Part-out Based Spares Provisioning and Management

A Study for Aircraft Retirement

Jan Block

Operation and Maintenance
Part-out Based Spares
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A Study for Aircraft Retirement

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Dad, you are in my mind and heart always. I miss you!

Jan Martin Block, November 2017, Luleå.
Abstract

The operation and maintenance phase of a complex technical system may deal with strategic decisions for asset retirement and end-of-life management. When a fleet of aircraft reaches the retirement phase, the operation of remaining fleet should still be kept at a defined level of availability. Obviously, the provisioning of spares is a key issue to support the maintenance and operation of the remaining fleet. The best practice within the aviation industry is to re-use the spares of retired aircraft to support the operational fleet. This is referred to parting-out.

The purpose of the research conducted for this thesis has been to develop decision support methodologies, models and tools for the management of a sustainable part-out-based spares provisioning for an aircraft fleet during its retirement period. The proposed methodology will be used to support the retirement process of aircraft fleet and enhance the organisation’s capability of making efficient and cost-effective decisions concerning the re-use of spare parts during the retirement period. To achieve the purpose of this research, literature studies, case studies, algorithm development and simulations have been conducted. Empirical data have been collected through document studies, interviews, and the perusal of archival records from Saab Support and Services AB. The data analysis performed for this research has been based on theories and methodologies within reliability analysis, cost modelling, spares forecasting, stock provisioning and decision making, in combination with the best practices implemented by the aviation industry for the end-of-life management and retirement of aircraft.

In the present thesis, part-out-based spares provisioning (PBSP) program is proposed to utilise retired aircraft units effectively as spare parts. The proposed approach is illustrated and verified through a case study performed on the “Saab-105” military aircraft fleet within Swedish air force fleet. A PBSP programme is proposed, associated management activities are described, the key decision criteria are presented, and a functional framework for an effective PBSP is suggested. The proposed PBSP program provides a foundation for further measures and tasks to be performed within the retirement period, such as terminating maintenance contracts, discarding internal maintenance capabilities, reviewing stocks, scaling down administrative processes (e.g. spares procurement and obsolescence monitoring), etc.

An important part of the PBSP programme is the reliability analysis of multiple repairable units, and this has been investigated, using parametric and non-parametric reliability approaches. The aim is to identify a practical approach for estimation of the future spare demand at fleet level. Furthermore, a set of computational models and search algorithm have been developed for the identification of applicable termination times, of both the parting-out process and the maintenance and repair actions performed on the units. This includes termination of the parting-out process (PO), the sending of parted-out units directly to storage (POS), and repair actions performed on the units received at the repair shops owing to corrective (CM) and preventive (PM) maintenance, as well as the parted-out units that need to be repaired (POM). The feasible termination alternatives are compared with regard to their respective costs and the most cost-effective solutions are identified.

The results of the research study show that a PBSP programme can yield large reductions in maintenance and spares procurement costs, while supporting operation of existing fleet at highest required availability. It also contributes positively to implement a green supply chain during the retirement phase. The methodology and approaches introduced within the thesis can be applied in other civil applications, such as energy, mining, process industry and transportation sectors.

Keywords: Aircraft retirement, End-of-life management, Parting-out, Part-out-based spares provisioning, Reliability analysis, Repairable units, Spare parts provisioning.
List of appended papers

Paper I

Paper II

Paper III

Paper IV
List of related publications (not appended)

Paper A
A. Ahmadi, J. Block and U. Kumar, “Risk based maintenance deferral for components subject to hidden failure”, in Proceedings of RAMS Symposium, Reno, Nevada, USA, January 2012.

Paper B

Paper C
J. Block, P. Söderholm and T. Tyrberg, “No fault found events during the operational life of military aircraft items”, in Proceedings of the ICRMS Conference, Chengdu, Sichuan, China, July 2009.

Paper D

Paper E
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<th>Description</th>
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<tbody>
<tr>
<td>AFRA</td>
<td>Aircraft Fleet Recycling Association</td>
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<tr>
<td>AJ-37</td>
<td>The Strike version of the FPL 37 VIGGEN multirole aircraft system</td>
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<tr>
<td>CM</td>
<td>Corrective Maintenance</td>
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<td>CMMIS</td>
<td>Computerized Maintenance Management Information System</td>
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<td>DIDAS FLYG</td>
<td>The Swedish Armed Forces Aircraft Maintenance Information System</td>
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<tr>
<td>DOA</td>
<td>Dead On Arrival</td>
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<tr>
<td>EOL</td>
<td>End of Life</td>
</tr>
<tr>
<td>F21</td>
<td>Swedish Air Wing (F21)</td>
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<td>F7</td>
<td>Swedish Air Wing (F7)</td>
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<tr>
<td>FM</td>
<td>Swedish Air Force</td>
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<td>FMV</td>
<td>Swedish Defence Materiel Administration</td>
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<td>GRP</td>
<td>General Renewal Process</td>
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<td>HPP</td>
<td>Homogenous Poisson Process</td>
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<tr>
<td>IATA SPEC 2000</td>
<td>International Air Transport Association Specification 2000</td>
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<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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<td>IID</td>
<td>Identical Individual Distribution</td>
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<tr>
<td>IJPE</td>
<td>International Journal Performability Engineering</td>
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<tr>
<td>ISO</td>
<td>International Standard Organisation</td>
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<tr>
<td>LTU</td>
<td>Luleå University of Technology</td>
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<tr>
<td>MCF</td>
<td>Mean Cumulative Function</td>
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<td>MLE</td>
<td>Maximum Likelihood Estimation</td>
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<tr>
<td>MRO</td>
<td>Maintenance Repair and Overhaul</td>
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<td>NFF</td>
<td>No Fault Found</td>
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<td>NFFP</td>
<td>Swedish National Aeronautics Research Programme</td>
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<td>NHPP</td>
<td>Non-homogenous Poisson Process</td>
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<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
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<td>PAMELA</td>
<td>Process for Advanced Management of End of Life of Aircraft</td>
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<td>PBSP</td>
<td>Part-out based Spare Provisioning</td>
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<tr>
<td>PhD</td>
<td>Philosophise Doctor</td>
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<tr>
<td>PLM</td>
<td>Product Life Management</td>
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<td>PLP</td>
<td>Power-law Process</td>
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<td>PM</td>
<td>Preventive Maintenance</td>
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<td>PO</td>
<td>Parting-out Process</td>
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<td>POM</td>
<td>Parting-out Maintenance</td>
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<tr>
<td>POS</td>
<td>Parting-out Storage</td>
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<tr>
<td>PS-37</td>
<td>The radar set installed in the AJ-37</td>
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<tr>
<td>RAMS</td>
<td>Reliability, Availability, Maintainability and Sustainability</td>
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<tr>
<td>ROCOF</td>
<td>Rate of Occurrence Of Failures</td>
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<td>RP</td>
<td>Renewal Process</td>
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<td>RQ</td>
<td>Research Question</td>
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<tr>
<td>TTT</td>
<td>Total Time on Test</td>
</tr>
<tr>
<td>VIGGEN FPL 37</td>
<td>Former Swedish fighter (VIGGEN FPL 37)</td>
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1 Introduction

This chapter provides a brief introduction to the research topics covered in this thesis, to make the reader acquainted with the problem area. Moreover, the research purpose, questions and delimitations, as well as the thesis structure, are presented within this chapter.

The management of complex technical systems such as aircraft fleets and associated support systems necessitates employing a product lifecycle management (PLM) programme for the fleet throughout its lifecycle. A PLM programme is defined by Ameri and Dutta (2005) as a knowledge management solution for product lifecycles within the extended enterprise. PLM originates from two roots. One root is enterprise management, which can be subdivided into the following four areas: material resource planning, enterprise resource planning, customer relationship management and supply chain management. The other root is the management of product information throughout the product lifecycle (Lee et al., 2008).

From the point of view of an original equipment manufacturer (OEM), the lifecycle of a product comprises the following five phases: concept, definition, realization, support and retirement (Lee et al., 2008) and (Stark, 2005). During the conceptual phase, the market requirements are identified and a product design concept is developed. The definition phase consists of the detailed design of the product, the planning of the manufacturing process and the development of a prototype. The actual production and the subsequent warehousing take place in the realization phase. During the support phase, the OEM is dealing with the selling and delivery of the product, and the installation, maintenance and supply support. In fleet management, this phase is also known as the operation and maintenance phase, which includes the acquisition, introduction, operation and maintenance of an aircraft fleet. In general, the supply support for repairables is crucial, and includes not only support from the OEM, but also maintenance, repair and overhaul (MRO) facilities for continuous repair actions. Having an efficient supply support is necessary for continuous operational performance, for example Pettersson and Segerstedt (2012) describe and suggest measures for achieving an efficient supply support chain.

Obviously, as is the case with any product, an aircraft depreciates in value with time. The reduction in value arises from a number of factors, including the increased cost of maintenance, repair and upgrading to comply with legislation. At some stage, the operation, maintenance, repair and upgrading become uneconomic, and at this point, the owner will consider taking the aircraft out of service (Towlle, 2007). Hence, the operation and maintenance phase may also deal with the strategic decisions for asset retirement, which is the case in this study.

Retirement includes all the activities involved in managing assets that are still owned, but no longer being used, including decommissioning, protection and disposal (Ouertani et al. (2008). The optimal time to retire an aircraft is dependent on the characteristics and history of that aircraft and the economic and regulatory environment in which it operates. If one plots the aggregated retirements with the aircraft age, one finds a remarkably consistent S-curve relationship, and aircraft purchases as a whole behave in a predictable way with respect to economic cycles and the availability of new aircraft models (Dray, 2013).

In the global market forecast for Airbus for the period 2009–2028, it is projected that 8,453 aircraft will be retired during that period (Van Heerden and Curran, 2011). Based on a report by Boeing, the potential market for aircraft disposal will be nearly 6,000 per annum by 2028 (Boeing, 2010). Boeing has also estimated that the company, by 2028, will have retired more than 8,000 aircraft from the current global fleet.
Furthermore, according to the Airbus forecast, by 2032, 10,334 aircraft will have been retired, (Airbus-Report, 2014). Concerning Military aircraft fleets, it is expected that 7,094 aircrafts will be retired globally during 2017–2026, while USA itself comprises the 4,457 aircrafts retirement (AviationWeek, 2017). The number of aircrafts at the end of life (EoL) is continuously increasing. Dealing with retired aircraft taking into account the environmental, social, and economic impacts is an emerging aerospace industry problem for the near future. According to Airbus and Boeing estimations, nearly 10,000 to 15,000 planes will be retired in the next 18 years, see Airbus-Report (2014) and Boeing-Report (2013). It is estimated that over 2,000 passenger aircraft are currently inactive and in storage, with an average age of 21 years. Over 60% of these (and almost 80% of those over 15 years old) will not return to commercial service, see Forsberg (2015), and the number of military aircraft in storage is considerably greater, see report from AFRA (2006).

In Europe, there is the consideration of the high cost of space to store airframes, as well as adverse climate conditions that quickly undermine the end-of-life value (Pena, 2009). The international aerospace community continues to focus on environmental issues and landfill regulations are increasing in number. Many options for mitigating the environmental impact of aviation rely on the introduction of new aircraft technology, retrofits or the early retirement of older aircraft (Dray, 2013). The aviation community is seeking efficient, revenue-increasing and environmentally sound methods for aircraft disposal (retirement) (AFRA, 2006). It is evident that the aviation industry is being compelled to confront the significant new problem of what to do with large numbers of useless aircraft and, of course, how to address the associated environmental issues (Van Heerden and Curran, 2011). To tackle these challenges, the concept of “green supply chain” has been introduced; see, for example Sarkis (1995) and Sarkis (2003).

Alternatives improving the environmental performance and enabling adjustment to a greener supply chain may include technological, process or organizational characteristics. An example of such an alternative is the setting of an organizational goal to improve the total quality of environmental management (Oakley, 1993). Various systems, requirements and alternatives that can aid the development of green supply chains can be found in Sarkis (1995) and Wu and Dunn (1995).

Figure 1:1 below shows the “product lifecycle” in a green supply chain. As is shown, when a product reaches the retirement phase, the reverse logistics starts and the asset, or some of the associated components, can be reused, re-manufactured or recycled. If these alternatives are not applicable, disposal is the only option. Airplane recycling concerns the process of harvesting parts and materials from end-of-life (retired) aircraft (LeBlanc, 2016). Remanufacturing is the rebuilding of a product to the specifications of the original manufactured product using a combination of reused, repaired and new parts (Johnson and McCarthy, 2014).

Several initiatives have been started to promote the implementation of a green retirement process. WINGNet (2010) is a network that provides a platform for the exchange of research regarding material recycling innovation (Keivanpour et al., 2013). This network is focused on the development of the technologies and infrastructure required to meet the challenges in the sustainable use and reuse of aircraft materials. The scope of WINGNet's activities was formulated in consultation with the United Kingdom aerospace industry to identify critical materials science research required to improve the United Kingdom’s performance in the sustainable use of materials WINGNet (2010).
Airbus is evaluating the management of dismantling sites through its process for advanced management of end of life of aircraft (PAMELA) pilot project, which aims to demonstrate that up to 95% of an aircraft and its components can be recycled. Boeing has established a non-profit industry association, known as the aircraft fleet recycling association (AFRA), whose mission is to enable airlines to manage their retired airplanes in an environmentally responsible way while maximizing the value of aging commercial airplanes. AFRA was formed in 2006, partly in response to operators’ desire for clear guidance on the most effective and efficient methods to retire their airplanes. In the two years since its inception, AFRA has produced a “best management practice” document on the management of used airplanes and reclaimed parts, and has defined the minimum performance standards for companies that manage end-of-service airplanes.

Within aviation companies, the process of dismantling an aircraft at the end of its service is referred to as parting-out. Obviously, the asset value of the components and materials parted-out from the retired airframes can be very considerable. The benchmarked best practice within the aviation industry is to dismantle the retired aircraft and use the parted-out spares to support the remaining fleet or to offer them on the surplus market. The retirement of an aircraft fleet includes reducing the stock of spare parts, allowing the option of satisfying orders received up until the retirement (phase-out) date, and giving customers product discontinuation notices. Through dismantling aircraft and recycling materials and parts, aerospace managers are developing new strategies for the management of end-of-life aircraft.

Part-out-based spares provisioning (PBSP) has been strongly considered by aviation companies. The PBSP approach is a complex task that requires a multidisciplinary and integrated decision-making process. Successful retirement and end-of-life solutions for vehicles have been developed during the past decade; see, for example, Newcamp et al. (2016) and Zhao et al. (2017). In contrast, a review of the literature exposes the fact that less research has addressed issues concerning part-out-based spares provisioning during the retirement phase. The following are some of the challenges facing the aviation industry in relation to the implementation of a PBSP programme: the absence of a relevant framework for spare part provisioning, part selection criteria in the PBSP programme, a practical method for the estimation of spares demand, dynamic modelling of stock levels, and methods for optimizing the stock level within the retirement period and identifying repair termination times. Obviously, the number of aircraft reaching the end of their life is increasing.
The average age of aircraft fleets is also increasing and retirement planning tools and methodology are necessary to aid fleet managers through the retirement decision process as discussed by Newcamp et al. (2017). Innovative management practice for aircraft retirement can be considered as a transdisciplinary context. Moreover, regarding the dynamics and multidimensionality of aircraft retirement projects, conventional management systems cannot be adequate and sufficiently responsive (Keivanpour et al., 2013).

1.1 Statement of Problem

A decision is to retire a fleet of aircraft; the fleet will be scrapped gradually during an often-protracted period, in which the number of operational aircraft will gradually decrease. In this context, the remaining fleet should still be kept at a defined level of availability, and spares provisioning and storage are still required to support the maintenance and operation of the remaining fleet at a minimum cost and risk. Obviously; an effective spare provisioning during retirement requires accurate estimation of spare demand. Forecasting demand for repairable units during retirement period is challenging. This is due to the fact that the demand changes gradually due to the fleet retirement, having intermittent demand, for example described by Wallström and Segerstedt (2010). The shortages of spares also may occur in extremely high costs (Hua et al., 2007).

According to Love (1979), demand forecasts are absolutely necessary for stock level planning in all phases. As discussed by Gu et al. (2015), the aviation industry is unique with regard to forecasting the demand for spare parts, owing to a combination of four market characteristics: the industry’s global need for spare parts, the demand unpredictability, the need for traceability of spare parts for safety reasons, and the high cost of not having a spare part available. The gain to be derived from an accurate demand forecasting system can be very large.

In fact, the spare part demand is driven mainly by modification and maintenance actions, which include actions performed during preventive and corrective maintenance, which is mainly governed by the field reliability of spares and the aircraft utilization. Hence, an accurate estimation of demand requires a more robust and accurate reliability model. There are two major approaches to the reliability analysis of repairable units, namely the parametric and the non-parametric approach. A variety of parametric methods are discussed and used to model the reliability of repairable units, for example the power law process described by Modarres (2006); Kijima and Sumita (1986); Rausand et al. (2004); Kijima (1989); Proschan (1973); Rigdon and Basu (2000) and the simulation-based approach, presented by Srividya and Shantharaju (2004).

The application of these methods for a single system or unit is quite clear and straightforward. However, in practice the analyst is often dealing with multiple similar systems which are installed in different aircraft and which are running in different operating environments and under different influencing factors. The challenge of the reliability analysis of multiple repairable units is to track field failures to provide information regarding failure rates and the expected number of failures at the fleet level and not at the individual component level.

The application of parametric reliability analysis methods for multiple repairable units, even if it is very limited in scope, is quite complex and time-consuming for a variety of reasons. For instance, failure analysis is made more difficult by the highly multi-censored nature of the reliability data belonging to different failure modes. The analysis of time-censored data and that of failure-censored data require the application of different treatment methods (Proschan, 1973); (Meeker and Escobar, 2014).
Moreover, drawing conclusions at the fleet level from these individual analyses requires statistical assumptions which in practice entail a degree of uncertainty. Non-parametric statistics are statistics which are not based on parameterised families of probability distributions and include both descriptive and inferential statistics, and parameters such as the mean, variance, etc. Unlike parametric statistics, non-parametric statistics make no assumptions about the probability distributions of the variables being assessed. The difference between parametric models and non-parametric models is that the former has a fixed number of parameters, while in the latter the number of parameters increases with the amount of data, for example failure data. Nelson (2003) gave a comprehensive presentation of the most important non-parametric methods for analysing recurrence data; see also for example Millar et al. (2009) for an example of a non-parametric study of a propulsion system.

In addition to a reliability method, a formal reliability programme is needed which ensures the collection of important information about the aircraft systems’ reliability performance throughout the operational phase, and which directs the use of this information in the implementation of analytical and management processes. Millar (2008) and Karim et al. (2016) discusses the importance of maintenance and reliability databases for operational effectiveness and suitability during the whole lifecycle. Furthermore, Murthy et al. (2015) discuss the special case, when maintenance, repair and overhaul is outsourced.

Moreover, when pooling data for units belonging to an operational fleet, the associated failure data require an analysis of the statistical characteristics to assure the applicability of the pooling. In general, using parametric methods requires a degree of statistical sophistication and sound statistical knowledge and experience on the part of the analyst.

Furthermore, the management and the engineers and field service teams who maintain and support the aircraft systems can easily be daunted by such complex techniques. However, according to Misra (2008), monitoring a recurrent failure in a complex system such as an aircraft does not necessarily require complicated methods. In order to forecast the demand, the challenge remains of how to employ an appropriate reliability approach that is statistically valid, practical and yet communicates appropriate information to the stakeholders (Misra, 2008).

The retirement process should also include a set of tasks to be performed in order to phase-out the stock of spares at the end of their useful life, as well as to recycle and dispose of the spares which the system consists of, see Knezevic (1997). This process should adequately address the future maintenance volume, as well as fulfil the associated requirements for spares availability, at the lowest possible cost. Many actors or operators have been faced with large write-offs of excess stock after products have been retired, due to a lack of proper planning for the retirement phase. Valuable fleets of retired aircraft, for example, contain valuable spares that retain some operational or monetary value. The benchmarked best practice within the aviation industry is to use these spares to support the remaining fleet or to offer them on the surplus market.

When reclamation takes place, i.e. when units from discarded aircraft are collected for reuse, the stock fill rate will increase due to the parts received through reclamation, as well as the repair actions due to the scheduled and unscheduled maintenance of the operational fleet. At the same time, the number of operational aircraft will decrease over the retirement period, and obviously the demand for spares will normally decrease. The increase in the fill rate and the simultaneous decrease in the demand for parts will lead to an excessive level of spares in stock; see Figure 1.2 for an illustration of the flow of units when the reclamation process is included, i.e. when units are collected from disposed aircraft.
Aircraft phase-out processes have been paid less attention in the existing scientific literature. No specific methods are available for modelling, analysing and improving the phase-out process of an operator (Burhani et al., 2016). Once the parting-out process has started, the stock fill rate will increase due to the parts received through parting-out, as well as receiving units due to the scheduled and unscheduled maintenance of the operational fleet. At the same time, the number of operational aircraft will decrease over the retirement period, and obviously the demand for spares will normally decrease.

The increase in the fill rate and the simultaneous decrease in the demand for parts will lead to an excessive level of spares in stock. In fact, the implementation of an effective end-phase provisioning programme should be governed by criteria for minimizing the stock level, reducing it to zero, or at least close to zero, at the end of the retirement period, minimizing the risk of backorders throughout the retirement phase, and minimizing the total cost of stocks and provisioning. In order to control the stock level and fulfil the decision criteria, it is necessary to make decisions on the termination, at specific times, of both the parting-out process and the repair actions performed by the repair shops on the units received.

The identification of feasible and effective alternatives for repair termination times is a combinatorial problem by nature. Identifying the applicable and effective solutions by searching among all the combinations of possible solutions, including both feasible and infeasible solutions, would be time-consuming. Therefore, searching for solutions to this combinatorial problem needs to be accomplished using an algorithm, on the basis of an initial state (e.g. using the time since overhaul and maintenance history) and an initial input (e.g. using the operational time and initial stock) which existed prior to entering the retirement period.
The applicable and feasible alternatives should also be compared with regard to their respective costs, and the most cost-effective solution should be selected. Hence, a challenge in this process is the identification of the applicable alternatives for repair termination times, a repair termination plan, and stopping times for the parting-out process, i.e. alternatives that will minimize the number of remaining spares in stock at the end of the retirement period, while still fulfilling the availability requirement for spares, at the lowest possible cost.

The assessment performed in this connection should also facilitate the identification of possibilities and cost-effective ways of implementing the decisions that are needed to sustain the aircraft availability, and should result in the reduction of the business risks and uncertainties, as well as the operational costs. Moreover, assessment of the spares planning strategy requires knowledge of the various factors which indicate the appropriateness of the strategy, according to the associated decision criteria. In addition, the provisioning during the retirement period is a complex task dealing with strategic planning, fleet management, maintenance management, logistic support management and data management. Examples of the major tasks of a strategic planning include an aircraft disposal schedule, a flight operations plan for the retirement period, and a restructuring of both the flight operation and the maintenance organization.

The implementation of the PBSP approach can be quite complex, due to a variety of decision factors that affect the spares provisioning plan, modification plans, operational requirements, the parting-out process, the maintenance (repair times and turn-around-times) and the failure pattern of the units. Consequently, another remaining challenge is the identification of the decision factors and the development of a framework for management of the PBSP programme. This will reduce the complexity and increase the efficiency of the PBSP decision-making process. Despite the fact that several studies have been conducted on the analysis and management of spare part provisioning and planning, much less attention has been paid to issues connected to the retirement phase. In summary, there is a need to develop concrete decision support methodologies and tools for the management of spare part provisioning during retirement when the part-out-based provisioning approach is used.

1.2 Research Purpose and Objectives

The purpose of the research for this thesis has been to develop decision support methodologies, models and tools for the management of a sustainable part-out-based spares provisioning of an aircraft fleet during its retirement phase.

The proposed methodologies will be used to enhance the capability of making efficient and cost-effective decisions for reusing spares reclaimed from disposed aircraft and reducing the stock levels during the retirement period.

The research purpose is characterized by the following objectives:

i. to determine a practical approach for estimation of the spare part demand at the fleet level during the retirement phase,

ii. to develop a framework for management of the part-out-based spares provisioning during the retirement phase,

iii. to propose a computational approach for identification of the applicable and cost-effective alternatives for part-out-based spares provisioning.
1.3 Research Questions

In order to fulfil above-stated research objectives, the following research questions have been formulated:

**RQ 1**: how to estimate expected number of failures for multiple repairable units at fleet level during fleet retirement?

**RQ 2**: what are the prerequisites for an effective part-out-based spares provisioning?

**RQ 3**: how to determine the repair termination times at the end of the retirement period?

1.4 Scope and Limitations

Based on the available resources and according to the research purpose and objectives, as well as industrial interests, the scope and limitation of this study are as follows:

- The present research focuses on the part-out base spare provisioning (PBSP) of a military aircraft fleet during the retirement phase. The industrial partner in the present study prioritized the retirement phase of military aircraft fleet. This is because there is a large number of aircraft retirement proposal during recent and upcoming years around the world.

- The maintenance and organization of a military system includes multi-indenture operational and maintenance sites. In this study a single site is considered.

- The over-stock spares in the case of this study cannot be sold in surplus market, due to the military application. Spare parts either can be used on the operational aircrafts or should be scrapped.

1.5 Authorship of the Appended Papers

The contribution made by each author of the appended papers to the respective papers is shown in Table 1:1, according to the following activities:

1. formulation of the fundamental ideas of the problem,
2. performing the study and analysing the results,
3. writing the paper,
4. revision with regard to important intellectual content,
5. final approval for submission.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Appended Papers</th>
</tr>
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<tbody>
<tr>
<td>Jan Block</td>
<td>1,2,3,4,5</td>
</tr>
<tr>
<td>Alireza Ahmadi</td>
<td>1,2,3,4,5</td>
</tr>
<tr>
<td>Uday Kumar</td>
<td>4, 5</td>
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<td>Peter Söderholm</td>
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<td>Tommy Tyrberg</td>
<td>1, 4</td>
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<td>Xiao Xun</td>
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Table 1.1. Authorship of appended papers.
1.6 Structure of Thesis

The thesis is divided into five chapters as follows.

Chapter 1:
“Introduction” – This chapter presents a brief background to the research field covered in this thesis, deals with the importance of stock management, and provides an introductory discussion of the planning and control of part-out-based spares provisioning performed when a fleet consisting of technical systems, for example an aircraft fleet, enters its retirement period. The chapter also discusses the problems and challenges associated with the selected research area, as well as describing, explaining and outlining the research objectives, questions and limitations.

Chapter 2:
“Theoretical framework” – This chapter presents the theoretical framework related to the research subject. A short introduction is provided to the concepts of product lifecycle and system lifecycle, discussing maintenance and spares provisioning when technical systems (e.g. aircraft) reach their retirement period and are being phased out. Also discussed and illustrated are the importance of the reliability of multiple repairable units on the fleet level, and common and applicable reliability models (parametric and non-parametric). The chapter also describes theories of stock management and forecasting demand for repairable units during the retirement period of an aircraft fleet. Moreover, a brief description is provided of the application and use of search algorithms. The theoretical framework presented in this chapter has been used to achieve an understanding of the research area.

Chapter 3:
“Research methodology” – This chapter describes the methodology used in the research for this thesis. The different phases of the research and the different aspects of the research methodology are explained, including the approaches, purpose and strategies of the research, as well as the data collection and analysis. Also explained are the reasons for making the research choices related to these aspects. The selection of research methodologies has been performed based on the research objective and the research questions, as described in Chapter 1, and the theoretical framework described in Chapter 2.

Chapter 4:
“Summary of appended papers” – The four appended papers are summarized and the important findings of each appended paper are highlighted.

Chapter 5:
“Discussion and conclusions” – This chapter draws conclusions from the research and discusses them. The discussion is structured based on the stated research objectives. The chapter also treats the data collection and analysis, and discusses the results obtained in the case study. Furthermore, the research contributions are summarized and some suggestions for further research are presented.

References: A list of references used in this thesis is provided.

Appended Papers: This part of the thesis consists of four appended papers.
2 Theoretical framework

This chapter provides the theoretical framework and the basic concepts used within the research presented in this thesis.

2.1 Product life cycle and Spare Part Provisioning

The lifecycle of a system or product begins at the moment when the idea of a new system or product is born and ends at the moment when the system is safely disposed of (Knezevic, 1997), or, in other words, the lifecycle spans “from its cradle to its grave”. The lifecycle includes the entire spectrum of activities for a given product, commencing with the identification of needs and extending through system design and development, production and/or construction, operational use, maintenance and support, and system retirement and material disposal. According to Knezevic (1997) and Blanchard (2004), the product-development lifecycle consists of five phases; see Figure 2:1 for the connection between the phases.

Specification phase: This phase consists of a set of tasks performed to identify the needs and requirements for the system, as well as transform the needs and requirements into a technically meaningful description.

Design & development phase: The main objective of this phase is to determine and define all the items which a future system will consist of, and to define their attributes and relationships so that the system will meet a needed function according to the specified requirements and needs.

Production and/or construction phase: The production and/or construction phase contains a set of tasks performed in order to transform the full technical definition into the physical existence of the system or product, in accordance with the design process. At the end of this process, a system physically exists which fully satisfies all the needs and requirements and is ready to be utilized.

Operational use and maintenance support phase: The objective of this phase is to utilize the inherent functionality of the developed system in order to satisfy the identified operational needs and requirements according to the specification process. In addition, a system in the operational phase requires continuous maintenance. Continuous maintenance is an engineering service that allows systems and products to achieve the required performance throughout their lifecycle.

Retirement and material disposal phase: This phase consists of a set of tasks performed to phase out a system from operational use and from the stocks at the end of its useful life, together with the recycling or disposal of the units which it consists of. The tasks identified to be part of the retirement process are the following: management, phase-out, disposal and documentation.

The lifecycle phases are only outlined broadly in Figure 2:1 and the specific activities (and the duration of each) may vary somewhat, depending on the nature, complexity, and purpose of the system or product. Requirements may change, obsolescence may occur, and the levels of activity may be different, depending on the type of system and where it fits into the overall hierarchical structure of activities and events (Blanchard, 2004). Once the operational functions have been described, the system development process leads to the identification of maintenance and support functions. For instance, there are specific performance expectations or measures associated with each phase. The support stage of a system’s lifecycle starts with the provision of maintenance, logistics and other support for the system of interest during its operation and use, see Standardization (2008) and lasts during the whole lifecycle.
The maintenance performed throughout the lifecycle is an essential aspect of any system’s operation (Blanchard, 2004). Maintenance actions are performed for many reasons, for example to ensure safety and the proper functioning of the equipment, and to realize the maximum return on the investment across the lifecycle of the asset.

As described by Wentz (2014), maintenance-related issues vary during each of the three lifecycle phases of design and construction, sustainment and operations, and retirement and disposal. Maintenance managers need to be cognizant of the unique issues which each lifecycle phase is associated with, what tools are available, and what type of questions should be asked, to ensure that the asset’s maintenance programme is providing a safe, reliable and cost-effective system or product for the operators.

One of the most important functions within the operation and maintenance phase is spare part provisioning. In practice, spares provisioning is carried out in the initial provisioning phase and the on-going provisioning phase. The initial provisioning phase is called the “maintenance honeymoon”, with its limited demand for spare parts (Cai et al., 2017). Initial provisioning concerns, for example, the support of a new aircraft fleet or an end item for an initial period of operation. The transmission of provisioning data starts well in advance of the first delivery, to permit ordering and the establishment of support stocks in time for the initial operations (ATA-SPEC-2000, 2004). The provisioning activities continue within the “operational use and maintenance support phase”.

2.2 Spare part provisioning

Approaches for solving provisioning problems can be divided into three categories: service-level-driven, cost-driven and forecasting-based approaches. In a service-driven approach, a service level is optimized regardless of the cost incurred by the system. A cost-driven approach gives a monetary value to the unserved part of the demand by means of back-order or penalty costs, and then adopts a policy to minimize the total cost. Forecasting-based approaches ignore the production and stock costs and build models to follow the demand behaviour. Readers are referred to Fortuin (1980b), Van Kooten and Tan (2009), Teunter and Fortuin (1999), Moore Jr (1971), (Hong et al., 2008), Teunter and Fortuin (1998), and Pourakbar (2011) for further discussions of provisioning categories. Spare part provisioning is a part of the system’s lifecycle. Spare part provisioning may occur at several points in the life of any system with a relatively long life. When establishing a new system (e.g. an aircraft) on the market, the manufacturer needs to have a well-defined plan, for the acquisition phase of the system, concerning a spare part strategy (covering repairables, non-repairables and consumables).
Throughout the process of spare part commissioning during the whole lifecycle of a product, it is also crucial to consider the minimization of waste when the product has a long life and to comply with the various regulatory requirements; the complexity of the problem is described by Patil et al. (2013). Fortuin (1980a) suggested that there are three phases in a spare part life history, the initial, normal and final phase. The initial phase is often a period of growing demand, as more and more original units tend to fail, for example through mortality failure. The normal phase may be more stable, subject to shorter-term trends and reflecting wider market trends. In the final phase, there is generally a long-term decline in the demand, as the original spares are replaced by models updated through modification or replacement, and original spares are required less frequently. As discussed and described by Lendermann et al. (2012), the complexity of determining the optimal quantities of the initial spare part package for any technical system with large fleets is a complex task, and this is especially true of the aviation industry, where the spare part stock network is highly complex.

During the normal phase of spares provisioning, the main task is to review and monitor stock levels continuously, using various models and approaches for reordering policies etc. and including units with high, low and intermittent demand. High-demand spares are relatively easy to handle and require operational considerations. However, low-demand spare parts are affected more by variations in variables like demand and lead times and therefore require more long-term considerations, which are especially true of high-cost low-demand spares, and the consequences of a back-order can be severe. Several authors have addressed intermittent demand forecasting for spare parts, for example Croston (1972), Syntetos and Boylan (2001), Ghoobbar and Friend (2003), Eaves and Kingsman (2004), Willemain et al. (2004), Regattieri et al. (2005), Hua et al. (2007), Gutierrez et al. (2008), Gomez (2008), and Teunter and Duncan (2009).

The final phase of spares provisioning includes the process of fleet retirement. The actual retirement phase is normally initiated by a decision made either by the owner or the operator, and the process ends with the system being sold on the surplus market or disposed of. The final spares provisioning phase and the retirement of a technically advanced fleet are aspects of the product lifecycle that are gaining more attention in the market. Companies are becoming more aware of how to improve their systems or products so that the environmental impact will be lower during the end-of-life phase, at the same time as the systems or products are still economically feasible (Airbus-Report, 2014) and (Boeing, 2010).

In the field of aviation, Van Heerden and Curran (2011) addressed the topic of retirement, or the end-of-life (EoL) concept, for an aircraft fleet. These authors tried to answer five important questions about aircraft recycling: “Why, when, what, who, and where?” They focused on the process of EoL aircraft recycling, the components and the economics of recycling them. Furthermore, Franz et al. (2012) provided an assessment of lifecycle engineering in preliminary aircraft design. They proposed an interdisciplinary approach to the integration of sustainability issues in the aircraft design stage. For the recycling and disposal phase, they considered the “ladder of Lansink” approach to aircraft dismantling, which had already been proposed by Van Heerden and Curran (2011). In this approach, the first choice from an environmental point of view is to use aircraft parts in other aircraft which are still being operated.Keivanpour et al. (2017b) describe how handling retired aircraft, taking into account the environmental, social, and economic impacts, is emerging as an air transportation problem to be dealt with in the near future. Furthermore, the players involved in the problem wish to solve this challenge in a systematic way to benefit from the value extracted from the core activities of end-of-life (EoL) aircraft treatment, to decrease the environmental impacts, and at the same time maximize the social value.
Furthermore, Keivanpour et al. (2017b) discuss three problems regarding the retirement or EoL phase. Firstly, the literature on the handling of EoL aircraft treatment can hardly be said to be rich and well developed, and few studies have considered the EoL aircraft problem. Secondly, the classical frameworks for logistics networks for product recovery are not adequate for use in this context. Considering all the involved stakeholders and the context of the aviation industry, the sustainability of the value chain involved in handling EoL aircraft constitutes a complex problem. Thirdly, the cost and availability of information are another challenge when tackling such problems. EoL product recovery, reverse logistics, and closed-loop supply chains are areas of research that have been developed considerably in recent years. One needs to take the ecological impact of retired aircraft into account to have an integrated environmental view of the whole product lifecycle. Manufacturers in the aviation industry are increasing their efforts to achieve a sustainable development which can be presented in their annual environment or sustainability reports. Their accomplishments in this area can be summarized as the development of pioneering ways to address the global issue of climate change and effective technologies for reducing environmental impacts (Keivanpour et al., 2013). By incorporating environmental thinking into supply chain management, including product design, material sourcing and selection, manufacturing processes, the delivery of the final product to the consumers, and EOL management of the product after its useful life, one is creating a green supply chain (Srivastava, 2007).

Environmental awareness and recycling regulations have been putting pressure on many manufacturers and consumers, forcing them to produce and dispose of products in an environmentally responsible manner, and Ilgin and Gupta (2010) presented an extensive literature review on this topic. One method for achieving a more sustainable approach and reducing environmental impacts is to make use of the parts reclaimed from systems entering the retirement phase, and utilize them in the fleet still being operated, as suggested by Keivanpour and Ait Kadi (2017a). Entering the retirement phase of an aircraft fleet, the unavoidable question arises as to whether there are sufficient spares for the whole retirement period for the fleet being phased out, whether one needs to purchase more spares, or whether, through cannibalization one can reclaim units from retired systems etc. If there is a need to purchase more spares, when should such a last-time buy take place, a problem discussed by Cattani and Souza (2003). The final stages of the product lifecycle can create undesirable and unavoidable issues for the stock management of a product. Furthermore, while the demand for the product is declining in the retirement period, the total remaining demand can be very difficult to predict. The uncertainty of that demand can be due to an inherent variability, as well as external factors such as the introduction of competing products Cattani and Souza (2003). The challenges of managing the EoL phase of a product have intensified with shorter product lifecycles, and failures can lead to disastrous results. Pourakbar et al. (2014) propose that, when entering the EoL phase, one should apply a method involving the use of spares from phase-out returns. According to Pourakbar et al. (2014), a phase-out return occurs when an operator or customer replaces an old system with the next generation of the system and returns the old spares to the original equipment manufacturer (OEM); this return can then be used in other applications. Such phase-out returns can fulfil the demand for spares of other customers still using the old generation of the system. Spares provisioning management and planning and inventory control are mainly applied during the operational phase, and impressive results have been presented in the academic literature in this field. Accordingly, there is a substantial amount of literature on spares planning and provisioning in the operational phase, but there are few publications dealing with spares management during the retirement period and the phase-out process of an aircraft fleet, or fleets of other complex technical systems for that matter.
According to Love (1979), demand forecasts are absolutely necessary for spares provisioning planning during all phases. As discussed by Gu et al. (2015), the aviation industry is unique when it comes to forecasting the demand for spare parts, due to a combination of four market characteristics: the industry’s global need for spare parts, the demand unpredictability, the need for traceability of spare parts for safety reasons, and the high cost of not having a spare part available. Furthermore, the assets in stock normally consist of both repairable and non-repairable units. Non-repairable units (Fortuin and Martin, 1999) or consumables/expendables (Botter and Fortuin, 2000) are spare parts which cannot be repaired or whose repair is not economically justifiable. Non-repairable units wear out quickly and are discarded after replacement, and new units are bought from the supplier; they are usually considerably cheaper compared to repairable units (see Figure 2:2 for an illustration of a typical stock process for non-repairable units).

![Figure 2:2. Illustration of non-repairable inventory process, adapted from Jardine and Tsang (2013).](image)

Stocks of consumables and expendables are by default scrapped with a 100% scrapping rate, and therefore there is a replacement for every unit used during the operational period, as illustrated in Figure 2:2 above. The cost of repairing a repairable spare is lower than that of producing a new one. When a repairable is defective, it can be replaced by a serviceable part and the failed part can be sent to a repair shop for repair (Fortuin and Martin, 1999) and (Botter and Fortuin, 2000). According to Sherbrooke (2004), repairables should receive more attention than non-repairables. That is because repairables often compose the largest part of the spare part budget and tend to have longer lead times than non-repairables. Stocks of repairable units are replenished by repairing the defective units; repairable unit stock systems are thus closed loop systems that implicitly dictate base-stock levels, see Figure 2:3. More information on forecasting the demand for non-repairable units can be found in (Kontrec et al., 2015).

![Figure 2:3. Illustration of repairable inventory process, adapted from Jardine and Tsang (2013).](image)
Demand forecasting is of vital importance in spare parts stock management. Forecasting the demand for repairable units is difficult in general, and becomes even more challenging during the EoL period due to the intermittent demand prevailing during that period.

Intermittent demand is particularly difficult to predict, and shortages may take place, incurring extremely high costs (Hua et al., 2007). To the best of our knowledge, Fortuin (1980b), Geurts and Moonen (1992), Haneveld and Teunter (1997), Teunter and Fortuin (1998), Teunter and Fortuin (1999) and Teunter and Haneveld (1998) are the only authors who also focus on the service parts logistics of the final phase. Except for Geurts and Moonen (1992), all these authors discuss situations where it is impossible to order parts after the beginning of the final phase. On the other hand, stock management and spare parts provisioning within the operation and maintenance phase of the product lifecycle have attracted a large volume of research. Many researchers have studied the joint-optimization of maintenance and stock provisioning policies for spare parts logistics; see, for example, Chen et al. (2006), Geiger et al. (2007), Scarf and Cavalcante (2011), Ilgin and Tunali (2007), Wang et al. (2008), Wang (2011), Zeng and Wang (2010), Liu et al. (2013), and Lynch et al. (2013).

2.3 Reliability of Repairable Units

Reliability is described as the characteristic behaviour of a unit, expressed by the probability that the unit will perform its defined function under certain conditions for a stated interval in time. A system, for example an aircraft system, comprises both non-repairable and repairable units. A non-repairable unit is removed permanently upon failure.

A non-repairable unit is discarded upon failure and no repair actions are performed on the unit (Rigdon and Basu, 2000). A repairable unit, on the other hand, is a unit that is restored to a satisfactory performance by any method other than replacing it after it fails to perform one or more of its functions satisfactorily (Ascher and Feingold, 1984).

The reliability analysis of repairable units includes the task of modelling the number of recurrent failure events over time rather than the time to the first failure (as in the case of non-repairable units). There are two major approaches to the reliability analysis of repairable units, namely parametric and non-parametric methods.

2.3.1 Parametric Approach

Parametric methods are a branch of statistics which assumes that failure data come from a population and follow a probability distribution based on a fixed set of parameters. Since a parametric model relies on a set of fixed parameters, it assumes more about a given population than a non-parametric approach does. When the assumptions made by the parametric model are correct, this model will produce more accurate and precise estimates than a non-parametric method.

Consider a repairable unit which is put into operation at \( t = 0 \) and whose first failure will occur at \( T_1 \). When the unit has failed, it is replaced or restored to a functioning condition through a repair process, and further failures will occur at time \( T_2 \) and so on.

The failure times \( T_i \) are referred to as global failure times, recorded as the time since the initial start-up of the operational units. \( T_i (T_1 < T_2 < T_3 \ldots T_{N-1} < T_N) \) represent the failure times of single repairable units or several similar multiple repairable units.

The times \( X_i \) represent the times between failures and are called inter-occurrence times, or local failure times (Rausand et al. 2004). Furthermore, the number of recurrent failures is represented by \( N(t) \), shown in Figure 2:4 as an example.
Figure 2.4: Relation between number of recurrent failures $N(t)$ and inter-occurrence times $X_i$, global time $T_i$.

The rate of the counting process $N(t)$, the rate of occurrence of failures (ROCOF), is defined as follows:

$$w(t) = W'(t) = \frac{d}{dt} E(N(t)),$$

where $W(t) = E(N(t))$ describes the mean number of failures in the time interval $[0, t]$.

The function $w(t)$, describing the rate of occurrence of failure is often referred to as the ROCOF function. Using the ROCOF, repair rate models are defined by first picking a functional form for $W(t)$, the expected number of cumulative failures by time $t$. Taking the derivative of this gives the repair rate function $w(t)$.

Parametric methods entail stochastic point processes, which include the homogeneous Poisson process (HPP), the non-homogeneous Poisson process (NHPP), the renewal process (RP), and the generalized renewal process (GRP); the GRP was introduced by Kijima and Sumita (1986).

The HPP approach implies that the repairable unit in question does not age, i.e. that it does not show any reliability improvement or deterioration, and the ROCOF in an HPP is a constant. Furthermore, the HPP also implies that the condition of the repairable unit is the same at any point in time, and that this condition is independent of the previous pattern of failures.

This means in particular that, after a repair, the unit is in exactly the same condition as a brand new unit, i.e. in an “as good as new” condition, see Figure 2.5. Thus, the HPP model cannot be used to model units that deteriorate or show reliability improvement; see Rausand et al. (2004) and Rigdon and Basu (2000) for further details.

The NHPP differs from the HPP by the fact that the ROCOF is not constant over time. The NHPP corresponds to the situation where there is a minimal repair assumption, meaning that a repair leaves the system in the state in which it was before failing or in a state which is “as bad as old”, see Figure 2.5. The NHPP is often used to model trends in the inter-occurrence reliability data for improving or deteriorating systems (Ascher and Feingold, 1984).

A renewal process (RP) is a counting process where the inter-occurrence times are independent and identically distributed with an arbitrary life distribution; upon a failure the unit is replaced with a new unit or restored to an “as good as new” condition, which is often referred to as the perfect repair assumption and also holds for the HPP approach, see Figure 2.5.
The generalized renewal process (GRP) is applicable for modelling the reliability of repairable units under an imperfect repair assumption (Kijima, 1989). Brown and Proschan (1983) suggested an imperfect repair model, which is based on one probability that there is a perfect repair and the system will be brought back to a state which is “as good as new”, and another probability that the repair action will be a minimal repair and the system will be brought back to a state which is “as bad as old”. In addition, the GRP allows the goodness of repairs to be modelled as ranging from “as-good-as-new” repair (RP) to “same-as-old” repair (NHPP). The RP and the NHPP are generalizations of the HPP, and both processes have the HPP as a special case. The RP is defined as a process in which the different times to failure of a unit, local times ($X_i$), are considered to be independent and identically distributed (I.I.D.) random variables, and if the $X_i$ are exponentially distributed, then the RP becomes an HPP process. Concretely, a repairable unit characterized by the RP is restored to its original condition or an “as good as new” condition.

One example of an NHPP process is the power law process (PLP), which is sometimes also referred to as a Weibull process. The PLP model was first proposed by Duane (1964) and was further developed by Crow (1974), who formulated it as a non-homogeneous Poisson process (NHPP) with a power intensity law:

$$\lambda(t) = \frac{\beta}{\theta} \left( \frac{t}{\theta} \right)^{\beta - 1},$$

where $t$ is the operational time, $\beta$ denotes the shape-parameter and $\theta$ represents the scale-parameter; in the case where $\beta = 1$, the PLP reduces to an HPP, if $\beta > 1$, it models a deteriorating reliability unit, and when $\beta < 1$, it provides a model for reliability growth. Crow (1974) discussed applications of the PLP model and provided some associated inference procedures.

Moreover, Finkelstein (1976) discussed the confidence bounds on the parameters of the PLP, while Lee and Lee (1978) and Bain and Engelhardt (1980) discussed point estimation and proposed tests for the parameters (the shape- and scale-parameters) of the intensity function. Rigdon and Basu (2000), Baker (1996), Jani et al. (1997) and Muralidharan (1999) proposed various tests for the PLP.
When dealing with the reliability of repairable units, it is important to examine the reliability characteristics. There are various ways to examine whether there is a trend in the observed reliability data for repairable units. Examples of common trend tests are the Laplace trend test, the Military Handbook-189 (MIL-HDBK-189) test, the Mann test, and the Anderson–Darling test, described in Rigdon and Basu (2000), Rausand et al. (2004), Ascher and Feingold (1984), Pecht (2009) and Taghipour and Banjevic (2011).

Dealing with multiple repairable units on the fleet level, there are a number of applicable models Rigdon and Basu (2000). The applicability of these models depends on the engineering assumptions which one is willing to make. Examples of questions to be answered are as follows: “Are the units in the studied population identical? Is it possible to model all the units with a reasonable HPP process for each unit? Are the systems or units so dissimilar that the process parameters for each system or unit should be estimated independently? Are the systems or units so similar that some pooling of the reliability data across the units can be applied?

In the ISO-standard (ISO-11459-1997, 1997), homogeneity is defined as “the condition of being of uniform structure or composition with respect to one or more specified properties”. Homogeneity certification or assessment requires that statistical tests should be conducted on the results obtained for different parts of the material in order to verify that the same properties are observed. When data are collected from different sources, the “true” reliability of a unit will generally be dependent on a number of external and internal factors (Lydersen and Rausand (1989). To clarify whether a population of multiple repairable units can be pooled, there are statistical tests that can be performed.

Considering multiple repairable units on the fleet level, it is necessary to take into account the possibility of heterogeneity among the units, even though the repairable units may appear to be identical. For instance, differences in the operational environment or manufacturing process may alter the characteristics of failures from unit to unit and lead to differences in the distribution of failure times for the population of studied units. If simultaneous trend analysis can be justified, this will in general be more powerful than analysing each repairable unit separately. Furthermore, Kvaløy and Lindqvist (1998) proposed the extended total-time-on-test TTT - based Laplace and MIL-HDBK-189 trend tests for more than one repairable unit. This approach is based on the TTT-transformation introduced by Barlow and Davis (1977).

When several units are considered simultaneously, there is a possibility of heterogeneity among the units, even if the repairable units appear to be identical. Considering this effect in the model structure may affect the failure intensities. Differences in failure intensity are called heterogeneities and can be either observed or unobserved, see Cook and Lawless (2007) and Lawless (1987) . Furthermore, Lindqvist et al. (2003), Kvaløy (1998) and Kvist et al. (2008) have studied the heterogeneity effect on the NHPP. Simultaneous trend analysis can be performed on more than one repairable unit, for example by combining the individual trend test statistics for single repairable units, or by using a one-unit trend test on the TTT-based test, see Barlow and Davis (1977), i.e. through transformed observations.

The difference between these two approaches is that the latter relies on the stronger assumption of identical intensity functions for each system, while the former allows for heterogeneity among the units. Relying on the stronger assumption, the TTT approach leads to more powerful tests if the assumption holds, but can be quite misleading with the presence of heterogeneity. Therefore, TTT-based tests should only be used when there is strong evidence that the systems are homogeneous. The null hypothesis for the TTT-based tests (the MIL-HDBK-189 and Laplace tests) is that the failure data come from a homogeneous Poisson process (HPP) with the same intensity function for each unit (Kvaløy and Lindqvist, 1998).
Thus, rejection of the null hypothesis could mean either that there is a trend in the failure data or that the failure data come from heterogeneous units. The hypothesis testing for the TTT-based tests, the MIL-HDBK-189 and the Laplace test, is described as follows:

$H_0$: No trend: the process is an HPP with the same intensity function for all units.

$H_1$: Montonic trend or units are heterogenous: the process is an NHPP.

The test statistics for the TTT-based Laplace test ($L_T$) and the TTT-based MIL-HDBK-189 test ($M_T$) (Kvaløy and Lindqvist, 1998) are as follows:

$$L_T = \sum_{k=1}^{N} \frac{T(S_k)}{T(S)} - \frac{\tilde{N}}{2} \sqrt{\frac{\tilde{N}}{12}}$$

$$M_T = 2 \sum_{k=1}^{N} \ln \left( \frac{T(S)}{T(S_k)} \right)$$

where;

$$\tilde{N} = \begin{cases} N, & \text{if the processes are time truncated.} \\
N - 1, & \text{if the processes are failure truncated.} \end{cases}$$

Furthermore, the combined Laplace test and the combined MIL-HDBK-189 test can also be applied for multiple repairable units, as described by Kvaløy and Lindqvist (1998). As discussed in Kvaløy (1998), if more than one process is observed, it is necessary to decide whether to test the null hypothesis of identical HPPs or whether to allow for heterogeneous HPPs under the null hypothesis. In the former case, the TTT-based MIL-HDBK-189 test and the TTT-based Laplace test have the best all-round properties, see Kvaløy (1998). In the latter case, the combined Laplace test or the combined MIL-HDBK-189 test should be used.

Typically, heterogeneities are assumed to lead to differences in the scale-parameter from unit to unit. Being able to detect such heterogeneities is important when using TTT-based tests to detect trend, since these tests do not allow for such heterogeneities under the null hypothesis (Kvaløy, 1998). This implies that if the assumption of equal scale-parameters is violated, the TTT-based tests may reject the null hypothesis even if there is no trend.

The general strategy suggested for the trend testing of failure data from more than one unit is first to check and form a hypothesis about the heterogeneity of the population, to decide if there are heterogeneities in the failure data, and then either to use a combined trend test, if the heterogeneity test detects statistically significant heterogeneities, or otherwise to use a TTT-based test.

A number of authors have proposed different methods for the selection of a statistical approach based on various trend tests and have used these to select models for time-to-failure data. Ascher and Feingold (1984), Vaurio (1999) and Louit et al. (2009) introduced a flowchart, and Rausand et al. (2004) generalized the framework created by Ascher and Feingold (1984) adding the homogeneity concept to analyse multiple repairable units, see Figure 2:6. Furthermore, Louit et al. (2009) introduced a procedure for the selection of time-to-failure models based on the assessment of trends in maintenance data, but the proposed method does not distinguish between the pooled and the combined trend test when dealing with multiple repairable units.
In addition to the model proposed by Rausand et al. (2004), shown in Figure 2.6, Garmabaki et al. (2016) suggested an extended framework dealing with multiple repairable units on the fleet level. The method suggested by Garmabaki et al. (2016) added a study of whether the trend-free group (HPP) of units had equal or different intensities by performing the TTT-based and the combined Laplace and MIL-HDBK-189 tests. Furthermore, Garmabaki et al. (2016) also included the possibility of unobserved heterogeneities for the group with trends.

Applying the PLP on multiple repairable units on the fleet level is slightly different from applying it on single repairable units. It is possible through the TTT-based and combined Laplace and MIL-HDBK-189 tests to conclude that there is a monotonic trend (reliability improving or deteriorating) in the reliability data (Kvaløy, 1998). There may be a situation where all the units are identical and the failure patterns can actually be modelled by the same PLP for the whole population of multiple repairable units, although the assumption of equal units is quite a strong assumption and should be verified through some justification (Rigdon and Basu, 2000).
Testing the equality for the shape-parameter \( \beta \) can be performed through hypothesis testing and the likelihood ratio test for testing the null hypothesis is as follows:

\[
\begin{align*}
H_0 : \beta_1 &= \beta_2 = \beta_3 = \cdots = \beta_k \\
H_1 : \beta_i \neq \beta_j, & \text{where } i = 1, \ldots, k \text{ and } j = 1, \ldots, k.
\end{align*}
\]

The null hypothesis states that all the shape-parameters, \( \beta_i \), are the same, while the alternative hypothesis states that there is at least one pair \((i, j)\) that has a different \((\beta_i, \beta_j)\). The likelihood ratio test, taken from Rigdon and Basu (2000), is in accordance with:

\[
M \cdot \ln(\beta^*) - \sum_{i=1}^{k} m_i \ln(\bar{\beta}_i),
\]

where \(\bar{\beta}_i\) are the so-called CMLEs (conditional maximum likelihood estimates) for the \(i:th\) unit Rigdon and Basu (2000), i.e.

\[
\bar{\beta}_i = \frac{m_i}{\sum_{j=1}^{n_i} \ln(T_{ij})},
\]

and where \(\beta^*\) is the weighted harmonic mean of \(\bar{\beta}_i\),

\[
\beta^* = \frac{M}{\sum_{i=1}^{k} \frac{m_i}{\bar{\beta}_i}}.
\]

Using the approximation according to Bartlett (1937), the test statistic \(T = \frac{-2LR}{a}\) is chi-square distributed with \(k - 1\) degrees of freedom, according to:

\[
\frac{-2LR}{a} \sim \chi^2(k - 1),
\]

where \(a\) is as follows:

\[
a = 1 + \frac{1}{6(k - 1)} \sum_{i=1}^{k} \frac{1}{m_i} - \frac{1}{M}
\]

The null hypothesis \(H_0\) is rejected at a significance level of \(\alpha\) if,

\[
\frac{-2LR}{a} > \chi^2_\alpha(k - 1)
\]

Working through the above calculations gives an indication as to whether the reliability pattern of the units can be modelled by a PLP with a single shape-parameter \(\beta\) for the intensity function \(\lambda(t)\). If one ascertains that it is appropriate to estimate a whole population of repairable units by using only one shape-parameter \(\beta\), it is then possible to treat the whole population of repairable units as a single repairable system with multiple units Rigdon and Basu (2000). Making the assumption that the shape-parameter \(\beta\) and scale-parameter \(\theta\) can be used to model the whole population with one power law model, the parameters can be estimated by using the maximum likelihood function; see Rigdon and Basu (2000) and Meeker and Escobar (2014).
\[ \hat{\beta} = \frac{\sum_{i=1}^{k} \frac{n_i}{T_i}}{\theta - \sum_{i=1}^{k} T_i \ln(T_i) - \sum_{i=1}^{k} \sum_{j=1}^{n_i} \ln(t_{ij})} \]

\[ \hat{\theta} = \left( \frac{\sum_{i=1}^{k} T_i \hat{\beta}}{M} \right)^{1/\hat{\beta}} \]

In most situations, \( \hat{\beta} \) must be solved iteratively, for example by using either the fixed-point iteration method or the Newton-Raphson method Meeker and Escobar (2014). The shape-parameter \( \hat{\beta} \) can only be solved explicitly in the case where the whole population is time-truncated at the same time, i.e. \( T_i = T \) for all \( i = 1, 2, \ldots, k \) units, but this very rarely applies in practice. Furthermore, if the units are considered different and cannot be treated as one group, having different shape-parameters (\( \beta \)) and scale-parameters (\( \theta \)), then a separate analysis of each unit must be made according to the above description of the PLP. However, it may be rational to assume that all the units have the same shape-parameter (growth parameter), but different scale-parameters, \( \theta_1, \theta_2, \theta_3, \ldots, \theta_k \), and under such an assumption, a closed-form expression for the MLEs of the parameters can be derived; see Rigdon and Basu (2000) for further details.

Furthermore, it is also of great importance to study the confidence intervals for the shape-parameter (\( \beta \)) and scale-parameter (\( \theta \)), and how these confidence intervals can be estimated. The variation of the shape- and scale-parameter adds value to the possibility of modelling the whole population with one PLP; see Gaudoin et al. (2006) for further details. Using the failure intensities \( \lambda(t) \) with the estimated shape- (\( \hat{\beta} \)) and scale-parameter (\( \hat{\theta} \)), the expected number of failures can be estimated for any time interval (\( \Delta t \)), and, for example, during the retirement period of an aircraft fleet, this is very useful.

\[ E[N(\Delta t)] = \int_{t_1}^{t_2} \lambda(t) dt = \frac{1}{\hat{\theta}^{\hat{\beta}}} \left( t_2^{\hat{\beta}} - t_1^{\hat{\beta}} \right) \]

This allows the possibility of estimating the demand for repairable units during a certain period of time, which also allows operators and maintenance providers to make quantifiable and rational decisions which are based on logistics and maintenance needs and which include the associated costs.

2.3.2 Non-Parametric Approach

Non-parametric statistics are statistics which are not based on parameterised families of probability distributions, and which include both descriptive and inferential statistics. Typical parameters are the mean, variance and corresponding confidence interval, etc. Unlike parametric statistics, non-parametric statistics make no assumptions about the probability distributions of the variables being assessed (Nelson, 2003). The difference between parametric models and non-parametric models is that the former has a fixed number of parameters, while for the latter the number of parameters increases with the amount of data, for example failure data. The term “non-parametric” does not mean that there is a complete lack of parameters; rather, it implies that the number and the nature of the parameters are not fixed in advance, which they are for parametric methods. For a more comprehensive treatment of the most important non-parametric methods for analysing recurrence data, see Nelson (2003). Recurrent event data analysis is time-to-event analysis, meaning that the outcome of interest is the time until an event occurs.
Examples of times-to-events are the times to infection, reocurrence of a disease, or recovery in health sciences, the time to unemployment in economics, the time to the failure of a unit or the lifetime of light bulbs in engineering, etc. (Zuo et al., 2008). Recurrence data are collected to analyse and estimate times-to-events and other quantities of interest, and usually to cover the type and number of events over time. There are several ways to represent recurring failure data without entering the area of parametrically based complex statistical analysis, and Nelson (1998) provides an example of the graphical analysis of failure recurrence. However, an initial step prior to any form of data analysis, is to filter and clean the collected data. In the case of recurring failure data, data sets may be incomplete because they have been right-, left- or interval-censored; see Gįmiz et al. (2011) or Nelson (2003) for a thorough description of the censoring of recurrent failure data.

To gain further understanding of recurrent failure data for a population of repairable units, one can create a straightforward event plot, which can increase one’s understanding of the failure characteristics of the studied systems or units. An event plot is especially effective when there is a large array of multiple repairable units on the fleet level, see Figure 2:7. Nelson (2003) and Gįmiz et al. (2011) provide further descriptions of useful non-parametric graphical methods. Graphical methods based on the mean cumulative function (MCF), O’connor et al. (2012); Nelson (1988); Wang and Coit (2005) permit the monitoring of system failures while maintaining statistical rigour without resorting to complex stochastic techniques.

Furthermore, the MCF can be used to produce information on the reliability pattern and the repair behaviour of a population of repairable units and to describe the reliability characteristics of that population. The MCF is a non-parametric approach, since it does not use a parametric model for the population. Therefore, estimations of the MCF involve no assumptions about the form of the mean function or the process generating the failures. Non-parametric MCF estimation methods have been described by Nelson (1988), Lawless and Nadeau (1995), Meeker and Escobar (2014) and Nelson (2003). The MCF is easy to understand, prepare and present. It can be used successfully to track failures, and to identify failure trends, anomalous systems, unusual behaviour, the effect of various parameters (e.g. maintenance policies, environmental and operating conditions, etc.) on failures, etc.

![Figure 2:7. Example of event plot for recurrent failure data.](image-url)
The MCF is a counting process. Let us suppose, for example, that there are \( M \) repairable units of a specific type, and let \( N(t) \) be the cumulative total number of recurrences for unit \( i \), with \( i = 1, 2, \ldots, M \), over a given time \( t \). Then it follows that the counting process which counts the total cumulative number of failures \( N(t) \) for a whole population of units is given by:

\[
N(t) = \sum_{i=1}^{M} N_i(t)
\]

A plot illustrating an example of a cumulative number of failures for a population of repairable units is provided in Figure 2:8. In this figure, the step-function represents the number of successive numbers of failures, and each step function represents a repairable unit with a certain number of failures.

![Figure 2:8. Cumulative number of failures for a population of repairable units.](image)

The mean cumulative number of failures, \( \mu(t) \), also referred to as the MCF, is expressed as follows:

\[
\mu(t) = E[N(t)] = \sum_{i=1}^{M} N_i(t)
\]

The rate of the MCF, often referred to as the recurrence rate or the repair rate \( \gamma(t) \), is given by the following relation:

\[
\gamma(t) = \frac{E[N(t)]}{dt} = \frac{d\mu(t)}{dt}
\]
During the late 1980s, Nelson (1988) provided an appropriate point-wise estimator for the MCF, the so-called Nelson’s estimate, \( \hat{\mu}(t_j) \), which is calculated as follows:

\[
\hat{\mu}(t_j) = \sum_{k=1}^{j} \left( \frac{\sum_{i=1}^{M} \delta_i(t_k) \cdot d_i(t_k)}{\sum_{i=1}^{M} \delta_i(t_k)} \right)
\]

where \( \delta_i(t_k) \);

\[
\delta_i(t_k) = \begin{cases} 
1, & \text{if units } i \text{ is still functioning} \\
0, & \text{otherwise}
\end{cases}
\]

and where \( d_i(t_k) \) represents the number of recurrences for unit \( i \) at the time \( t_k \). Plotting the point-wise estimated MCF \( \hat{\mu}(t_j) \) gives a step function with jumps at the recurrence times, which is illustrated in Figure 2:9.

Figure 2:9. Cumulative number of failures for a population of repairable units, including the MCF-curve.

Studying the point-wise estimated MCF, one is normally also interested in gaining an understanding of the variance in the studied population, and the confidence level is therefore of great importance. Using a point-wise normal approximation, a confidence interval for the MCF can be estimated using a method suggested by Meeker and Escobar (2014). By using the MCF estimation described above and a corresponding plot of the MCF-curve, one obtains very valuable reliability information about the studied population, for example the number of repairs/unit, the trends and the anomalies, and information for estimating the future reliability behaviour. Much work has been carried out on the development of methods for the analysis of recurrence data. Nelson (1988) presented a non-parametric estimator of the mean cumulative function (MCF) and showed how to use the estimator to make predictions. Further, Nelson (1995) provided an unbiased variance estimator for the MCF estimator, and this variance estimator could (generally with a small probability) be negative, along with the confidence limits for the MCF.
Moreover, Lawless and Nadeau (1995) provided an alternative variance estimator for the non-parametric MCF estimator. Using the MCF approach to estimate the future expected number of failures within a certain time frame, there is no directly applicable method. However, the rate of the MCF curve, or the recurrence rate (repair rate), can be applied and used for the extrapolation of parametric estimations. This makes the MCF a significant decision support tool which allows manufacturers, operators and maintenance providers to make quantifiable and rational decisions in fields that have previously typically been in the domain of anecdotal data, guesswork and experience. This useful and simple concept has been available for nearly two decades, but the literature on this topic remains highly theoretical and difficult to penetrate for average practitioners, and reported applications have been very limited, (Al-Garni et al., 2007); (O'connor et al., 2012); (Nelson, 2003).

The main reason for using the MCF is that this approach provides a relatively simple way to describe the reliability behaviour of a whole population of repairable units, and that the MCF also provides a way to estimate the expected number of failures for large arrays of repairable units, for example units installed in an aircraft fleet. The MCF approach is particularly effective when there is a need to produce such estimates relatively quickly and simply, without having to use complex parametric methods.

2.4 Decision making and search algorithm

An algorithm can be defined as a well-defined computational procedure. Typically, an algorithm is associated with the processing of information, taking some value, or set of values, as the input and producing some value, or set of values, as the output. An algorithm is thus a sequence of computational steps, conducting a series of specified actions that transform the input data into the output results. In mathematics and computer science, an algorithm usually means a procedure that solves a recurring problem (Cormen, 2009). An algorithm can also be viewed as a tool for solving a well-specified computational problem. The statement of the problem specifies in general terms the desired input-output relationship. The algorithm describes a specific computational procedure for achieving that input-output relationship.

Algorithms are often applied to computational problems which involve searching for and sorting data in large arrays, and such problems are often combinatorial by nature. A search algorithm can be defined in several ways, for example as a procedure for performing linear, binary and half-interval searches, etc. Depending on the defined search algorithm and the complexity of the problem, the maximum computational time will be defined. With a high complexity and a badly chosen search algorithm, the computational time will be long. However, search algorithms can be specially designed to limit the search and find applicable solutions with the optimal exploitation of computational resources (Cormen, 2009).

Due to the practical importance of combinatorial (optimization) problems, many algorithms have been devised for their solution. Normally algorithms are divided into two types, namely exact and approximate algorithms (Stützle, 1998). For finite-size problems, a straightforward exact algorithm consists simply of enumerating the full solution space. Yet, such an algorithm is infeasible in the present case due to the exponential size of the solution space. To increase their efficiency, all modern exact methods use pruning rules to discard those parts of the search space in which the (optimal) solution cannot be found. These approaches perform an implicit enumeration of the search space. For optimization problems, the best-known examples are branch and bound algorithms (Lawler and Wood, 1966) (Pearl, 1984). Branch and bound algorithms can be (and often are) slow, however. In the worst case scenario, they require an effort that grows exponentially with the problem size, but in some favourable cases the methods converge with much less effort (Boyd and Mattingley, 2007).
The use of algorithms provides a number of advantages. One advantage resides in the development of the procedure itself, which involves identification of the processes, the major decision points, and the variables necessary to solve the problem. Developing an algorithm allows and even forces one to examine the solution process in a rational manner. Identification of the processes and decision points reduces the task into a series of smaller steps of more manageable size. By using an algorithm, decision-making becomes a more rational process. Algorithms are used as decision support in many different applications, for example transportation and logistics (route planning and packaging), medicine and finance, etc.; see, for example, for the application of algorithms as a decision support tool.
3 Research Methodology

Research methodology is a term that means the science of methods applied in the performance of scientific research. Kothari (2011) has defined research methodology as a “systematic method consisting of enunciating the problem, formulating a hypothesis, collecting the facts or data, analysing the facts and reaching certain conclusions either in the form of solutions towards the concerned problem or in the form of certain generalizations for some theoretical formulation”. The goal of research is to formulate the problem area and define the research questions describing the problems, and, if possible, find the answers to them, as described by Dane (1990).

3.1 Research Design

Depending on the research purpose, the research methodology can be subdivided into three different categories: exploratory, descriptive and explanatory approaches; see Table 3:1 for a summary of each approach.

<table>
<thead>
<tr>
<th>Explorative Method</th>
<th>Descriptive Method</th>
<th>Explanatory Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Become familiar with the basic facts, setting and concerns.</td>
<td>Provide a detailed, highly accurate picture.</td>
<td>Test a theory's prediction or principle.</td>
</tr>
<tr>
<td>Create a general mental picture of conditions.</td>
<td>Locate new data that contradict past data.</td>
<td>Elaborate and enrich a theory's explanation.</td>
</tr>
<tr>
<td>Formulate and focus on questions for future research.</td>
<td>Create a set of categories or classify types.</td>
<td>Extend a theory to new issues or topics.</td>
</tr>
<tr>
<td>Generate new ideas, conjectures, or hypotheses.</td>
<td>Clarify a sequence of steps or stages.</td>
<td>Support or refute an explanation or prediction.</td>
</tr>
<tr>
<td>Determine the feasibility of conducting research.</td>
<td>Document a causal process or mechanism.</td>
<td>Link issues or topics with a general principle.</td>
</tr>
</tbody>
</table>

Exploratory strategy: This strategy aims to explore a phenomenon or to achieve new insights into the defined research problem. It attempts to gain familiarity with the phenomenon and carry out the groundwork for future studies. Exploratory studies are undertaken in order to create an understanding of basic relationships and events. This method is suitable for unstructured research problems which are difficult to delimit (Marshall and Rossman, 2014); (Yin, 2013). Furthermore, exploratory research often adopts qualitative approaches and may involve a literature study, focus group interviews or other methods.

Descriptive strategy: This approach is suitable when the research problem is structured to identify the relations between particular events. The aim of a descriptive study is to make generalizations on an empirical basis (Marshall and Rossman, 2014). It can adopt a qualitative, quantitative or mixed approach. It often involves gathering data describing events, after which the collected data are organized, tabulated, depicted and described.

Explanatory strategy: The type of research conducted using this strategy aims to determine relationships between phenomena, and these relationships do not need to be causal (Dane, 1990). An explanatory study can therefore be used to analyse causes and relations which, taken together, explain a particular entity or phenomenon.
Normally, quantitative approaches are applied in explanatory research. Statistical techniques, especially hypothesis testing, provide a way to disclose the relationships within a phenomenon. The strategy selected for the research described in this thesis combines exploratory, descriptive and explanatory approaches. Table 3.2 below illustrates the linkage between the defined research questions and the applied research approaches.

Table 3.2: Relationship between research strategy and research questions.

<table>
<thead>
<tr>
<th>RQ. 1</th>
<th>How to estimate expected number of failures for multiple repairable units at fleet level during fleet retirement?</th>
<th>Exploratory</th>
<th>Descriptive</th>
<th>Explanatory</th>
</tr>
</thead>
<tbody>
<tr>
<td>RQ. 2</td>
<td>What are the prerequisites for an effective part-out-based spares provisioning?</td>
<td>Exploratory</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>RQ. 3</td>
<td>How to determine the repair termination times at the end of the retirement period?</td>
<td>Exploratory</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

The first research question was suitable for a descriptive and an explanatory research approach. An explanatory approach was selected since two different statistical approaches (parametric and non-parametric) were possible. These were examined and compared (see Paper I and II). Furthermore, it was investigated whether there was any existing methodology which could be used to estimate the expected number of failures for repairable units on the fleet level, and which was both good enough for practical use and simultaneously not too computationally demanding. Research question 1 is also descriptive in nature, since it was structured to identify the relations between unit utilization and failure times. Moreover, it also aimed to find a generalized approach for estimation of the expected number of failures at the fleet level on an empirical basis. For studies based on empirical data, see Marshall and Rossman (2014). Moreover, research question 1 involved the gathering of maintenance and operational data and description of the relationships between failure events.

For research question 2, an exploratory research approach was applied. This question deals with the prerequisites for an effective part-out based sparing (PBSP) programme, exploration of the dynamics of a part-out process during the retirement phase, and the acquisition of insight into the PBSP approach. This represents a multidisciplinary task with a number of linked processes, tasks, factors and decision nodes, which made an exploratory strategy suitable. The objective was to gain familiarity with the complexity of the PBSP programme and establish the basis for research question 3.

The third research question was suitable for a descriptive and an explanatory research approach. This research question involved the identification of applicable repair termination alternatives and finding the most cost-effective solution. The formulated problem is data-driven, multi-objective and combinatorial, consisting of many decision nodes and conditions, which made a descriptive approach applicable. The use of an explanatory approach was justified by the mutual interactions between the linked processes, tasks, factors and decisions in a PBSP programme, which affect the analysis of repair termination alternatives, stock levels, fleet availability, etc.
3.2 Research Approach

The selected research approach can be based on deduction, induction or adduction (Alvesson and Sköldberg, 1994). The deductive approach endeavours to generate testable hypotheses based on existing theory, using general rules and theories to explain a specific case (Monette et al., 2013). The results from a deductive study are based on logical inferences, see Sullivan (2001) for more details.

Adductive reasoning is a combination of the deductive and inductive approaches. The researcher can select a deductive approach to collect empirical data based on a theoretical framework, subsequently switching to an inductive method to develop theory based on the collected empirical data. During the research process, an improved understanding of the studied subject is developed and the related theory is modified based on the new findings (Alvesson and Sköldberg, 1994).

The research in this thesis was based on a combination of all three types of reasoning (deductive, inductive and adductive). In Paper I and II, a mix of inductive and deductive (adductive) reasoning was used. Empirical field data for two types of repairable units were collected at the aircraft fleet level for their whole lifecycle as a part of the study. The aim of the study was to identify an appropriate failure model for multiple repairable units, including hypothesis testing, and to make conclusions based on the experience drawn from the study at the fleet level.

In Paper III, an inductive approach was applied. Within the study, five main decision nodes of the part-out based spare provisioning (PBSP) programme were identified, to support the provisioning function within the PBSP. The prerequisites for the PBSP programme were identified, and associated key decision criteria for an effective phase-out management process were presented, to minimize the stock level and reduce it to zero (ideally) at the end of the retirement period, while ensuring the availability of spares within the retirement period.

The purpose of creating the computational models and algorithm presented in Paper IV was to find applicable maintenance termination time alternatives, and these models and objectives were developed using a “top-down” approach, proceeding from a general description to a deductive approach which was more specific. The study started by first defining theories, models and algorithms concerning the topic of interest, after which there was a narrower focus on more specific hypotheses, which were then tested using a case study of a Saab-105 fleet. Furthermore, research approaches can broadly be divided into quantitative, qualitative and mixed approaches. Quantitative information is expressed as numbers (or more precisely intervals and ratios), while qualitative information is usually expressed in words (or more precisely ordinal and nominal scales). In simple terms, quantitative research uses numbers, counts and measures, while qualitative research uses questioning and content analysis (Monette et al., 2013). The quantitative method emphasizes measurements and the analysis of causal relationships between variables (Richardson et al., 2000). The qualitative methodology aims at explaining causality between events and consequences (Miles et al., 1984). Both quantitative and qualitative approaches have been used in the research conducted for this thesis.

Applying a quantitative approach, the field data were collected and analysed to estimate the expected number of failures and spares demand at the fleet level. This was carried out in such a way that the selected method could be validated by comparison with empirical data (see research question 1). In addition, a data-driven approach was developed to identify the time for termination of repair and parting-out during the retirement period.
The research for this thesis also included a qualitative approach. The proposed PBSP framework is of a descriptive nature, based on experience gathered through interviews held with experienced experts, expert judgements, document studies and observations.

3.3 Research Process

The overview of the research process used in this thesis is presented in Figure 3.3. The process is divided into eight different steps; the process involves a systematic process that focuses on being objective and gathering information for analysis so that the research can come to a conclusion at the end of the process.

Figure 3.3. The Research Process Implemented in this Thesis, adopted from Hassel (2010).

**Step I: Defining the research problem**: The problems dealt with in the research documented in this thesis were formulated in cooperation with the two main actors within military aviation in Sweden, i.e. Saab Support and Services AB and the Swedish Air Force (FM). This contributed to understanding what is needed by industry in practice and what the requirements for usefulness are. Moreover, in order to address the research problem, the background and experience of the subject experts were used. In this step, a preliminary literature study was performed to identify the research gaps and the problems associated with supply chain and stock provisioning within aviation companies during the retirement of an aircraft fleet. The outcome of this literature study resulted in the formulation of the research purpose and the more precise research questions. The outcome of this phase is summarized mainly in the introduction of this thesis. Thereafter, a tentative research methodology was constructed.

**Step II: Specifying the research purpose or goal**: The research purpose was formulated according to the defined research problem and based on the interests of the project partners engaged in the studies. Interactions took place between the various steps in the research process, and the research purpose was modified as new ideas and better reasoning were presented during the other steps. Hence, the formulation of the purpose was subjected to continuous improvement and required changes.
Step III: Specifying the requirement criteria and constraint conditions: Considering the availability of the required resources (e.g. time, data, expertise and budget), and in accordance with the purpose and objectives of the research, as well as the industrial interests, the scope and limitation of the research were defined. Based on the empirical evidence, the research literature and some experience gained from the other steps of the research, the limitations, and constraint conditions were changed occasionally.

Step IV: Identification of alternative methodologies: In this step, the methodologies which were preliminarily identified in steps 1 and 2 were investigated further. These methodologies were identified as capable of addressing the problems associated with estimation of the spare part demand at the fleet level, identification of the prerequisites for an effective PBSP programme, and finding applicable and cost-effective alternatives for maintenance termination times.

Step V: Construction of the methodology of choice: In this step, additional literature studies were performed concerning methodologies for estimation of the spare part demand, identification of the prerequisites for an effective part-out based spare provisioning (PBSP) programme, and finding applicable and cost-effective alternatives for maintenance termination times. The goal for this step was to make a further attempt to develop and identify the methodologies that would address the research questions and fulfil the purpose and objectives of the study in accordance with the research limitation and scope.

Step VI: Verification of the proposed methodology: The purpose of this step was to ensure the applicability, feasibility and effectiveness of the proposed methodology for solving the stated problems. The verification step was conducted with the collaboration of experts from Saab Support and Services and the operator, the Swedish Air Force, through an iterative process, by matching the developed methodologies to a specific case study on an Saab-105 aircraft fleet. In addition, colleagues of the author at Luleå University of Technology (LTU) were engaged and provided valuable comments on the research design.

Step VII: Evaluation of the proposed methodology: Within this step, the shortcomings, gaps and weaknesses of the candidate methodologies were identified. This was achieved through interviews held with experienced practitioners and customers of the Saab 105 fleet. Through meetings and discussions, conclusions were drawn, and the effectiveness of the proposed methodologies was identified in practice. This step played a crucial part for the continuous process of improving methodologies.

Step VIII: Application and modification of the proposed methodology: Within this step, the suggested improvements coming from the evaluation phase were applied and verified once again to assure the applicability and effectiveness of the methodology.

3.4 Data Collection

There are six main sources of information that are applicable for a case study, as discussed by Yin (2013). These six sources are documentation, archival data, interviews, direct observations, participant-observations and physical artefacts (Marshall and Rossman, 2014). An overview of the six sources and their comparative strengths and drawbacks can be found in Marshall and Rossman (2014). Data sets can be classified into primary and secondary data sets. Data collected by the researcher in connection with the study are called primary, while data collected by others, but used by the researcher are classed as secondary (Dahmström, 2005). One advantage of secondary data is that they often provide a simple and cheap source of information. The drawbacks are that it may be difficult to find fully relevant information and that the quality and appropriateness of secondary data can be difficult to determine.
Consequently, the robustness of the results can be difficult to evaluate when secondary data have been used. It is important to have a generally applicable analysis strategy for each particular study, in order to guide decisions as to what should be analysed and why it should be analysed. Data analysis comprises the following tasks: examining, categorizing, tabulating, and recombining the data to address the postulates of a study (Yin, 2013).

Two main types of data were collected in the research for this thesis, i.e. theoretical and empirical data. Theoretical information was collected in order to address the identified research questions. Empirical data were mostly useful in connection with research questions 1 and 3. The empirical data were used to verify and test the suggested methodology, based on research question 1 (see Paper I and II), and based on research question 3 (see Paper IV). In connection with research question 2, theoretical data were collected from both Saab AB and the operator Swedish Air Force (FM) and Swedish Defence Materiel Administration (FMV) about the prerequisites for the suggested part-out based spare provisioning (PBSP) programme, for example the decision nodes, “strategic planning”, “fleet management”, “maintenance management”, “logistic support management” and “data and data management”.

The theoretical data were collected from academic sources and practitioners in the field, Saab AB, FM and FMV. Information and data were collected from the experience of subject experts and the project partners, Saab AB, FM, FMV and Luleä University of Technology (LTU). Literature in the form of relevant monographs was obtained from academic sources, having been located through LIBRIS (the Swedish National Library’s search system). Several other databases were employed to locate papers and reports, for example Scopus, Compendex, Scirus, Science Citation Index, Emerald and Science Direct, etc. A number of search-terms were formulated, such as phase-out, parting-out, end-of-life management, reliability, repairable units, maintenance, spare part management, retirement process, etc. These terms were used in various combinations to search in the databases for relevant papers and reports.

Somewhat surprisingly, it was found that little had been published on the effective use of repairable units at the fleet level during the retirement phase, although there were a number of papers on the obsolescence problem and the so-called “last buy”, for both repairable and non-repairable units. Empirical data were collected using four methods: archival data sources, interviews, personal observations and documentary data. The archival data were retrieved from databases containing historical operational and maintenance data, specifications of technical configurations, and manuals relevant to the units belonging to the aircraft types selected for the study (the FPL 37 and Saab 105).

The documentary data consisted of various manuals, regulations, and approved procedures for support and maintenance. In addition, a number of contracts regarding performance-based business solutions were studied, due to the fact that Saab 105 undergoes such as contract. The data acquisition from operation, maintenance and logistics etc. is crucial when dealing with performance-based contracts (Lopes et al., 2017). In this thesis study two data sets from two different aircraft types (FPL 37 and Saab 105) have mostly been used. Empirical data for the Radar Transmitter and the Cooling Turbine belonging to the former Swedish military aircraft system FPL 37 Viggen, includes information on all maintenance significant events for the individual turbines, i. e. date of delivery, storage time, storage maintenance, installations, failures, preventive and corrective maintenance, modifications and discard. These events are associated with calendar dates and accumulated operating time. All the data concerning the FPL 37 Viggen and the Saab 105 were collected from the Swedish armed forces aircraft maintenance information System (DIDAS FLYG). This arrangement permitted complex post-processing and data-mining despite the limitations of the old DIDAS FLYG system.
The DIDAS FLYG system contains comprehensive information on all the FPL 37 Viggen and Saab 105 aircraft (among others) and all the tracked transmitter and turbine units. This made it possible to trace all the maintenance-significant events throughout the lifecycle of each item, such as manufacture, installations, removals, modifications, preventive and corrective maintenance and finally scrapping and disposal. All the events are associated with dates and the number of accumulated flight hours, and the corrective maintenance actions are almost always accompanied by plain text describing the type of fault and the actions taken to correct it. Further, the DIDAS FLYG system was primarily used as a maintenance planning and scheduling system, tracking the time remaining to maintenance tasks based on calendar time, flight hours and other operational parameters.
4 Summary of Appended Papers

This chapter provides a summary of the four appended papers in the thesis, and describes their contributions to answering the research questions, see Table 4:1. Further information can be found in the appended papers.

<table>
<thead>
<tr>
<th>RQ</th>
<th>How to estimate expected number of failures for multiple repairable units at fleet level during fleet retirement?</th>
<th>Paper I</th>
<th>Paper II</th>
<th>Paper III</th>
<th>Paper IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>RQ 1</td>
<td>X X</td>
<td>X X X X</td>
<td>X X X X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RQ 2</td>
<td>What are the prerequisites for an effective part-out-based spares provisioning?</td>
<td>X X X X</td>
<td>X X X X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RQ 3</td>
<td>How to determine the repair termination times during the end of the retirement period?</td>
<td>X X X X</td>
<td>X X X X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Paper I


**Purpose:** In the study presented in this paper, the non-parametric approach was investigated to assess its performance in estimating the expected number of failures at the fleet level. Similarly to the study presented in Paper II, the study documented in Paper I considers multiple repairable units at fleet-level during the aircraft retirement period.

**Methodology:** In the study presented in Paper I, the reliability of the radar transmitter and cooling turbine units was studied using the concept of the mean cumulative function (MCF). The expected number of failures ($N_{MCF}$) was estimated using the MCF within each observation window (500 operational hours) and was compared with the actual number of failure events ($N$), see Table 4:2a and Table 4:2b. The proposed methodology includes the use of interval-based linear parametric estimations using the local “rate of occurrence of failure” (ROCOF) of the MCF curve per observation window (500 operational hours), to extrapolate the MCF with linear estimates. Applying this approach, the local ROCOF was used to estimate the expected number of failures for the subsequent observation window.

**Findings:** The results obtained for the radar transmitter using the local ROCOF show that the expected number of failures ($N_{LMCF}$) is underestimated at the beginning of the unit’s utilization and overestimated towards the end of the unit’s life. These results and the actual number of failure events ($N$), over the 3,500 hours of observed operational time, are shown in Table 4:3a for comparison. For the cooling turbine, the expected number of failures ($N_{LMCF}$) is slightly overestimated during the first increment, underestimated in the middle of the lifecycle, and fairly accurate towards the last increments, compared with the actual number of failure events ($N$), over the 3,000 hours of observed operational time, see Table 4:3b. The results for both units show that the estimation of $N_{LMCF}$ is not consistent regarding $N$, and less accurate compared to $N_{PLP}$.
Table 4.2a. Comparison between actual failure events and modelled number of failures (radar transmitter).

<table>
<thead>
<tr>
<th>Observation Window (Operation Time [h])</th>
<th>Actual Failure Events N</th>
<th>Local MCF</th>
<th>( N_{LMCF} (50%) )</th>
<th>( \Delta LMCF (50%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-500</td>
<td>39</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>500-1000</td>
<td>35</td>
<td>100</td>
<td>-30</td>
<td></td>
</tr>
<tr>
<td>1000-1500</td>
<td>41</td>
<td>112</td>
<td>+15</td>
<td></td>
</tr>
<tr>
<td>1500-2000</td>
<td>28</td>
<td>80</td>
<td>+24</td>
<td></td>
</tr>
<tr>
<td>2000-2500</td>
<td>11</td>
<td>34</td>
<td>+19</td>
<td></td>
</tr>
<tr>
<td>2500-3000</td>
<td>2</td>
<td>3</td>
<td>+2</td>
<td></td>
</tr>
<tr>
<td>3000-3500</td>
<td>39</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2b. Comparison between actual failure events and modelled number of failures (cooling turbine).

<table>
<thead>
<tr>
<th>Observation Window (Operation Time [h])</th>
<th>Actual Failure Events N</th>
<th>Local MCF</th>
<th>( N_{LMCF} (50%) )</th>
<th>( \Delta LMCF (50%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-500</td>
<td>39</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>500-1000</td>
<td>35</td>
<td>40</td>
<td>+5</td>
<td></td>
</tr>
<tr>
<td>1000-1500</td>
<td>41</td>
<td>31</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td>1500-2000</td>
<td>28</td>
<td>24</td>
<td>-4</td>
<td></td>
</tr>
<tr>
<td>2000-2500</td>
<td>11</td>
<td>11</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2500-3000</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

**Practical Implications:** Non-parametric methods provide an estimate of the number of recurrences (of repairs and failures) per unit and for the whole population, versus the utilization or age.

The MCF is simple in that it is easy to understand, prepare and present, and the method can be used successfully to track field failures and identify failure trends, anomalous systems and unusual behaviour. By using the MCF method, the mathematical manipulation of operational data is greatly simplified, albeit at the cost of losing some analytical rigour. In an actual operational situation, the iterations will be performed at much shorter intervals than the suggested observation window (500 operational hours). Furthermore, in a real situation the individual units in a population will have quite different numbers of operational hours at any given time. This means that, for most units, the actual MCF will be available as a more reliable estimate until they reach the number of operational hours of the current “lead unit”, and that the linear estimate will only need to be invoked beyond this point.

**Contribution:** The MCF method provides a simple and straightforward approach to the analysis of reliability data from multiple system-level repairable devices. However, the MCF model has a disadvantage when it comes to forecasting the future need for units due to failures, because the model is non-parametric.

However, by estimating linear segments using the MCF curve, the ROCOF, it is possible to forecast the future need for units according to these linear estimates.
Paper II


**Purpose:** The purpose of the research study presented in this paper was to investigate and assess the performance of parametric reliability methods for estimation of the expected number of failures at the fleet level, using a pooling approach. The study considers multiple repairable units during the aircraft retirement phase.

Within the study, routines for the selection of reliability models were applied, including data collection (cleaning and filtering), trend tests, checks for homogeneity and heterogeneity, model selection, etc.

**Methodology:** In the study, trend analysis was performed to examine the existence of monotonic or non-monotonic trend in the failure data. Furthermore, the homogeneity and heterogeneity behaviour of the data sets was examined and the units were classified based on the trend tests.

The total time on test (TTT) - based MIL-HDBK-189 and Laplace trend tests were used, and the reason for choosing TTT-based tests was that there was no reason to believe that either of the two populations of units was non-homogeneous. A rejection of the null hypothesis in both the Laplace and the MIL-HDBK-189 test gave an indication that there was a trend in the failure data, leading to the conclusion that the samples came from heterogeneous populations and the units could be pooled. In the study, the shape- and scale-parameters of the power law process (PLP) were estimated using maximum likelihood estimates (MLEs) with an iterative process (Newton-Raphson method).

The confidence interval was estimated for both the shape- and the scale-parameter, and besides studying the confidence interval, Bartlett’s test was performed to study the possibility of modelling the PLP with an equal shape-parameter. Paper II illustrates the applicability of the power law process (PLP) when used to estimate the number of corrective maintenance events (failures) at the fleet level during the retirement period, using a pooling approach. Empirical operational and maintenance data for two repairable units were used, i.e. data on the cooling turbine and radar transmitter belonging to the former Swedish fighter aircraft the VIGGEN FPL 37. The expected number of failures was estimated using the PLP and compared with the empirical failure data. The comparison was made based on an observation window set to be 500 operational hours for the studied units.

**Findings:** The results show that for the radar transmitter (see Table 4:3a), there are overestimations and sometimes underestimations of the expected number of failures within the operational segment, and the estimates of the PLP are not consistent. Concerning the cooling turbine (see Table 4:3b), there are mostly underestimations of the expected number of failures within the operational segment, but the variation is small and the results of the PLP are more consistent for the cooling turbine.

**Practical Implications:** The application of parametric methods for a single unit is quite clear and straightforward. However, in practice the analyst is often dealing with multiple similar systems which are installed in different aircraft and which are running in different operating environments, with other and different influencing factors. The aim of the reliability analysis performed in this study was to track field failures to provide information regarding the failure rates and the expected number of failures at the fleet level, and not at the individual component level.
The purpose was to provide a relatively simple method for estimating the expected number of failures for large arrays of repairable units belonging to an operational aircraft fleet. This task was motivated by the need to produce such estimates relatively quickly and reasonably accurately, when making decisions during the retirement period.

Table 4:3a. Comparison between actual failure events and modelled number of failures (radar transmitter).

<table>
<thead>
<tr>
<th>Observation Window (Operation Time [h])</th>
<th>Actual Failure Events N</th>
<th>PLP</th>
<th>∆PLP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-500</td>
<td>113</td>
<td>133</td>
<td>+20</td>
</tr>
<tr>
<td>500-1000</td>
<td>130</td>
<td>104</td>
<td>-26</td>
</tr>
<tr>
<td>1000-1500</td>
<td>97</td>
<td>91</td>
<td>-6</td>
</tr>
<tr>
<td>1500-2000</td>
<td>56</td>
<td>66</td>
<td>+10</td>
</tr>
<tr>
<td>2000-2500</td>
<td>15</td>
<td>27</td>
<td>+12</td>
</tr>
<tr>
<td>2500-3000</td>
<td>1</td>
<td>2</td>
<td>+1</td>
</tr>
<tr>
<td>3000-3500</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4:3b. Comparison between actual failure events and modelled number of failures (cooling turbine).

<table>
<thead>
<tr>
<th>Observation Window (Operation Time [h])</th>
<th>Actual Failure Events N</th>
<th>PLP</th>
<th>∆PLP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-500</td>
<td>39</td>
<td>37</td>
<td>-2</td>
</tr>
<tr>
<td>500-1000</td>
<td>35</td>
<td>43</td>
<td>+8</td>
</tr>
<tr>
<td>1000-1500</td>
<td>41</td>
<td>38</td>
<td>-3</td>
</tr>
<tr>
<td>1500-2000</td>
<td>28</td>
<td>27</td>
<td>-1</td>
</tr>
<tr>
<td>2000-2500</td>
<td>11</td>
<td>12</td>
<td>+1</td>
</tr>
<tr>
<td>2500-3000</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Contribution: Paper II presents the results of a study which examined a parametric model, the power law process, as used to estimate the number of failures for multiple repairable units at the fleet level. Using a parametric approach can result in a large amount of special cases, for example the homogeneous and the non-homogeneous case, and the necessity of applying various statistical methods. Furthermore, parametric methods are relatively time-consuming due to the concomitant necessary procedures for trend testing, testing for dependence, testing for homogeneity, model selection, parameter estimation, etc. However, extensive information can be extracted concerning the reliability behaviour of a unit. According to the results obtained through this study, it can be concluded that the parametric approach, compared with the non-parametric approach, is more practical and provides more accurate results for estimation of the expected number of failures, for the purpose of predicting the spare part demand.

Paper III


Purpose: The purpose of this paper was to present the prerequisites for a part-out-based spares provisioning (PBSP) management programme during the phase-out of an aircraft fleet. A novel framework was proposed for implementation of the PBSP, the prerequisites for a PBSP management programme were identified, and associated key decision criteria for an effective phase-out management process were presented.
Methodology: The problem addressed in this paper was formulated on the basis of a real case, in cooperation with the two main actors within military aviation in Sweden, i.e. Saab Support and Services AB and the Swedish Air Force (FM). The proposed framework is based on a case study performed on the phasing-out of a military aircraft system, the VIGGEN FPL 37, operated by the Swedish Armed Forces. Within the study, a comprehensive literature review was carried out and interviews were held with subject experts to identify the decision nodes and the prerequisites in the context of military aviation. The results of the interviews and discussions were documented and the framework was presented to the expert team on different occasions, to obtain their comments and to make modifications.

Findings: Within the study the main decision nodes of the PBSP were identified for a military application. These include “strategic planning”, “fleet management”, “maintenance management”, “logistic support management” and “data and data management”, see Figure 5:7 in Section 5.

In addition, the tasks and processes within the decision nodes were identified, and the prerequisites for PBSP management were defined. The framework presented in this study supports the operator by increasing their understanding of the dynamics of the PBSP and by providing solutions with the lowest possible risk. This is also potentially helpful for the termination of contracts during the aircraft retirement phase. If the operator has engaged several external subcontractors, it is vital to give them timely notice of contract termination. In some cases, operators are interested in ending the contract at an early stage of the PBSP. However, this might result in a very dangerous situation where a unit is needed, but the maintenance capability has been terminated.

Obviously, the decision variables and objectives change dynamically during the retirement phase, which necessitates comprehensive and dynamic planning, and tight communication between the stakeholders (e.g. experts, maintenance technicians, analysts, the management, the operator, etc.), which requires effective communication and interactions to be in place. Moreover, the time horizon for implementing new tasks, functions and routines, etc. can be quite long and the work involved can be substantial and intensive.

The prerequisites must be fulfilled, the processes initiated, the decisions taken, and the tasks performed as soon as the decision has been taken to retire the aircraft fleet. During the implementation of PBSP, there will be a frequent exchange of information and data and frequent interaction between different decision nodes and stakeholders in multiple ways. In addition, there will be plenty of local rules and decisions that are not necessarily harmonized, which will generate a high level of complexity in the implementation of the PBSP programme.

Practical implications: Considering the high number of both military and commercial aircraft in the world that have been subjected to retirement in recent years, it is highly recommended that one should establish a standard for the part-out-based provisioning concept, to ensure the availability of a higher level of instruction and more adequate definitions of terms, with a view to enhancing the possibility of good interaction. Such a standard should also define the requirements for different stakeholders, the associated decision nodes, and the protocol for data exchange, and should point out the analytical methodologies needed for logistic support. This would eventually reduce the complexity of the PBSP and contribute to the success of the programme.

Although the PBSP method is quite commonly applied within both the military and the civilian sector, a surprisingly small amount of literature has been published on the subject. Indeed, remarkably little has been published on any aspects of maintenance during the end-of-life period.
Contribution: A novel framework was proposed for the implementation of spare part provisioning during the retirement phase of an aircraft fleet using the reclamation of spare parts as a source for provisioning. A PBSP management programme was identified, and associated key decision criteria for an effective phase-out management process were presented. This constitutes a relatively new approach to the systematic description of a management framework to be used for spares provisioning during the retirement phase of an aircraft fleet based on the reclamation of spares from disposed aircraft.

Somewhat surprisingly, although the PBSP method is quite commonly applied within both the military and the civilian sector, there are very few publications on the subject. Indeed, very little has been published on any aspects of maintenance during the end-of-life period.

Paper IV


Purpose: The aim of the study presented in this paper was to propose a computational model which could be used to identify the applicable repair termination alternatives that would minimize the number of remaining spares at the end of the retirement period, while fulfilling the availability requirement for spares during the period, at the lowest possible cost.

The repair termination alternatives include ending the repair of units due to corrective maintenance (CM), preventive maintenance (PM) and Parting-out Maintenance (POM) tasks at specific times, including stopping the reclaiming process, i.e. the process of sending reclaimed units directly to storage, parting-out storage (POS). The paper introduces a spares availability model based on a dynamic spares provisioning approach. The model is intended to act as a decision support tool for PBSP management.

Methodology: The stock level will increase due to the spares received through the parting-out process (PO), i.e. the units sent to storage due to POS and POM, as well as the spares received through the repair actions due to the PM and CM of the operational fleet. At the same time, the number of operational aircraft will decrease over the retirement period, and obviously the demand for spares will normally decrease, which will give an increase in the number of units in storage. The increase in the fill rate and the simultaneous decrease in the demand for parts will lead to an excessive level of spares in stock. Therefore, to adjust and minimize the stock level at the end of the retirement period, the proposed computational model and algorithm can be applied to find suitable stopping points for CM, PM, POM and POS.

The applicable and feasible alternatives can be compared with regard to their respective costs, and the most cost-effective solution can be selected. In this study, two different approaches were applied, one of which creates a controlled scenario, while the other creates a non-controlled scenario. In the non-controlled scenario, the parting-out process is not terminated and continues to the end of the retirement period. In the controlled scenario, on the other hand, at specific times (corresponding to the part-out-based spares provisioning (PBSP) control gates), one ceases to part out units and send them directly to storage (POS), and one stops performing repair actions on the units received at the repair shops owing to CM, PM and POM.

However, identifying the applicable and effective repair termination alternatives by searching among all the combinations of possible solutions, including both feasible and infeasible solutions, would be too time-consuming. Therefore, to limit the search and find applicable solutions more rapidly, a search algorithm was developed; the proposed algorithm is a global searching algorithm with pruning.
Findings: The proposed PBSP approach and computational model provide added value from a sustainability point of view, since the use of existing resources is maximized during the retirement process, through the process of reclaiming units and the applicable maintenance termination alternatives. The implementation of the proposed computational model in a PBSP programme provides a detailed and situation-based overview of the stock level dynamics, and contributes to the spares provisioning process by providing solutions to issues such as obsolescence, last-time buys and cannibalization. The non-controlled scenario involves a continuous parting-out of spares and continuous repair activities towards the end of the retirement period. The results obtained for the non-controlled scenario within the case study show that there will be 69 cooling turbines in stock at the end of the retirement period and the total cost of this scenario is estimated to be 4,6 MSEK.

In the controlled scenario, the flows of spares to the repair shop and storage are controlled through the PBSP decision gates for CM, PM, POM and POS. Using the proposed search algorithm and the defined computational model, the successive states and applicable alternatives fulfilling the boundary conditions have been identified. The studied case shows that there is a set of 129,212 applicable solutions for combinations of repair termination alternatives, all of which fulfill the defined conditions. The highest cost for a solution in the controlled scenario is 1,888,000 SEK, and compared with the cost of the non-controlled scenario, this constitutes a substantial saving of 2,712,000 SEK.

Practical implications: When dealing with the retirement of an aircraft fleet, one must take into account the environmental, social, and economic impacts of the retirement phase. The proposed PBSP framework makes it possible to compare different business models, dismantling strategies and network structures that impact the efficiency of a spares provisioning strategy during the retirement phase. The PBSP framework, with the suggested computational model and algorithm, contributes to an integrated approach for analysing spares provisioning during the retirement phase of an aircraft fleet, and provides a decision-making framework for sustainable eco-efficiency and profitability.

Contribution: Utilisation of the proposed computational model and algorithm in the PBSP programme approach provides the possibility of making substantial savings. The most vital benefit of the approach is that the results obtained by applying the proposed computational model and search algorithm provide transparency concerning the applicable repair termination alternatives and their associated costs.
5  Discussion and conclusions

This chapter draws conclusions from the results of the conducted research work and discusses those conclusions. The structure of the chapter is based on the stated research objectives.

5.1  Research objective I

“To determine a practical approach for estimation of the spare part demand at the fleet level during the retirement phase:”

The first objective of the study conducted for this thesis was formulated as follows: “to determine a practical approach for estimation of the spare part demand at the fleet level during the retirement phase”. This objective is mainly linked with the first research question: “how to estimate expected number of failures for multiple repairable units at fleet level during fleet retirement?” This question is answered mainly by research presented in Paper I and Paper II.

In order to create an appropriate and cost-effective maintenance resource planning during the end-phase period, it is crucial to have an accurate estimate of the inter-arrival of maintenance events, including both preventive and corrective actions. The estimation of preventive maintenance (PM) events of an aircraft system is quite straightforward and is based on the defined frequencies and intervals tabulated in the maintenance planning document offered by the manufacturer. The major challenge is the estimation of the corrective maintenance (CM) events, i.e. the failure events of repairable units, which are highly dependent on the reliability performance of the units in the operational field.

There are established methods for the reliability analysis of a single repairable unit. However, in practice, the reliability analyst is often dealing with multiple similar units which are installed in different assemblies and which are operating with different profiles in different environments. In the case of the study performed for this thesis, the phase-out manager is interested in knowing the inter-arrival of the CM events or the failures at the fleet level, and needs a practical method for his estimation. Hence, in order to fulfil the first objective, we investigated the possibilities that parametric and non-parametric methods can provide for estimating the failures at the fleet level, with a view to supporting the maintenance resource planning for a specific operational increment.

In Paper I, a parametric approach was used for estimation of the CM events (failures) at the fleet level. The failure of radar transmitter and cooling turbine units was studied, and for this purpose the empirical data of the Swedish military aircraft system FPL 37 VIGGEN was used; see Figure 5:1 and Figure 5:2 for failure data including censoring for both types of units, for the cooling turbine, the failure history for every third units is show, this due to the vast number of units. The radar transmitter is part of the main surveillance radar (the PS-37) of the AJ 37 strike aircraft. The cooling turbine is the principal unit of the environmental control system that delivers cooling air to the electronics and the cockpit air conditioning. The number of failure events for the radar transmitter and cooling turbine was studied at the fleet level through an observation window equal to 500 operational flight hours, see Figure 5:3 and Figure 5:4 for respective unit.

In the study, a pooling approach was used to extract the reliability characteristics of the selected units at the fleet level, and the homogeneity and heterogeneity were analysed. Concerning the homogeneity, the units had been operated by the Swedish Air Force in Sweden, had the same design characteristics, had undergone similar maintenance procedures within the same maintenance facilities, and had been used in similar operating conditions.
In addition, the production and operation of the units were highly regulated and controlled through certification by European and international authorities. Accordingly, these units can be said to be identical and interchangeable. Hence, the selected units can be regarded as a homogeneous set of units. If instead one were to consider pooled data from different operational environments, there might be a source of non-homogeneity and the data should be checked for pooling possibilities.
The total time on test (TTT) based and combined versions of both the Laplace and the MIL-HDBK test were used to test the trend within both units (the radar transmitter and cooling turbine). Having obtained a statistical trend in both populations, Bartlett’s test also showed that the failure data of individual units follow a similar intensity function for each population, meaning that the populations are heterogeneous and, therefore, data pooling is justified for both types of units.

The power-law process (PLP) was used to model the expected number of failures based on the pooled data for both types of units, and the model parameters were estimated using maximum likelihood estimation (MLE) with an iterative process, using the method of Newton Rapson. The shape-parameters were estimated at a significance level of 5 % to be $(0.83 < \beta_A = 0.90 < 0.98)$ and $(1.07 < \beta_B = 1.19 < 1.32)$ for the radar transmitter and cooling turbine, respectively. Moreover, the scale-parameters were estimated to be $(348.6 < \theta_A = 416.6 < 497.9)$ and $(2946.9 < \theta_B = 3312.5 < 3723.5)$ at a significance level of 5 % for the radar transmitter and cooling turbine, respectively, where unit A is the radar transmitter and unit B is the cooling turbine.

The expected number of failures ($N_{PLP}$) was estimated using the PLP within each observation window of 500 flight hours (as a practical operational increment) and was compared with the actual number of failure events ($N$), see Table 5:1a. As is shown in Table 5:1a, the $\Delta_{PLP}$ value for the radar transmitter changes inconsistently, showing an over- and underestimation of $N_{PLP}$ in comparison with $N$, over the 3,500 hours of observed operational time. The reason is that the failure rate of this unit changes inconsistently and several changes have been made in the maintenance programme over the lifecycle of the units (see Paper I and II for further details). Table 5:1b shows $N$, $N_{PLP}$ and $\Delta_{PLP}$ for the cooling turbine. As shown, there is over- and underestimation of $N_{PLP}$ in comparison with $N$, over the 3,000 hours of observed operational time. Although the variation, $\Delta_{PLP}$, is smaller for the cooling turbine than for the radar transmitter, there is still no real consistency with $N$.

In Paper II, the reliability of the radar transmitter and cooling turbine units was studied using the concept of mean cumulative function (MCF). The expected number of failures ($N_{MCF}$) was estimated using the MCF within each observation window (500 operational hours) and was compared with the actual number of failure events ($N$), see Table 5:1a. As is shown in Table 5:1a, the $\Delta_{MCF}$ values for both the radar transmitter and the cooling turbine are consistent in respect of $N$ for both the units.

The results of the analysis using the MCF show that the estimation of the expected number of failures is rather close to the empirical failure data per increment, see Table 5:1a-5:1b. A minor underestimation and slight overestimation can be noticed in the middle of the studied increments for the radar transmitter, but otherwise the estimation is closely comparable to the empirical failure. Concerning the cooling turbine, there is minor deviations, with one failure over- or underestimated per studied increment. In another attempt to use the capability of the MCF to estimate the expected number of failures, the median rate of occurrence of failure (ROCOF) of the MCF curve was calculated for each observation window and is herein called the local ROCOF. Applying this approach, the local ROCOF was used to estimate the expected number of failures for the next coming observation window, see below Figure 5:3 and Figure 5:4.
Using the local ROCOF, the results for the radar transmitter show an underestimation of the expected number of failures ($N_{LMCF}$) at the beginning of the unit’s utilization and an overestimation towards the end of its life, compared with the actual number of failure events ($N$), over the 3,500 hours of observed operational time, see Table 5:1a. For the cooling turbine, the expected number of failures ($N_{LMCF}$) was slightly overestimated during the first increment, was underestimated in the middle of the lifecycle, and was fairly accurate towards the last increments, compared with the actual number of failure events ($N$), over the 3,000 hours of observed operational time, see Table 5:1b. The results for both units show that the estimation of $N_{LMCF}$ is not consistent with $N$ and is less accurate compared to $N_{PLP}$.
Compared to the radar transmitter, the cooling turbine shows a recurrence rate change throughout the lifecycle of the units, although this change is consistent and unidirectional and is, consequently, tracked well by the local recurrence rates of the MCF function per increment, see Figure 5:5 and Figure 5:6 below.

Figure 5:5. Cumulative number of failures using PLP estimation for the radar transmitter.

Figure 5:6. Cumulative number of failures using PLP estimation for the cooling turbine.
Table 5:1a. Comparison between actual failure events and modelled number of failures (radar transmitter).

<table>
<thead>
<tr>
<th>Observation Window (Operation Time [h])</th>
<th>Actual Failure Events N</th>
<th>Expected Number Of Failures(N) And Deviation with Actual Number Of Failure Events(∆)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PLP</td>
<td>MCF</td>
</tr>
<tr>
<td>0-500</td>
<td>113</td>
<td>133</td>
</tr>
<tr>
<td>500-1000</td>
<td>130</td>
<td>104</td>
</tr>
<tr>
<td>1000-1500</td>
<td>97</td>
<td>91</td>
</tr>
<tr>
<td>1500-2000</td>
<td>56</td>
<td>66</td>
</tr>
<tr>
<td>2000-2500</td>
<td>15</td>
<td>27</td>
</tr>
<tr>
<td>2500-3000</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3000-3500</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5:1b. Comparison between actual failure events and modelled number of failures (cooling turbine).

<table>
<thead>
<tr>
<th>Observation Window (Operation Time [h])</th>
<th>Actual Failure Events N</th>
<th>Expected Number Of Failures(N) And Deviation with Actual Number Of Failure Events(∆)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PLP</td>
<td>MCF</td>
</tr>
<tr>
<td>0-500</td>
<td>39</td>
<td>37</td>
</tr>
<tr>
<td>500-1000</td>
<td>35</td>
<td>43</td>
</tr>
<tr>
<td>1000-1500</td>
<td>41</td>
<td>38</td>
</tr>
<tr>
<td>1500-2000</td>
<td>28</td>
<td>27</td>
</tr>
<tr>
<td>2000-2500</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>2500-3000</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

A comparison of the three methods shows that using the MCF results in minor deviations compared with the actual number of failure events. A comparison of the power-law process with the local ROCOF shows that the former gives a better estimation, having a total failure deviation of 75 and 15 failures for the radar transmitter and cooling turbine, respectively. This can be compared to the corresponding total failure deviation of 90 and 19 failures obtained using the local ROCOF; see Table 5:1a-5:1b for the summaries of the comparisons.

The results show that using the MCF method directly for estimation of the number of failures is not a reasonably applicable approach, because that method is non-parametric, in the sense that it is a distribution-free method. The MCF does not rely on assumptions that the data are drawn from a given probability distribution, and the interpretation does not depend on the population fitting any parameterized distribution.

In conclusion, if one uses a parametric approach, it is most likely that the analysis will be divided into a large amount of special cases, for example the homogeneous and the non-homogeneous case, and that various statistical methods will have to be applied. With all special cases, the data cleaning or filtering process becomes substantially complex. Furthermore, parametric methods are relatively time-consuming due to the concomitant necessary procedures for trend testing, testing for dependency, testing for homogeneity, model selection, parameter estimation, etc. However, extensive information can be extracted concerning the reliability behaviour of a unit. According to the results obtained through the study performed for this thesis, it can be concluded that the parametric approach is more practical and provides more accurate results for estimation of the expected number of failures, for the purpose of estimating the spare part demand.
5.2 Research objective II

“To develop a framework for management of the part-out-based spares provisioning (PBSP) during the retirement phase:”

The second research objective of the study performed for this thesis was formulated as follows: “to develop a framework for management of the part-out-based spares provisioning during the retirement phase”. This objective is linked with the second research question: “what are the prerequisites for an effective part-out-based spares provisioning?” This question is answered mainly by the research presented in Paper III.

When a fleet of aircraft reaches the retirement phase, the fleet will be scrapped gradually during a specified period in which the number of operational aircraft will dynamically decrease. In this context, the remaining fleet should still be kept at a defined level of availability. Obviously, the provisioning of spares is still required to support the maintenance and operation of the remaining fleet.

One of the objectives of the provisioning function within the PBSP programme is to minimize the stock level, reducing it to zero (ideally) at the end of the retirement period, while ensuring the availability of spares within the retirement period. This necessitates making decisions on when to terminate the maintenance contracts and close repair shops. It is also vital to identify when to terminate both the parting-out process and the maintenance of the units received from operational and retired aircraft (due to the parting-out process).

In fact, the implementation of PBSP is governed by several other issues, including managerial, economic and operational preferences. These preferences may be dynamically subject to changes during the retirement phase. In addition, a number of routines concerning operations, logistics, maintenance and storage are affected, and functions, processes, tasks and routines need to be changed and new ones may need to be introduced to support the decision-making process.

This necessitates identification of the prerequisites of the PBSP management programme, to establish a standard structure for the management and decision processes. These processes ensure that the PBSP activities are aligned with the defined goals, i.e. fulfil the availability requirements of the fleet at the minimum cost during the retirement period. In Paper III, a novel framework was proposed for the implementation of PBSP, the prerequisites for a PBSP management programme were identified, and associated key decision criteria for an effective phase-out management process were presented. The proposed framework was based on a case study conducted to collect the experience of organizations involved in the phasing-out of the FPL 37 VIGGEN military aircraft systems operated by the Swedish Armed Forces. However, the framework is intended to be generic and useful for other applications.

Within the study, the main decision nodes of the PBSP were identified within a military application. These include “strategic planning”, “fleet management”, “maintenance management”, “logistic support management” and “data and data management”, see Figure 5:7.

In addition, the tasks and processes within the decision nodes were identified, and the prerequisites of PBSP management were defined. One of the essential prerequisites identified was the “development of a phase-out master plan” within the strategic planning. This includes the development of an aircraft disposal schedule, a recycling method and fleet operational plans, and potential organizational changes in the maintenance, repair and overhaul (MRO), as well as the definition of spares provisioning approaches, see Figure 5:7.
These tasks are highly dependent on the strategic decisions taken at a high management level and need to be fulfilled accordingly and conveyed further to other decisions nodes.

![Diagram of management framework](image)

Figure 5.7. Proposed framework for a PBSP management programme during a phase-out scenario.

The second set of prerequisites identified is associated with the fleet management. This includes the establishment of a reliability programme to control the reliability and the residual life of the units, to enable proper demand estimation.

Based on the results presented in Paper I and II, the most challenging issues concerning reliability are a lack of adequate advance reliability knowledge and inadequate data concerning the reliability and maintenance history. It is highly recommended that the PBSP programme should include a well-established reliability database and expertise.

In addition, a part-out plan needs to be developed which defines the list of spares that will be subjected to reclamation within the PBSP programme, the resources required for parting out spares, including maintenance resources (e.g. hangar slots, man-hours, ground-support equipment and tools) and a budget. In fact, since the retirement plan for an individual aircraft may change due to operational requirements, it is essential that the part-out plan should be adjusted in accordance with input from the operation phase-out plan.

The third set of prerequisites concerns the logistic support management. This includes forecasting the demand for maintenance and spare parts, and setting the stock fill rates. This specific set of prerequisites was defined and studied in Paper I-II, and is adapted to suit the forecasted corrective maintenance (CM) needs within the suggested framework of PBSP. Also included are mathematical modelling to identify alternative solutions for repair planning options, a repair termination plan, and the identification of cost-effective solutions. Due to the complexity of the task and the effect which it will have on the estimation and decisions, the analytical skills of experts are highly influential.

In addition, the logistic support management also includes the task of identifying whether a specific unit is worth reclaiming. Also involved are the tasks of selecting and procuring equipment, spares and material of the range and quantity necessary for supporting the operation and maintenance of the aircraft fleet, and the associated support equipment. Furthermore, the logistic support management also comprises the distribution of spares to operational sites according to foreseen requirements and their redistribution as required.
During the retirement period, obsolescence issues often arise as a spare part problem, and a lack of understanding of the importance of proactively addressing obsolescence problems can have a major impact on the spares availability. This issue must be included in the PBSP programme, especially in the part where decisions are taken to terminate maintenance capabilities and stop the parting-out process.

The fourth set of prerequisites concerns the maintenance management and includes the establishment of a quality control to ensure the integrity of reclaimed spares. This task includes physical inspection to detect any damage, defects and improper disassembly, as well as checking the history of the rotables for any scheduled maintenance or modifications. The task also includes ensuring that the fleet meets and will continue to meet established availability performance goals, for example for operational readiness, dispatch reliability and cost-efficiency.

The fifth set of prerequisites concerns data and data management. Normally, when the retirement period commences, an established computer maintenance management information system (CMMIS) already exists. During the whole retirement period, the CMMIS must be continuously updated; scrapped units must be deleted from the system and information on reclaimed units must be recorded in the system. Prior to the performance of data analysis within the logistic support management, it is vital to evaluate the data quality in the CMMIS to analyse the context of the PBSP.

Indeed, the framework presented in this study supports the operator by helping him or her to understand the dynamics of the PSBP and provide solutions with the lowest possible risk. This is also potentially helpful for the termination of contracts during the retirement phase. If the operator has engaged several external subcontractors, it is vital to give the contractors timely notice of contract termination. In some cases, operators may be interested in ending the contract at an early stage of the PBSP. However, this might result in a very dangerous situation where a unit is needed, but the maintenance capability has been terminated.

Obviously, the decision variables and objectives change dynamically during the retirement phase, which necessitates comprehensive and dynamic planning, and tight communication between the stakeholders (e.g. experts, maintenance technicians, analysts, the management, the operator, etc.), which requires effective communication and interaction to be in place. Moreover, the time-horizon for implementing new tasks, functions and routines, etc. can be quite long and the work involved can be substantial and intensive. The prerequisites must be applied, the processes initiated, decisions taken and the tasks performed as soon as the decision has been taken to retire the aircraft fleet.

During the implementation of PBSP, there will be a frequent exchange of information and data, and frequent interaction between different decision nodes and stakeholders in multiple ways. In addition, there will be an abundance of local rules and decisions that are not necessarily harmonized, which will generate a high level of complexity in the implementation of the PBSP programme.

Summing up, considering the high number of both military and commercial aircraft in the world that have been retired in recent years, it is highly recommended that one should establish a standard for the part-out-based provisioning concept, to ensure the availability of a higher level of instruction and more adequate definitions of terms, with a view to enhancing the possibility of interaction. Such a standard should also define the requirements for different stakeholders, the associated decision nodes, and the protocol for data exchange, and should point out the analytical methodologies needed for logistic support. This would eventually reduce the complexity of the PBSP and contribute to the success of the programme.
5.3 Research objective III

“To propose a computational approach for identification of the applicable and cost-effective alternatives for part-out-based spares provisioning:”

The third research objective of the study performed for this thesis was formulated as follows: “to propose a computational approach for identification of the applicable and cost-effective alternatives for part-out-based spares provisioning”. This objective is linked with the third research question: “how to determine the repair termination times at the end of the retirement period?” This question is answered mainly by the research presented in Paper IV, and partly by that presented in Paper III.

Identifying the plethora of repair termination alternatives is a central and vital part of the PBSP programme. This also includes identifying a set of termination times for the parts received due to the preventive maintenance (PM), corrective maintenance (CM) and part-out maintenance (POM), and for part-out storage (POS). This work provides a foundation for the further necessary measures and tasks to be performed within the retirement period, such as terminating maintenance contracts, discarding internal maintenance capabilities, reviewing stocks, and identifying repair termination times.

The identification of repair termination times is by nature a complex operational research (OR) task, for several reasons. It is a combinatorial problem in which the combinations are dictated by several operational and theoretical conditions. An example of an operational condition is that the POM should be stopped before the POS and, further, that the CM and PM should be stopped before the POM.

In addition, there are several other restrictions and boundaries which should be applied to control the applicability of alternative combinations and to fulfil managerial preferences. These restrictions include, for each combination of alternatives, limiting the risk of back orders, limiting the overstocking level, and minimizing the stock level, reducing it to zero at the end of the retirement period. Moreover, there are several other restrictions that must be applied to control the cost efficiency of the combinations, such as limiting the total cost incurred by a combination. Such a multi-objective combinatorial problem is composed of many decision nodes and conditions which interact with each other to a high degree. This requires the employment of an approach to investigate how relationships between factors give rise to the collective behaviour of a problem and how interaction takes place within the system. Searching among all the combinations of possible solutions, including both feasible and infeasible solutions, would be very time-consuming. To solve such a problem, one needs a computational model and extensive computational resources.

In Paper IV, the dynamics of spares flow and the associated decision nodes within PBSP were modelled. A set of computational models was proposed to estimate the stock level for both the non-controlled and the controlled scenario. The non-controlled scenario is characterised by a continuous parting-out of spares and repair planning towards the end of the retirement period.

In the controlled scenario, the flow of spares to repair shops and the stock is controlled through the decisions taken to stop the CM, PM, POM and POS. A computational model was proposed to estimate the stock level for any possible repair termination alternative. A search algorithm was proposed to apply the initial and boundary conditions to identify the applicable solutions. The search algorithm is an effective method starting from an initial state and initial input to describe a computation that, when executed, proceeds through a finite number of well-defined successive states, and then produces a result for a final end-state.
In addition, a cost function was developed to identify the cost-effective solutions among the applicable ones. The proposed computational approach was illustrated and verified in a case study on the cooling turbine installed on the 90 aircraft in a Saab-105 fleet. The Saab-105 is a two-seater twin-engine aircraft which is used as a trainer plane by the Swedish Armed Forces, and which is planned to be phased out within a period of eight years.

The results obtained for the non-controlled scenario within the case study show that there will be 69 cooling turbines in stock at the end of the retirement period, see Figure 5:8, and the total cost of this scenario is estimated to be 4.6 million SEK, see Figure 5:9.

One of the main conditions set for the controlled scenario was that the number of spares in stock each month must be greater than the demand. In addition, at the end of the retirement phase, there should be one unit in stock. In addition, it was decided in consultation with the experts in this field that the POM should be stopped before the POS, and that the CM and PM should be stopped before the POM.

Using the search algorithm and the defined computational model, the successive states and the applicable alternatives that would fulfil the boundary conditions were identified. The studied case shows that there is a set of 129,212 applicable solutions representing combinations of repair termination alternatives which all fulfil the conditions. The alternatives were ranked using the proposed cost function, in order to select the feasible ones.

The results show that there are 36 alternatives with the lowest possible cost of 765,000 SEK, see Figure 5:10 and Table 5:2. In fact, these alternatives are quite similar, specifying that the PM should stop within the first two months, that the CM and POM should stop during months 32-35, and that the POS should stop in the later stages, i.e. during months 91-96.
The results also show that the solutions associated with specific costs are very close, and there is a margin for stopping the CM, PM, POM and POS which provides an operational flexibility, as seen in Table 5:3. In other words, it is not necessary to follow a set of stopping times exactly and there are several similar applicable solutions in the same region of validity.

The highest cost for a solution within the controlled scenario is 1,885,000 SEK, see Figure 5:10. If one compares this cost with the corresponding highest cost for the non-controlled scenario, one finds that the controlled scenario results in a large saving of 2,712,000 SEK. Comparing the lowest cost for a solution in the non-controlled scenario with that in the controlled scenario, one finds that, with the latter scenario, a saving of 3,835,000 SEK is expected for cooling turbines during the whole retirement period.

Considering that an aircraft comprises approximately 200-300 repairable units, the PBSP approach provides the possibility of making large savings. According to the results obtained, the applicable solutions and their stopping times for CM, PM, POM and POS are relatively scattered. Naturally, from the point of view of PBSP management, it is desirable to terminate all the maintenance-related activities at about the same time, and just continue to collect units from the reclamation process to fulfil future spares requirements. However, selecting a solution with early maintenance stopping times entails an increased risk that maintenance resources may need to be reinstated, which is associated with a high cost.

If one waits longer to stop the maintenance, there is less risk that unforeseen events will occur and affect the spares provisioning process, but this approach does not provide the same possibility of making savings.
From the operator’s perspective, there may in fact be several other preferences which dictate that a different alternative solution is the effective one. Such preferences may include keeping the contract longer for strategic reasons, or cancelling the retirement completely due to the operational requirements.

The methodology proposed in Paper IV can easily be adapted to civil aviation and other industrial areas with technically complex fleets of vehicles (e.g. trains, boats, dumpers, etc.), for a provisioning planning during the retirement period which will provide the possibility of making large savings.

Decisions on maintenance contract termination are highly complex and critical, since stopping a maintenance capability too early in the retirement period can make a large impact on the fleet availability and cause financial problems. Decisions on maintenance termination must therefore be treated with a high degree of confidence and care. The results from the proposed computational model and search algorithm provide a transparency concerning the applicable maintenance termination alternatives, as well as adjustable safety margins.

The study has been done considering a fixed retirement plan. However, there might be more cost effective solutions with different retirement periods as well. Hence would be beneficial to make a further analysis to identify the optimum retirement period, using iterative process. It should be noted that the proposed model is developed for single inventory indenture.
If the organization use multi indenture level inventory, then the model should be adapted considering a multi indenture dynamics of spare flow.

If there is good planning and a good organisational structure, and if the stakeholders share common goals, the implementation of the proposed PBSP framework will lead to greater savings. In addition, the implementation of the PBSP programme itself is not associated with any large overhead costs.

The proposed PBSP approach provides added value from a sustainability point of view, in that the use of existing resources is maximized by applying the retirement process, through the process of reclaiming units and the applicable maintenance termination alternatives. The implementation of a PBSP programme provides a foreseeable, detailed and situation-based picture of the stock level dynamics, and contributes to the spares provisioning process, providing solutions to crucial issues such as obsolescence, last-time buys and cannibalization.
6 Research contribution

The aim of the research conducted for the current thesis was to investigate the implications of a part-out-based spares provisioning (PBSP) strategy applied during the retirement phase of an aircraft fleet. The contributions of this research can be summarized as follows.

Firstly, the research problem, research objectives and research questions were identified, to ascertain and describe the gap in the literature in the field of cost-effective spares provisioning during the retirement phase of an aircraft fleet.

Secondly, a decision support framework was proposed for the management guidance of a PBSP programme implemented during the retirement of an aircraft fleet and involving the reuse of parts from the retired aircraft. The framework includes the definition of decision nodes, functional elements and routines. In addition, it provides an integrated approach to the modelling of strategic and managerial decisions considering spare part management, global and local logistics, networking structure, dismantling strategies, performance management, and management of the value chain. This framework was made flexible to incorporate the different stakeholders continuously in the decision-making process via an interactive procedure.

Within the PBSP programme, a set of computational models, as well as a search algorithm, were developed to identify termination times for both the parting-out process and the maintenance and repair actions performed on the units. The proposed models make it possible to control the stock level and identify the applicable and effective PBSP solutions. The feasible alternatives are compared with regard to their respective costs, and the most cost-effective solution is selected. The results show that the proposed PBSP approach and computational models provide added value from a sustainability point of view, since the use of existing resources is maximized during the retirement process, through the process of reclaiming units and the applicable maintenance termination alternatives.

Also examined in the research for this thesis were the existing reliability decision methodologies within parametric and non-parametric approaches, to identify a practical approach for estimating the expected volume of spares demand at the aircraft fleet level. A basis was established for the employment of an appropriate reliability approach that is statistically valid, practical and yet communicates appropriate information to the stakeholders.

The implications of this research are both theoretical and practical. From a theoretical perspective, it demonstrates a starting point for developing an integrated framework for the analysis of part-out-based spares provisioning performed during the retirement of an aircraft fleet. From a practical point of view, it creates guidelines for decision makers for handling the provisioning and maintenance challenges related to aircraft retirement.

The proposed framework contributes to an improved understanding of PBSP and highlights the importance of a PBSP programme from a sustainability point of view, i.e. its importance in ensuring that the existing resources (spares) are maximized during the retirement process. In addition, the present research is based on the three aspects of sustainability, lean spares provisioning, and reduction of maintenance volumes in a cost-effective manner.

Accordingly, the research results have provided many possible perspectives in this context, enriching the literature in the field of aircraft retirement as a new aerospace industry challenge and opportunity.
7 Further Research

During the progress of the research presented in this thesis, several interesting new research ideas emerged. However, it was not possible to pursue all of these within the framework of that research. Hence, in this section, some of these ideas are presented as suggestions for further research.

The computational models can be extended with refined features such as storage maintenance, the implementation of modification programs on the unit level, and cycle- and parameter-controlled maintenance. Furthermore, selection criteria should be developed to guide which units to be taken from storage, to maximize availability and utilization and to reduce cost.

The approach can be improved by considering risk of back orders and monitoring the obsolescence. The cost function can be extended in which other factors such as inflation rate, net present value, cost of storage, cost of maintenance resources and possible increase in maintenance cost with during the retirement period etc.

The proposed method in this thesis has been focused on a simple scenario including only a single storage ore repair shop sit, but the same method can be applied to a scenario with multiple-stock locations. In addition, multi-component removal and installation should be considered to identify the optimal PBSP solution.

Considering the high number of retired aircraft during the upcoming years, the methodology can be applied in civil aviation fleet to extend the application area, in which several other issues should be considered, such as surplus market of the over stock parts. The other industrial sectors where fleets of equipment are used would be considered for another application area.

For estimation of the demand of spares, issues such as dead-on arrival (DoA), no fault found (NFF) residual life of the components should be considered to make more accurate demand estimation during the retirement period.

It is highly recommended that one should establish a standard for the part-out-based provisioning concept, to ensure the availability of a higher level of instruction and a definition of the various possible interactions. The standard should also define the requirements for different stakeholders, associated decision nodes and the protocol for data exchanges, and should point out the analytical methodologies needed for logistic support.
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Fleet-level reliability analysis of repairable units: a non-parametric approach using the mean cumulative function

Fleet-Level Reliability Analysis of Repairable Units: A Non-Parametric Approach using the Mean Cumulative Function

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Abstract: This paper describes the use of the mean cumulative function (MCF) and linear estimates based on the recurrence rate to predict the expected number of failures in the future. Reliability data from two repairable units are used to verify the procedure and comparison. The empirical data used in the paper is based on field data gathered during the operational life of the Swedish military aircraft system FPL 37 Viggen from 1977 to 2006, which essentially is the whole life cycle of the system.

Keywords: Non-parametric analysis, repairable units, maintenance, aviation, reliability, mean cumulative function.

1. Introduction and Background

Complex technical systems are normally repaired rather than replaced when they fail. It is often desirable to analyse the reliability characteristics of these systems based on data generated in a customer use environment, in order to assess reliability, frequency of failure or other parameters which may be influenced by the systems’ age and usage. Despite the advantages of continuously analysing reliability data to be able to improve the maintenance programme continuously, methods such as parametric and non-parametric analysis are often ignored due to a belief that the mean time between failures (MTBF) is sufficient to describe the reliability pattern of repairable units.

Complex technical systems such as military and civil aircraft are continuously maintained to assure a specific level of safety and availability at the lowest possible cost. When dealing with complex technical systems in a competitive environment, maintenance departments are required to ensure that their fleet will meet, or continue to meet, their established performance goals (e.g., operational readiness, dispatch reliability, cost-effectiveness, etc.) and to make sure that demands for deliveries will be met. Moreover, during the development a maintenance programme, the quantification of the operational risk of aircraft system failure is a great challenge. The reason includes the inadequacy of in-service information, and a lack of understanding of the influence of failures [1].

Therefore, a formal reliability programme is needed which ensures the collection of important information about the aircraft system’s reliability performance throughout the operational phase, and directs the use of this information in the implementation of analytical and management processes.

Aircraft systems can be classified into non-repairable and repairable systems. Non-repairable systems are those which are not repaired when they fail to perform one or more of their functions satisfactorily, and are instead discarded. The discard action does not necessarily mean that the unit cannot be repaired. In some cases repair actions are not economically effective since a repair would cost almost as much as acquiring a new unit. Repairable units are those which, after failing to perform one or more of their functions satisfactorily, can be restored to satisfactory performance by any method other than...
replacement of the entire system [2]. The reliability analysis of repairable units includes modelling the number of recurrent failure events over time rather than the time to the first failure, and the reliability of such units strongly depends on the effectiveness of the repair action. The quality or effectiveness of the repair action can be classified into three categories [2-3]:

- **Perfect repair**: *i.e.*, restoring the system to the original, a “like-new” condition.
- **Minimal repair**: *i.e.*, restoring the system to a functional but “like-old” condition.
- **Normal repair**: *i.e.*, restoring the system to any condition between 1 and 2.

Based on the quality and effectiveness of the repair action, a repairable system may end up in five different possible states after repair, *i.e.* an as-good-as-new, an as-bad-as-old, a better-than-old but worse-than-new, a better-than-new, and a worse-than-old condition [2-3]. If through a repair action a major modification takes place in the unit, it may end up in a condition better than new; and if a repair action causes some error or an incomplete repair is carried out, the unit may end up in a worse-than-old condition [3].

There are two major approaches to the reliability analysis of repairable units, namely parametric and non-parametric methods. The parametric approach includes the stochastic point process, and the analysis includes mainly the homogeneous Poisson process (HPP), the renewal process (RP), the non-homogeneous Poisson process (NHPP) and the generalized renewal process (GRP), introduced by Kijima [4]. A renewal process is a counting process where the inter-occurrence times are s-independent (*i.e.*, the inter-occurrence times are mutually stochastically independent) and identically distributed with an arbitrary life distribution [5]. The NHPP is often used to model repairable systems that are subject to a minimal repair. The HPP describes a sequence of s-independent and identically distributed (IID) exponential random variables. Conversely, an NHPP describes a sequence of random variables that are neither statistically independent nor identically distributed [5]. The GRP allows the goodness of repairs to be modelled from as-good-as-new repair (RP) to same-as-old repair (NHPP). The GRP is particularly useful in modelling the failure behaviour of a specific unit and understanding the effects of repair actions on the age of that system. An example of a system to which the GRP is especially applicable is a system which is repaired after a failure and whose repair does not bring the system to an as-good-as-new or an as-bad-as-old condition, but instead partially rejuvenates the system [6]. Different parametric methods are implemented to model the probability of failure for repairable units, *e.g.*, the power law process [4-9].

The application of these methods for a single system/unit is quite clear and straightforward. However, in practice the analyst is often dealing with multiple similar systems which are installed in different aircraft and which are running in different operating environments, with different other influencing factors. The aim of reliability analysis in this paper is to track field failures to provide information regarding failure rates and the expected number of failures at the fleet level, and not at the individual component level.

The application of parametric reliability analysis methods at the fleet level, even if it is very limited in scope, is quite complex and time-consuming for a variety of reasons. For instance, failure analysis is made more difficult by the highly multi-censored nature of the reliability data belonging to different failure modes. The analysis of time-censored and failure-censored data needs different treatment [8 and 10], with the application of different methods. Moreover, drawing conclusions at the fleet level from these individual analyses requires statistical assumptions which in practice entail a degree of uncertainty.

Moreover, when pooling data for units from an operational fleet, the associated failure data require that one should consider the statistical characteristics to assure the
The applicability of the pooling. This means that the analyst should test the similarity of the distribution between failures, for the whole population, which in practice is quite difficult and time-consuming.

In general, using these parametric methods often requires some degree of statistical sophistication and sound statistical knowledge and experience on the part of the analyst. There is also often a problem communicating the results and ideas to customers and management within the industry [11]. Moreover, the management and the engineers and field service teams who maintain and support the aircraft systems can easily be daunted by such complex techniques. Hence it is very important to employ a failure analysis methodology which is statistically valid, yet communicates to the managers and engineers in a professional language with which they are familiar [12]. According to [12], monitoring a recurrent failure in a complex system such as an aircraft does not necessarily require complicated methods.

Non-parametric methods provide a non-parametric graphical estimate of the number of recurrences (repairs/failures) per unit and per the whole population, versus the utilization/age. The model used to describe a population of systems in this paper is based on the mean cumulative function (MCF) at the system age t. The MCF is non-parametric in the sense that it does not use a parametric model for the population. This estimation involves no assumptions about the form of the mean function or the process generating the system histories. Graphical methods based on the MCF [13-16] allow the monitoring of system failures and the maintenance of statistical rigour without resorting to complex stochastic techniques. The MCF is simple in that it is easy to understand, prepare, and present. It can be successfully used to track field failures and identify failure trends, anomalous systems, unusual behaviour, the effect of various parameters (e.g., maintenance policies, environmental and operating conditions, etc.) on failures, etc. Thus it is a significant decision support tool which permits operators, maintenance providers, and manufacturers to make quantifiable and rational decisions in fields that have typically been the domain of guesswork and experience. This very useful and simple concept has been in existence for nearly two decades, but the literature remains highly theoretical and difficult for the average practitioners, and the reported applications have been very limited [12, 13 and 15].

The objective of this paper is to provide a relatively simple method for estimating the expected number of failures for large arrays of repairable units from an operational aircraft fleet. This task is motivated by the need to produce such estimates relatively quickly and simply, without having to use complex parametric methods. Since an aircraft, whether it is commercial or military, comprises a large number of repairable units with differing failure distributions, there is in practice neither the time nor the resources to study each type of unit in a detailed manner using parametric methods, and such methods are thus impractical. By using non-parametric methods, the mathematical manipulation of operational data is greatly simplified, albeit at the cost of losing some analytical rigour.

However, this is acceptable, since the objective is to find a procedure that is suitable for large-scale use, on a fleet-level basis, i.e., to estimate the future maintenance requirements for an aircraft fleet typically comprising hundreds of separate types of units, and tens to hundreds of thousands of individual repairable units. Furthermore, the fact that operation profiles and operational environments frequently vary greatly between individual aircraft and over time means that the total number of relevant parameters becomes large, and that many of them are difficult to determine with any precision. This means that, by the time enough data (especially for military aircraft systems) have
accumulated to allow parametric methods to become useful, a large part of the life cycle of the studied system will already have passed.

Therefore, what is needed is a method which can be applied to a large number of populations of repairable units with a reasonable expenditure of resources, and which requires only relatively basic operational information about the studied unit. Furthermore, it should be simple to iterate the method and improve the estimates as more data becomes available.

The paper is organized as follows. In Section 2 the approach is described using the mean cumulative function for recurrence reliability data. The empirical reliability data and data collection process is described in Section 3. In Section 4 the results of the reliability data process is described. The paper ends with a summary and conclusions.

2. Non-Parametric Model for Recurrent Event Reliability Data using MCF

In reliability theory and many other applications, e.g., public health, engineering, sociology, economics and medicine, the focus of interest is directed on the study of processes which generate events repeatedly over time, i.e., recurrent processes [17]. In the field of reliability analysis for repairable units, the focus of interest concerning recurrent events is on the number of repairs for a unit, the time to failure and the effectiveness of repair, for example.

Having \( n \) repairable units in the operational aircraft fleet, let \( N_i(t) \) be the total number of cumulative recurrences for unit \( i \), were \( i = 1, ..., n \) over a given time \( t \). Then it follows that the counting process which counts the total observed cumulative number of failures for the whole fleet is given by equation (1).

\[
N(t) = \sum_{i=1}^{n} N_i(t) \tag{1}
\]

The mean cumulative number of failures \( \mu(t) \), also described as the mean cumulative function (MCF), is given by equation (2).

\[
\mu(t) = E[N(t)] = \sum_{i=1}^{n} \mu_i(t) \tag{2}
\]

If \( \mu(t) \) is differentiable, then the recurrence rate is given by equation (3).

\[
\nu(t) = \frac{dE[N(t)]}{dt} = \frac{d\mu(t)}{dt} \tag{3}
\]

In the context of reliability \( \nu(t) \) is also referred to as the failure intensity or the rate of occurrence of failures (ROCOF) [7]. During the late 1980’s, Nelson [14] provided an appropriate point-wise estimator for the MCF, the so-called Nelson’s estimate \( \hat{\mu}(t) \).

Having the recurrence times \( t_{ij} \) of all the units \( n \), let \( m \) be the unique recurrence times; i.e., unit \( i \) has \( j = 1, ..., m_i \) recurrences. Order the recurrence times from the lowest to the highest, \( t_1 < t_2, ..., < t_m \). The MCF is then estimated according to equation (4).

\[
\hat{\mu}(t_j) = \sum_{k=1}^{j} \left[ \frac{\sum_{l=1}^{m_i} \delta_l(t_k) d_i(t_k)}{\sum_{l=1}^{m_i} \delta_l(t_k)} \right] \tag{4}
\]

where, \( \delta_i(t_k) = \begin{cases} 1, & \text{if unit } i \text{ is still functioning,} \\ 0, & \text{otherwise,} \end{cases} \)

and \( d_i(t_k) \) is the number of recurrences for unit \( i \) at the time \( t_k \). Plotting the point-wise estimated MCF, \( \hat{\mu}(t_j) \), gives a step function with jumps at the recurrence times; see Section 4 for examples. When studying the point-wise estimated MCF, one is normally also interested in gaining an understanding of the variance in the studied data population, and the confidence level is therefore of great importance. Using a point-wise normal approximation, a confidence interval is estimated for the MCF [9] according to equation (5).
Fleet-level Reliability Analysis of Repairable Units: A Non-parametric Approach
Using the Mean Cumulative Function

\[
\hat{\mu}(t_j) e^{\left(\frac{\bar{x}}{\sqrt{1-\frac{\bar{x}}{\mu(t)}}}\right) \hat{\mu}(t)} < \hat{\mu}(t) < \hat{\mu}(t_j) e^{\left(\frac{\bar{x}}{\sqrt{1-\frac{\bar{x}}{\mu(t)}}}\right) \hat{\mu}(t)}
\]

(5)

where \( s \hat{\mu}(t) \) is the standard error for the estimated MCF, and \( z_{1-\alpha/2} \) is the value of a normal distribution at significance level \( \alpha \).

The process of estimating the MCF can be described by the following steps [9]:

i. Order the ages (e.g., the operation times, calendar times, etc.) for the recurrences from the lowest to the highest times, \( i.e., \ t_1 < t_2, ..., < t_m \) for unit \( i \) according to equation (4) above, and note the censoring age. Of course, the censoring and recurrence age can be the same, and it may also happen that different units have the same censoring and recurrence time.

ii. Calculate the number of units at risk \( i.e., \) the number of units that have a recurrence probability greater than zero; at each unit age calculate the number of remaining units at risk at that age, \( i.e., \) the number of units that risk a recurrence at a specific age, this number is given by \( \delta(t_i) \) in equation (4) above.

iii. Calculate the mean numbers; for each recurrence, calculate the observed incremental mean number of recurrences per unit at that recurrence age as \( 1/n \); \( i.e., \) one out of the \( n \) units passing through that age had a recurrence.

iv. Calculate the MCF according to \( \tilde{\mu}(t_i) \) given in equation (4) above; calculate the value of the sample MCF at each recurrence by adding the increment obtained in step iii and the preceding increments from the previous recurrences.

By using the MCF estimation described in equation (4) and a corresponding plot of the MCF-curve, one obtains very valuable reliability information about the studied population, \( i.e., \) the number of repairs/unit, trends and anomalies, and information for estimating the future reliability behaviour.

By using the recurrence rate \( v(t) \) to extrapolate the MCF with linear estimates, it is possible to estimate the future failure behaviour of the units. Based on the definition of the derivative, \( v(t) \) can be approximated by equation (6).

\[
v(t) \approx \frac{\hat{\mu}(t_{j+1}) - \hat{\mu}(t_j)}{(t_{j+1}) - t_j}
\]

(6)

where \( j = 1, ..., m - 1 \), and \( m \) is the total number of recurrences for the studied population. Instead of taking the derivative between the two consecutive points \( (\Delta = 1) \) in the MCF estimation, we use overlapping derivatives, according to equation (7).

\[
v(t) \approx \frac{\hat{\mu}(t_{j+\Delta}) - \hat{\mu}(t_j)}{(t_{j+\Delta}) - t_j}
\]

(7)

where \( j = 1, ..., m - \Delta \). By calculating the derivative over overlapping segments with a certain step length, \( \Delta \), greater than one, we obtain an estimate of the variability of the recurrence rate over the operational time. Calculating this “local recurrence rate” according to equation (7), and then dividing the calculated rates into different percentiles, we use the median of the derivatives as a nominal estimate and the 5th and 95th percentiles as the maximum and minimum estimates of the predicted recurrence rates. The 95th percentile is the value below which 95 percent of the derivatives are found, and the 5th percentile limit is the value below which 5 percent of the derivatives are found. These three measurements (the 95th percentile, the median, and the 5th (percentile) define the slope of the linear estimates used to predict the future expected number of failures. See Section 4 for two empirical examples.
3. Data Collection Process

The data analysis performed in this paper is based on two types of repairable components, see Table 1. The studied units were in operational service in the Swedish military aircraft system FPL 37 Viggen from 1974 to 2006, which is essentially the whole life cycle of the system. The data concern about 330 aircraft with a total of 615,000 flight hours, and include information about all the maintenance-significant events for the physical units, \textit{i.e.}, the date of delivery, storage time, storage maintenance, installations, removals, failures, corrective maintenance, modifications, and discard. These events are associated with calendar dates and accumulated operating time in flight hours.

The first repairable unit studied was a radar transmitter (henceforth referred to as unit A). The radar transmitter was for the main surveillance radar (PS-37) of the AJ 37 strike aircraft. The fault modes for this unit were dominated by failures of a variety of electronic components, the most common being failures of thyatrons, magnetrons and pulse transformers. Since this unit was only subjected to corrective maintenance, there is only one failure category, \textit{i.e.}, failures in service. The data were right-hand censored by two processes: failure and discard. The second unit studied was a cooling turbine (henceforth referred to as unit B), which was the principal unit of the environmental control system that delivered cooling air for the electronics and the cockpit air conditioning in all versions of the FPL 37 aircraft system. The cooling turbine was a heavily stressed mechanical unit with a fairly high failure rate in service, despite receiving preventive maintenance.

Table 1: Number of Units Included in the Study

<table>
<thead>
<tr>
<th>Item</th>
<th>Hardware</th>
<th>#</th>
<th>Maintenance Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Radar Transmitter</td>
<td>124</td>
<td>Corrective Maintenance</td>
</tr>
<tr>
<td>B</td>
<td>Cooling Turbine</td>
<td>372</td>
<td>Preventive/Corrective Maintenance</td>
</tr>
</tbody>
</table>

For units A and B, the failures and censoring are shown in event plots, see Figure 1 and Figure 2. Among the 124 units of type A, there are 18 units that were time-censored without any failures at all, and for unit B there are 257 units that were time-censored without failures among the 372 units, which can also be seen in the event plot.

Table 2 presents the number of units that have suffered a given number of failures, showing that for unit A there are 106 units which have encountered 1 failure, 96 units which have encountered 2 failures, \textit{etc}. Based on Table 2, one can calculate the total number of failures for the whole population of unit A, \textit{i.e.}, 413 failures. The corresponding data are presented for unit B, and the total amount of accumulated failures for unit B can be calculated to be 156 over the whole life cycle.

Table 2: The Number of Units that have Suffered a Given Number of Failures

<table>
<thead>
<tr>
<th>Failures (#)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit A (#)</td>
<td>18</td>
<td>106</td>
<td>96</td>
<td>82</td>
<td>60</td>
<td>33</td>
<td>21</td>
<td>8</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Unit B (#)</td>
<td>257</td>
<td>115</td>
<td>37</td>
<td>4</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

These two types of components were both relatively maintenance-intensive. The radar transmitter was only subjected to corrective (on-condition) maintenance, while the cooling turbine, as a heavily stressed mechanical unit, received preventive maintenance (periodic overhauls). The differences between unit A and B (A being an electronic unit and B being a mechanical unit, and B receiving both preventive and corrective maintenance and A receiving corrective maintenance only) resulted in the failure patterns for the two units being quite different; see Figure 3 and Figure 4 for the estimated MCFs.
Table 3 and Table 4 describe the number of failures and units in service for each 500-flight-hour interval for unit A and unit B, respectively. As mentioned above, the units were right-hand censored by two processes, either by discard or failure, and in the case of aircraft crashes, the units were, of course, time-censored at the operational time for the unit at the time of the crash.

Table 3: Failures and Units of Type A in Service for Each 500-Flight-Hour Interval

<table>
<thead>
<tr>
<th>Operation Time [h]</th>
<th>Units in service [#]</th>
<th>Accumulated failures [#]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-500</td>
<td>124 – 104 (20 discards)</td>
<td>0 – 113 (113 failures in interval)</td>
</tr>
<tr>
<td>500-1000</td>
<td>104 – 98 (6 discards)</td>
<td>113 – 243 (130 failures in interval)</td>
</tr>
<tr>
<td>1000-1500</td>
<td>98 – 85 (13 discards)</td>
<td>243 – 340 (97 failures in interval)</td>
</tr>
<tr>
<td>1500-2000</td>
<td>85 – 50 (35 discards)</td>
<td>340 – 396 (56 failures in interval)</td>
</tr>
<tr>
<td>2000-2500</td>
<td>50 – 9 (41 discards)</td>
<td>396 – 411 (15 failures in interval)</td>
</tr>
<tr>
<td>2500-3000</td>
<td>9 – 1 (8 discards)</td>
<td>411 – 412 (1 failure in interval)</td>
</tr>
<tr>
<td>3000-3500</td>
<td>1 – 0 (1 discard)</td>
<td>412 – 413 (1 failure in interval)</td>
</tr>
</tbody>
</table>

Table 4: Failures and Units of Type B in Service for Each 500-Flight-Hour Interval

<table>
<thead>
<tr>
<th>Operation Time [h]</th>
<th>Units in service [#]</th>
<th>Accumulated failures [#]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-500</td>
<td>372 – 338 (34 discards)</td>
<td>0 – 39 (39 failures in interval)</td>
</tr>
<tr>
<td>500-1000</td>
<td>338 – 286 (52 discards)</td>
<td>39 – 74 (35 failures in interval)</td>
</tr>
<tr>
<td>1000-1500</td>
<td>286 – 217 (69 discards)</td>
<td>74 – 115 (41 failures in interval)</td>
</tr>
<tr>
<td>1500-2000</td>
<td>217 – 113 (104 discards)</td>
<td>115 – 143 (28 failures in interval)</td>
</tr>
<tr>
<td>2000-2500</td>
<td>113 – 33 (80 discards)</td>
<td>143 – 154 (11 failures in interval)</td>
</tr>
<tr>
<td>2500-3000</td>
<td>33 – 1 (32 discards)</td>
<td>154– 156 (2 failures in interval)</td>
</tr>
</tbody>
</table>

In Figure 1 and Figure 2 the decrease in the number of units over the operational time is plotted (for reasons of legibility only every third unit is plotted). The decrease in the number of units before 500 operating hours is largely due to losses through aircraft crashes during the early life of the aircraft system, while from about 1,500 hours the losses are mostly due to the discard of complete aircraft and surplus units. The difference between the slopes of the two event plots is largely due to the fact that Unit B was also installed in the JA 37 interceptor version of FPL 37, which had a slightly longer operational life than the AJ 37 strike version.

4. Reliability Data Analysis - MCF and Recurrence Rate

The first part of the analysis involved sorting and filtering the life data into an analysable format, i.e., cleaning and censoring the data used (modifications, discards, suspensions,
and failures), and eliminating units that had been used for accelerated life testing in test
rigs etc. Performing the MCF estimation as described in Section 2 according to equation
(4), the estimation plots shown in Figure 3 and Figure 4 are obtained.

These figures present the MCF and its two-sided confidence levels at a significance
level of 5% for our two studied types of units.

![Figure 3: MCF for units of type A](image1.png)

![Figure 4: MCF for units of type B](image2.png)

It is clear from Figure 3, that for the type A units the recurrence rate increased
during the first ~700 flight hours, and then there seems to have been a reliability
improvement around ~1,250 flight hours; the reason for this might be that the repair
process became more efficient. In Figure 4 (showing the MCF for the units of type B), it
is obvious that the trend indicates that the units deteriorated with operational time, which
is not surprising since they are mechanical and wear out. In this particular case the repair
process was clearly not perfect (i.e., did not result in an as-good-as-new condition).

Calculating the “local recurrence rates” for Unit A, as described in Section 2 and
according to equation (7), gives the results illustrated in Figure 5. This figure shows the
variation of the “local recurrence rates” obtained with equation (7), divided into twenty
equal bins, as well as the positions of the percentiles used (the 95th percentile, the median
and the 5th percentile) on the x-axis. The “local recurrence rates” presented in Figure 5 are
based on the first 500 hours of operation for unit A. This means that the three linear
curves used to estimate the next 500 hours of operation are based on the first 500-hour
segment, i.e., on a measure of the variability of the MCF from the time when the units
were new until the point where we start estimating the future MCF with linear
approximation. The 500-hour interval was chosen as a realistic interval for estimates for
this particular aircraft system, being equivalent to 3-5 years of operation.

In Figure 5 and all the other examples presented in the paper, the step length Δ is
set to 15 recurrences (i.e., points 1 to 15, 2 to 16, 3 to 17, etc.). Of course, varying the step
length will affect the difference between the three estimated curves. Having a smaller step
length will, of course, increase the “noisiness” of the data. The step length was selected as
a compromise between not losing information about the reliability behaviour of the
studied population and a reasonable spread of the estimates.

The illustrated example is based on estimates for 500-hour-long segments to
evaluate the goodness of fit of the estimated linear curves against the actual MCF. This
procedure is repeated at 500-hour intervals over the life cycle of the studied units to
evaluate how good the estimate of the failure intensity is over the entire life cycle of the units; see Figure 6 and Figure 7 for the estimates for the two different types of units. As shown in Figure 6 and Figure 7, the linear estimates of the expected number of failures for the succeeding 500-hour segments are in most cases well within the three estimates.

The median-based estimate underestimates the expected number of failures at the beginning of the life cycle and overestimates it towards the end of life for unit A. A probable reason for this change is that the MCF curve in this case seems to have several inflection points which prevent constraint of the derivative within narrow limits. For unit B the estimation of the expected number of failures is quite accurate throughout the whole life cycle of the unit, perhaps with some underestimation in the middle of the life cycle. The reason for this good approximation for unit B is that, although the recurrence rate changes throughout the life cycle of the units, this change is consistent and unidirectional and is consequently well tracked by the estimation algorithm.

The estimated numbers of failures for unit A and unit B are compared to the actual numbers of failures for all the 500-hour segments in Table 5 for unit A and Table 6 for unit B. The actual number of failures for each 500-hour interval is given in column two, the low (5%), nominal (median) and high (95%) estimates are given in column three, and the difference between the actual number of failures and the nominal estimates is given in column four. As seen in Table 6, the estimations for unit B are much better, with an
average error of 10% during the whole life cycle, which is rather better than one would expect. Even the estimates for unit A, with an average error of 32% over the life cycle, must be considered to be reasonably good results.

Table 5: A Comparison between Empirical and Modelled Number of Failures (Type A)

<table>
<thead>
<tr>
<th>Operation Time [h]</th>
<th>Empirical Failures [#]</th>
<th>Estimated Failures [#] (5%, 50%, 95%)</th>
<th>Δ</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-500</td>
<td>0 – 113 (113)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>500-1000</td>
<td>113 – 243 (130)</td>
<td>(59,100,223)</td>
<td>+30</td>
<td>23%</td>
</tr>
<tr>
<td>1000-1500</td>
<td>243 – 340 (97)</td>
<td>(61,112,251)</td>
<td>-15</td>
<td>13%</td>
</tr>
<tr>
<td>1500-2000</td>
<td>340 – 396 (56)</td>
<td>(41,80,177)</td>
<td>-24</td>
<td>30%</td>
</tr>
<tr>
<td>2000-2500</td>
<td>396 – 411 (15)</td>
<td>(17,34,75)</td>
<td>-19</td>
<td>56%</td>
</tr>
<tr>
<td>2500-3000</td>
<td>411 – 412 (1)</td>
<td>(1,3,6)</td>
<td>-2</td>
<td>67%</td>
</tr>
<tr>
<td>3000-3500</td>
<td>412 – 413 (1)</td>
<td>(1,1,1)</td>
<td>0</td>
<td>0%</td>
</tr>
</tbody>
</table>

Average = 32%

Table 6: A Comparison between Empirical and Modelled Number of Failures (Type B)

<table>
<thead>
<tr>
<th>Operation Time [h]</th>
<th>Empirical Failures [#]</th>
<th>Estimated Failures [#] (5%, 50%, 95%)</th>
<th>Δ</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-500</td>
<td>0 – 39 (39)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>500-1000</td>
<td>39 – 74 (35)</td>
<td>(21,40,78)</td>
<td>-5</td>
<td>13%</td>
</tr>
<tr>
<td>1000-1500</td>
<td>74 – 115 (41)</td>
<td>(18,31,67)</td>
<td>+10</td>
<td>24%</td>
</tr>
<tr>
<td>1500-2000</td>
<td>115 – 143 (28)</td>
<td>(12,24,50)</td>
<td>+4</td>
<td>14%</td>
</tr>
<tr>
<td>2000-2500</td>
<td>143 – 154 (11)</td>
<td>(6,11,21)</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>2500-3000</td>
<td>154 – 156 (2)</td>
<td>(1,2,3)</td>
<td>0</td>
<td>0%</td>
</tr>
</tbody>
</table>

Average = 10%

5. Conclusion

The objective of this paper has been to find a simple and easily understandable methodology for estimating the expected number of failures of repairable units, particularly during the latter part of the life cycle of the system concerned. This is a highly relevant and very important objective for military aircraft, whose planning horizon is longer than that of commercial aircraft and for which very long intervals between aircraft generations mean that spares and maintenance may become difficult and expensive to obtain towards the end of the system’s life.

The method described above for estimating the expected number of failures seems to estimate the number of future failures with a reasonable precision due to its simplicity. The estimate for Unit B is remarkably good, because of the consistent change in the failure rates over the life cycle of the unit. The fit for Unit A is much worse, since the MCF for this unit has several inflection points and changes in a much more inconsistent way. For Unit A it would probably be very hard to find a good parametric estimate, and if this were at all possible, it would probably only be achieved quite close to the end of the units’ life cycle.

In an actual operational situation, iterations will be performed at much shorter intervals. Furthermore, in a real situation the individual units in a population will have quite different numbers of operational hours at a given time. This means that for most units the actual MCF will be available as a more reliable estimate until they reach the number of operational hours of the current “lead unit”, and that the linear estimate will only need to be invoked beyond this point. However, in this paper we have not been able to use this method of estimation, since we cannot obtain the exact number of operational hours for all the units of the studied types at a specific date from the available historical records.
In the analysis performed in this study, we have only considered failures in operation for unit B. Since this unit received preventive maintenance, a considerable number of incipient failures were actually found and repaired during overhauls. While these failures are significant for the total maintenance costs, spare parts requirements and decisions on the maintenance interval for preventive maintenance, they do not affect the rate of failure during operation, provided that there are no changes in the scope of the preventive maintenance, which is the reason why we have not included them in our study. The motivation for carrying out preventive maintenance is, of course, to minimize the number of operational failures. However, since this is never completely successful, estimating the number of operational failures that will occur for units receiving scheduled preventive maintenance and corrective maintenance is at least as important as doing so for units receiving corrective maintenance only. In an actual operational situation the number of overhauls (or other preventive maintenance actions) over an interval in the future can easily be calculated from the number of hours since the previous overhaul (the time since overhaul or TSO) for the individual units, and can be added to the estimated corrective maintenance actions.

In short, the described method is probably sufficiently good to be useful for the operational planning of maintenance requirements, even though the estimates used are purely heuristic and have no explanatory power concerning the underlying causes of the failure process. In this connection we might well cite Sir Robert Watson-Watt, Head of British Radar Development during World War Two: “Give them the third best to go on with, the second best comes too late, the best never comes.”

Further studies will concern an application of the method to units in a currently operational aircraft fleet. In this phase the actual MCF will be calculated as far as the “lead unit” of each population. The failure of units trailing after the lead unit will be estimated by following this actual MCF until the operational time of the lead unit is reached, and the linear estimate described above will be used from that point onwards.

Furthermore, the changes over time in the distribution of the “local recurrence rates” (as shown in Figure 5) will be studied and applied to more types of components to search for recurring patterns in the distributions.

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References


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Fleet-level reliability analysis of repairable units: a parametric approach using the power law process

Fleet-level Reliability of Multiple Repairable Units: A Parametric Approach using the Power Law Process

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Abstract: The application of parametric reliability analysis methods for repairable units, such as Power law process, is quite clear and straightforward for a single repairable unit. However, in practice, the analyst needs to know the reliability characteristics of units at a fleet level. The application of parametric reliability analysis methods at the fleet level, even if it is limited in scope, is quite complex. The aim of this paper is to describe the use of the power law process for multiple repairable units with differing reliability characteristics, to predict the expected number of failures at fleet level. The empirical data used in the paper are based on field data gathered during the operational life of two types of multi repairable units used in the Swedish military aircraft system FPL 37 Viggen from 1977 to 2006. The paper performs the trend test using TTT-based MIL-HDBK-189 and Laplace tests, and assesses the equality of shape-parameters for the intensity function of the power law process for multiple units. Estimation of the scale- and shape-parameters using maximum likelihood estimation is also performed. The parametric approach using power law process was found to yield relatively accurate estimations of number of failures, compared to empirical data.

Keywords: Repairable units, NHPP, HPP, aviation, maintenance, reliability analysis, power law process.

1. Introduction

When dealing with highly capital-intensive systems and associated fleets, such as fleets of aircraft, trains, trucks, etc., it is crucial to have a formal reliability programme to assure the collection of important information about the system reliability performance throughout the life cycle. Usually such technically complex systems comprise a large set of both repairable and non-repairable units. In order to assess important reliability metrics, e.g., the number of failures during a specific operation period, it is essential to analyse the reliability characteristics of the repairable units based on the data generated in the customer use environment. Hence, a formal reliability programme is needed that ensures the collection of important information about the system reliability performance throughout the life cycle.

The two main approaches to the reliability analysis of multiple repairable units are non-parametric and parametric methods. The non-parametric method provides a graphical estimate of the number of recurrences (repairs/failures) per unit and per the whole population, versus the utilization/age. The method is called non-parametric in the sense that it does not use a parametric model for the population. This estimation involves no assumptions about the form of the function or the process generating the system histories.

The parametric method entails stochastic point processes, including the homogeneous Poisson process (HPP), the non-homogeneous Poisson process (NHPP), the
renewal process (RP) and the generalized renewal process (GRP), the last of which was introduced by Kijima and Sumita [1]. A renewal process is a counting process where the inter-occurrence times are independent of $s$ (i.e., the times between failures are stochastically independent) and identically distributed with an arbitrary distribution function [2]. The HPP describes a sequence of $s$-independent and identically distributed (IID) exponential random variables. The NHPP is often used to model repairable systems that are subject to a minimal repair and describes a sequence of random variables that are neither statistically independent nor identically distributed [2]. The GRP is a generalization of the repair process that allows the goodness of repairs to be varied from as-good-as-new repair (RP) to same-as-old repair (NHPP). The GRP is therefore useful in modelling the failure behaviour of a specific unit and studying the effect of repair actions, e.g., on a system which is repaired after a failure and where repair only partially rejuvenates the system [3]. A commonly applied parametric method which is relatively simple to use is the power law process (PLP) [2, 4], which allows estimation of the expected number of failures for large arrays of repairable units.

The application of these methods for a single unit is fairly straightforward. However, in practice the reliability analyst is often dealing with multiple similar systems which are installed in different higher assemblies and which are operating with different profiles in different environments. The aim of this paper is to study failures which have occurred in the field, to obtain information regarding the failure rates and the expected numbers of failures at the fleet level, and not at the individual component level.

In [5] a non-parametric approach, the mean cumulative function (MCF), was used to estimate the expected number of failures. The empirical data used in [5] are the same as the data used in this paper, and therefore the results from the two different approaches are easily compared. The purpose of the two papers, the present paper and [5], is to compare the estimations of the future expected number of failures obtained using a non-parametric method, i.e., the MCF, and a parametric method, i.e., the PLP, respectively.

The analysis of the multiple repairable units in this study will follow the logic depicted in Figure 1 and consists of the following steps, adapted from [4]: first checking if there is a trend in the failure data, and secondly studying whether the PLP is an applicable approach to estimation of the expected number of failures.

The empirical data used in this paper are from two types of repairable components; see Table 1 for a summary of the studied units. The units were in operational service in the Swedish military aircraft system FPL 37 Viggen from 1974 to 2006, which is essentially the entire life cycle of the system. The data are derived from about 330 aircraft with a total flight time of 615,000 hours, and consist of information about all the maintenance-significant events for the physical units, i.e., the date of delivery, storage periods, storage maintenance, installations, removals, failures, maintenance actions, modifications, and discard. These events are associated with calendar dates and accumulated operating time in flight hours.
2. Description of the Empirical Data

The first repairable unit studied (henceforth referred to as unit A) was a radar transmitter. This transmitter was part of the main surveillance radar (PS-37) of the AJ 37 strike aircraft. The most common fault modes for this unit were failures of electronic components, particularly thyatron, magnetrons and pulse transformers. The data were right-hand censored by two processes: failure and discard. The right-hand censoring by failures occurred because, towards the end of the aircraft life cycle, failed units were not always repaired.

The second unit was a cooling turbine (henceforth referred to as unit B), which was the principal unit of the environmental control system that delivered cooling air to the electronics and the cockpit air conditioning in all versions of the FPL 37 aircraft system. The cooling turbine was a heavily stressed mechanical unit with a relatively high failure rate in service, despite preventive maintenance. Consequently, for this unit the right-hand censoring can also be due to preventive maintenance not always being carried out when due, towards the end of the system life cycle.

Table 1: Number of Units Included in the Study

<table>
<thead>
<tr>
<th>Unit</th>
<th>Hardware</th>
<th>Units [#]</th>
<th>Maintenance Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Radar Transmitter</td>
<td>124</td>
<td>Corrective Maintenance</td>
</tr>
<tr>
<td>B</td>
<td>Cooling Turbine</td>
<td>372</td>
<td>Preventive and Corrective Maintenance</td>
</tr>
</tbody>
</table>

Among the 124 units of type A, there are 18 units that were time-censored without any failures at all, while for unit B there are 257 out of 372 units that were time-censored without any failures. Table 2 below presents the number of units that suffered a given number of failures, showing that for unit A there are 106 units with 1 failure, 96 units with 2 failures, etc. From Table 2 the total number of failures for the whole population of unit A can be calculated, i.e., 413 failures. The corresponding data for unit B are shown, and the total number of failures for unit B can be calculated to be 156 over the whole life cycle.
Table 2: The Number of Units that have Suffered a Given Number of Failures

<table>
<thead>
<tr>
<th>Failures [#]</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit A [#]</td>
<td>18</td>
<td>106</td>
<td>96</td>
<td>82</td>
<td>60</td>
<td>33</td>
<td>21</td>
<td>8</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Unit B [#]</td>
<td>257</td>
<td>115</td>
<td>37</td>
<td>4</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

These two types of units were both relatively maintenance-intensive. The radar transmitter was only subjected to corrective (on-condition) maintenance, while the cooling turbine, being a heavily stressed mechanical unit, also had preventive maintenance (flight-time based overhauls). The differences between unit A and B (A being an electronic and B a mechanical unit, and B having both preventive and corrective maintenance while A had corrective maintenance only) resulted in quite different failure patterns; see Figure 2 and Figure 3 for the estimated intensity function $\lambda(t)$ using the power law process.

Table 3 and Table 4 describe the number of failures and units in service in each 500-flight-hour interval for unit A and B, respectively. As mentioned before, the units were right-hand censored by two processes, either discard or failure/maintenance (with maintenance only being applicable to unit B), and in the case of aircraft crashes, the units were, of course, time-censored at the operational time for the unit at the time of the crash.

Table 3: Failures and Units of Type A in Service for Each 500-Flight-Hour Interval

<table>
<thead>
<tr>
<th>Operation Time [h]</th>
<th>Units in Service [#]</th>
<th>Accumulated Failures [#]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-500</td>
<td>124 – 104 (20 discards)</td>
<td>0 – 113 (113 failures in interval)</td>
</tr>
<tr>
<td>500-1000</td>
<td>104 – 98 (6 discards)</td>
<td>113 – 243 (130 failures in interval)</td>
</tr>
<tr>
<td>1000-1500</td>
<td>98 – 85 (13 discards)</td>
<td>243 – 340 (97 failures in interval)</td>
</tr>
<tr>
<td>1500-2000</td>
<td>85 – 50 (35 discards)</td>
<td>340 – 396 (56 failures in interval)</td>
</tr>
<tr>
<td>2000-2500</td>
<td>50 – 9 (41 discards)</td>
<td>396 – 411 (15 failures in interval)</td>
</tr>
<tr>
<td>2500-3000</td>
<td>9 – 1 (8 discards)</td>
<td>411 – 412 (1 failure in interval)</td>
</tr>
<tr>
<td>3000-3500</td>
<td>1 – 0 (1 discard)</td>
<td>412 – 413 (1 failure in interval)</td>
</tr>
</tbody>
</table>

Table 4: Failures and Units of Type B in Service for Each 500-Flight-Hour Interval

<table>
<thead>
<tr>
<th>Operation Time [h]</th>
<th>Units in Service [#]</th>
<th>Accumulated Failures [#]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-500</td>
<td>372 – 338 (34 discards)</td>
<td>0 – 39 (39 failures in interval)</td>
</tr>
<tr>
<td>500-1000</td>
<td>338 – 286 (52 discards)</td>
<td>39 – 74 (35 failures in interval)</td>
</tr>
<tr>
<td>1000-1500</td>
<td>286 – 217 (69 discards)</td>
<td>74 – 115 (41 failures in interval)</td>
</tr>
<tr>
<td>1500-2000</td>
<td>217 – 113 (104 discards)</td>
<td>115 – 143 (28 failures in interval)</td>
</tr>
<tr>
<td>2000-2500</td>
<td>113 – 33 (80 discards)</td>
<td>143 – 154 (11 failures in interval)</td>
</tr>
<tr>
<td>2500-3000</td>
<td>33 – 1 (32 discards)</td>
<td>154 – 156 (2 failures in interval)</td>
</tr>
</tbody>
</table>

3. Methodology and Data Analysis

3.1 Trend Testing

To gain further understanding of the reliability behaviour of multiple repairable units, it is important to examine if any trend exists in the failure data, i.e., whether the time between failures becomes shorter or longer, or fluctuates over time, with either a monotonic or a non-monotonic trend. The tests used are a generalization of the Laplace and MIL-HDBK tests, adjusted for studying trends in multiple repairable systems [6]. In this paper we only use the TTT-based versions of the MIL-HDBK-189 and Laplace tests. The reason for choosing the TTT-based tests is that there is no reason to believe that either of the two populations of units is non-homogeneous [6].

The hypothesis for the TTT-based Laplace test is as follows:

$H_0$: The process is an HPP with equal MTBFs.

$H_1$: The process is an NHPP with equal $\lambda(t)$.

The test statistic for the TTT-based Laplace test [6] is according to equation (1) below:
In equation (1), \( v = 1, 2, \ldots, \bar{N} \) is the number of failures for the whole population of units, e.g., the whole population of units of type A and B respectively. The failure times for the units are described by \( S_v \), where \( S_1 \leq S_2, \ldots, \leq S_{\bar{N}} \). The function \( \frac{T(S_v)}{T(S)} \) (the normalized total operating time at time \( u \)) is given by equation (2):

\[
T(S_v) = \int_0^{S_v} p(u)du
\]

(2)

In equation (2), \( p(u) \) is the number of units that is still in operation at time \( u \), and \( \int_0^{S_v} p(u)du \) is the total operating time that has been observed up to time \( u \) for the population \( p(u) \), [6]. In equation (3), \( \bar{N} \) is defined as:

\[
\bar{N} = \begin{cases} 
N, & \text{if the processes are time-truncated.} \\
N - 1, & \text{if the processes are failure-truncated.} 
\end{cases}
\]

(3)

where \( N \) is defined by equation (4):

\[
N = \sum_{i=1}^{k} n_i
\]

(4)

where \( n_i \) is the number of failures for unit \( i, i = 1, 2, \ldots, k \), where \( k \) is the number of units studied in each population (A and B).

Using the same hypothesis for the TTT-based MIL-HDBK-189 test [6, 7], the TTT-based MIL-HDBK-189 test becomes according to equation (5):

\[
M_T = 2 \sum_{v=1}^{\bar{N}} \ln \left( \frac{T(S_v)}{T(S_v')} \right)
\]

(5)

A rejection of \( H_0 \) for the TTT-based trend tests, both the Laplace and the MIL-HDBK-189 tests, gives an indication that there is a trend in the failure data and that it is possible to model the multiple repairable units with only one non-stationary intensity function, or that the sample comes from a heterogeneous population, as discussed by Kvaloy in [6].

The results of the trend tests are presented in Table 5 below. The test statistics \( (L_T, M_T) \) are calculated from equation (1) and equation (5) and the p-value is calculated using the Minitab software (version 16.2). The p-value in Table 5 is the probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true [8].

<table>
<thead>
<tr>
<th>Test procedure for respective units (A/B)</th>
<th>Test Statistic ((L_T, M_T))</th>
<th>p-value</th>
<th>(H_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIL-HDBK-189 TTT-based (( M_1 )), Unit A</td>
<td>913.58, -3.28</td>
<td>0.03, 0.00</td>
<td>Rejected, Rejected</td>
</tr>
<tr>
<td>Laplace TTT-based (( L_2 )), Unit A</td>
<td>259.90, 2.75</td>
<td>0.03, 0.01</td>
<td>Rejected, Rejected</td>
</tr>
</tbody>
</table>

3.2 Estimation of Shape- and Scale-Parameters in the PLP

The results from the trend tests thus indicate that there is a trend in the failure data at a significance level of 5% for both unit A and B. Now, knowing that there is a trend in the
failure times for each population, we examine if the power law process is a suitable model for estimating the number of the expected future failures for the populations; see equation (6) for the intensity function of the power law process with shape-parameter ($\beta$) and scale-parameter ($\theta$):

$$\lambda(t) = \frac{\beta}{\theta} \left( \frac{t}{\theta} \right)^{\beta - 1}.$$  

Dealing with the parameters in the intensity function for the power law process when having multiple repairable units, there are four different combinations that can occur. The first two combinations arise when there are different shape-parameters ($\beta_1, \beta_2, ..., \beta_k$) and either approximately similar or differing scale-parameters ($\theta_1, \theta_2, ..., \theta_k$). If one of these two cases is applicable, the individual units must be analysed separately and modelled with different PLPs.

The other two combinations occur when it is possible to estimate one shape-parameter $\beta$ for the whole population, while the scale-parameters ($\theta_1, \theta_2, ..., \theta_k$) are all either approximately the same or different.

However, since we have already rejected the null hypothesis that the process is an HPP with equal MTBFs, we already have an indication that we can use the same intensity function to model each population of units A and B.

Making the assumption that the shape-parameter ($\beta$) and scale-parameter ($\theta$) can be used to model the whole population with one power law model, the parameters can be estimated by using the maximum likelihood function; see equations (7) and (8) for estimation of the shape-parameter ($\beta$) and the scale-parameter ($\theta$), [8, 9],

$$\hat{\beta} = \frac{\sum_{i=1}^{k} n_i}{\sum_{i=1}^{k} T_i^\beta \ln(T_i)} - \frac{1}{\beta} \sum_{i=1}^{k} n_i \ln(t_{ij})}.$$  

$$\hat{\theta} = \frac{\sum_{i=1}^{k} T_i^\beta}{\sum_{i=1}^{k} n_i^{\beta/\theta}}.$$  

In equations (7) and (8), $k$ is the number of units in the respective populations (A and B), $n_i$ is the number of failures for unit $i$, and $t_{ij}$ is the failure times for unit $i$ at failure number $j = 1, ..., n_i$, while $T_i$, is the termination time, whether this is time- or failure truncated.

In most situations equation (7) must be solved iteratively, for example by using the fixed-point iteration method or Newton-Raphson’s method [9]. Equation (7) can only be solved explicitly in the case when the whole population is time-truncated at the same time, i.e., $T_i = T$ for all $i = 1,2, ..., k$ units, which very rarely applies in practice.

The shape-parameters ($\beta_A, \beta_B$) were calculated with equation (7) and the scale-parameters ($\theta_A, \theta_B$) with equation (8) for both units, using the fixed-point iteration method, see Table 6 and Table 7 for ($\beta_A, \theta_A$) and ($\beta_B, \theta_B$).

<table>
<thead>
<tr>
<th>Scale/Shape-parameter</th>
<th>Value of Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_A$</td>
<td>0.90</td>
</tr>
<tr>
<td>$\theta_A$</td>
<td>416.59</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scale/Shape-parameter</th>
<th>Value of Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_B$</td>
<td>1.19</td>
</tr>
<tr>
<td>$\theta_B$</td>
<td>3 312.54</td>
</tr>
</tbody>
</table>

Table 6: The Estimated Scale-/Shape-parameters for Unit A

Table 7: The Estimated Scale-/Shape-parameters for Unit B
Calculating the corresponding confidence interval for the shape-parameter (\( \beta \)) and the scale-parameter (\( \theta \)) is important in order to determine whether the range of \( \beta \) is above or below 1 (\( \beta < 1 \) and \( \beta > 1 \) mean decreasing and increasing failure trends respectively). Crow [7] suggests a method for calculating the confidence interval for the scale-parameter (\( \theta \)) when the shape-parameter (\( \beta \)) is known. In the case where the shape-parameter is unknown, one solution is to find an appropriate asymptotic confidence interval. Gaudoin et al. [10] suggest some different asymptotic confidence intervals for estimating the scale-parameter (\( \theta \)). In this paper a simpler method is used to estimate the confidence interval for the shape- and scale-parameters by applying a normal distribution approximation [10]. Such interval estimations are easy to calculate and are also widely implemented in various software packages, e.g., Minitab (version 16.2).

The confidence interval for the shape- and scale-parameters can then be estimated by using equations (9) and (10).

\[
\frac{\hat{\beta} - z_\alpha \sigma_\beta}{e^{-\frac{\hat{\theta}}{\beta}}} \leq \theta \leq \frac{\hat{\beta} + z_\alpha \sigma_\beta}{e^{-\frac{\hat{\theta}}{\beta}}},
\]

(9)

\[
\frac{\hat{\theta} - z_\alpha \sigma_\theta}{e^{-\frac{\hat{\theta}}{\beta}}} \leq \theta \leq \frac{\hat{\theta} + z_\alpha \sigma_\theta}{e^{-\frac{\hat{\theta}}{\beta}}},
\]

(10)

where, \( z_\alpha \) is the value of the normal distribution at significance level \( \alpha \) and \((\sigma_\beta, \sigma_\theta)\) is the standard error of the estimated shape- and scale-parameters. The results obtained by calculating the confidence intervals provide an indication as to whether it is possible to characterise a whole population of repairable units with a single shape-parameter (\( \beta_A, \beta_B \)) for each population. As shown in Table 8, the whole confidence interval for the shape-parameter for unit A is below \( \beta = 1 \), while for unit B the confidence interval lies above \( \beta = 1 \); and both intervals were obtained at the significance level, \( \alpha = 0.05 \). Since the confidence intervals are either completely above or below \( \beta = 1 \), this indicates that it is suitable to use one shape-parameter for each population. See Table 9 for the confidence intervals for the scale-parameters, calculated at significance level \( \alpha = 0.05 \).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Confidence Interval for the Shape-parameters, ( \alpha = 0.05 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta_A )</td>
<td>( 0.83 &lt; \beta_A &lt; 0.98 )</td>
</tr>
<tr>
<td>( \beta_B )</td>
<td>( 1.07 &lt; \beta_B &lt; 1.32 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Confidence Interval for the Scale-parameters, ( \alpha = 0.05 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta_A )</td>
<td>( 348.57 &lt; \theta_A &lt; 497.89 )</td>
</tr>
<tr>
<td>( \theta_B )</td>
<td>( 2946.94 &lt; \theta_B &lt; 3723.49 )</td>
</tr>
</tbody>
</table>

### 3.3 Testing for Equality of Shape-parameters

In addition to estimating the confidence intervals for the shape-parameters (\( \beta_A, \beta_B \)) and the TTT-based trend tests, there are other methods for verifying or rejecting the use of a single \( \beta \) parameter. Crow [7] and Bartlett [12] suggest a test for equal shape-parameters, \( \beta_i \)'s, for the power law process. This leads to a test of the following hypothesis:

\[
H_0: \beta = \beta_1 = \cdots = \beta_k
\]

\[
H_1: \beta_i \neq \beta_j, \text{ at least one pair } (i, j). \]
The null hypothesis states that all the shape-parameters, $\beta_i$'s, are the same, while the alternate hypothesis states that there is at least one pair $(i, j)$ that has a different $(\beta_i, \beta_j)$. The likelihood ratio test, taken from [8], is in accordance with equation (11):

$$LR = M \ln(\beta^*) - \sum_{i=1}^{k} m_i \ln(\tilde{\beta}_i),$$

where $m_i$ is given by equation (12):

$$m_i = \begin{cases} n_i, & \text{if the data is time-truncated.} \\ n_{i-1}, & \text{if the data is failure-truncated.} \end{cases}$$

and $M$ is given by equation (13):

$$M = \sum_{i=1}^{k} m_i.$$ 

In equation (11) $\tilde{\beta}_i$ are the so-called CMLEs (conditional maximum likelihood estimates) for the $i$:th unit [8], see equation (14):

$$\tilde{\beta}_i = \frac{m_i}{\sum_{j=1}^{n_i} \ln(\tilde{\tau}_{ij})}.$$ 

$\beta^*$ in equation (11) is the weighted harmonic mean of $\tilde{\beta}_i$, see equation (15):

$$\beta^* = \frac{M}{\sum_{i=1}^{k} \frac{m_i}{\tilde{\beta}_i}}.$$ 

Using the approximation according to Bartlett [11], the test statistic $T = \frac{-2LR}{a}$ is chi-square distributed with $k - 1$ degrees of freedom, according to equation (16):

$$\frac{-2LR}{a} \sim \chi^2(k - 1),$$

where $a$ is as follows in equation (17):

$$a = 1 + \frac{1}{6(k-1)} \sum_{i=1}^{k} \frac{1}{m_i} - \frac{1}{M}.$$ 

The null hypothesis $H_0$ is rejected at a significance level of $\alpha$ if equation (18) is valid,

$$\frac{-2LR}{a} > \chi^2_{\alpha}(k - 1)$$

Working through the calculations from equation (11) to equation (18) gives an indication as to whether the reliability pattern of the units makes the power law process with a single shape-parameter a suitable model for the intensity function $\lambda(t)$. If one ascertains that it is appropriate to estimate a whole population of repairable units using only one shape-parameter ($\beta$), it is then possible to treat the whole population of repairable units as a single repairable system with multiple units. The trend tests thus indicate that there is a trend in the failure data at a significance level of 5% for both unit A and B.

The values of the calculated test statistic $T = \frac{-2LR}{a}$ for the respective populations are presented in Table 10, calculated in Minitab (version 16.2). The corresponding p-values given in Table 10 strongly indicate that the null hypothesis cannot be rejected at a significance level of $\alpha = 0.05$ for either population. This is also verified by using
equation (16), *i.e.*, calculating $\chi^2(k-1)$ for the degrees of freedom $(k-1)$, where $k$ is the number of units in the respective populations, at a significance level of $\alpha = 0.05$, and by comparing the result of this calculation with the calculated test statistic $T$, see Table 10. It is clear that the null hypothesis cannot be rejected, and therefore we conclude that there is no evidence that the $\beta$'s are different for the respective populations (A and B).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DF $(k-1)$</th>
<th>Test Statistic, $T$</th>
<th>p-value</th>
<th>Table-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_A$</td>
<td>105</td>
<td>79.10</td>
<td>0.97</td>
<td>$\chi^\text{table}(106-1) = 129.92$</td>
</tr>
<tr>
<td>$\beta_B$</td>
<td>90</td>
<td>105.40</td>
<td>0.13</td>
<td>$\chi^\text{table}(91-1) = 113.10$</td>
</tr>
</tbody>
</table>

### 3.4 Estimation of Expected Number of Failures Using PLP

Using the estimated shape-parameters ($\beta$) and scale-parameters ($\theta$) given in Table 6 for unit A and Table 7 for unit B, the intensity functions for the power law process become in accordance with equations (19) and (20):

$$
\lambda_A(t) = \frac{\beta_A}{\theta_A} \left( \frac{t}{\theta_A} \right)^{\beta_A-1} = \frac{0.90}{416.59} \left( \frac{t}{416.59} \right)^{0.90-1} 
$$

(19)

$$
\lambda_B(t) = \frac{\beta_B}{\theta_B} \left( \frac{t}{\theta_B} \right)^{\beta_B-1} = \frac{1.19}{3312.54} \left( \frac{t}{3312.54} \right)^{1.19-1}
$$

(20)

Fitting the intensity function $\lambda(t)$ of the power law process to the failure data and plotting the estimations for the two populations with a confidence level of 95%, together with the mean cumulative function (MCF) for the two types of units, yields Figure 2 and Figure 3 below:

![Figure 2. Estimation of Intensity Function, Unit A.](image)

![Figure 3. Estimation of Intensity Function, Unit B.](image)

As shown in Figure 2, the estimate is imprecise for unit A and the MCF of unit A goes slightly outside the 95% confidence level around 1,100 flight hours, while the approximation using the power law process gives a rather better result for unit B, in Figure 3. This difference is presumably due to the presence of multiple inflection points for the MCF of unit A.

Using the estimated failure intensities $\lambda_A(t)$ and $\lambda_B(t)$ from equations (19) and (20) above, one can calculate the number of expected failures between the times $t_1$ and $t_2$ [9], using equations (21) and (22):
\[ E_A[N(\Delta t)] = \int_{t_1}^{t_2} \lambda(t) dt = \frac{1}{\beta_A} \left( t_2^\beta_A - t_1^\beta_A \right) = \left( \frac{1}{416,59} \right)^{0.90} \left( t_2^{0.90} - t_1^{0.90} \right) \]  
\[ E_B[N(\Delta t)] = \int_{t_1}^{t_2} \lambda(t) dt = \frac{1}{\beta_B} \left( t_2^\beta_B - t_1^\beta_B \right) = \left( \frac{1}{3312,54} \right)^{1.190} \left( t_2^{1.190} - t_1^{1.190} \right) \]  

Equations (19) and (20) give the number of expected failures per unit in the interval \( t_1 \) to \( t_2 \). To calculate the total expected number of failures for the whole population, A and B, respectively, we need to know how many units can be expected to be in operation in that specific interval. In the case in question we are using the average number of units in each 500-hour interval; i.e., we are calculating the total operating time in each 500-hour interval and dividing by the length of the interval (500 hours).

The results for the number of expected failures are presented in Table 11 and Table 12. In column two from the left, the number of empirical failures in operation is presented, and these can be compared with column three, the number of failures predicted by the power law process. As can be observed in the tables, the power law process is more accurate for units of type B than for units of type A. The probable reason for this is that unit B is a mechanical unit subject to wear and has a consistent failure trend without the inflection points seen for unit A.

**Table 11: Comparison between Empirical and Modelled Number of Failures for Unit A**

<table>
<thead>
<tr>
<th>Operation Time [h]</th>
<th>Empirical Failures [#]</th>
<th>Estimated Failures [#]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-500</td>
<td>0 – 113 (113)</td>
<td>0 – 133 (133)</td>
<td>-20</td>
</tr>
<tr>
<td>500-1000</td>
<td>113 – 243 (130)</td>
<td>133 – 237 (104)</td>
<td>+26</td>
</tr>
<tr>
<td>1000-1500</td>
<td>243 – 340 (97)</td>
<td>237 – 328 (91)</td>
<td>+6</td>
</tr>
<tr>
<td>1500-2000</td>
<td>340 – 396 (56)</td>
<td>328 – 394 (66)</td>
<td>-10</td>
</tr>
<tr>
<td>2000-2500</td>
<td>396 – 411 (15)</td>
<td>394 – 421 (27)</td>
<td>-12</td>
</tr>
<tr>
<td>2500-3000</td>
<td>411 – 412 (1)</td>
<td>422 – 432 (2)</td>
<td>-1</td>
</tr>
<tr>
<td>3000-3500</td>
<td>412 – 413 (1)</td>
<td>423 – 424 (1)</td>
<td>0</td>
</tr>
</tbody>
</table>

Average = 21%

**Table 12: Comparison between Empirical and Modelled Number of Failures for Unit B**

<table>
<thead>
<tr>
<th>Operation Time [h]</th>
<th>Empirical Failures [#]</th>
<th>Estimated Failures [#]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-500</td>
<td>0 – 39 (39)</td>
<td>0 – 37 (37)</td>
<td>+2</td>
</tr>
<tr>
<td>500-1000</td>
<td>39 – 74 (35)</td>
<td>37 – 80 (43)</td>
<td>-8</td>
</tr>
<tr>
<td>1000-1500</td>
<td>74 – 115 (41)</td>
<td>80 – 118 (38)</td>
<td>+3</td>
</tr>
<tr>
<td>1500-2000</td>
<td>115 – 143 (28)</td>
<td>118 – 145 (27)</td>
<td>+1</td>
</tr>
<tr>
<td>2000-2500</td>
<td>143 – 154 (11)</td>
<td>145 – 157 (12)</td>
<td>-1</td>
</tr>
<tr>
<td>2500-3000</td>
<td>154 – 156 (2)</td>
<td>157 – 159 (2)</td>
<td>0</td>
</tr>
</tbody>
</table>

Average = 7%

4. Conclusions

The objective of this paper was to apply and evaluate a parametric approach using the power law process to estimate the expected number of failures on a fleet level for aircraft systems. This is quite a realistic and important objective for military aircraft, for which the planning horizon is typically much longer than that for commercial aircraft fleets and for which the extreme spacing of aircraft generations means that providing spares and maintenance can be difficult and expensive towards the end of the system life cycle.

The method described above seems to estimate the number of future failures with reasonable precision. The estimate for unit B is very good, presumably due to the
consistent changes in the failure rates over the life cycle of the unit. The fit for unit A is not quite as good, presumably because the failure rate of this unit changes in an inconsistent manner and has several inflection points. One of the reasons for the relatively satisfactory estimates is probably the homogeneity of the two populations.

In this study, we have only included failures in operation for unit B. Since this unit had preventive maintenance, a number of incipient failures were found and repaired in connexion with the preventive maintenance. While such incipient failures affect the maintenance costs, the spare part demand and the choice of a maintenance interval for the preventive maintenance, they have no effect on the operational failure rates.

A serious disadvantage when applying this implementation of the PLP is the necessity for testing each population, usually consisting of several hundreds of units, for homogeneity before estimating the intensity function for the PLP. In the case of non-homogeneous populations, each subpopulation must be identified and modelled with a separate intensity function. Furthermore, in cases where several subpopulations exist, there may not be sufficient data for each subpopulation to allow robust modelling.

A comparison with the results in [5], which used a non-parametric heuristic estimate of the failure rates, shows that the parametric method gave a significantly better estimate for both units. As already mentioned, this is probably at least partly due to the homogeneity of the studied populations. Furthermore, in this study the shape- and scale-parameters were estimated over the whole life cycle and applied to each 500-hour segment, while in [5] only data earlier than the 500-hour segment to be estimated were used, which most likely contributes to the better performance of the PLP-based estimates.

Further studies will concern piece-wise estimates of the intensity function of the PLP, performed to estimate future failure rates, since such estimates would be necessary in the case of a currently operational aircraft fleet, where data are only available up to the present. In parallel with this, the effects on the suitability of the parametric and non-parametric methods for inhomogeneous populations will also be studied.

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Part-out-based spares provisioning management: a military aviation maintenance case study

Part-out-based spares provisioning management
A military aviation maintenance case study

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Abstract
Purpose – The purpose of this paper is to present the prerequisites for a part-out-based spares provisioning (PBSP) programme during the phase-out of an aircraft fleet. Furthermore, associated key decision criteria are identified and a framework for the phase-out management process is presented.

Design/methodology/approach – Once a decision has been taken to phase-out an aircraft fleet, a number of routines for operations, maintenance and storage are affected and new tasks and functions must be introduced before initiating the actual parting-out process. A decision-making system and a management framework is needed to manage spares planning during the end-of-life phase to ensure availability at minimum cost and to ensure a manageable risk of backorders.

Findings – For PBSP programme during the phase-out of an aircraft fleet to succeed and be cost-effective, a number of linked processes, tasks and decisions are required, e.g., those included in the framework proposed in this paper (see Figure 3). A successful implementation of PBSP also requires that these processes and tasks are carried out in a timely manner and that the communications between the concerned parties are prompt, clear and direct. One experience from the studied case is that close and trustful contacts and cooperation between the operator and maintenance provider(s) will greatly facilitate the process.

Originality/value – Although the PBSP method is fairly commonly applied within both the military and the civilian sector, somewhat surprisingly very little has been published on the subject. Indeed, remarkably little has been published on any aspects of maintenance during the end-of-life period.

Keywords Maintenance, Aircraft, End-of-life management, Parting-out, Spares, Stock management, Disposal, Phase-out, Rotables

Paper type Research paper

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1. Introduction
When dealing with pools of complex technical systems, such as aircraft fleets and associated support systems, it is critical to introduce a product lifecycle management (PLM) programme for the fleet throughout its whole lifecycle. Ameri and Dutta (2005) define PLM as a knowledge management solution for product lifecycles within the extended enterprise.

PLM originates from two roots. One root is enterprise management, which can be further subdivided into the following four areas: material resource planning, enterprise resource planning, customer relationship management and supply chain management. In this context, PLM serves as a decision support tool. The other root is the management of product information throughout the product lifecycle (Lee et al., 2008). From the point of view of an original equipment manufacturer (OEM) the lifecycle of a product comprises the five phases of concept, definition, realization, support and retirement (Lee et al., 2008; Stark, 2005). During the conceptual phase, the market requirements are identified and a product design concept is developed. The definition phase consists of the detailed design of the product, the planning of the manufacturing process and the development of a prototype. The actual production and the subsequent warehousing take place in the realization phase. During the support phase, the OEM is often responsible for supporting the product. This phase is also known as the operation and maintenance phase, which from the customer’s or operator’s perspective includes acquisition, introduction and operation and maintenance activities. When the product is retired, it is disposed of, or recycled, and in this phase the operator and/or the OEM should consider environmental issues, scrap technologies, the scrapping process and associated standards and regulations, as well as classification issues (Lee et al., 2008).

When an aircraft type reaches the retirement phase, one out of two scenarios may occur, i.e., re-operation or retirement. If re-operation is an option, the aircraft can either be operated as previously, or it may be transferred to another role, such as training and communications, in which case regulatory issues may apply (e.g. environmental requirements). If the decision is complete retirement of an aircraft fleet, which is the case considered in this paper, the aircraft will be scrapped. It should be noted that, for populations of very capital-intensive systems, such as an aircraft fleet, it is common for the retirement process to stretch over a decade or more, during which the number of operational aircraft gradually decreases.

Hence, material resource planning within PLM is still required to ensure that the remaining fleet continues to meet the established operational profile goals and to make sure that the demands for performance are met. To this end, product end-of-life management plays a significant role.

This requires management of the operational resources for the remaining fleet with acceptable levels of cost and uncertainty. Examples of operational resources include maintenance personnel, repair shops and maintenance slots. Another important operational resource is spares, which is the focus of this paper. In addition, “spares” are in this paper viewed as line replaceable units (LRU), shop replaceable units (SRU), partly repairable units (PRU), discardable units and consumables. The group of LRU, SRU and PRU will henceforth be referred to as “rotables”, since they are partly or fully repairable.

In many cases, a retired aircraft contains valuable spares that retain some operational or monetary value, and can be returned to service. These spares can be used to support the remaining fleet, or offered on the surplus market. In this case,
the retired aircraft will be dismantled and a “parting-out” process will be undertaken to collect the valuable spares that would otherwise be expensive or difficult to obtain.

When resources are usually limited, the interchangeable spares which are necessary for repair can also be removed from another similar device rather than from the inventory. This is called cannibalization. In general, cannibalization is used due to the unavailability of spares, when there are, e.g., long supply times during line operation. In this case, the source aircraft is usually unserviceable. Hence, it is a temporary solution to make the recipient aircraft available.

It should be noted that cannibalization is different from parting-out. Cannibalization is an *ad hoc* process that is used to create instant operational availability, and it is always necessary to restore the cannibalized aircraft to a normal operational condition, using normal supplied spares. However, experience indicates that overuse of cannibalization may result in a so-called “hangar-queen”, i.e., the aircraft will be used more or less permanently as a source of spares for other aircraft (see Salman et al., 2007 for a discussion of the operational and financial benefits of cannibalization of aircraft spares).

However, in a phase-out scenario, the number of operational aircraft will decrease over time, and the demand for spares (due to corrective and preventive maintenance (CM and PM)) will normally decrease as well. This combination may ultimately increase the relative spares level in stock when approaching the time of retirement, which is an unwanted capital investment. To this end, an end-phase spares management programme is needed to identify when to terminate CM and PM efforts, as well as when to stop collecting parts from retired aircraft.

Currently, spares planning is mainly applied in the operational phase, with impressive results. Accordingly, while there is a substantial amount of literature on spares planning in the operational phase, there are very few publications dealing with spares management during the phase-out process of an aircraft fleet, or fleets of other complex technical systems for that matter. There is a certain amount of literature treating this, so-called “last buy”, which is due to the obsolescence of both non-repairable and repairable units (e.g., Cattani and Souza, 2003), although the emphasis is mostly on non-repairable units. However, very little has been published on spares supply during the actual phasing-out process. In fact, the importance of spares during the retirement process has not been properly emphasized in the literature. It has been shown that PLM is used nearly ten times less frequently in the service phase than in the product design phase, and that the use of PLM in the phase-out phase is insignificant (Lee et al., 2008).

The aim of this paper is to present the prerequisites for a part-out-based spares provisioning (PBSP) management programme during the phase-out of an aircraft fleet. In addition, associated key decision criteria and a framework for a phase-out management process are presented.

The remaining part of the paper is organized as follows. In Section 2, the applied study approach is briefly presented. The PBSP management programme is described in Section 3, followed by a description of the proposed framework and associated processes in Section 4. Finally, in Section 5, a summary and some conclusions are presented.

### 2. Study approach

The study presented in this paper is part of the research project “Enhanced Life Cycle Assessment for Performance-based Logistics”, which was initiated by the combined
need to document systematically empirical experience based on best practice and to identify additional possibilities provided by state-of-the-art research. The project is in turn part of the Swedish National Aeronautics Research Programme.

Based on the systematic selection criteria proposed by Yin (2013) (i.e. the type of research question, no control required over behavioural events, and a focus on contemporary events, as well as the criticality and extremeness of the case) a single case study was judged to be relevant.

Hence, the empirical knowledge presented in the paper is based on experience gained during the phasing-out of military aircraft systems within the Swedish Armed Forces. The theoretical material used was identified through a literature review covering the problem area.

Empirical data were collected through interviews, document studies, observations and databases. The material has been structured according to a combination of empirical experience and the theories encountered during the literature review.

When describing the PBSP management programme we make some assumptions and assume some limitations, partly due to the fact that our experience is mostly within the military aviation sector. For example, we assume that the operational profile and phase-out time tables are approximately known by the time the phase-out starts for the aircraft fleet, this is usually true for military systems, but less certain in the civilian case. Another assumption is that no surplus spares are sold on the open market, this assumption is due to regulatory problems connected with selling military hardware on the civilian market. A limitation is that we do not illustrate all feedbacks, information flows and relationships in the proposed framework (see Figures 1 and 3), since this would make them impossibly cluttered.

Notes: The four decision gates (1-4) are: (1) stop reclaiming spares; (2) stop part-out maintenance (POM); (3) stop corrective maintenance (CM); and (4) stop preventive maintenance (PM).
The literature review also supported an analytical validation of the empirical findings and the proposed framework. Finally, the paper has been reviewed by key informants and experts in key roles to verify its content. See, for example, Yin (2013) and Miles and Huberman (1994) for the rationale of the applied study approach.

3. PBSP

During the phase-out process, aircraft rotables will be removed from operational aircraft for line-level maintenance (i.e. PM and/or CM), and to fulfil possible modification requirements. If the condition of the rotable shows that restoration/repair is not economically viable or the unit is not restorable/repairable, it will be classified as non-fixable and will be scrapped directly. Otherwise, the unit proceeds for further investigation and inspection at the repair shop level. Of course, a detailed investigation at the repair shop level may show that the most effective decision is still to scrap the unit, due to safety, operational or economic reasons. The units that receive a successful repair will be tagged as serviceable and sent to storage.

Once a decision has been taken to phase-out an aircraft fleet, and if parting-out is an option for provisioning, the retired individual aircraft will be dismantled and a parting-out process will be undertaken to support the remaining operational fleet; see the right-hand side of Figure 1 for the parting-out process. In this process, the useful spares are removed from the retired aircraft, and if they are worth repairing/reconditioning, they may be tagged in one of the following three ways (see Figure 1):

- usable (serviceable, sent directly into storage);
- repairable (unserviceable, but can be reused after a repair action, sent to the repair shop); and
- unfit for service (neither reusable nor worth repairing and should be scrapped).

In some cases, some unserviceable rotables may be kept as a buffer for possible restoration at a later time, if this should become necessary. When phasing-out an aircraft fleet it may also be possible to sell units, subsystems or entire aircraft to other operators, but this scenario is not treated in this paper. In this context, it should be noted that statutory rules often make it impracticable to sell military aircraft or aircraft parts to civilian operators, even when they are identical to parts used in the civilian sector.

In a phase-out scenario, the number of operational aircraft will decrease over time, as will often the demand for spares required for CM and PM. Accordingly, when the retirement date of the fleet is approaching, the relative spares level in stock may increase, thereby causing an unwanted capital investment.

As shown in Figure 1, the reclaimed spares from phased-out aircraft (due to the part-out process) are either put directly into storage, sent for repair/overhaul and then put into storage (parting-out maintenance (POM)), or scrapped when not in a state where they are worth repairing (see decision gate 2). Decision gate 1 in Figure 1 concerns which spares are worth reclaiming (see Section 4.3.1). For normal operation, decision gates 3 and 4 concern decisions as to whether it is worth repairing a failed rotable or to perform preventive maintenance. These decisions are particularly critical during the phase-out process, since it may be possible to stop CM and PM at some point due to the parting-out process.

An effective PBSP management programme requires a multidisciplinary and integrated decision-making process where different factors must be considered. The key
decisions deal with when to stop maintenance activities on the parts removed due to CM, PM as well as reclaimed rotables (POM). Another key decision is when to stop the parting-out process itself. In a fact variety of alternatives can be created to fulfil the minimum availability requirement of the remaining fleet. However, the main question remains as to which alternative is the most cost-effective solution and leads to the minimum risk for unavailability.

Figure 2 presents a schematic description of the problems, when two different spares provisioning scenarios are used. In one scenario (see Figure 2) continuous repairs and parting-out during the whole PBSP period are considered. It is obvious that due to the high number of spares provisioned and the decrease in the demand for spares for the existing fleet, the total number of available units at the end of the lifecycle of the aircraft fleet is too high (see the grey curve in Figure 2).

In the second scenario (see Figure 2, the continuous black curve) an effective PBSP management programme is applied to fulfil the availability requirements. This second scenario comprises decisions on stopping CM, PM and POM, as well as stopping the parting-out process, at suitable stages of a PBSP period.

As shown in Figure 2, applying the PBSP methodology not only fulfils the demand for rotables during the whole phase-out period, but also reduces the total number of spares in stock during the phase-out period. In fact, in this second scenario, the total cost is reduced due to the lower number of maintenance tasks, the lower number of purchased spares, the lower cost for parting-out and reduced storage costs. The risk for backorders of spares must, of course, be controlled during the phase-out period by making sure that there is always a safety margin (see $\Delta$ in Figure 2) between the available spares and the demand.

When the decision has been taken to phase-out an aircraft fleet, a number of routines concerning operations, maintenance and storage are affected and new functions and tasks need to be introduced before starting the actual parting-out process. A decision-making system is needed to manage spares planning during the system’s end-of-life phase to fulfil the availability requirements at the minimum cost and to ensure a manageable risk of backorders. The management decisions should identify when to stop PM, CM and POM, as well as when to stop the parting-out process. In addition, the decision-making system must address the issue of which spares are worth parting out. The management decision process can play a vital role in
the optimization process for the stock handling during the retirement process. By having the right spares available at the right place at the right time, it is possible to reduce the risk of unavailability, and protect against extra costs due to maintenance, excessively high stock levels and excessive parting-out. Furthermore, storage costs can be minimized and turn-around times can be reduced during the phase-out process. This means reduced costs and increased revenues for the operator. In fact, the retirement process should include a set of tasks to be performed in order to phase-out the system’s stock of spares at the end of its useful life, as well as to recycle/dispose of the spares which the system consists of (Knezevic, 1997). This process should adequately address the future maintenance volume, as well as fulfil the requirements for associated spares availability, at the lowest possible cost.

The problems associated with an effective PBSP programme are linked to the two main areas of availability and cost, of which availability is paramount. This means that the possible solutions for stopping the maintenance and the reclamion of used spares must always satisfy the availability requirements. However, to make rational and justifiable decisions concerning spares planning, one needs to have a clear idea of the advantages and disadvantages of each decision.

To evaluate the appropriateness of any decision, one must have a set of evaluating criteria that adequately address the effectiveness of the spares planning strategy and the cost of implementing it. Moreover, assessment of the spares planning strategy requires knowledge of the various factors which indicate the appropriateness of the strategy, according to the associated decision criteria. The assessment should also facilitate the identification of opportunities and cost-effective ways to implement the decisions that are needed to sustain aircraft availability, resulting in the reduction of business risks and uncertainties, as well as operational costs. Hence, it is necessary to apply a PBSP management programme during the end-of-life phase of an aircraft fleet.

4. Framework for spares planning and control for the end-of-life phase

Figure 3 presents an overview and grouping of the main processes and decisions within the proposed framework, including their interactions. As shown, the general

![Figure 3. Proposed framework for a PBSP management programme during a phase-out scenario](image-url)
The PBSP management programme is divided into five main segments: "strategic planning", "fleet management", "maintenance management", "logistic support management" and "data and data management".

Each segment contains a set of processes which in turn contain a number of tasks that must be performed to fulfil the PBSP management programme for an aircraft fleet during the end-of-life period; of course, most of the processes and functions/tasks are also needed during normal operation, as is noted in the following sections.

The overall responsibility for the PBSP programme could be placed either in "strategic planning" or in "fleet management". However, the experience gathered from the cases studied in this paper shows that this responsibility has been located within "fleet management" (see the bold frame and text in Figure 3) and that this probably is the best solution given the on-going day-to-day character of a PBSP programme.

The arrows in Figure 3 illustrate how data, information and/or decisions flow from one process to another. It should be emphasized that there are many interactions, a large amount of feedback, and many feed-forward loops between the various processes. For example, a feedback loop occurs when input from the "phase-out operation plan" and "fleet management" leads to an unusual flight demand and this implies that the "phase-out master plan" should be reconsidered. However, in order to increase the lucidity of Figure 3, this sort of interaction loop is ignored in Figure 3.

It should be noted that the framework presented in this paper is according to the best practices for a military aircraft fleet. Consequently, it might need to be adapted and refined when used within a civil aviation context.

4.1 Strategic planning
The initiation of the phase-out process is the result of a strategic decision to phase-out the existing aircraft fleet. This decision must also consider other aspects, such as a surplus of parts, the provisioning strategy, flight operations and maintenance and operational organization structures. These issues are often described in a so-called "phase-out master plan", developed to provide guidance for the stakeholders during the implementation of the phasing-out process (see Section 4.1.2).

4.1.1 Aircraft phase-out decision. In a military context, the decision to phase-out an aircraft fleet is often taken at a political level according to criteria such as national security and defence requirements, the status of the fleet performance, and operational requirements, as well as operation and maintenance costs.

There are several models for determining whether it is more profitable to keep maintaining an aging fleet or to replace it, e.g., the model suggested by (Keating and Dixon, 2004), which is an extension of the model by (Greenfield and Persselin, 2003).

However, (Keating and Dixon's, 2004) model does not include the effects of technological advances or the effects of enhanced capabilities on national security (or competitiveness in the civilian case), but is exclusively concerned with availability and the costs of maintenance and procurement. However, decisions about the phasing-out and replacement of an aircraft fleet frequently hinge more on the question of new or enhanced capabilities than on economics, particularly in the military context.

Once a decision on a phase-out has been taken, the phase-out period may take five to 15 years and includes decisions on aircraft retirement and a timeframe for disposal. When the retirement of an existing aircraft fleet is due to the introduction of a new fleet, a phase-out decision must also include the potential phase-in plan for the new aircraft fleet.
An example of a phase-out plan for the FPL 37 Viggen in Sweden is shown in Figure 4. As seen in Figure 4 the intention in 1992 was to phase-out the aircraft type by 2010. However, major reductions of the Swedish armed forces after the collapse of the Soviet Union resulted in the phase-out actually being completed as early as 2005.

4.1.2 Phase-out master plan. In order to complete a successful fleet phase-out process, a “phase-out master plan” should be developed which acts as a road map for the involved stakeholders, i.e., for “fleet management”, “logistic support management” and “maintenance management”.

The “phase-out master plan” states how to complete the phase-out project within a certain timeframe, and specifies the major tasks, milestones and designated resources (e.g. the budget and the number of man-hours allocated).

The major tasks of a “phase-out master plan” include the following:

1. aircraft disposal schedule;
2. a flight operations plan for the phase-out period;
3. a restructuring of both the flight operation and the maintenance organization;
4. a decision on a spares provisioning approach, including parting-out; and
5. recycling/disposal of the scrapped aircraft.

The first task in the “phase-out master plan” is to draw up a fleet disposal schedule specifying which aircraft is to be disposed of at a specific time, and containing the actual number of aircraft to be in service during the whole phase-out period. In fact, the decision on prioritizing aircraft for retirement should be based on systematic selection criteria. These criteria may include, but are not limited to, the airframe life, the operation cost, the technological requirements, the future scheduled maintenance and mandatory modifications. There exists a variety of methods for describing aircraft replacement strategies. A fairly extensive method is described by Hsu et al. (2011) and is applied to Taiwan Airlines.

It should be noted that there are differences between the civilian and the military cases. In the civilian case a replacement must be profitable, above all, while in the military case, although economics is an important factor, issues such as capabilities...
and national security, as well as political considerations, will often outweigh the economic factors.

The second task is to define the total volume of the flight operations during the phase-out period, to define the operational sites on a short- and long-term basis, specifying the number of aircraft at each operational site, and to define the operational profile and the type of exercises and training to be carried out. This is accomplished on an outline level. Best practices indicate that the "phase-out master plan" should include a definition of the total amount of flight hours for the whole fleet on an annual basis, assigning the flight hours to operating sites and decisions on implementing heavy modifications.

The third task is to restructure the organizations for flight and maintenance according to the demands and required capacity. This restructuring is required because the maintenance needs will change due to fewer operational aircraft, and because the use of parting-out spares will reduce the required maintenance volumes. Moreover, the organization of the flight operations also needs to be adjusted, since there may be a need to merge operational sites for economic or tactical reasons. In addition, the storage facilities may also need to be adjusted due to changing operational circumstances.

The fourth task is to define the approved approach for provisioning. This may include parting-out, pooling agreements, etc. In fact, this approach should be defined with input from all the stakeholders to fulfil the availability and cost criteria. The implementation of this approach can be quite complex due to a variety of decision factors that affect the spares provisioning plan, e.g., modification plans, operational requirements, the parting-out process, the maintenance (repair times and turn-around-times) and the failure pattern of the units.

The fifth task is to decide how to handle the actual dismantling and disposal of the discarded aircraft, and, if parting-out is to be used, one must ensure that the personnel and tooling comply with the airworthiness regulations. Furthermore, the disposal of the discarded aircraft must comply with the environmental regulations, end-user restrictions, etc.

4.2 Fleet management

"Fleet management" can be defined as the set of tasks performed to fulfil the fleet performance requirements in accordance with the "phase-out master plan". These tasks include planning for the maintenance/Modification defined by the plan, drawing up a daily operation plan, aircraft tail number assignment, training and crew assignment, etc. One key issue is to utilize as fully as possible the remaining life of a specific aircraft (airframe) by the phase-out date of that aircraft. Another issue is assigning rotatables to serviceable aircraft so that the remaining life of the rotables is utilized as much as possible before the aircraft is discarded.

This will reduce the number of required spares in store, as well as the total maintenance and supply costs. In order to achieve an effective PBSP, the fleet management should include the tasks treated in the following sections.

4.2.1 Fleet monitoring and reliability programme. A central part of the “fleet management” process is the “fleet monitoring and reliability programme”. This programme monitors the performance of the fleet and identifies any deviations from the expected performance. The results of this analysis are vital input for “logistic support analysis” (LSA), as well as the maintenance planning. The “fleet monitoring and reliability programme” is responsible for extracting information from the...
computerized maintenance management information system (CMMIS) which is a central part of the process of data and data management (see Figure 3). And also to some extent for specifying what operational and maintenance information must be tracked and analyzed. This information should be quality-assured, processed into the format needed for further analysis, and transferred to "LSA".

The data collected from the CMMIS are analyzed with respect to reliability, availability, lifecycle cost, spares requirements, etc. These analyses must be updated continuously if there are any changes in significant factors such as the operational profile, failure pattern, maintenance or procurement costs. A central part of the reliability analysis is to estimate the expected number of failures for rotables during the phase-out period. This analysis is basic and critical for the establishment of an efficient PBSP management programme. Since there are a number of different types of equipment and systems installed in an aircraft (e.g. electronic, mechanical, hydraulic and pneumatic equipment), the rotables tend to have different failure characteristics (Block et al., 2013a). Normally, there are two different approaches used to estimate the expected number of failures for rotables, i.e., either reliability-based forecasting or time-series-based forecasting. (Nelson, 1982) discusses the most important methods of reliability-based forecasting, and (Silver et al., 1998) describe the use of time-series-based forecasting to evaluate spares demand for stock control. In our case reliability-based forecasting is used (see Block et al., 2013a, b) for two different approaches to estimating the number of expected failures for repairable units. Note that, for reliability-based forecasting, it is crucial that historical reliability, availability, maintainability and sustainability (RAMS) data should be available for the whole lifecycle.

4.2.2 Phase-out operation plan. In military operations, the aircraft type for each flight mission is defined by the fleet manager. However, specific aircraft assignment per aircraft tail number must be performed as a daily activity. Through aircraft tail number assignment, it is decided which individual aircraft is assigned to each flight mission. The flight mission assigned to an aircraft represents specific tasks, e.g. radar surveillance, training and weather reconnaissance.

The first constraint that must be satisfied is which tail numbers to use in certain flight missions, and ensure that limitations concerning technical performance, manoeuvrability, altitude performance and equipment, for example is met. The second constraint that must be satisfied is maintenance and airworthiness requirements. These requirements ensure that the assigned aircraft are released for service after previous operation, and that, for aircraft being assigned, an adequate time remains before the next scheduled maintenance/Modification.

During the phase-out project, the available flight hours in the fleet being phased-out must be distributed over the phase-out period, to fulfil the availability and capacity requirements defined by the “phase-out master plan”. With regard to a PBSP, one important task within the “phase-out operation plan” is to perform an exchange of rotables within the fleet in order to use the life of the units as fully as possible before retirement. This maximizes the units’ utilization and reduces the maintenance and part-out process cost. However, since exchanging units between operational aircraft also entails costs and disrupts operation, this is normally only carried out for very maintenance-intensive units, such as engines and auxiliary power units.

On the other hand, routing units in stock with a limited life to aircraft with a similar remaining lifetime in connection with ordinary replacements does not entail any economic or operational drawbacks. However, this issue is a matter that is handled by “stock control” (see Section 4.3.3).
4.2.3 Part-out planning. The operator’s reason for deciding to part-out the aircraft is given in the “phase-out master plan”, and the decision may be taken for a number of different reasons. In the case presented in this paper, parting-out is carried out during the phase-out period to use the spares for the remaining fleet, i.e., to use the remaining life of reclaimed spares efficiently.

The “part-out plan” should be defined according to the input from “provisioning management”, which specifies which spares are to be reclaimed (mainly rotables, but also other spares), the number of spares to be reclaimed, and how long the reclamation of specific spares should continue. The content of this “part-out plan” should consider the following aspects:

- The resources required for parting-out spares, including maintenance resources, e.g. hangar slots, man-hours, ground support equipment, tools and a budget.
- A list of spares (for each retired aircraft) that are to be reclaimed, including the part numbers and serial numbers, and how the reclaimed units are to be distributed after being reclaimed. This removal list is also used as a tally sheet.

As a matter of fact, since the retirement plan for an individual aircraft may change due to operational requirements, it is essential that the “part-out plan” should be adjusted in accordance with input from the “phase-out operation plan”. Units that have been reclaimed for maintenance or storage must have their status updated in the CMMIS, while discarded units must similarly be “scraped” in the CMMIS. For reliability analysis purposes, the reason for discarding a unit should be recorded as well.

4.3 Logistic support management

Logistic support management is a collective term covering the related tasks and services that are needed in order to operate and maintain a fleet of aircraft and its support systems. In a PBSP, the main issue within “logistic support management” is to provide effective and efficient solutions that identify when to stop maintenance on the rotables removed for PM, CM and POM, as well as to suggest the time to stop the parting-out process (see Figure 2), which describes one solution for this. Since the problems associated with an efficient PBSP scenario are linked with availability and cost, specific tasks need to be performed to achieve an efficient solution.

4.3.1 LSA. “LSA” is a structured approach to forecasting the demand, as well the support (such as spares and tools) required to fulfill the operation and maintenance requirements. In a PBSP, one major task for LSA is to identify candidate units to be reclaimed as spares. This task relies on specific decision criteria which identify whether the spares are worth reclaiming. The criteria may include the following:

- existing stock in storage (relative to re-ordering points);
- maintenance cost per flight hour;
- cost/market value of spare;
- removal and storage cost;
- preventive maintenance interval (including shelf-life limits) and/or failure rate;
- anticipated demand for each type of unit;
- lead time for maintenance and procurement; and
- obsolescence.
Generally speaking, rotables with high maintenance costs, long maintenance intervals and low removal/storage costs are most profitable to reclaim.

For practical reasons, rotables with less operational time remaining than the interval between major checks for the aircraft type concerned are usually not reclaimed. Rotables with calendar time-based preventive maintenance, i.e., units where maintenance must be carried out by a certain fixed date, are normally not profitable to reclaim, unless they can be reused more or less immediately. The reason is that the remaining operating time will often be largely or completely used up while they are in storage. In addition to rotables, non-repairable spares may also be profitably reclaimed. Of course, far from all non-repairable spares are suitable for reclamation; e.g., consumables and wearing parts are unsuitable for reclamation.

Very expensive spares may, of course, be of interest, but most commonly it is spares that have become difficult or impossible to procure that are very much worth reclaiming. These spares are often ostensibly cheap or trivial parts. However, it can be extremely expensive or even impossible to re-start the production of seemingly simple electrical components like fuses or relays, while replacing them with new types of components frequently entails large and expensive modifications. Another type of part that may be worth reclaiming is those parts which require expensive and specialized tooling to produce, e.g. drop forgings.

In addition to the task of selecting the appropriate candidates for reclaiming, it is also the responsibility of “LSA” to analyze and identify alternative solutions for PBSP that fulfill both availability and cost criteria (see Figure 2) for an example of a solution. In fact LSA is responsible for making appropriate mathematical modelling, to perform calculations and to identify the set of alternative solutions on when to stop maintenance activities on the spares due to CM, PM, POM as well as stopping the parting-out process itself.

Figure 2 shows two different scenarios for PBSP. As seen, one scenario that fulfils the availability criteria for rotables during the phase-out period for the existing fleet involves stopping CM, PM and POM in month 44, 82 and 98, respectively, as well as stopping unit reclamation in month 105. However, this is not the only solution that will meet the availability criteria; a different set of months may create another possible solution that would fulfil the availability requirement too. According to a study that has been conducted within this research project, it was found that the number of possible solutions that would fulfil the availability requirements is of the magnitude of 10,000. However, one is still faced with the main question of selecting the most efficient alternative that will also satisfy the other managerial preferences, e.g., low cost, less waste and a manageable risk of backorders. Therefore, one of the major tasks within LSA is to select a suggested course of action from this large set of possible solutions, and robustness and sensitivity analyses should be used to support this selection. The most cost-efficient solution is an obvious choice, but the risk of backorders must also be considered. The PBSP programme is an iterative process, meaning that the analysis of spares provisioning must be updated more or less continuously as circumstances change (e.g. the operational profile, failure rate and maintenance intervals). Since re-starting discontinued maintenance is often very expensive, and sometimes impossible, it is very important that decisions about stopping maintenance should be carefully prepared and implemented. It is, of course, much simpler to re-start maintenance in cases where other aircraft fleets which are being retained contain identical or closely similar rotables that are still being maintained. Normally, maintenance is only stopped when there is an ample safety
margin between the foreseen requirement for units and the number of rotables in stock (see $A$ in Figure 2).

4.3.2 Provisioning management. “Provisioning management” consists of the set of tasks involved in selecting and procuring equipment, spares and material of the range and quantity necessary for supporting the operation and maintenance of the aircraft fleet and associated support equipment.

The input to “provisioning management” comes from “LSA”. One task for “provisioning management” is to implement the suggested course of action for each rotable.

This includes transmitting information about which spares are to be reclaimed, including the number of spares to be reclaimed and the time period for the reclamation.

In addition, “provisioning management” must also communicate with suppliers about the discontinuation of contracted maintenance and deliveries of spares when the parting-out process has yielded enough spares for the remaining life of the aircraft fleet.

Moreover, obsolescence issues are controlled within the process of “provisioning management” and information on these issues is communicated through the CMMIS to “stock control” and LSA. The communication of obsolescence information is a critical task, since one of the main criteria for collecting spares is potential obsolescence issues. Moreover, it is not unusual for the prices of units (both procurement and maintenance costs) to increase markedly for systems that have been in service for a long time. Such price increases are due to decreasing demand, lower production rates and decreasing competition as the number of vendors decreases. Procuring spares for aging aircraft therefore requires a difficult balancing act to avoid both obsolescence problems and the problem of being stuck with a large unused and unsellable stock of spares when all the aircraft in a fleet have been discarded.

4.3.3 Stock control. An immense number of papers have been published dealing with stocking strategies including spares planning and procurement, mainly during the initial part of the lifecycle of a system and during the operating phase, while there are much fewer papers dealing with spares strategies for the end-of-life phase. Teunter and Klein Haneveld (2002) and Teunter and Fortuin (1998) have discussed stock control during the end-of-life phase. However, the present paper will not describe methods for maintaining an optimal stock of spares or discuss associated issues such as re-order points, quantities, lead-times, etc., but confine itself to referring to the works already mentioned.

One of the main tasks of “stock control” is to distribute spares to operational sites according to foreseen requirements and redistribute them as required. An additional task is to track the spares availability, either through the CMMIS or a separate follow-up system for spares. This information is an important input for “LSA”, which uses the information to plan for an efficient PBSP, and for “provisioning management”, which uses the information to update the procurement planning. Furthermore, “stock control” is also responsible for inspecting all units on arrival, whether they are new, reclaimed or returned from maintenance, and for keeping the CMMIS updated with the results from the inspections. Other duties include updating the CMMIS with information about units issued and returned, sending units for storage maintenance and modifications as required, and handling the discard of expired life-limited units.

In the case where pooling (involving more than one operator) of spares (usually rotables) is being implemented, the principles for a PBSP management programme
do not really change. The main difference is that it is logistically more complex for the OEM to supply several operators (often based in different countries), which requires larger safety margins, and that “logistic support management” (see Section 4.3) becomes more complex, since the CMMIS system and the quality of the data that can be delivered may differ between the operators. In the military case, there is also the need for a high level of information security and confidentiality to meet defence and national security requirements, normally necessitating even greater stringency than in the civil aviation case, where business requirements must be managed.

4.4 Maintenance management

In the phase-out period, “maintenance management” focuses on the tasks involved in managing technical and administrative actions carried out to retain the aircraft in, or restore the aircraft to, an airworthy state, and to fulfil the requirements of the “phase-out master plan”. In fact, the “maintenance management” tasks ensure that the fleet meets and will continue to meet established availability performance goals (e.g. operational readiness, dispatch reliability and cost-efficiency) and that the demands of the “phase-out master plan” will be met.

Within a PBSP management programme, the main issue within “maintenance management” is still the planning and execution of part-out tasks, as specified in “part-out project planning”.

4.4.1 Maintenance operation. In the context of this paper, “maintenance operation” refers to the execution of parting-out tasks, along with the complementary actions required for the dismantling of phased-out aircraft, described as follows.

Dismantling aircraft units. When the part-out tasks are planned, the maintenance operation will remove the spares from the aircraft, visually inspect them and complete the related and required documentation. In some cases, some minor maintenance tasks (e.g. cleaning, applying protective covers and minor repair) may be required to put the spares in a suitable state for storage.

Quality control and evaluation. In order to ensure the integrity of the reclaimed parts supplied by the parting-out process, the following quality control tasks should be performed:

(1) The spares should be physically inspected for any damage, defects and improper disassembly.

(2) The spares should be checked for conformance and identification (part number, serial number and modification status).

(3) The history of the rotable should be checked for any scheduled maintenance or modifications.

(4) Depending on their condition when being reclaimed, the units should be tagged as follows:
   • usable: sent directly to storage;
   • repairable: unserviceable, but can be reused after a repair action, sent to the repair shop; and
   • unfit: neither reusable nor worth repairing and should be scrapped.

Packaging and shipping. Finally, the usable or repairable units are packaged as prescribed and sent to a suitable storage location or repair shop.
It should be noted that the actual number of spares reclaimed will almost always be less than planned, due to “unfit for service” spares. It is, therefore, important that the number of units recommended to be reclaimed should be appreciably larger than the number theoretically forecasted as being required. As has already been mentioned, it is essential to have large safety margins so as not to encounter backorder problems. It is important that the CMMIS should be continuously updated as rotables are parted out, based on the removal list.

4.4.2 Scrapping process. As discussed earlier, the parts which are removed due to CM, PM or parting-out and which are not suitable for restoration are scrapped. In addition, scrapping might be an option after detailed inspection at repair shops. The scrapping process does not support the stock of spares and it is one of the costlier activities within the phasing-out process.

The scrapping process includes the handling and routing of discarded units for recycling or disposal in accordance, for example, with the safety or environmental requirements. “Problem units” found in aircraft include, but are not limited to, pyrotechnic units, batteries, units containing carbon fibre composites, units containing lithium or other toxic materials, and units containing hydraulic fluid. Each such unit must be handled properly and routed to facilities where they can be disposed of in a safe manner.

In addition, especially in the case of military aircraft systems, classified material and units with end-user restrictions must be removed, handled, documented and disposed of in accordance with the existing regulations and agreements. This may be accomplished either with or without the normal CMMIS, but in practice there are often specific systems for handling such units. Finally, the aircraft structure will normally be sent for recycling.

However, in the case of military aircraft, the scrapped aircraft may also be used as, e.g., an instructional airframe, as a live-firing target or for fire-fighting/rescue training. In such situations, the removal list must prescribe the state in which the airframe should be delivered.

4.5 Data and data management
A CMMIS greatly facilitates data collection and management, and facilitates proper control of maintenance activities (Wireman, 1994).

Data and data management is needed for a variety of purposes such as documenting hardware airworthiness, planning, monitoring, benchmarking, evaluating and improving the performance of PBSP. In addition, data are vital to build models for estimation of input parameters for decision-making process. These parameters includes, e.g., availability of fleet, failure rate and associated patterns, repair rate, remaining useful life, failure and repair costs, depreciation cost, salvage value, number of spares and associated cost, etc. Some models which have been developed to support PBSP, are discussed in Block (2009), Block et al. (2013a, b, 2014), Ahmadi et al. (2012), Ahmadi and Kumar (2011) and Ahmadi (2010).

Data management deals with data collection and analysis. Hence, the specific form and type of data should be collected within the “strategic planning”, “fleet management”, “maintenance management”, “logistic support management” (see Figure 3). Data can be collected through internal or external sources. Internal data sources are generated from segments of the PBSP framework (e.g. failure data, reliability level, maintenance cost, inventory back order, finance, etc.) while external data sources belong to the partners in the supply chain and vendors (e.g. supplying
material, components, etc.). This may include subcontractors, if a part of PBSP is outsourced. Each of these data have their own sources. As an example the prime source of failure data include: pilots reports, technical logs, aircraft maintenance access terminal/on-board, maintenance system readouts, maintenance worksheets, workshop reports, reports on special inspections, stores issues/reports, air safety reports, reports on technical delays and incidents.

Prior to data analysis, it is vital to perform an evaluation of data quality for analysis in the context of PBSP. As an example, the analysis in the context of fleet monitoring and reliability programme (see Section 4.3.1) includes, e.g., reliability pattern recognition, estimation of the mean number of removals etc. The purposes of the preliminary evaluation include verification of the source of the data and the units of measurement (e.g. flight cycle or flight time or calendar age), identification of outliers or unusual results, etc. Obviously, using a proper CMMIS facilitates assurance of data quality, and enhances the analysis and decision-making process.

In addition, CMMIS generates work orders to plan and schedule inspections, PM, CM and modifications. This may include assigning personnel, reserving materials, recording costs and tracking the history of maintenance actions (Wireman, 1994). In this paper, the details of the CMMIS and related information logistics are not covered, and it is simply noted that, during the phase-out period, it is essential to have a well-functioning CMMIS to manage related information. See Labib (2004) and (Wandt et al., 2012) for further details about information logistics and the CMMIS and their importance and usefulness.

5. Conclusions and discussion

To succeed with a cost-effective PBSP programme during the phase-out of an aircraft fleet, a number of linked processes, tasks and decisions are needed, e.g., those described in the framework proposed in this paper (see Figure 3). A successful implementation of PBSP also requires that these processes and tasks should be carried out in a timely manner and that the communication between the parties concerned should be prompt, clear and direct. One experience from the studied case is that fast and trustful contacts between the operator and the maintenance provider will greatly simplify the process.

Another crucial point for success is that there should be a reliable system for follow-up and analysis of the aircraft and its subunits and for recording information about operation and maintenance events. In this case too, it is highly advantageous if the operator and the maintenance provider use the same CMMIS, or at least have CMMIS that can communicate quickly and reliably with each other.

The proposed framework is based on experience collected from organizations involved in the successful phasing-out of military aircraft systems related to the Swedish Armed Forces. However, the framework is intended to be generic and useful for others. Experience from the studied case, which includes the phase-out of the FPL 37 aircraft system, shows that a PBSP programme can yield large reductions in maintenance and spares procurement costs. These costs will, of course, vary greatly on a case-by-case basis, but the experience gathered from the case study shows that the annual savings can amount to several million US dollars for a major military aircraft fleet.

For military systems, there is always a sizable risk that the basis for the phase-out master plan will be changed due to political factors during the phase-out period. It is therefore necessary to ensure that there are always large margins for unforeseen
requirements and demands for spares. In addition, there is also a technical risk that
must be allowed for, such as large increases in failure intensities at a late stage, when
maintenance efforts have been terminated. Unexpected major modifications and
new service actions related to them can also make the reclaimed units unusable in
their original state.

While a phase-out process may stretch over a five to 15-year period, maintenance
closure will usually only take place at a fairly late stage in the process. The reason for
this is that it is typically very expensive to re-initiate maintenance efforts once they
have been terminated, and such a re-initiation might be necessary, e.g., due to political
changes that extend the phase-out period. Conversely, a shortening of the phase-out
period will entail an acceleration of the processes of maintenance termination and
reclaiming of units, as was the case illustrated in Figure 4.

Somewhat surprisingly, although the PBSP method is fairly commonly applied
within both the military and the civilian sector, there are very few publications
on the subject. Indeed, very little has been published on any aspects of maintenance
during the end-of-life period in general. A possible reason for this is that the methods
are often applied by consultants who may not have any major incentives to publish
their knowledge. Hence, further research within the area covered in this paper that
would result in publications would be of great interest to both practitioners and the
scientific community.

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Spares provisioning strategy for periodically replaced units within the fleet retirement period

Spares Provisioning Strategy for Periodically Replaced Units within the Fleet Retirement Period

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Abstract: Within aviation enterprises, the process of dismantling an aircraft at the end of its life is referred to as parting-out. Obviously, the asset value of the units and materials parted out from the retired airframes can be considerable. The benchmarked best practice within the aviation industry is to dismantle the retired aircraft and use the parted-out spares to support the remaining fleet or to offer them on the surplus market. Part-out-based spares provisioning (PBSP) has been a major focus of attention for aviation companies. The PBSP approach is a complex task that requires a multidisciplinary and integrated decision-making process. In order to control the stock level and fulfil the decision criteria within PBSP, it is necessary to make decisions on the termination, at specific times, of both the parting-out process and the maintenance and repair actions performed on the units.

This paper considers repairable units and introduces a computational model to identify the applicable alternatives for repair termination times that will minimize the number of remaining spares at the end of the retirement period, while fulfilling the availability requirement for spares during the PBSP period, at the lowest possible cost. The feasible alternatives are compared with regard to their respective costs, and the most cost-effective solution is selected. The cost model uses estimates of future maintenance requirements, the turnaround times, the cost of the various maintenance tasks, the future spares consumption, and the estimated salvage of spares from retired aircraft. The output of the model is a set of applicable alternatives which satisfy the availability requirements for spares for the active fleet. The method is illustrated using a case study performed on the Saab-105 training aircraft.

The results show that the proposed PBSP approach and computational model provide added value from a sustainability point of view, since the use of existing resources is maximized during the retirement process, through the process of reclaiming units and the applicable maintenance termination alternatives. The implementation of the proposed computational model in a PBSP programme provides a detailed and situation-based overview of the stock level dynamics, and contributes to the spares provisioning process by providing solutions to issues such as obsolescence, last-time buys and cannibalization.

Keywords: Provisioning, Spare parts, End-of-Life, Maintenance, Retirement, Parting-out, Repairable units, Stock level, Dismantling.

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Abbreviations

Table 1. Abbreviations used in paper.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM</td>
<td>Corrective maintenance on units</td>
</tr>
<tr>
<td>PBSP</td>
<td>Part-out-based spares provisioning</td>
</tr>
<tr>
<td>PM</td>
<td>Preventive maintenance on units</td>
</tr>
<tr>
<td>POM</td>
<td>Parting-out maintenance</td>
</tr>
<tr>
<td>POD</td>
<td>Parting-out discard</td>
</tr>
<tr>
<td>PO</td>
<td>Parting-out process</td>
</tr>
<tr>
<td>POS</td>
<td>Parting-out storage</td>
</tr>
<tr>
<td>SEK</td>
<td>Swedish crowns</td>
</tr>
<tr>
<td>USD</td>
<td>US dollars</td>
</tr>
</tbody>
</table>

Mathematical Notation

Table 2. Mathematical notation used in this paper.

<table>
<thead>
<tr>
<th>Math Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C(\tau_1,\tau_2,\tau_3,\tau_4))</td>
<td>Cost function associated with termination times for CM, PM, POM and POS</td>
</tr>
<tr>
<td>(c_{CM})</td>
<td>Cost for a CM action</td>
</tr>
<tr>
<td>(c_{PM})</td>
<td>Cost for a PM action</td>
</tr>
<tr>
<td>(c_{POM})</td>
<td>Cost for a POM action</td>
</tr>
<tr>
<td>(c_{PO})</td>
<td>Cost for a PO action</td>
</tr>
<tr>
<td>(D_0)</td>
<td>The demand for units during month (i), due to CM and PM actions</td>
</tr>
<tr>
<td>(D)</td>
<td>Total demand for units for the whole retirement period, (1) to CM and PM actions</td>
</tr>
<tr>
<td>(i)</td>
<td>Number of units received for storage from POS actions for month (i)</td>
</tr>
<tr>
<td>(I_{CM},I_{PM},I_{POM},I_{PO})</td>
<td>The status of CM, PM, POM and POS actions, either stopped (0) or on-going (1)</td>
</tr>
<tr>
<td>(L_{CM},L_{PM},L_{POM},L_{PO})</td>
<td>Matrix describing status of CM, PM, POM and POS with termination times ((\tau_1,\tau_2,\tau_3,\tau_4)) for month (i)</td>
</tr>
<tr>
<td>(M_{CM})</td>
<td>Number of successfully repaired units during month (i), due to CM actions</td>
</tr>
<tr>
<td>(M_{PM})</td>
<td>Number of successfully maintained units during month (i), due to PM actions</td>
</tr>
<tr>
<td>(M_{POM})</td>
<td>Number of successfully maintained units during month (i), due to POM actions</td>
</tr>
<tr>
<td>(M_{PO})</td>
<td>Number of successfully maintained units during month (i), due to PO actions</td>
</tr>
<tr>
<td>(M_{PO,CM})</td>
<td>Number of units received for storage from POS actions for month (i)</td>
</tr>
<tr>
<td>(M_{PO,CM})</td>
<td>Number of units received for storage during month (i), due to PO actions</td>
</tr>
<tr>
<td>(M_{PO,CM})</td>
<td>Number of units discarded during month (i), due to PO actions</td>
</tr>
<tr>
<td>(N_{CM})</td>
<td>Expected number of corrective maintenance actions during month (i) (a stochastic measure)</td>
</tr>
<tr>
<td>(N_{PM})</td>
<td>Number of preventive maintenance actions during month (i) (a deterministic measure)</td>
</tr>
<tr>
<td>(N_{PO})</td>
<td>Number of parted-out units from retired aircraft during month (i)</td>
</tr>
<tr>
<td>(P_{CM})</td>
<td>The probability of a successful repair of units on starting a CM action</td>
</tr>
<tr>
<td>(P_{PM})</td>
<td>The probability of a successful repair of units on starting a PM action</td>
</tr>
<tr>
<td>(P_{POM})</td>
<td>The probability that the parted-out unit will be classified as a unit for POM</td>
</tr>
<tr>
<td>(P_{PO})</td>
<td>The probability that the parted-out unit will be classified as a unit for PO</td>
</tr>
<tr>
<td>(R_{CM})</td>
<td>The probability that the parted-out unit will be classified as a unit for PM</td>
</tr>
<tr>
<td>(R_{POM})</td>
<td>The probability that the parted-out unit will be classified as a unit for POS</td>
</tr>
<tr>
<td>(R_{PO})</td>
<td>The probability that the parted-out unit will be classified as a unit for POD</td>
</tr>
<tr>
<td>(S_{CM})</td>
<td>The stock level for the non-controlled scenario at the start of the retirement period</td>
</tr>
<tr>
<td>(S_{CM})</td>
<td>The stock level for the non-controlled scenario at the end of the retirement period, i.e. (i = T)</td>
</tr>
<tr>
<td>(S_{CM})</td>
<td>The stock level for the controlled scenario at the end of the retirement period, i.e. (i = T)</td>
</tr>
<tr>
<td>(T)</td>
<td>Retirement period (months)</td>
</tr>
<tr>
<td>(t_{CM},t_{PM},t_{POM},t_{PO})</td>
<td>Total number of units received for storage during month (i), due to CM, PM, POM and POS actions</td>
</tr>
<tr>
<td>(T_{PO,CM})</td>
<td>Total number of units discarded during month (i), due to PO actions</td>
</tr>
<tr>
<td>(U_{CM})</td>
<td>The probability that units coming from POM actions will be discarded at the repair shop</td>
</tr>
<tr>
<td>(U_{CM})</td>
<td>The probability that units coming from POM actions will be discarded at the repair shop</td>
</tr>
<tr>
<td>(Q)</td>
<td>Order or magnitude of an algorithm or a number</td>
</tr>
</tbody>
</table>
1 Introduction and Background

Provisioning the maintenance stock is one of the most important functions for the operational success of any asset-intensive industry, such as the aviation industry. The goal of maintenance stock management in aviation is to find a cost-effective stock provisioning, allocation and management system. The main purpose in aviation is to provide upon demand the parts required to maintain a fleet of aircraft, and to achieve a specific level of aircraft availability. According to Díaz and Fu [1], approximately one third of all assets correspond to stocks. In a survey conducted by Aero Strategy [2] in 2010, the average value of the maintenance spares stock per aircraft was reported to be equal to 1.9 million USD, with the weighted average holding cost being estimated to be 21.5%. A properly managed stock also ensures that the human capital of the maintenance personnel is efficiently utilized.

Keeping a reasonable stock service level or “fill rate”, coupled with efficient maintenance practices, ensures a high level of fleet readiness. Key profits can be increased by the improvement of logistics and maintenance performance through more efficient stock management for costly components whose faultless functioning is crucial in asset-intensive industries [3].

Therefore, stock management and spare parts provisioning within the operation and maintenance phase of the product lifecycle have attracted a large volume of research. Many researchers have studied the joint-optimization of maintenance and stock provisioning policies for spare part logistics, see e.g. [4, 5, 6, 7, 8, 9, 10, 11, 12, 13]. In addition, Ferreira and Wang [14] proposed a hybrid of simulation and analytical models for spare parts optimization, taking into account the residual life of equipment estimated by using condition monitoring techniques. Liao and Rausch [15] addressed the issue of a joint production and spare parts stock control strategy driven by condition-based maintenance (CBM). It can be noted that most maintenance policies assume that failed or used components are replaced with identical units. Actually, such a hypothesis neglects the possible obsolescence of components and the existence of alternative components and suppliers, which affects stock forecasting [16]. Some researchers have considered the obsolescence problem in their optimization models, see e.g. [17]. The design of a spare parts stock by its very nature involves risk management. It is a multi-phase task to meet the associated economic and technical requirements. A typical target is to optimize the size of the stock by balancing the costs against the stock-out risk [18]. To this end, Bharadwaj et al. [19] introduced a risk-based methodology for spare parts stock optimization, and Hagmark and Pernu [18] studied the risk evaluation of a spare parts stock by stochastic simulation. Many others have studied the optimization of spares allocation for multi-echelon spare parts stock systems, see e.g. [20, 21, 22, 23, 24, 25, 26, 27, 28]. In addition, several research studies have dealt with the classification of spare parts to facilitate decision making, see e.g. [29, 30, 31, 32, 33, 34].

It should be noted that most of the literature in this field covers the operation and maintenance phase of the equipment lifecycle, where the main source of spares provisioning is the parts removed from the operational fleet due to preventive and corrective maintenance (PM and CM), as well as the purchase of new parts. When a fleet of aircraft reaches the retirement phase, which is the case considered in this paper, the fleet will be scrapped gradually during a specified period, during which the number of operational aircraft will gradually decrease. In this context, the remaining fleet should still be kept at a defined level of availability, and spares provisioning and storage are still required to support the maintenance and operation of the remaining fleet, preferably at a minimum cost and risk.

In many cases, a retired aircraft contains valuable spares that retain some operational or monetary value. The benchmarked best practice within the aviation industry is to use these spares to support the remaining fleet or to offer them on the surplus market. The process of dismantling aircraft systems and collecting the valuable spares is called the parting-out process, see [35].

To achieve cost-effective spares provisioning strategies during a phase-out scenario, a part-out-based spares provisioning (PBSP) programme was developed by Block et al. [35]. A spares management framework was proposed for the phase-out scenario, the prerequisites for a PBSP management programme were detailed, and associated key decision criteria for an effective phase-out management process were presented.
Figure 1 illustrates the dynamics of a typical PBSP programme. During normal operation, aircraft rotables will be removed from operational aircraft due to CM and PM actions. If the condition of a rotatable shows that restoration or repair is not economically viable, the unit is classified as non-fixable and is discarded. Otherwise, the unit proceeds for further investigation and inspection at the repair shop. For normal operation, decision gates 1 and 2 in Figure 1 concern decisions as to whether it is worth repairing a failed unit, or performing preventive maintenance on the unit. A detailed investigation at the repair shop level may show that the most effective decision is to discard the unit, for safety, operational or economic reasons. The units that receive a successful repair will be tagged as serviceable and sent to storage.

As shown in Figure 1, once the retirement period has started and the parting-out process has commenced, the useful spares are removed from the retired aircraft. Decision gate 3 concerns which spares are worth reclaiming. In this process, the total volume of parted-out spares (during the PO) from the retired aircraft is put directly into storage (parting-out storage, POS), sent for repair (parting-out maintenance, POM) and then put into storage, or discarded (POD) when not in a state in which they are worth keeping or repairing, see decision gate 4.

Figure 1. Schematic diagram of the PBSP dynamics and decision gates: (1) stop corrective maintenance (CM) and (2) stop preventive maintenance (PM); (3) stop the parting-out process (PO), i.e. stop parting-out storage (POS), meaning stop sending units directly to storage; (4) stop parting-out maintenance (POM).

When the PBSP is taking place, the stock fill rate will increase due to the spares received through the parting-out process (PO), i.e. the units sent to storage owing to POS and POM, as well as the spares received through the repair actions due to the scheduled maintenance (PM) and unscheduled maintenance (CM) of the operational fleet. At the same time, the number of operational aircraft will decrease over the retirement period, and obviously the demand for spares will normally decrease.

The increase in the fill rate and the simultaneous decrease in the demand for parts will lead to an excessive level of spares in stock. In a real-life context, the implementation of an effective PBSP should be governed by the preferences of the PBSP manager, which in the case of this study were as follows:

- minimizing the stock level to a certain level, e.g. one unit, at the end of the full retirement period,
- minimizing the risk of back-orders throughout the retirement period,
- minimizing the total cost of stocks and provisioning.
In order to fulfil these preferences, the methodology presented in this paper requires the termination, at specific times, of the parting-out process (PO), the sending of parted-out units directly to storage (POS), and repair actions performed on the units received at the repair shops owing to CM and PM, as well as the parted-out units that need to be repaired (POM).

The CM, PM, POM and POS activities are referred to as PBSP control gates, which will either be open or closed. A CM activity involves the restoration of a failed unit to a sufficiently functioning state so that the unit can be re-installed and used in the operational aircraft fleet. A PM activity maintains units in operation according to a predetermined maintenance schedule based on calendar time, cycles, operational hours or other operational parameters. A PO activity includes the actual process of reclaiming units from retired aircraft. A reclaimed unit may be sent for a POM activity, including the maintenance tasks necessary to restore that unit to an adequate state for operational use. A second option for a reclaimed unit is a POS activity, which includes visual inspection and sending the unit to storage as an additional asset for the operational fleet. Finally, the third option for reclaimed units is to discard them, referred to as part-out discard (POD), an activity which involves a visual inspection of units before sending them for discard.

The termination times for the PBSP control gates are conditions which are predefined in the proposed computational model, and these times will arrive in consecutive order. The PM and CM will always be stopped at the same time as or earlier than the POM. Additionally, the POM will always be stopped at the same time as or before the POS. This implies that the termination times for the PO and POS must occur at the same time, i.e. there will therefore be a maximum of four termination times \((t_1, t_2, t_3, t_4)\) to be considered in the model. These conditions reduce the total number of possible solutions, see Section 2.2.

For example, an applicable solution for such termination times for the CM, PM, POM and POS which fulfils the above conditions can be represented by \((t_1, t_2, t_3, t_4)\). Using the results from the presented case study, one obtains the respective termination times \((27, 25, 53, 63)\), given in months counted from the start of the retirement period. As seen, the termination of the POM precedes that of the POS, and since there is no reason to continue the parting-out process after both the POM and POS have been terminated, the PO is also stopped in month \(t_4\), which in this case is month 63.

The identification of feasible and effective alternatives for the repair termination times is a combinatorial problem by nature. Dividing the whole retirement time horizon into \(T\) months, there are \(T^4\) possible choices of months for closing the four PBSP control gates (CM, PM, POM and POS). It should be noted that when \(T\) is large, e.g. 100 months, the total number of possible combinations is quite large (in this particular case 100^4, i.e. 100 million combinations). Therefore, the proposed methodology involves taking all the possible solutions and then discarding the infeasible alternatives. The availability of spares and the risk of back-orders in each time period are computed for all the \(T^4\) possible choices of months, to avoid both under-stocking and overstocking. However, identifying the applicable and effective solutions by searching among all the combinations of possible solutions, including both feasible and infeasible solutions, would be time-consuming. Therefore, finding a solution to this combinatorial problem requires the use of an algorithm, starting from an initial state (e.g. using the time since overhaul and the maintenance history) and an initial input (e.g. using the operational time and the initial stock) which existed prior to entering the phase-out period. In this study, branch-and-cut techniques were used to help identify and prune away the infeasible solutions, i.e. those solutions which could not satisfy the total spares demand.

The applicable and feasible alternatives are compared with regard to their respective costs, and the most cost-effective solution is selected. The cost model considers the estimated future maintenance requirements (for PM and OM), the turn-around times, the cost of the various maintenance tasks, the future spares consumption, the salvage of spares from retired aircraft, etc. The output of the model is a set of applicable alternatives which satisfy the availability requirements for spares for the active fleet.

The method is illustrated using a case study with data from a unit (the cooling turbine) from a Saab-105 trainer fleet. In the computational model, a number of conditions and simplifying assumptions have been applied. As mentioned above, the termination times arrive in consecutive order.
Furthermore, the number of faults and maintenance actions are calculated by monthly increments. Another simplification is that, if a preventive maintenance action is due to be performed on a unit during a certain month, the unit in question is replaced at the beginning of the month, and the probability for corrective maintenance (failure) is then calculated for the replacement unit over the whole month, rather than calculating an exact replacement date and estimating the failure probabilities for both units before and after this date. Another condition is that, once a termination has taken place, i.e. a PBSP control gate has been closed, this termination applies for the whole remaining phase-out period and is not reversed again in the model.

The rest of this paper is organized as follows. In Section 2, the computational model is described and the non-controlled scenario is presented in 2.1, followed by a presentation of the controlled scenario in Section 2.2. The algorithm used for finding feasible repair termination alternatives is presented and illustrated in Section 2.3, and finally the cost function is presented in Section 2.4. The case study performed to illustrate the proposed computational model is presented in Section 3. Finally, the results of the study are discussed and the conclusions are presented in Section 4.

2 Proposed Model for Spare Part Provisioning in the Retirement Period

The PBSP programme is planned over a discrete time domain \( \{1, 2, \ldots, T\} \), where the time resolution is set to monthly increments and \( T \) is the total length of the retirement period. Moreover, the operational fleet generates repair actions due to unscheduled maintenance (CM) and scheduled maintenance (PM), representing the demand due to CM and PM, see Node 1 in Figure 2.

The estimation of the PM events of an aircraft system is quite straightforward and is based on the defined frequencies and intervals tabulated in the maintenance planning document offered by the manufacturer. The major challenge is the estimation of the CM events, i.e. the failure events of repairable units, which are highly dependent on the reliability performance of the units in the operational field. In the study presented in this paper, the CM estimations were made using the non-parametric approach of the mean cumulative function (MCF), see [36].

In Figure 2, the flow of units from operational and retired aircraft is illustrated. A number of units reclaimed from retired aircraft are sent directly to storage (POS), sent to the repair shop (POM) or discarded (POD) with the predefined probabilities \( q_1, q_2, q_3, q_4 \) respectively, as shown in Figure 2. Furthermore, for a unit entering the repair shop due to a POM action, there is the probability \( 1 - w_1 \) that the unit will be repaired and sent to storage.

For a unit sent to the repair shop due to a CM action there is a probability, \( p_1 \), that the unit will be successfully repaired and thereafter sent to storage. The corresponding probability of repair and storage for a unit sent to the repair shop due to a PM action is denoted by \( p_2 \). The numbers of units being successfully repaired and sent to storage after CM, PM and POM are added up in Node 2, see Figure 2. The predefined probabilities are measured or defined based on the experience of experts in the operation and maintenance field.

In addition, the total number of units sent to storage in month \( i \) (including the units sent directly to storage (POS)) is given in Node 3, see Figure 2. The flow of units finally determines the stock levels for the non-controlled scenario and the controlled scenario, respectively, see Figure 2 and Section 2.1 - 2.3.
2.1 Non-controlled Spares Provisioning Management

In the PBSP programme, the total demand for units, $D_t$, is generated by the PM and CM activities performed on the still-operational aircraft fleet during the whole retirement period, see Node 1 in Figure 2. The total demand for the whole retirement period $T$ is formulated in Eq. 1 as follows:

$$D = \sum_{i=1}^{T} D_{i}$$  \hspace{1cm} (1)

where $D_i$ represents the demand for units for month $i$, due to both PM and CM actions, see Figure 2.

The monthly demand $D_i$ is formulated as:

$$D_i = N_{CM} + N_{PM}$$  \hspace{1cm} (2)

where $N_{CM}$ is the expected number of CM actions for month $i$, and $N_{PM}$ refers to the monthly number of PM actions performed. $N_{CM}$ is stochastic in nature, while $N_{PM}$ is a deterministic value, because PM actions are predetermined through a fixed maintenance schedule.

As shown in Figure 2, there is a probability $p_1$, that the units entering the repair shop due to a CM action will be successfully repaired and sent to storage, while the probability that the units sent to the repair shop for a PM action will be successfully maintained is $p_2$. The total number of successfully repaired units sent to storage due to a CM action, for month $i$, is $M_{CM}$, and the corresponding number coming from PM actions is $M_{PM}$:

$$M_{CM} = N_{CM} \cdot p_1$$  \hspace{1cm} $M_{PM} = N_{PM} \cdot p_2$$

where $\Omega$ represents the repair lead time associated with PM, CM and POM actions, i.e. the time from the moment when the logistic manager places a repair order to the moment when the unit is placed in storage.
As shown in Figure 2, units reclaimed from retired aircraft are assigned to one of the following three categories:

- units sent for maintenance at the repair shop (POM) with the probability $q_1$,
- units sent directly to storage (POS) with the probability $q_2$,
- units sent directly for discarding (POD) with the probability $q_3 = 1 - (q_1 + q_2)$.

The number of reclaimed units entering the repair shop due to a POM action, $N_{POM}$, is estimated as follows:

$$M_{POM} = N_{POM} \cdot q_1,$$

where $N_{POM}$ represents the units parted out from retired aircraft during month $i$. However, there is a probability, $w_i$, that the units sent to the repair shop due to a POM action cannot be maintained successfully and will be discarded. The number of successfully maintained units sent to storage during month $i$, $M'_{POM}$, is estimated as follows:

$$M'_{POM} = M_{POM} \cdot (1 - w_i).$$

Furthermore, the number of units received for storage due to a PO action, $M_{POS}$, is estimated by:

$$M_{POS} = N_{PO} \cdot q_2.$$

The number of units discarded due to a PO action, $M_{POD}$, is estimated by:

$$M_{POD} = N_{PO} \cdot q_3.$$

Consequently, the number of units received for storage during month $i$ from the repair shop, $R_i$, is calculated as follows:

$$R_i = M_{CM} + M_{PM} + M'_{POM}.$$

Similarly, the number of units received directly for storage from parting-out during month $i$, $G_i$, is:

$$G_i = M_{POS}.$$

Consequently, the total number of units received for storage during month $i$, $U_i$, is:

$$U_i = R_i + G_i.$$

The stock level for the non-controlled scenario in month $i$ is estimated as follows:

$$S_i = S_0 + \sum_{j=1}^{i} (U_j - D_j),$$

where $S_0$ is the initial stock level at the start of the retirement period.

### 2.2 Controlled Spares Provisioning Management

To fulfill the objective of PBSP completely, the controlled scenario is needed. In this scenario, at specific times (the PBSP control gates), one ceases to part out units and send them directly to storage (POS), and one stops performing maintenance actions on the units received at the repair shops owing to CM, PM and POM.

The status of the PBSP control gates is binary, either closed (0) or open (1), at any particular time, depending on the termination of the respective activity flows of the units.
Once a termination has taken place, i.e. once a PBSP control gate has been closed, it stays closed for the rest of the retirement period and is not reopened in the model. The status of the PBSP control gates in month $i$ can be described as $(I_{CM},I_{PM},I_{POM},I_{POS})$, where $i = 1, ..., T$.

The possible termination times $(t_1, t_2, t_3, t_4)$ associated with CM, PM, POM and POS actions during month $i$ in the time domain $1 \leq t_1 < t_2 < t_3 < t_4 \leq T$ is presented through the following matrix:

$$I(t_1, t_2, t_3, t_4) = (I_{ij}) \in \{0, 1\}^{4 \times T},$$

where $I_{ij} \geq I_{ij+1}$ and $I_{ij} \geq I_{ij+1}$ for all $j = 1, 2, 3, 4$ and $i = 1, 2, ..., T$.

The total number of units received in storage during month $i$, $U^*_i$, is estimated as follows:

$$U^*_i = \begin{bmatrix} M_{CM} \\ M_{PM} \\ M_{POM} \\ M_{POS} \end{bmatrix}$$

where $(I_{CM},I_{PM},I_{POM},I_{POS})$ is the $i^{th}$ column of the matrix $I(t_1, t_2, t_3, t_4)$.

The set of values defined by $(t_1, t_2, t_3, t_4)$ represents the number of units sent to the repair shop and units coming directly from parting-out to storage. Considering the termination times $(t_1, t_2, t_3, t_4)$, the stock level on a monthly basis, $S^*_i$, is estimated as follows:

$$S^*_i = S^*_{i-1} + U^*_i - D_i$$

When $T$ becomes large, the number of possible solutions becomes unmanageable. For example, when the retirement period is set as $T = 96$ months, which is the case in this paper (Section 4), the total number of repair termination alternatives will be approximately $96^4 \approx 84 \cdot 10^8$. Consequently, the major challenge is to identify the applicable repair termination alternatives.

However, the viable solutions are limited to those satisfying the following three conditions.

I. The POM must be stopped before the POS, i.e. $t_3 \leq t_4$. This will reduce the total number of possible solutions from $T^4$ to $T^3(T + 1)/2$, which is still $O(T^4)$. Additionally, the PM and CM will be stopped before the POM, i.e. $t_1 \leq t_3$ and $t_2 \leq t_3$. If this measure is taken, the number of solutions will be reduced to the following number: $T^2(T + 1)^2(T + 2)/12$.

II. The number of spares in stock per month, $S^*_i$, must be greater than the demand for every month $i$, $D_{i+1}$, to eliminate the risk of back-orders.

$$S^*_i > D_{i+1}, (i = 1, ..., T - 1).$$

In addition, if any PBSP control gate (CM, PM, POM or POS) is closed in month $t_i$, the total number of available spares should fulfill the total demand $D_i$, which means that $S_T > 0$.

III. To ensure that no overstocking takes place, the difference between the stock level, $S^*_i$, and the sum of $D_i$ during the retirement period should not exceed a safety margin, $\Delta$, for any month $i$. This can be expressed as:

$$\left( S^*_i - \sum_{j=i+1}^T D_j \right) \leq \Delta (i = 1, ..., T).$$
2.3 Search Algorithm

In order to limit the search and find applicable solutions, a search algorithm was developed. The algorithm was developed in such a way that it would facilitate and expedite the computation process by limiting the search for applicable solutions. See Figure 3 for the flowchart and the corresponding steps and conditions.

The proposed algorithm is a global search algorithm with pruning. Roughly speaking, the search algorithm is a four-step for-loop, which is similar to the naive algorithm. The difference between the developed algorithm and the naive algorithm is that the estimate of $\hat{S}_t$ is obtained as an upper bound for the total number of solutions during the retirement period, before the next for-loop in the proposed algorithm. This estimate will rule out some obviously infeasible solutions and narrow the searching domain of the algorithm. As shown in the case study, this technique will improve the computational efficiency greatly.

![Flowchart for the search algorithm.](image)

Figure 3. Flowchart for the search algorithm.
The algorithm starts at \( t_1 = 1 \), and then the upper bound estimate \( \hat{S}_{t_1} \) is expressed as:

\[
\hat{S}_{t_1} = S_0 + \sum_{i=1}^{t_1} M_{CM,i} + \sum_{p=1}^{r} M_{PM,p} + \sum_{n=1}^{r} M_{POM,n} + \sum_{p=1}^{r} M_{POS,p} - D.
\]  \hspace{1cm} (12)

At this step, only \( t_1 \) is known and, therefore, if the upper bound cannot meet the requirement, i.e. \( \hat{S}_{t_1} > 0 \), the algorithm will test the next \( t_1 \rightarrow t_1 + 1 \). Otherwise, it will continue searching for \( t_2 \) from \( t_2 = 1 \).

Given \( t_1 \) and \( t_2 \), an updated estimate is then as follows:

\[
\hat{S}_{t_2} = S_0 + \sum_{i=1}^{t_1} M_{CM,i} + \sum_{p=1}^{t_2} M_{PM,p} + \sum_{n=1}^{r} M_{POM,n} + \sum_{p=1}^{r} M_{POS,p} - D.
\]  \hspace{1cm} (13)

This is then used to perform further pruning with the algorithm. Furthermore, the search starts from \( t_2 = \max(\{t_1, t_2\}) \), which ensures fulfilment of the condition that the termination times for PM and CM should happen before the termination time of POM, i.e. \( t_2 \geq t_1 \) and \( t_2 \geq t_2 \) are fulfilled.

Given \( t_1, t_2 \) and \( t_3 \), an updated estimate is obtained to prune away the infeasible solutions as follows:

\[
S_{t_3} = S_0 + \sum_{i=1}^{t_1} M_{CM,i} + \sum_{p=1}^{t_2} M_{PM,p} + \sum_{n=1}^{r} M_{POM,n} + \sum_{p=1}^{r} M_{POS,p} - D.
\]  \hspace{1cm} (14)

Furthermore, \( t_4 \) is started from \( t_4 = t_3 \), which ensures that \( t_4 \) is larger than any other termination time, \( t_1, t_2, t_3 \leq t_4 \), i.e. that the PM, CM and POM are terminated before the POS is terminated. In the last step, however, a check needs to be performed concerning the defined conditions (ii) and (iii) for all the months.

First, the stock level in the last month in the retirement period is given as follows:

\[
S_T = S_0 + \sum_{i=1}^{t_4} \sum_{j=1}^{z} M_{i,j}.
\]  \hspace{1cm} (15)

Moreover, by checking that the stock level \( S_T \) at the end fulfils the requirement, if \( \Delta \geq S_T > 0 \) is fulfilled, the stock level for each month \( i \) is as follows:

\[
S_i = S_0 + \sum_{j=1}^{\min(t_4,i)} \sum_{l=1}^{z} M_{i,j} - \sum_{p=1}^{T} D_p.
\]  \hspace{1cm} (16)

In addition, conditions (ii) and (iii) must be checked for the stock levels from month 1 to month \( T - 1 \) as follows:

\[
R_i + \Delta \geq S_i > D_{i+1}, i = 1, ..., T - 1.
\]  \hspace{1cm} (17)

If the above conditions are fulfilled for every month, the solution is feasible and recorded. Finally, all the feasible solutions, the corresponding stock levels and the total cost are recorded. When the applicable repair termination alternatives are identified, the most cost-effective alternative should be selected to be incorporated in the PBSP programme.

Furthermore, if the target is to find the plan with the lowest cost, the cost for the different actions should also be utilized in the pruning procedures, since the cost is monotone in all the \( t_i \). We can also store the current lowest cost and branch the possible solutions with a higher cost. Actually, the cost may not be the only key decision factor, as is argued in Section 4, “Discussion and Conclusions”.
2.4 Cost Model for Spares Provisioning Management

In order to identify the cost of the applicable solutions, a cost model is proposed. This cost model considers the costs associated with corrective and preventive maintenance, as well as the costs for removing the units from the aircraft being retired and restoring the reclaimed units to an operational condition. The applicable alternatives are compared with regard to their total cost, and the most cost-effective one is selected.

The cost function \( C \) for any given matrix \( I(t_1, t_2, t_3, t_4) \) is defined as follows:

\[
C(I) = C_{CM} \sum_{i=1}^{T} I_{CM} \cdot M_{CM} + C_{PM} \sum_{i=1}^{T} I_{PM} \cdot M_{PM} + C_{POM} \sum_{i=1}^{T} I_{POM} \cdot M_{POM} + C_{PO} \sum_{i=1}^{T} I_{PO} \cdot M_{PO} + C_{PPO} \sum_{i=1}^{T} I_{PPO} \cdot M_{PPO} \tag{18}
\]

where \( C_{CM} \) and \( C_{PM} \) are the costs for performing the CM and PM, respectively, and \( C_{POM} \) denotes the cost for the maintenance necessary to restore a parted-out unit to the condition of a serviceable unit. The actual cost for parting out a unit from retired aircraft is denoted by \( C_{PO} \). This cost is associated with the units reclaimed for POM and POS and the units sent for discard (POD). Note that in Eq. 19, the termination time for sending parted-out units for discard is the same as the termination time for sending reclaimed units to storage (POS).

Since \( I \) is determined by \( t_1, t_2, t_3, t_4 \), rewrite Eq. (20) as follows:

\[
C(I) = C_{CM} \sum_{i=1}^{t_1} I_{CM} \cdot M_{CM} + C_{PM} \sum_{i=1}^{t_2} I_{PM} \cdot M_{PM} + C_{POM} \sum_{i=1}^{t_3} I_{POM} \cdot M_{POM} + C_{PO} \sum_{i=1}^{t_4} I_{PO} \cdot M_{PO} + C_{PPO} \sum_{i=1}^{t_4} I_{PPO} \cdot M_{PPO} \tag{19}
\]

3 Case Study

A case study was conducted on the cooling turbine unit installed in the 90 aircraft in a Saab-105 fleet, to illustrate and verify the proposed approach. There is one cooling turbine per aircraft, and it is the main unit of the environmental control system that delivers cooling air for the electronics and the cockpit. This unit was selected because it is associated with a relatively high maintenance volume and cost.

The Saab-105 aircraft is a two-seat twin-engine training aircraft which is used by the Swedish Armed Forces, and which is planned to be phased out within a period of eight years, i.e. \( T = 96 \) months. As a part of the phase-out schedule, ten aircraft will remain operational at the end of the retirement period, due to practical considerations concerning flight training continuity. The phase-out plan was defined at a strategic level to be implemented over 96 months, as shown in Figure 4 below. Identifying which aircraft are to be discarded and when is, of course, influenced by a number of factors, which are discussed in Block et al. [35].
The predefined input values used in the computational model are tabulated in Table 3, and the initial stock level was set to $S_0 = 20$ in the studied case. As mentioned above, reclaimed units will be sent to the repair shop (POM) with the probability $q_1 = 0.30$, will be sent directly to storage (POS) with the probability $q_2 = 0.50$, or will be discarded with the probability $q_3 = 0.20$. The still-operative fleet generates CM and PM actions continuously, and the probability of repairing a unit sent for a CM action is $p_1 = 0.85$, while the probability of repairing a unit sent for PM is $p_2 = 0.85$. Furthermore, the cost associated with each activity and the lead time (TAT) are presented in Table 3.

### Table 3: Initial data entering the retirement period.

<table>
<thead>
<tr>
<th>Maintenance Interval [Fh]</th>
<th>TAT [(j) - (Month)]</th>
<th>Cost [SEK]</th>
<th>Probability of Repair Success</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM</td>
<td>N/A</td>
<td>3</td>
<td>$C_{CM} = 30,000$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_1 = 0.85$</td>
<td></td>
</tr>
<tr>
<td>PM</td>
<td>10</td>
<td>2</td>
<td>$C_{PM} = 50,000$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_2 = 0.85$</td>
<td></td>
</tr>
<tr>
<td>POM</td>
<td>N/A</td>
<td>2</td>
<td>$C_{POM} = 40,000$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$q_1 \cdot (1 - w_3) = 0.30 \cdot (1 - 0.15) = 0.26$</td>
<td></td>
</tr>
<tr>
<td>POS</td>
<td>N/A</td>
<td>N/A</td>
<td>$C_{PD} = 5,000$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$N/A$</td>
</tr>
</tbody>
</table>

As shown in Figure 5, the total demand is 27 units for CM and 51 units for PM (a total of 78 units) during the whole retirement period. As mentioned earlier, a fraction of these units will be discarded according to the $q$ values. When the retirement period starts, the number of operational aircraft decreases according to the retirement plan (see Figure 4), which affects the demand for spares, and the corrective and preventive maintenance volumes will normally decrease as well.

![Figure 5: Demand for units generated by the operational fleet due to CM and PM.](image)

The proposed methodology applied for the non-controlled scenario is referred to as alternative A. Within the non-controlled scenario, the parting-out process is not terminated and continues to the end of the retirement period ($T = 96$). In this case, 80 cooling turbines are planned to be reclaimed from retired aircraft during the retirement period.

Figure 6 shows the expected number of reclaimed units to be sent to the repair shop, sent to storage, and sent for discard during the retirement period ($T = 96$ months), as well as the expected frequency of these actions.
As shown, the expected numbers of units to be directed to the repair shop, to storage and for discard are equal to $POM = 22$, $POS = 43$ and $POD = 15$ units.

Figure 6. Expected number of reclaimed cooling turbines to be sent to the repair shop, to storage and for discard, and the expected frequency of these actions.

When the PBSP is taking place, the stock fill rate will increase due to the parts received through the parting-out process (PO), i.e. the units sent to storage due to POS and POM, as well as the spares received through the maintenance actions due to the scheduled maintenance (PM) and unscheduled maintenance (CM) of the operational fleet. At the same time, the number of operational aircraft will decrease over the retirement period, and the demand for spares will normally decrease.

Figure 7 shows the variation of the stock level in the non-controlled scenario. The monthly stock level in the non-controlled scenario is computed using Eq. 6 in Section 2.1, and the final stock level in the last month is calculated by letting $i = T$ (the last month) in Eq. 6. As shown in Figure 7, when applying the non-controlled scenario, there will be 69 cooling turbines in stock at the end of the retirement period.

Furthermore, the cumulative cost of applying the non-controlled scenario is presented in Figure 8. As shown, the total cost of applying the non-controlled scenario (alternative A) is estimated to be 4.6 MSEK. Obviously, the increase in the fill rate and the simultaneous decrease in the demand for parts will lead to an excessive level of spares in stock. This high stock level at the end of the retirement period represents an unwanted capital investment through unnecessary maintenance and storage.

Figure 7. Variation of the stock level in the non-controlled scenario.
In order to control the stock level and reduce the total cost, the controlled scenario method is applied to terminate the CM, PM, POM and POS actions. Applying the controlled scenario, the computational models and proposed algorithm were used to identify the set of termination alternatives that would fulfil the PBSP requirement. To control the risk of back-orders for spares, the safety margin for the minimum number of units in stock was set to $\Delta = 1$. The computation shows that there are 129,212 applicable solutions that can be used to fulfil the PBSP programme preferences.

Figure 9 presents a set of arbitrarily selected applicable alternatives and their corresponding stock levels for each month. The stock level in the controlled scenario is calculated according to Eq. 10 in Section 2.2, and in this case study the stock level at the end of the retirement period was set to be one remaining unit.

As can be seen from Figure 9, the results vary to quite a large extent from solution to solution, i.e. there are solutions with a rather low stock level continuously and solutions with an increased stock level at the beginning and a rapidly decreasing stock level at the end of the retirement period. Besides the stock level and cost, several other criteria may be considered in selecting repair planning alternatives. For example, an operator may be interested in closing down the repair shop at the earliest possible stage, perhaps because the operator would want to end the contracts with its subcontractors in order to protect against additional costs.

Figure 10 shows, with a higher resolution, the termination times for CM, PM, POM and POS for two applicable solutions selected arbitrarily (alternative # 46676 and 87387). When the termination period begins, there is a relatively large difference between the demand and the actual stock level. This difference decreases as soon as the closing of the PBSP control gates initiates. In Figure 10 one can observe that, in the presented alternative # 46676, the stock level starts to decrease when both the PM and CM terminate in month 9 and 17, respectively, and the stock level decreases continuously after the POM is terminated in month 53. The same pattern can also be seen for alternative # 87387.
Additionally, as shown in Figure 10, the termination times are relatively scattered. In alternative # 46676, there are 44 months between the PM and POM termination times, but there are only 28 months between those times for alternative # 87387. Such a variation in the gap between termination times for PM, CM and POM complicates the planning for the termination of maintenance contracts in that the planning time horizon for terminating maintenance contracts will be unpractically long. Furthermore, the difference between the stock levels for alternatives 46676 and 87387 and the demand is quite high at the beginning of the retirement period. The advantage of these alternatives is the additional safety margin, but they involve an unnecessary binding of capital. As the results in Figure 10 show, applying the proposed PBSP methodology and the associated computational models and algorithm not only fulfils the availability requirements and the demand for spares during the whole phase-out period, but also reduces the total number of units in stock at the end of the phase-out period ($S_1 = 1$).

In Figure 11 the termination times for CM, PM, POM and POS for all the 129,212 applicable solutions are presented. As is evident, the termination times for CM and PM can occur relatively early, in months ~1-60. The reason is that the number of active aircraft is decreasing, which means that fewer units are coming from a CM or PM action over time.

The results in Figure 11 also show that the termination times for POS actions are relatively late, in month ~35-95. The reason why POS can continue to the end of the phase-out period is that there is a continuous flow of units coming from POS during the whole phase-out process, and that there is no lead time connected to POS, while there is a lead time for CM, PM and POM. Concerning POM actions, the results show that the termination times can also occur rather late in the retirement period, between months ~20 and 90. It should be noted that in the case of POM, there is a continuous flow of units coming during the whole retirement period which is unaffected by the fact that the active fleet of aircraft is decreasing. Since there is a turn-around time for POM, it is not possible to collect units up to the end of the retirement period.
In order to identify the most economically applicable alternatives when applying the controlled scenario, the cost associated with each applicable alternative is calculated using the proposed cost model presented in Section 2.4. In Figure 13, the costs associated with the applicable alternatives are presented. In this figure, the alternatives are sorted based on their costs to enable identification of the alternatives with the lowest and highest costs.

Within the controlled scenario, there are 36 applicable alternatives resulting in the minimum cost of 765,000 SEK, referred to as alternative group B (see Table 4). As shown in the table, the CM actions should be terminated in month 32 for all the 36 alternatives, while there are two termination alternatives for the PM actions, month 1 and 2, three alternatives for the POM actions, months 16, 17 and 18, and, finally, six alternatives for terminating the POS actions, months 91-96.

The highest cost within the controlled scenario was incurred by three alternatives, referred to as alternative group C, and that cost is 1,888,500 SEK (see Table 5).

Furthermore, when implementing a PBSP programme, it is also of interest to identify those applicable alternatives that allow CM, PM and POM to be terminated at approximately the same time. Such alternatives provide the possibility of terminating all the associated maintenance contracts at the same time. Figure 12 presents the solutions that have a maximum mutual gap of six months between the CM, PM and POM actions. In this case, the number of applicable alternatives is 64, and within this set of alternatives there are 15 alternatives associated with the lowest cost of 1,750,000 SEK, and three alternatives associated with the highest cost of 1,850,000 SEK; these two sets of alternatives are referred to as alternative group D and E, respectively.
Table 6 lists the termination times for alternative group D, associated with the minimum cost of 1,750,000 SEK.

Table 6. Termination times for CM, PM, POM and POS for the alternatives within alternative group D.

Table 7 shows the termination times for alternative group E, associated with the maximum cost of 1,850,000 SEK.

Table 7. Termination times for CM, PM, POM and POS for the alternatives within alternative group E.

It is of interest to compare the solutions with one another with regard to cost, i.e. to compare the solutions within the controlled scenario with one another and with the non-controlled scenario. The results of such a comparison show that, in comparison with the non-controlled scenario, there is a 56% saving when an alternative within alternative group C (the alternatives with the highest cost) is selected and an 83% saving when alternatives within alternative group B (the alternatives with the lowest cost) are selected; the termination times are given in Table 4.

The alternatives within alternative group D and E give savings of 62% and 60%, respectively, and provide the added value of shutting down the repair shop facilities within a time period of six months.

Table 8. Alternatives within the controlled and non-controlled scenarios.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Number of solutions</th>
<th>Cost [SEK]</th>
<th>Saving %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-controlled Scenario</td>
<td>A</td>
<td>1</td>
<td>4,600,000</td>
</tr>
<tr>
<td>Controlled Scenario</td>
<td>Group B Minimum Cost</td>
<td>36</td>
<td>765,000</td>
</tr>
<tr>
<td></td>
<td>Group C Maximum Cost</td>
<td>3</td>
<td>1,888,500</td>
</tr>
<tr>
<td></td>
<td>Group D Minimum Cost</td>
<td>15</td>
<td>1,790,000</td>
</tr>
<tr>
<td></td>
<td>Group E Maximum Cost</td>
<td>3</td>
<td>1,850,000</td>
</tr>
</tbody>
</table>

4 Discussion and Conclusions

Identifying the plethora of repair termination alternatives is a central and vital part of the PBSP programme. This also includes identifying a set of termination times for the parts received due to the PM, CM, POM and POS, to determine individual termination alternatives. This provides a foundation for further necessary measures to be taken and tasks to be performed within the retirement period, such as terminating maintenance contracts, discarding internal maintenance capabilities, reviewing stocks, cutting back on administrative processes (e.g. spares procurement and obsolescence monitoring), etc.

In the study presented in this paper, the dynamics of spares flow and the associated decision nodes within PBSP have been modelled. A set of computational models have been proposed to estimate the stock level for both the non-controlled and the controlled scenario.
For the controlled scenario, the flows of spares to the repair shops and the stock are controlled through decisions to stop the CM, PM, POM and POS. A computational model is proposed to estimate the stock level for any possible repair termination alternative. A search algorithm is proposed to apply the initial and boundary conditions to identify the applicable solutions. The search algorithm is an effective method which starts from an initial state and initial input to describe a computation which, when executed, proceeds through a finite number of well-defined successive states and produces a result at a final end state. In addition, a cost function has been developed to identify the cost-effective solutions among the applicable ones.

The non-controlled scenario involves a continuous parting-out of spares and continuous repair activities until the end of the retirement period. The results obtained for the non-controlled scenario within the case study show that there will be 69 cooling turbines in stock at the end of the termination period and the total cost of this scenario is estimated to be 4.6 MSEK.

Within the controlled scenario, the flows of spares to the repair shop and storage are controlled through the PBSP decision gates, CM, PM, POM and POS. Using the proposed search algorithm and the defined computational model, the successive states and applicable alternatives fulfilling the boundary conditions have been identified. The studied case shows that there is a set of 129,212 applicable solutions for combinations of repair termination alternatives, all of which fulfill the defined conditions. The highest cost for a solution within the controlled scenario is 1,888,000 SEK, which, in comparison with the cost for the non-controlled scenario, represents a large saving of 2,712,000 SEK.

Comparing the results obtained for the non-controlled scenario with those obtained for the alternatives with the lowest cost in the controlled scenario (alternative group B), one can expect a saving of 3,835,000 SEK for the cooling turbine, for the whole retirement period, if one uses one of the alternatives in group B. Considering that an aircraft comprises approximately 200-300 repairable units, the PBSP programme approach provides the possibility of making substantial savings.

The results also show that, with regard to specific sub-costs, several solutions are economically very close, and that, consequently, there exists a margin of adaptability for terminating CM, PM, POM and POS, which provides an operational flexibility. In other words, it is not necessary to follow a set of termination times strictly and there are several similar applicable solutions in the same cost region.

In addition, as shown in this paper, the applicable solutions and their termination times for CM, PM, POM and POS are relatively scattered. Naturally, from the point of view of PBSP management, it would be desirable to terminate all the maintenance-related activities at about the same time, and simply continue to collect units from the reclamation process to fulfill future spares requirements. However, selecting a solution with early maintenance termination times entails an increased risk that it will be necessary to reinitiate the maintenance, which is associated with a high cost. If one waits longer to stop the maintenance, there is less risk that unforeseen events will occur which will affect the spares provisioning process, but this alternative does not provide the same possibility of making savings.

In a real-life context, the operator may have other preferences which may dictate that other solutions will be the most effective ones. For instance, the operator may prefer to keep a certain contract longer for strategic reasons, or to keep the option open of delaying the retirement significantly due to operational requirements.

It should be noted that the proposed model has been developed for single-indenture stock systems. For organizations using a multi-indenture stock system, the model should be adapted considering the dynamics of spares flow in a multi-indenture stock system. Furthermore, the study has been performed on the basis of a fixed retirement plan. However, there may be more cost-effective solutions if one uses different retirement periods. Hence, it would be beneficial to perform a further analysis to identify the optimum retirement period, using an iterative process.

With good planning, a well-structured approach, common goals shared by all the stakeholders and an implementation of the proposed PBSP framework, greater savings can be achieved. In addition, the implementation of a PBSP programme itself is not associated with any large overhead.
The most vital part is the application of the proposed computational model and search algorithm, whose results provide transparency concerning the applicable repair termination alternatives and their associated costs. This represents the most important contribution of the PBSP programme.

Somewhat surprisingly, although the PBSP method is quite commonly applied within both the military and the civilian sector, there are very few publications on the subject. Indeed, very little research work has been published on any aspects of maintenance during the end-of-life period. One possible reason for this is that the methods are often applied by consultants, who may not have any incentives to publish their knowledge. Hence, further research within the area covered in this paper that would result in publications would be of great interest to both practitioners and the research community.

The proposed methodology can easily be adapted to civil aviation and other industrial areas with technically complex fleets of vehicles, such as trains, ships, dumpers, etc., and can provide provisioning planning during the retirement period, resulting in the possibility of making substantial savings.

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6 References


