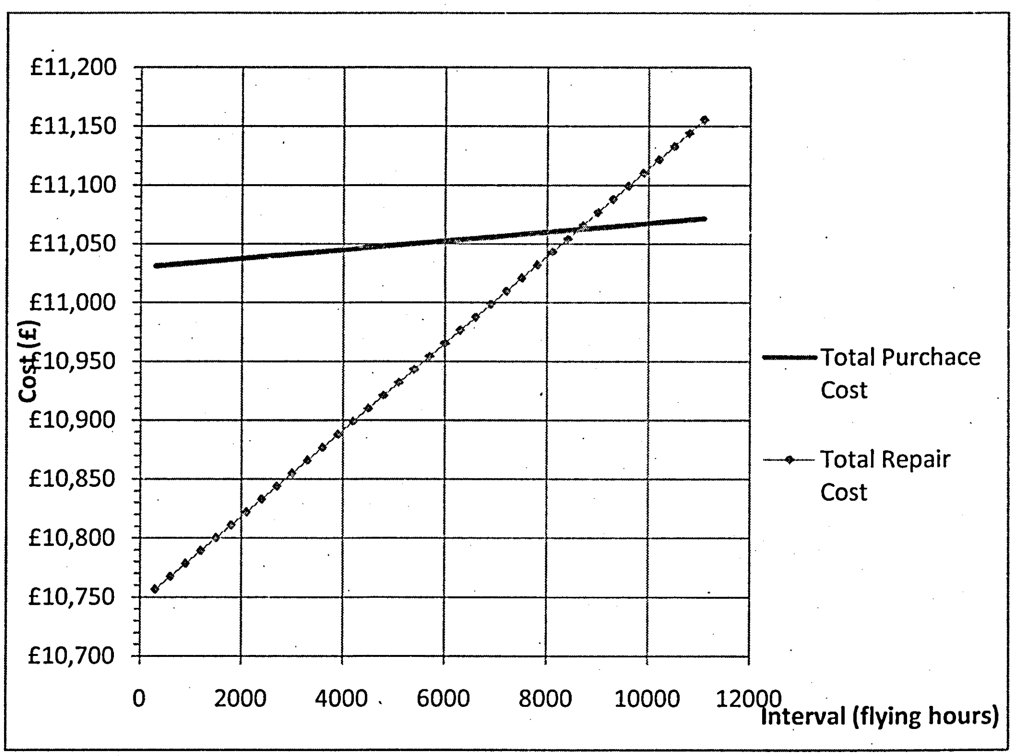

Figure 6.7 Rrelationship between the Total Repair Cost and the Total Purchase Cost for Case 3.

6.4 Conclusion

The Visual Basic 6.0 program was developed and linked with Database and Excel programs, and this helped the author to develop and integrate the two mathematical-models concerning the maintenance-scheduling and inventory-framework. Moreover, this will help the reader to understand and know the author's point of view easily. The outputs were supported by Tables and Figures for three different real case-studies relating to three different repairable jet components on the B737 aircraft. The integration software linking the maintenance-scheduling and inventory in aviation industry determined the minimum maintenance- cost and the decision-point between repairing and purchasing a repairable-component. This will enable the aircraft-technicians to identify the best interval for carrying out the maintenance and to take a good decision for repairing or replacing a failed component. This will optimise the maintenance and inventory costs, which will result in saving money and time. The next chapter will discuss the general conclusion and introduce recommendations and the future work.

Chapter Seven

Conclusions, Recommendations, and Future Work

7.1 Introduction

Two mathematical models for scheduling maintenance and inventory tasks in the aviation industry were developed within the integrated framework using Visual Basic software, database software and the Excel software. The Total Maintenance Cost and the repair-or-purchase decision were decided based on a balance between the cost of failure of an item during operation against the cost of planned maintenance in the first model; and, in the second model, this decision was based on the balance between the cost of repairing an item or purchasing a new one after the removal time. This can be considered as a distinctive feature of an optimal replacement-policy.

The mathematical models were applied in three case-studies represented by three real B737 aircraft-components in the jet-fuel system with different parameters such as price, life-time and the probability of failure and survival. The cost-calculation was done manually and using customised software developed using Visual Basic for verification purposes. The obtained results showed the optimum maintenance-interval in terms of minimum maintenance-cost. An aircraft includes many components in different systems estimated to cost thousands of pounds, and by applying the integrated framework proposed in this thesis, it is expected that a massive saving for the airline companies will occur. The author concluded the work in the next sections.

7.1.1 Proposed Maintenance-scheduling Model

A formulation for the calculation of the cost of the optimum life-limit for every component was developed. The cost was calculated from the proposed mathematical model, and was based on a balance between the cost of failure of a component during operation and the cost of planned maintenance. The model not only provides an optimum interval at which the preventive maintenance should be carried out, but it provides an optimum range within which the maintenance team may have flexibility to decide the time that suits the company production-load.

7.1.2 Proposed Inventory Model

The objective of this study was the development of a mathematical model to determine and to obtain the optimum replacement time and to minimise the total expected annual cost of repairable aircraft-components with infrequent demand and high cost. Repair or replace is the critical decision in aviation because it involves both cost and safety issues. Many investigations and studies have been carried out with respect to repair, replace and reliability which were discussed in the literature review. An inventory mathematical model was developed based on the cost and reliability of the component using Visual Basic 6.0. Then the model was implemented and applied in three real cases. This included Holding-cost, Delay-cost, Repair-cost, and Purchase Cost. Holding- and Delay-cost calculations were based on the stock-level in the warehouse. In the proposed inventory model, the demand-process for the component was assumed to be following a Poisson distribution. Any other appropriate demand process could have been used. The reliability of the component at any given time was calculated using Weibull distribution. There are many distribution-processes which could have been used to calculate the reliability. It is assumed that the Cumulative Failure Rate (CFR) increases constantly with the time. This makes Weibull distribution almost similar to exponential distribution. Hence exponential distribution also could be used to calculate the reliability of the system at any given time.

Removal Time (RT) or Failure-rate is based on the preventive maintenance plan that is at the fixed interval time.

The proposed mathematical model is best suited for those components which have a high purchase-price and repair costs, and where the difference between repair-cost and purchase-cost is small. As the difference between the purchase- and repair-cost increases, the replacement-time also increases in other words they are directly proportional.

In general, the required reliability in an engineering environment should be in the region of 95%. However, in aviation reliability is the prime concern; keeping that in mind, replacement of the component is proposed at 97% reliability or higher. For calculation purposes, the cumulative failure-rate was assumed, but in the real world it is the responsibility of the maintenance-engineers to find the exact value of the cumulative failure-rate.

Least square and regression method were used to estimate the Weibull distribution. It is also possible to estimate the scale and shape parameters of the Weibull distribution by using a graphical method. To obtain the regression equation Minitab 15 software was used to estimate the Weibull parameters.

7.1.3 Proposed Integrated Framework

In Chapters Four and Five, the models concerning maintenance and inventory were developed separately and applied manually. In Chapter Six, the two models were integrated to form the proposed framework by developing a Visual Basic program linked with a database program to save and print out the results as a report at any time. The integrated framework can be used as a maintenance model or as an inventory model or as an integration of both. The flexibility of the integrated framework enables the users to follow any repairable component on the aircraft.

The integrated framework output consists of important information such as Probability of Survival, Reliability of new and repaired components, Corrective Maintenance Cost, Preventive Maintenance Cost, Total Maintenance Cost, Total Repair Cost, and Total Purchase Cost.

7.2 Research Contributions to Knowledge

The contributions to knowledge from this study can be summarised in the following developments:-

- A maintenance decision-making model to determine the optimum preventive maintenance interval for expensive aircraft-components.
- A decision-making inventory model to balance the cost of repair and purchase for expensive components.
- An integrated framework to combine maintenance-scheduling and inventory control policy in an aircraft environment to minimise the maintenance-cost without compromising the safety.

In addition to above:

- The proposed framework can form the basis for a decision support-tool that could be used by airlines technical management to check the economic and operational conditions for all repairable components on an aircraft.
- The proposed framework can be applied to all repairable components at any stage of their life-time.

- The proposed framework could be used for different aircraft-systems, not just engine-components; and for different types of aircraft, not just the B737 aircraft.

7.3 Limitations and Future Work

In this research, the author found it difficult to collect information concerning the components' historical data from the Libyan Arab Airlines Company. Fortunately, the life-limit and spares-cost were available and real values were used in the case-studies. The standard deviation value has been assumed to be 11% of the components' life-limit, which was found to be appropriate, since, when the standard deviation increases, the probability of survival decreases. The components' probability of survival is an important issue that affects aircraft-safety. That is why reliability maintenance-centres definitely should be used in such an environment, as safety comes first.

Regarding the inventory model, the data concerning the demand and the average number of component-repairs in-house and out-house were not available, and this affected the information about the repair-cost significantly. The author assumed these data and because the repair-cost is a function of the Total Repair Cost value, this will affect its crossing-point with the Total Purchase Cost. In this case the author assumed the average number of repaired components alike in-house and out-house as 0.001 of demand, and, when this assumption changed up or down, the crossing-point changed and this affected the interval value. In addition the Weibull distribution-parameters, shape-parameter, and scale-parameter were calculated by assuming the Cumulative Density Function because of the absence of the components' historical data.

The limitations of the proposed work in this thesis can be summarised as follows:-

In the aviation industry, the availability of data concerning the reliability of the aircraft components is vital to guarantee that the results are reliable. Thus the proposed framework may be used under not only a cost-centred maintenance but also a reliability-centred maintenance strategy.

In the proposed framework, two probability distributions have been used: namely normal distribution was used in the maintenance-schedule model and Poisson distribution was used in the inventory model. However, different probability distributions could be added to the framework to handle special cases that may follow different distributions from those which were considered in the framework.

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Appendix A

Software Development and Application of the Proposed Integrated Framework

In order to implement the proposed framework, four main tasks were being considered namely, data-entry, maintenance-scheduling outputs, inventory outputs and the integration of maintenance and inventory.

Each task will be presented by a form and the four forms will be integrated in one project. In addition, the four forms will be linked with database software.

The design for each form is based on the type of data and its size included in the form:

- Form View includes the window-design that will be discussed and illustrated in this part. Each form used in this software is composed of different controls such as: frames, textboxes, labels, commands, data, date and time. All of these controls are created by using Control Box. The colours and font are created by using the Properties window and all forms are linked with each other.
- Form Code includes the Visual Basic language statements that execute the program-application. The language statements here include some of the main rules, such as the If rule statement and Select Case rule statement for choosing the available right solutions; and the For Next rule statement for looping.

In the use of any software, there are two kinds of data involved: entry-data and output-data. Every program has independent data which is related to the nature of the subject that the user is interested in.

A.1 Form View

Table A.1 includes the entry-data variables and symbols for both the maintenance-scheduling and inventory entry-data that are used in the Visual Basic 6.0 software.

Table A.1 Software Entry-data

Entry-data	Symbol
Case Study	CS
Aircraft Type	AT
Interval	I
Life Time	LT
Spares Cost	SC
Corrective time	CT
Preventive time	PT
In-house Labour Number	ILN
Out-house Labour Number	OLN
In-house Labour Cost	ILC
Out-house Labour cost	OLC
Stock Level	SL
In-house Repair Probability	IRP
Out-house Repair Probability	ORP
Non Repair Probability	NRP
In-house Repair Time	IRT
Out-house Repair Time	ORT
Purchase Lead Time	PLT

The symbols used in the software will be as indicated in chapters four and five.

The Form View includes the entry-data window and the output-data windows that were designed and created by the Visual Basic software for using the program easily, and to enable users to use this program for general calculation or for each case-study separately to avoid delay in entering all input-data. In the following sections the entry- data window and the output-data windows are illustrated.

A.1.1 Entry-data Window

The entry-data window created in Form One is composed of three frames (see Figure A.1).

1. Frame one include six different entry-data such as: Case- study (CS), Aircraft-type (AT), Interval (I), Technical-delay Cost (TDC), Life-time (LT) and Spares-cost (SC).
2. Frame Two is concerning with "the maintenance entry-data", include six texts and six labels such as: Corrective Time (CT), Preventive Time (PT), In-house Labour Number (ILN), Out-house Labour Number (OLN), In-house Labour Cost (ILC), and Out-house Labour Cost (OLC).
3. Frame Three is entitled "inventory entry-data", made of seven texts with seven labels such as: Stock-level (SL), In-house Repair Probability (IRP), Out-house Repair Probability (ORP), and Non-house Repair Probability NRP), In-house Repair Time (IRT), Out-house Repair Time (ORT), and Purchase Lead-time (PLT).

Moreover, each frame has two commands for entering data, the first command for entering data without saving them; and the other command for entering data to save them in the Database programme.

The remaining commands in Form One were created to perform different tasks such as:

- The "S*how the Maintenance Result*" command enables the user to show the maintenance-output in Form Two relates to the maintenance-scheduling model as a single interval.
- The "*Show the Inventory Result*" command enables the user to show the inventory-output in Form3 is concerned with the inventory model as a single interval.
- The "*Show the Integration Result*" command enables the user to show the integration-output for all intervals together (300, 600, 900, 1200…) in Form four; and in Form Five the user can show the integration-output for each interval as a single interval similar to the first interval (300 flying-hours).
- The "New" command to clear and delete previous unrequired data in the Database programme.
- The "Print" command to print the entry data window.
- The "Exit" command to stop the running of the program.
- Three data-controls (Data One, Data Two and Data Three) to link the Visual Basic programme with the Database programme.
- Date and time labels and texts to show the date and time when the user runs the programme.

The program enables the user to run it for each case-study separately and for general application as illustrated in the Figures A.1, A.2, A.3, and A.4.

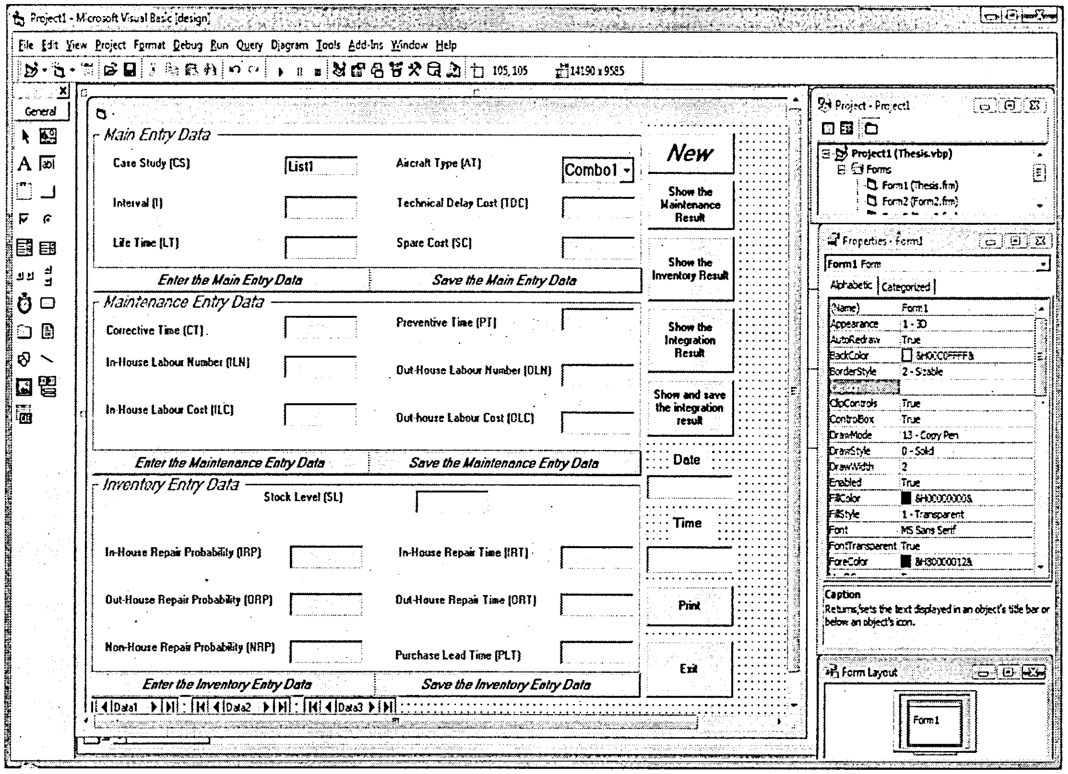

Figure A.1 Entry-data Window for General Application

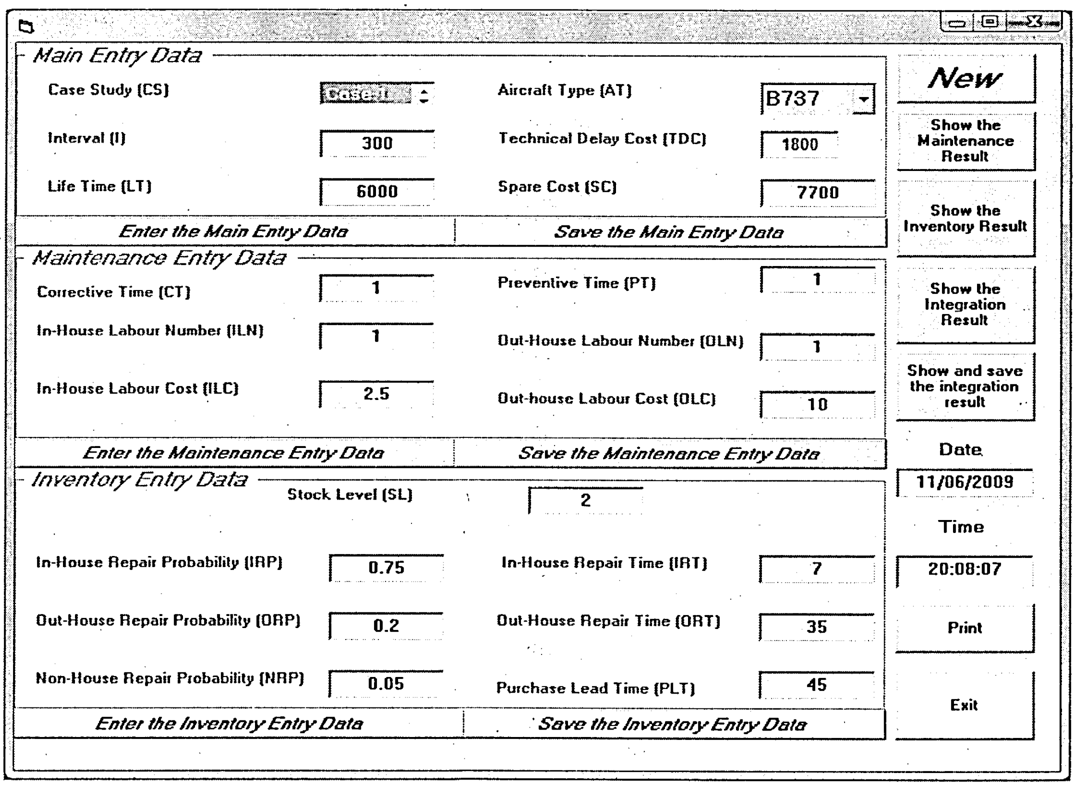

Figure A.2 Entry-data Window for Case One

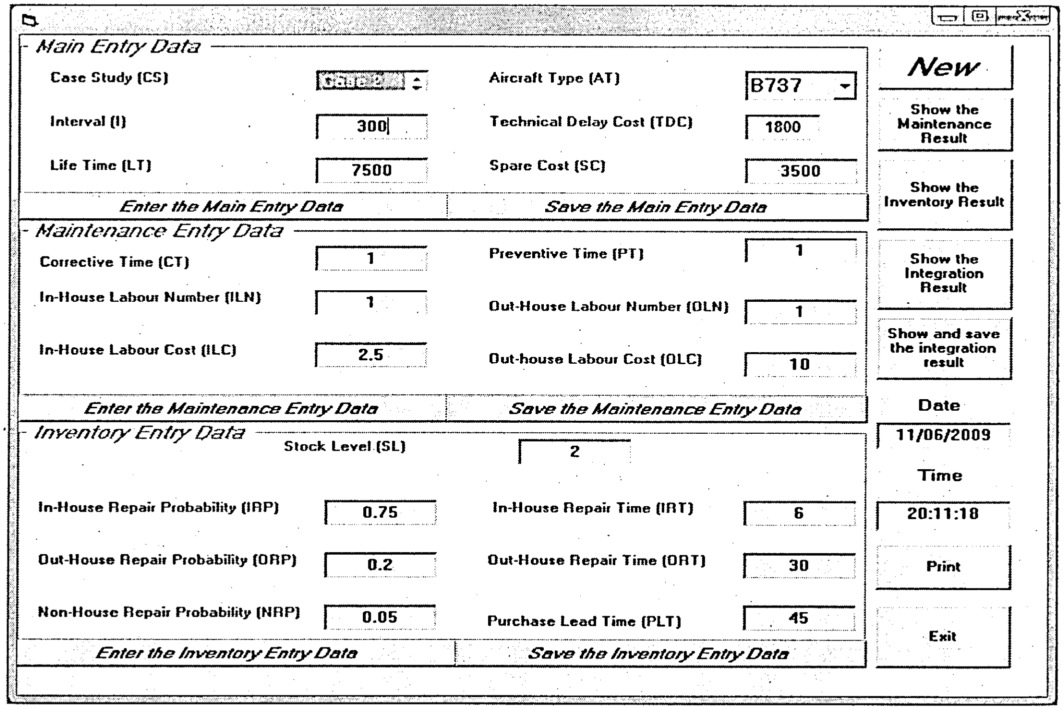

Figure A.3 Entry-data Window for Case Two

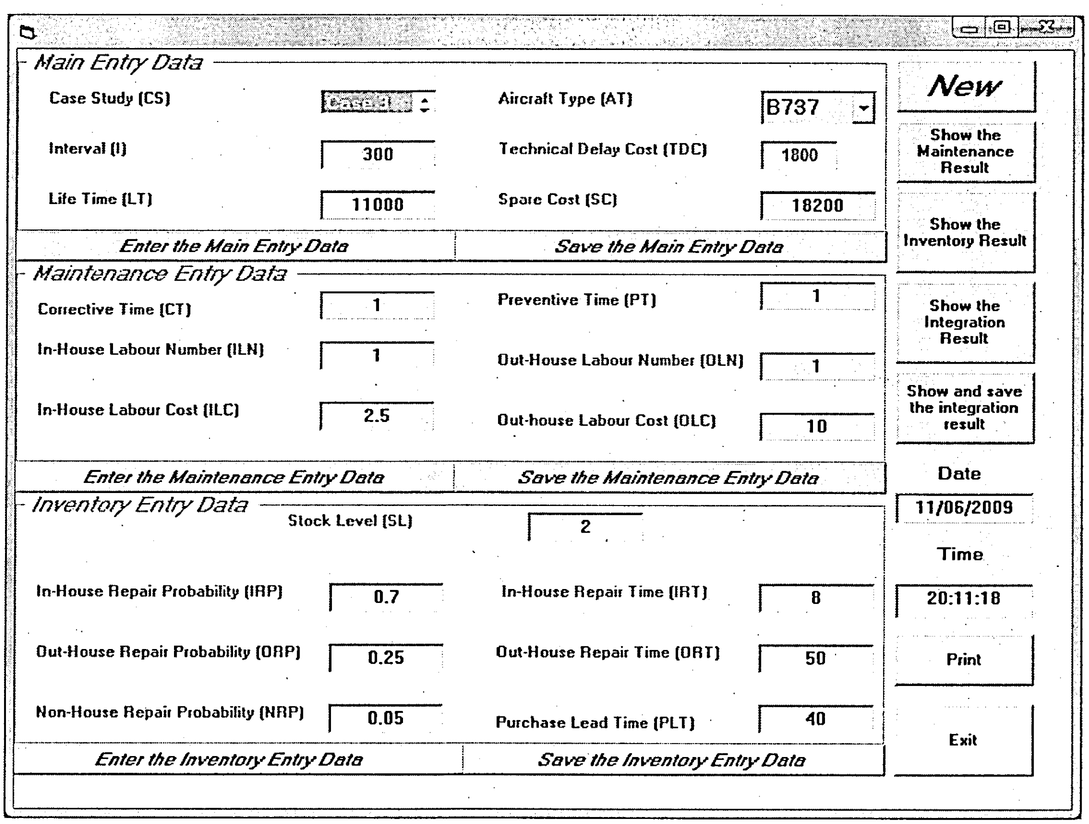

Figure A.4 Entry-data Window for Case Three

A.1.2 Output-data Windows

The second type of data is output-data that show the program results in executed windows concerning the maintenance-scheduling model, the inventory model, and the integration of the two models. The user in this program can save a project by clicking on the Save Project button from the File menu and by connecting the Visual Basic program with a database program from data buttons that exist in the control-box. The output variables and symbols that are used in the Visual Basic software program are shown in tables A.2 and A.3 in the following section:

Table A.2 Maintenance-scheduling Variables and Output Symbols Data

Maintenance-scheduling Output-data	Symbol
Interval	I
Life-time	LT
Spares-cost	SC
Normal Distribution Function	Z
Probability of Failure	PF
Probability of Survival	PS
Cost of Failure	CF
Cost of Failure-prevention	CP
Corrective Maintenance Cost	CMC
Preventive Maintenance Cost	PMC
Technical-delay Cost	TDC
Total Maintenance Cost	TMC

Table A.3 Inventory Output-data Variables and Symbols

Inventory Output-data	Symbol
Interval	I
Life-time	LT
Spares-cost	SC
Stock-level	SL
In-house Repair Cost	IRC
Out-house Repair Cost	ORC
Repair Reliability	RR
New Reliability	NR
Re-suply Time	RT
Holding Cost	HC
Repair Cost	RC
Purchase Cost	PC
Delay cost	DC
Total Repair Cost	TRC
Total Purchase Cost	TPC

Output Windows from Visual Basic software results consist of Form Two, Form Three, Form Four, and Form Five. Form Two belongs to the maintenance-scheduling output, Form Three is for the inventory output, and Form Four and Form Five relate to the integration output.

A.1.3 Maintenance-scheduling Output Window

The maintenance-scheduling output-window is represented in Form Two (see Figure A.5) and consists of:

1. Frame One. This contains twelve text-boxes for displaying texts and figures and twelve labels to display the model output-text that include information such as: Case-study (CS), Interval (I), Life-time (LT), Spares-cost (SC) and the results of calculations such as: Standard Normal Distribution (Z), Probability of Failure (PF), Probability of Survival (PS), Cost of Failure (CF), Cost of Failure-prevention (CP), Corrective Maintenance Cost (CMC), Preventive Maintenance Cost (PMC) and the Total Maintenance Cost (TMC).
2. Ten command buttons enable the user to execute and initiate different actions as follows:
    - Two command buttons: the first one is for displaying the maintenance results without saving them; and another command button for displaying and saving the results in the connected database program.
    - A command button to go back to the entry-data in Form One.
    - A command button to display and save the inventory results in Form Three.
    - A command button to just show the integration results in Form Four.
    - A command button to show and save the integration result.
    - A "New" command button to clear all texts.

- A "Print" command button to print the Total Cost of Maintenance results window.
- An "Exit" command button to stop running the program.
- Date and time to show date and time of running the program.
- Four Data buttons to connect the program to a database for saving the output.

Figure A.5 below illustrates the Total Cost of Maintenance output window created by the Visual Basic software:

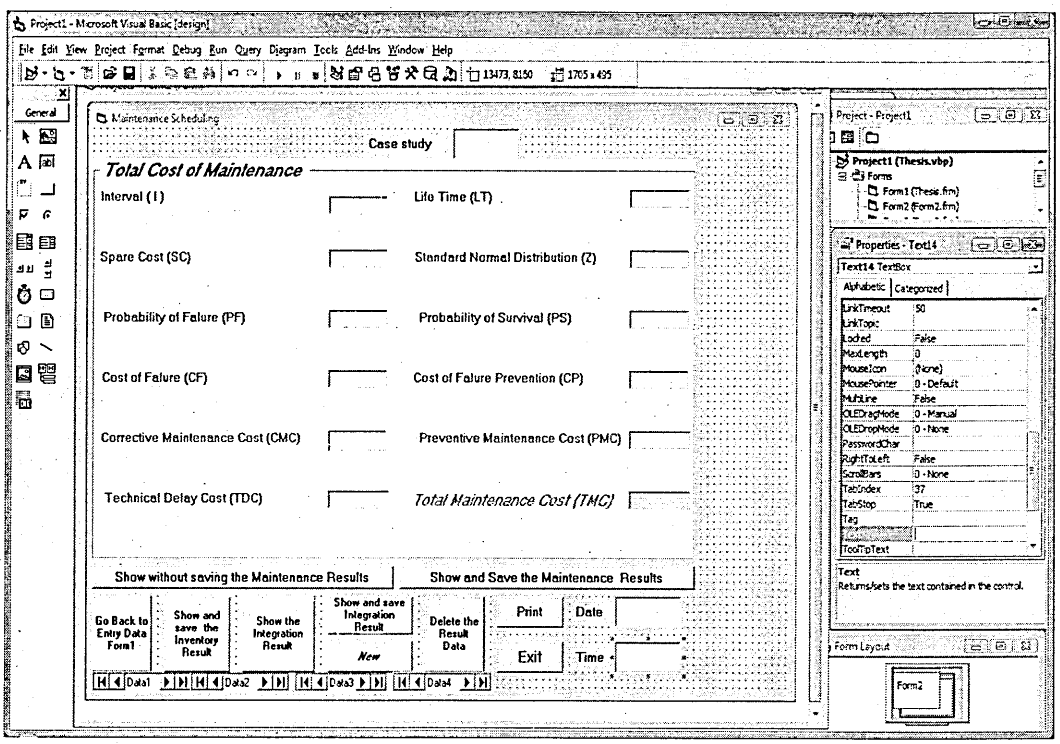

Figure A.5 Total Maintenance Cost Output Window

A.1.4 Inventory Output Window

The inventory output designed window represented by Form Three consists of:

1. Frame One. This contains fifteen text-buttons to display the texts and numbers and fifteen labels to display the model output-text that include information such as: Case-study (CS), Intervals (I), Life-time (LT), Spares-cost (SC), Stock-level (SL) and the results of calculations such as: In-house Repair Cost (IRC), Out-house Repair Cost (ORC), Repair Reliability (RR), New Reliability (RN), Re-supply Time (RT), Holding Cost (HC), Repair Cost (RC), Purchase Cost (PC), Delay Cost (DC), Total Repair Cost (TRC), and Total Purchase Cost (TPC).
2. Ten command buttons enable the user to execute and initiate different actions as follows:
    - Two command buttons: the first one for displaying, without saving, the maintenance results and the other command button for displaying the results and saving them in the connected database program.
    - A command button to go back to the entry-data in Form One.
    - A command button to go back to the maintenance results in Form Two.
    - A command button to just show the integration results in Form Four.
    - A command button to show and save the integration result.
    - A "New" command button to clear all texts.
    - A "Print" command button to print the Total Cost of Maintenance results window.

- An "Exit" command button to stop running the program.
- Date and time to show date and time of running the program.
- Four Data buttons to connect the program to a database for saving the output.

Figure A.6 below illustrates the Total Cost of Maintenance window created by the Visual Basic software:

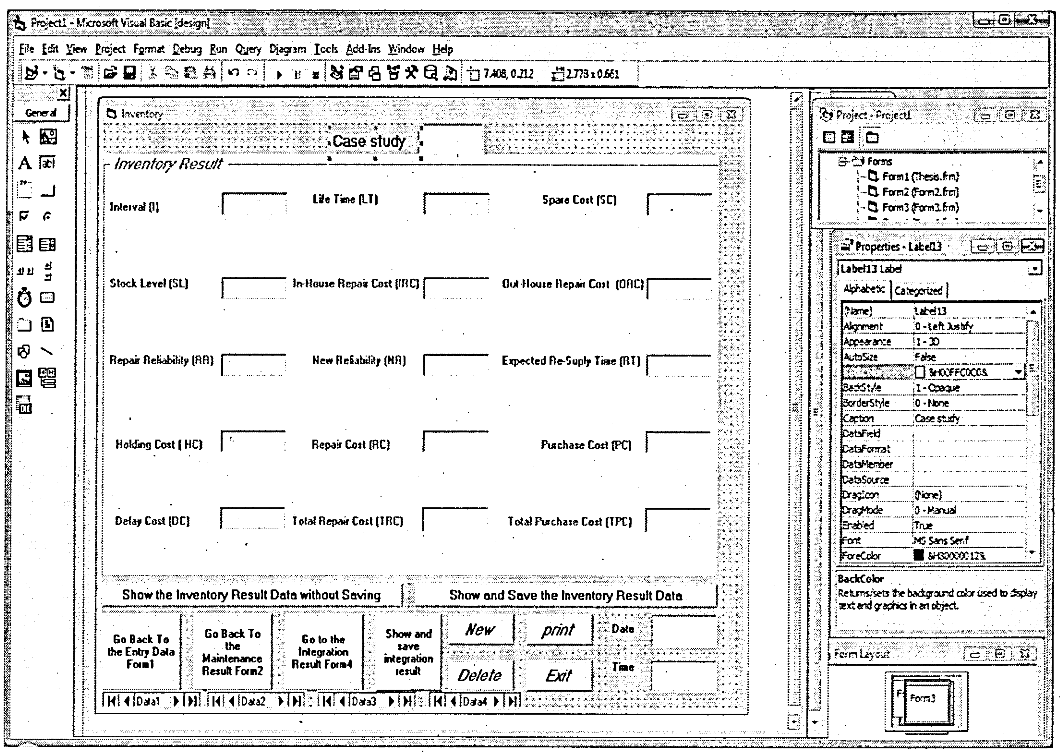

Figure A.6 Inventory Output Window

A.1.5 Integration Output Windows

There are two integration output windows:

1. The first window is just for showing the looping output for all intervals and it is represented in Form Four. The second window is for showing and saving the output that is connected to a database and is represented in Form Five. The first integration output window in Form Four is composed of:
   - Five labels and fourteen text-buttons for displaying texts and numbers and to display the model output-texts that include information such as: Case-study (CS), Life-time (LT), Spares-cost (SC), and six command buttons as follows:
     - A "Go back to Form One entry-data" command button.
     - A "Go back to Form Two maintenance output data" command button.
     - A "Go back to Form Three inventory output data" command button.
     - A "Go to Form Five for showing the integration output data" command button.
     - An "Initiate the calculation" command button.
     - An "Exit" command button.
     - Nine picture-box buttons serve as a container.
     - Date and time to display the date and time during running the program.

Figures A.7 and A.8 below illustrate the integration output window:

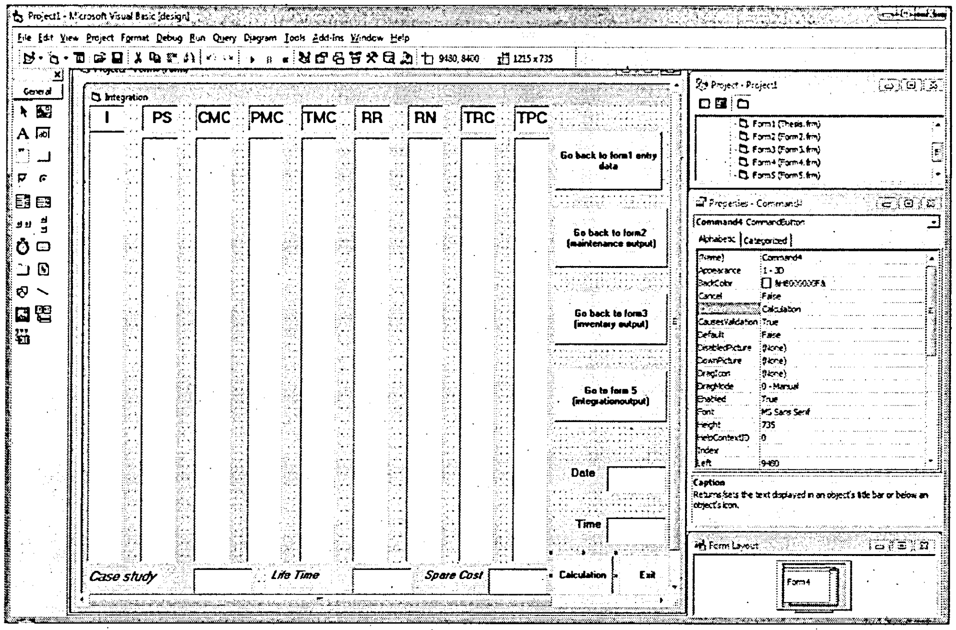

Figure A.7 Illustration of the Integration Output Window

2. The second integration output window is represented by Form Five and is made of:

    - Fourteen labels and fourteen text-buttons to display the description and output-figures for the integration of two models that include information such as: Interval (I), Case-study (CS), Life-time (LT), and eight command buttons as follows:

    - A "Go back to Form One entry-data" command button.
    - A "Go back to Form Two maintenance output-data" command button.
    - A "Go back to Form Three inventory output-data" command button.
    - A "Go to Form Four for showing the integration output data" command button.
    - An "Initiate the calculation" command button.

- An “Exit” command button.
- A “Print” command button.
- A “New” command button.
- Four data buttons.
- Date and time to display the date and time during running the program.

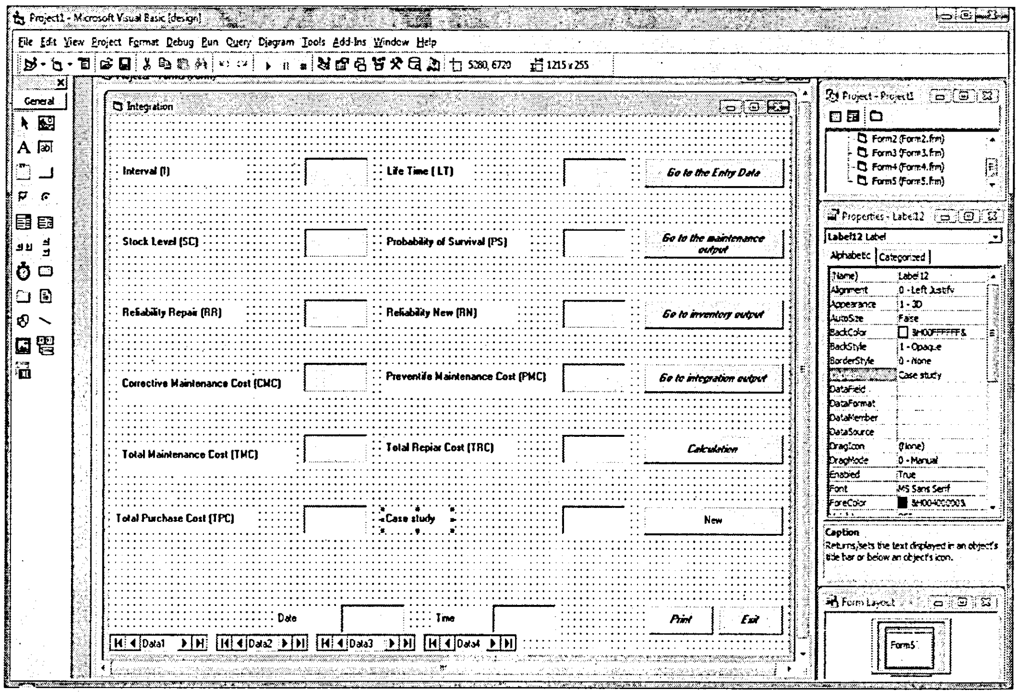

Figure A.8 Illustration of the Integration Output Window

A.2 Form Code

The first step was planning and designing the different view windows such as the entry-data windows and output-data windows. Moreover, because there are different studies or subjects and different users' ideas, every program has an independent design and application.

All program codes concerning Form One, Form Two, Form Three, Form Four and Form Five including the Visual Basic language and statements will be shown at the end of this Appendix. The code window appears when the user double clicks any command button such as the "Exit" command button by entering (End) between the private sub and End sub-statement as below:

Private Sub cmd Exit_click

(End)

End Sub

The application is executed after finishing the code by clicking the start button from the Run menu or by clicking the arrow or by pressing the F5 button. The execution screen for entry-data and output-data appears below.

A.2.1 Data-entry Execution-window

Figure A.9 shows the execution-window for entry-data as a general calculation, which enables the user to enter any data for any component on the aircraft. There are three entry-data command-buttons not connected to a database program and there are three entry-data command-buttons connected to a database program in order to store the entry-data. The design of this window and the different control buttons are described in the form-view section.

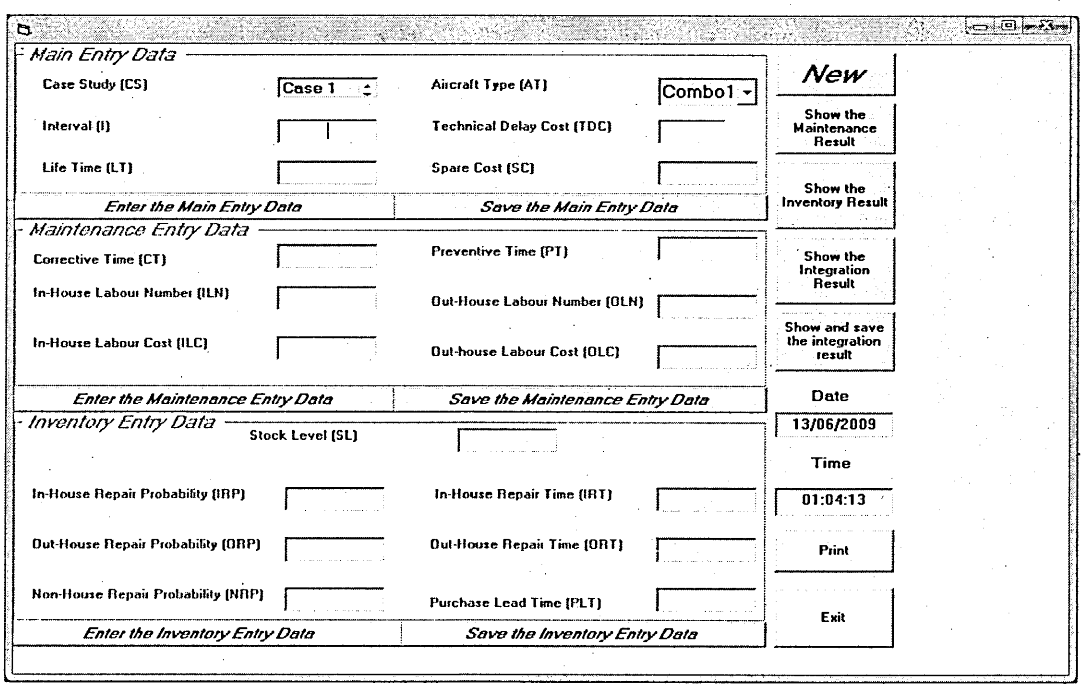

Figure A.9 General Entry-data Execution-window

A.2.2 Case-studies Entry-data Execution-windows

Figure 6.10 shows the entry-data execution-window related to Case One, includes three kinds of data: main entry-data, maintenance entry-data, and inventory entry-data. In addition, this applies to Case-studies two and three that are illustrated in Figures A.11 and A.12.

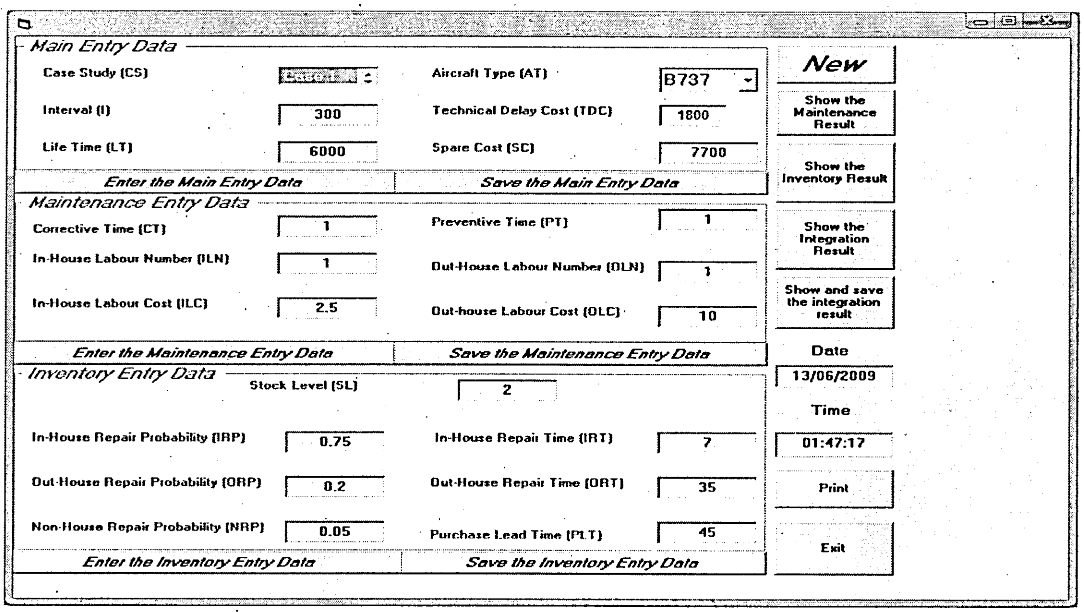

Figure A.10 Case One Entry-data Execution-window

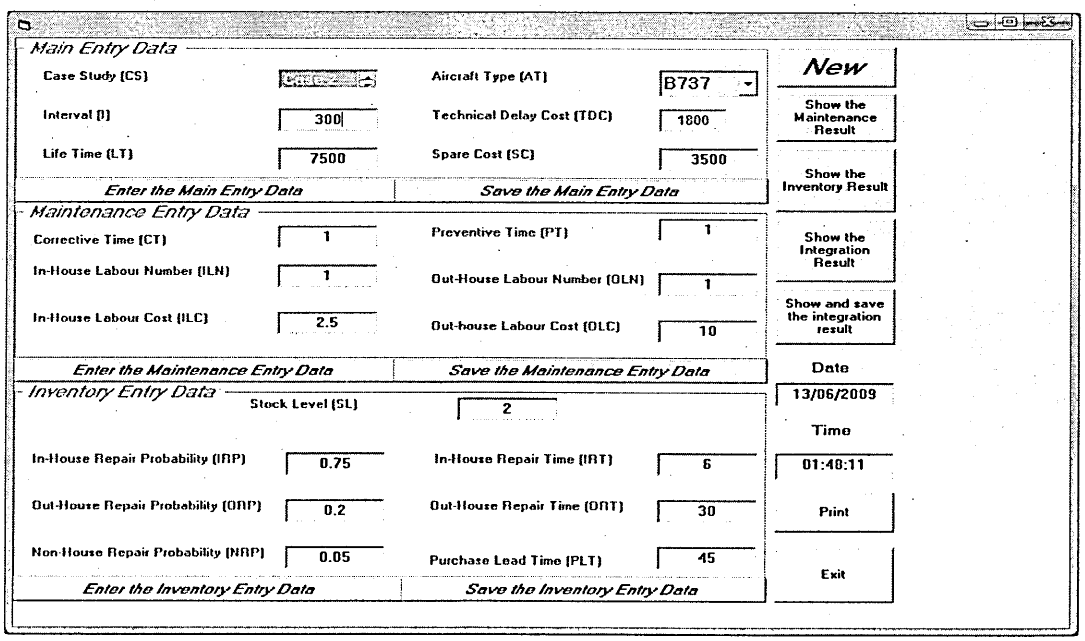

Figure A.11 Case Two Entry-data Execution-window

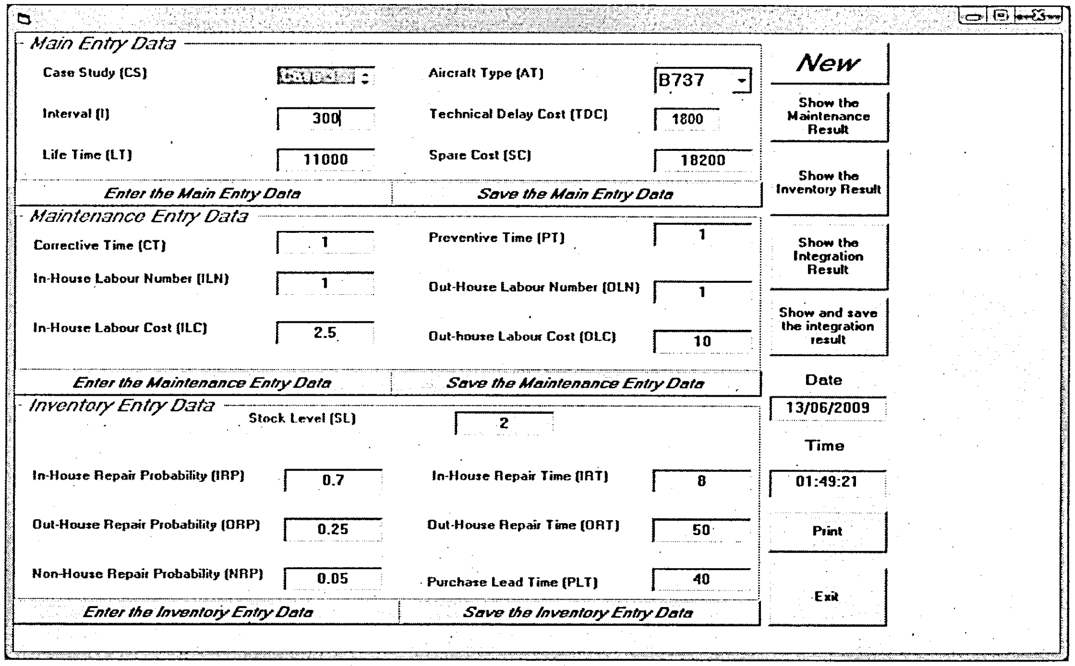

Figure A.12 Case Three Entry-data Execution-window

A.2.3 Output-data Execution-windows

The user executes the application by clicking the start-button from the Run menu or by pressing the F5 button. The execution-screen for entry-data appears at first to enable the user to enter data in general or for each case-study individually. By clicking on command-buttons related to the output-data execution-windows, the output-data execution-windows will appear directly such as the Total Cost of Maintenance execution-window, Inventory execution-window, or Integration execution-windows.

1. **Total Cost of Maintenance Output-data Execution-window for Case One:**

Figure A.13 shows the Total Cost of Maintenance output-data execution-window for Case One, which indicates the different maintenance output-data like Interval (I), Life-time (LT), Spares-cost (SC), Standard Normal

Distribution (Z), Probability of Failure (PF), Probability of Survival (PS), Corrective Maintenance Cost (CMC), Preventive Maintenance Cost (PMC), and Total Maintenance Cost (TMC). In this window there are two command-buttons concerning the output-data: the first button is just to show the data without saving it; the second command-button is for showing and saving the output-data in a database program. From the Case One output-data execution-window, by clicking on other output-command buttons, the user can move to any output-data execution-window to show the output-data, or back to the entry-data execution-window. In addition, the user can show the date and time of executing the program and print the window by clicking on the print command-button. Finally, the user clears the window by clicking on the "New" command-button and stops running the program by clicking on the "Exit" command-button.

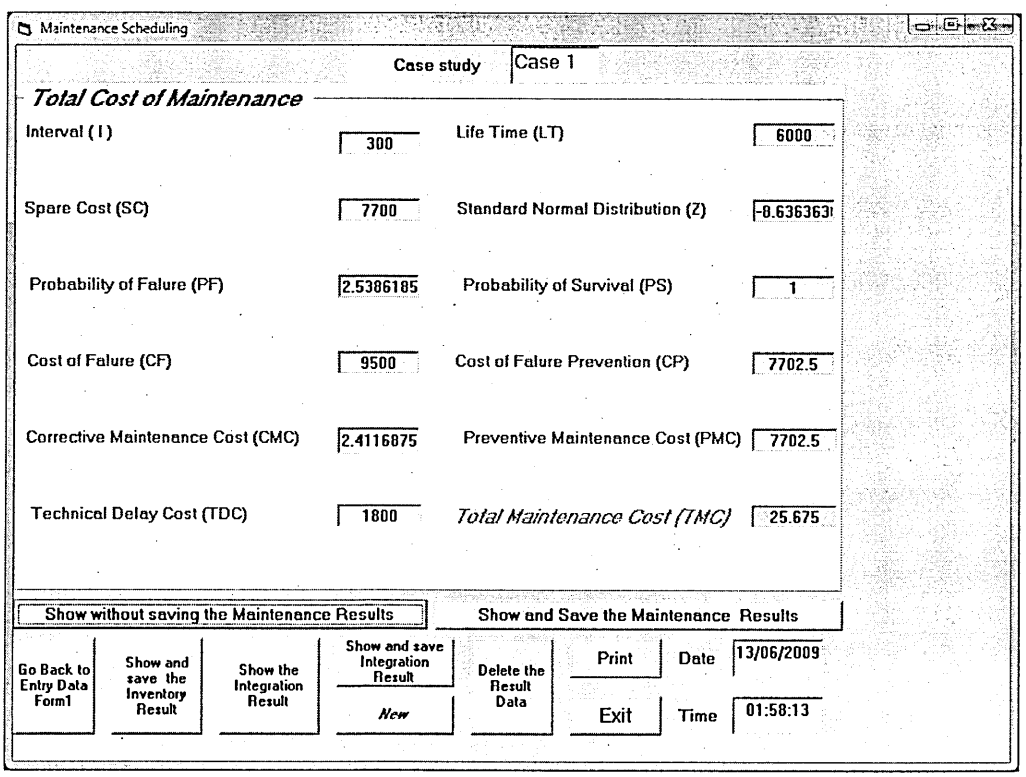

Figure A.13 Maintenance Output-data Execution-window for Case One

2. Inventory Output-data Execution-window for Case One

The user can move to, and show directly, the Inventory-output Execution-window from the Entry-data Execution-window or from any output-data execution-window by clicking the Inventory Output-data command-button in all windows.

Figure A.14 illustrates the Inventory Output-data Execution-window that is composed of Interval (I), Life-time (LT), Spares-cost (SC), Stock-level (SL), In-House Repair Cost (IRC), Out-House Repair Cost (ORC), Repair Reliability (RR), New Reliability (NR), Re-Supply Time (RT), Holding Cost (HC), Repair Cost (RC), Purchase Cost (PC), Delay Cost (DC), Total Repair Cost, And Total Purchase Cost (TPC). The output-data which appears in the execution-window is concerning the interval 300fh.

Command-buttons enable the user to execute the following:

- Show just the Inventory output-data.
- Show and save the Inventory output-data in a database program.
- Go to another execution-window.
- Clear and delete the included output-data from the window.
- Show the date and time during the running of the program.
- Print the output-data window.
- Stop running the program.

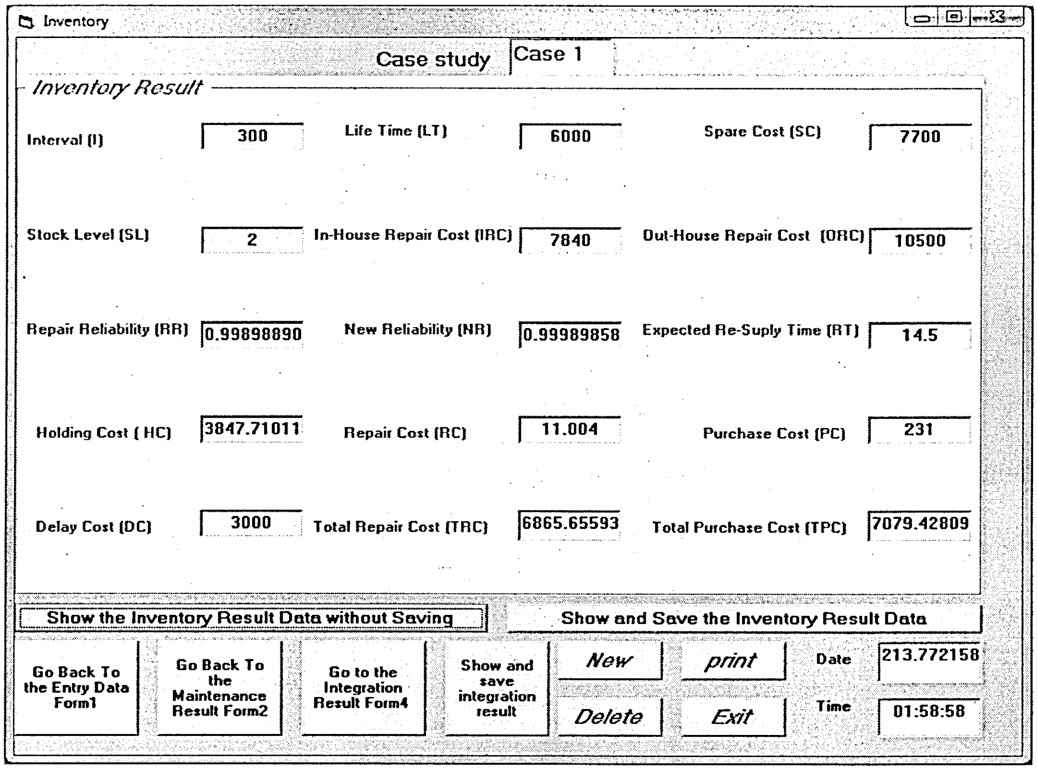

Figure A.14 Inventory Output-data Execution-window for Case One

3. Integration Output-data Execution-windows for Case One

There are two Integration Output-data Execution-windows as shown in Figures A.15, A.16 that are created and represented by Form Four and Form Five.

The first Integration Output-data Execution-window is just for showing the Integration Output-data concerning the maintenance and inventory-models for all intervals from 300fh to 12000fh. The user can go directly to these windows from the Entry-data Execution-window or from the other execution-windows such as the Maintenance Output-data Execution-window and Inventory Output-data Execution-window by clicking on the command-buttons to activate the Integration Output-data Execution-windows.

Both Integration Output-data Execution-windows contain the results such as Case-study (CS), Life-time (LT), Spares-cost (SC), Interval (I), Probability of Survival (PS), Corrective Maintenance Cost (CMC), Preventive Maintenance Cost (PMC), Total Maintenance Cost (TMC), Repair Reliability (RR), New Reliability (NR), Total Repair Cost (TRC), and Total Purchase Cost (TPC).

A set of command-buttons to activate the other windows includes:

- A "Go back to Form1 entry-data" command-button.
- A "Go back to Form 2 maintenance output-data" command-button.
- A "Go back to Form 3 inventory output-data" command-button.
- A "Go to Form 5 integration output-data" command-button.
- An "Execute the integration output-data" command-button.
- A "Print the integration output-data" command-button.
- An "Exit" command-button.
- The user can show the date and time while the program is running.

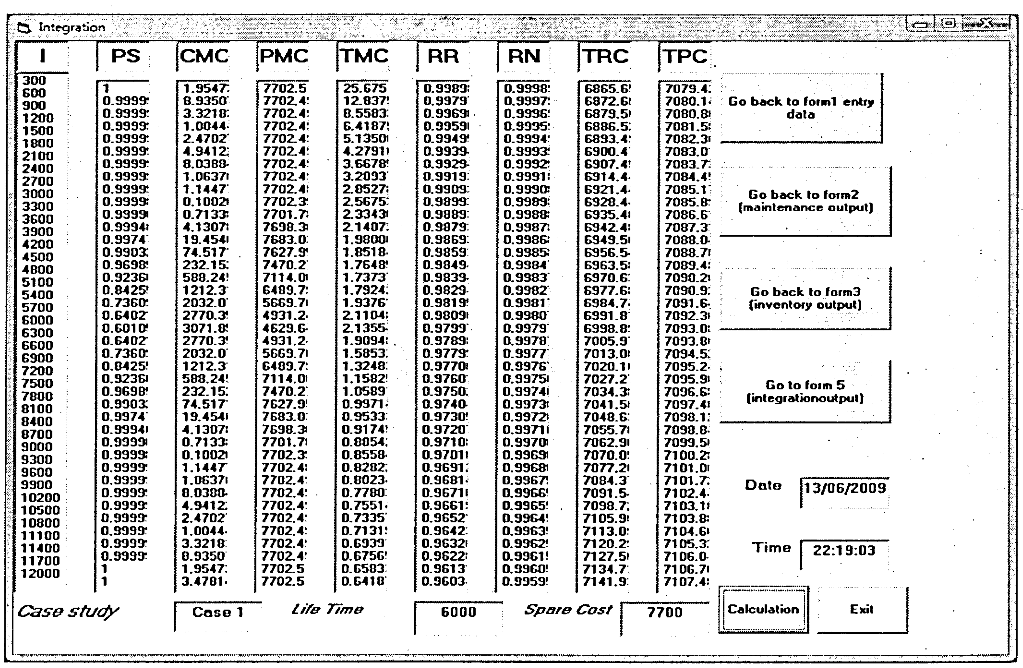

Figure A.15 Integration Output-data Execution-window for Case One

The second Integration Output-data window is for showing and saving output-data for a single interval that starts at 300fh in a database program. In addition, the window includes the same contents as the previous Integration Output-data execution-window.

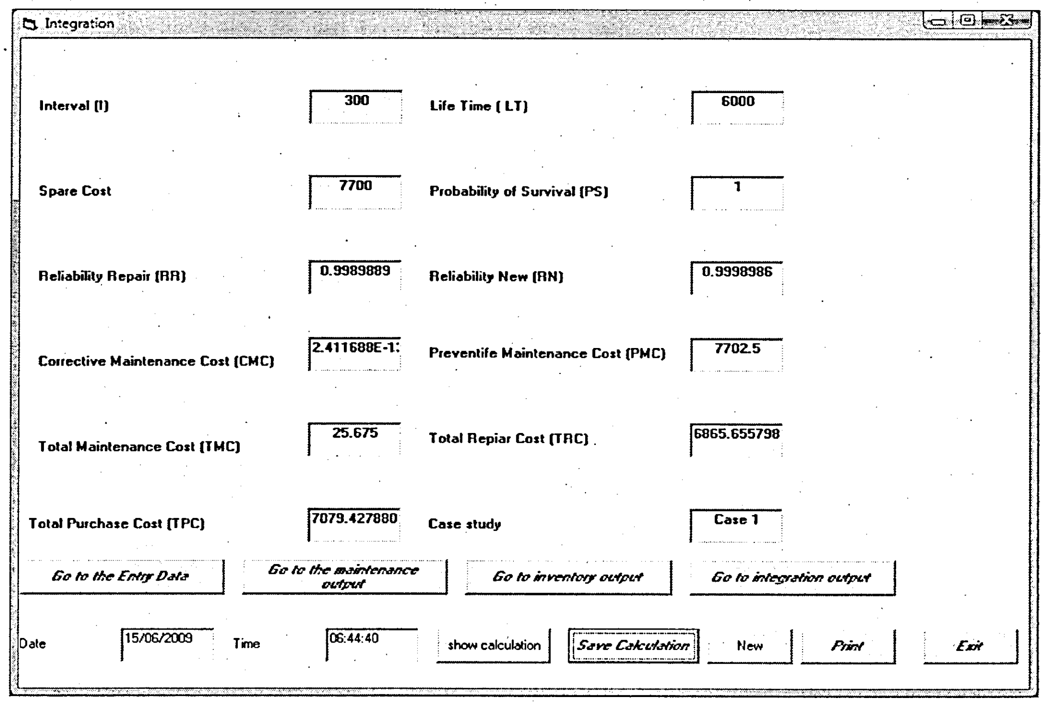

Figure A.16 Integration Output-data Execution-window for Case One

Appendix B

Definitions

Management: the organisation, control, and administration of the many facets of the maintenance operation.

Maintenance: Is every task carried out on the system or its components to assure that the aircraft or system is working properly according to predetermined needs or demands.

The common goal of maintenance: is to provide a fully serviceable aircraft when it is required by an airline at minimum cost.

The purpose of maintenance: is to extend the component life time or at least the mean time until the next failure.

Preventive maintenance (PM): Preventive (or scheduled maintenance) is done at predefined ages of the system in order to reduce the probability of (potentially expensive) failures of the system. Preventive maintenance is widely used to avoid unscheduled failures and the loss of production.

Corrective maintenance (CM): Corrective maintenance is performed to restore a system to state of functioning after the system has entered a state of failure.

Aircraft maintenance: Is an action that can restore an item to a serviceable condition, and consists of servicing, repair, modification, overhaul, inspection and determination of condition.

Maintenance zone: identified area on an aircraft where visual inspections are performed on all elements within the zone.

Planned maintenance: Work performed according to a scheduled plan, as in preventive maintenance.

Unplanned maintenance: Work performed promptly in order to avoid serious consequences on the resources and system performance and/or to keep the system safe.

Scheduled maintenance: including pre-flight, post-flight, daily and phase checks, calendar time changes, time limited component changes, in addition to A, B, C, and D checks (periodic aircraft PM/inspection programs of increasing intensity)

Unscheduled maintenance: to handle unplanned problems reported by flight or maintenance crews. As a rule of thumb, aviation department estimates unscheduled maintenance workload to be 50% of scheduled maintenance workload.

Special maintenance: as required to satisfy special instructions or directives by the manufacture, Federal Aviation Administration (FAA), or aviation management.

Optimization of maintenance plans and schedules: helps to preserve a stable production and low maintenance costs during a given time period by using mathematical models and algorithms.

Direct maintenance costs (DMCs): The labour and material costs directly expended in performing maintenance of an aircraft or related equipment (ATA, IATA and ICCAIO, 1992). The costs do not include the labour and material expenditures which contribute to activities such as administration, supervision, tooling, test equipment, facilities, and record keeping.

Maintenance Labour cost: That part of the cost of services attributable to maintenance team wages.

Crew Labour cost: That part of the cost of services attributable to operation team wages.

Purchasing cost: Is based on the price per unit of the item it may be constant or it may be offered at a discount.

Setup cost: Represents the fixed charge incurred when an order is placed it is independent of the order quantity.

Holding cost: Represents the cost of maintaining inventory in stock it includes the interest on capital and the cost of storage, maintenance and handling.

Shortage cost: Is the penalty incurred when we run out of stock it includes potential loss of income and the more subjective cost of loss in customer goodwill.

The actuation time: is the pre-determined period of time between two consecutive preventative actions.

Downtime: is the period of time when something, such as a system or aircraft, is not in operation, especially as the result of a malfunction.

Breakdown: is the act or process of failing a component or a system to its function.

Non linear system: systems in which the relationships between various variables and parameters are not linear in nature.

Delay: Is an event that causes the change in schedule of a flight and/or aircraft's planned departure or arrival.

Module*:* Is the major assembly that can be removed and replaced from the aircraft as a whole unit.

Component: Is the module sub-assembly one that is removed and replaced in the module.

Operational check: a task to determine if an item is fulfilling its intended purpose. This is a failure finding task and does not require quantitative tolerance.

Functional check: a quantitative check to determine if each function of an item performed within specified limits.

"A" check: A maintenance check performed approximately every month.

"C" check: a maintenance check performed approximately every 12 to 18 months or every about 4000 flight hours.

Airworthiness directive: A document issued by the FAA whenever an unsafe condition exists in an aviation product. AD may prescribe inspections, modifications, conditions or limitations under which the product may continue in operation. Incorporation of an AD is mandatory.

Aircraft on ground: an aircraft that is out of service (i.e., grounded) waiting for a part or parts before it can be returned to service.

Condition monitoring: a primary maintenance process for items that do not have characteristics that would allow the establishment of hard time or on condition intervals to determine serviceability. Condition monitoring items operated to failure.

Failure effect: the effect that a specific failure has on the operation of system.

Failure mode: the manner in which a system or component can fail.

Flight hours: actual flight time measured from takeoff (wheels up) to landing (touchdown).

Hard time: a primary maintenance process that requires replacement of component at a specific intervals (lifetime).

Inspection: an examination of an item and comparison against a specific standard.

Lubrication: an act of replenishing oil, grass, or other substances used for purpose of maintaining the inherent design capabilities of a unit or system by reducing friction and/or conducting away heat.

On condition: primary maintenance process that schedules periodic inspections or tests to determine remaining serviceability of a component or system.

Operating cycle: take off, flight, and landing of an aircraft.

Quality assurance: the maintenance organization responsible for setting standards of operation and for monitoring the operator units to ensure that such standards are met.

Quality control: the maintenance organisation responsible for conducting inspection of maintenance work (when required) and for calibration of tools and test equipment

Reliability: the probability that an item will perform a required function, under specified conditions without failure, for a specified amount of time.

Reliability program: a set of rules and practices for managing maintenance and controlling the maintenance program.

Dispatch reliability: dispatch reliability is a measure of the overall effectiveness of the airline operation with respect to on time departure.

Statistical reliability: Statistical reliability is based upon collection and analysis of failure, removal, and repair rates of systems or components.

Historical reliability: Historical reliability is a comparison of current event rates with those of past experience.

Event oriented reliability: Event oriented reliability is concerned with onetime events such as bird strikes, hard landing, in flight shutdowns, lightning strikes, or other accidents.

Reliability Centred Maintenance (RCM) approach: is designed to minimise maintenance costs by balancing the costs of different maintenance strategy taking into account the loss of potential life.

Restoration: the work necessary to return an item to a specific standard and it may vary from cleaning the unit or replacing a single part up to and including a complete overhaul.

Standard deviation: a statistical parameter identifying the relative dispersal of data points about a mean value.

Service letter: document issued by the manufacturer to identify a maintenance tip or new procedure.

System: a collection of components designed to work together to efficiently perform a certain function.

Transit check: a maintenance check performed prior to each flight (i.e., at aircraft turn around).

Troubleshooting: the process of studding and analysing a problem in order to pinpoint the cause and resolve the trouble.

Validation: accepting a test procedure after actually performing it successfully.

Verification: accepting a test procedure based on knowledge of the unit under test and understanding of the procedure.

Visual check: an observation to determine if an item is fluffing its intended purpose.

Zoned inspection: several visual inspection tasks performed in a specific area (zone) of the aircraft.

Engineering: is defined by the Engineers "profession in which knowledge of the mathematical and natural sciences gained by study, experience, and practice is applied with judgment to develop ways to utilize economically the materials and forces of nature for the benefit of mankind.

Engineer: is one who applies mathematical and scientific principles to the effort of resolving practical problems. Engineers are usually identified by some specialty: civil, mechanical, electrical, aeronautical, transportation, nuclear.

Goal: is a point in time or space where you want to be; a level of accomplishment you want to achieve.

Objective: is the action or activity you employ in order to help you achieve a specific goal. The definition of the preventive maintenance.

Aircraft spare parts: Means are the spare parts stored to ensure normal, safe flights for aircraft as well as engine ground maintenance.

Replacement: means any maintenance activity such as physical replacement or overhaul, which returns the age of the unit to zero.

Linear programming: it is designed for models with strict linear objective and constraint functions.

Integer programming: in which the variables assume integer values.

Dynamic programming: in which the original model can be decomposed into smaller sub problems.

Network programming: in which the functions of the modelled as a network.

Nonlinear programming: in which the problem can model are non linear.

Span of control: A supervisor or manager can effectively supervise or control three to seven people. Any less than three would be ineffective use of time and labour and any more seven would spread the boss to thin.

Cycle: Is the portion of total inventory that varies directly with size.

Anticipation: Is the inventory used to absorb uneven rates of demand or supply

Residual life: of the item, that is, the expected time to a failure or to reach an unacceptable condition, is a very important parameter in the condition based decision problem.

AHP Analytic Hierarchy Process: is a decision making procedure originally developed by Saaty in the 1970s.

Maintenance Free Operating Period (MFOP): is a period of time during which there is no need for scheduled or unscheduled maintenance.

Maintenance Recovery Period (MRP): is required to restore all aircraft systems to their fully serviceable state. The objective of the MRP is to ensure the aircraft can complete all the mission and mission types during the next MFOP

Residual life of the item: the expected time to a failure or to reach an unacceptable condition.