Applied repairable-item inventory modeling in the aviation industry

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Abstract

In the aviation industry, reliable spare parts supply is essential for continuous aircraft operation. Spare parts of high value are repaired and returned to stock after removal from the aircraft, forming a closed-loop supply chain. Current planning methods of maintenance, repair, and overhaul providers (MRO providers) as well as research findings published to date do not cover the requirements of the commercial aviation industry. This paper presents a spare part inventory planning method that calculates cost-optimal inventory levels for warehouses in a two-echelon supply chain for spare parts supply in the aviation industry and takes into account various input and output planning parameters, such as budget and inventory level limitations. The development and introduction of the planning method is accompanied by a change management process. For validation of the calculated inventory levels a simulation model is used and sensitivity analyses are conducted. Using the discrete-event simulation model, effects of the demand level at local warehouses and its influence on the central warehouse are investigated.

Keywords: logistics, planning, inventory, spare parts

1. Introduction

1.1. Problem Statement

Flight safety regulations, federal laws, and passengers’ expectations require airlines to maintain aircraft at the highest technical standards. A failed spare part can prevent take-off of the airplane until replacement. Randomly distributed part failures at different airports worldwide mean that a system of interconnected warehouses is required for rapid and economical spare parts supply. Bases, which are located close to airports where many part failures occur, provide spare parts to aircraft when urgently requested. A depot replenishes the base following delivery of spare parts. Due to great costs spare parts are repaired after removal from the aircraft and returned to stock. As accurate demand forecasting and stock keeping are challenging and important factors in order to maintain competitiveness, an applied repairable item method has been developed for inventory planning of spare parts in the aviation industry.

1.2. Content

An adaption of theoretical inventory models to the commercial aviation industry for calculating cost-optimal inventory levels in warehouses at different locations will be presented in this paper. An introduction to the tasks and challenges faced by maintenance, repair and overhaul providers and features of the closed-loop supply chain for repairable items is provided. The review of the literature presents relevant research and shows the lack of methods which are compatible with all the requirements of the commercial aviation industry. In Chapter 4 the key features of the applied repairable item planning method, cost optimization, topology planning, and consideration of constraints are explained. A presentation of input and output parameters used in the planning method follows. Chapter 5 explains the change management during the development and
introduction of the new method. Results are summarized in the conclusion.

2. MRO-Suppliers in the Aviation Industry

2.1. Economic Framework

Costs for maintenance, repair and overhaul (MRO) services for airlines are a particularly critical factor because strict federal and international laws and flight safety regulations on the one hand and technical issues on the other mean that any negligence may entail high costs because of grounded or delayed aircraft. Besides labor and infrastructure costs, an efficient and reliable supply of spare parts is the key to cost-effective MRO operations.

Spare parts for aircraft are either required for predictable mandatory changes after a predefined number of flight hours or for immediate replacement in case of random failures of aircraft components. As random failures can occur anywhere, the demand for these components is globally distributed.

Whereas extremely high-priced items, such as engines or landing gears, are not usually stockpiled and low-cost consumable items, such as washers, bolts, nuts etc. can easily be provided at any location worldwide, inventory levels for medium-range line replaceable units (LRU), such as flight computers or engine control units require careful planning.

For these items, combined LRU pooling by multiple airlines lowers costs [1]. A MRO provider supplies LRUs for a variety of airlines, exploiting the pooling effect. Thereby, LRU supply can be realized by the MRO provider at significantly lower costs compared to airlines maintaining their own LRU stock.

![Fig. 1. Two-echelon repairable item system for LRUs.](image)

2.2. Multi-Echelon Supply Chain for Repairable Items in the Aviation Industry

Worldwide distributed demand and the necessity of short delivery times require a two-echelon supply chain for on-time LRU delivery. Due to their high price LRU components are repaired after removal from the aircraft in order to be returned to stock.

Fig.1 shows the repairable item system for LRUs of a maintenance repair and overhaul provider. Six bases are located at the airports where the majority of the failed parts are replaced. A requested LRU will be delivered from the base, which is assigned to the requesting location. This is usually the closest one. Figure 1 shows the path of a LRU request that is fulfilled by base 2. The LRU is sent from base 2 to the location of the aircraft for replacement of the defective LRU. The defective LRU is sent to the repair shop, repaired and returned to stock in the depot. The bases have minimum stock levels which are maintained by means of replenishment from the depot. In case of multiple replenishment requests the earliest request will be served first.

If the base is out of stock when a request is submitted, the depot will provide the LRU. If both the assigned bases and the depot are out of stock the LRU will be loaned by a competitor. The LRU will be returned to the lender as soon as a repaired LRU from the repair shop arrives at the depot. Loan costs depend on the duration of the loan.

Cost-optimal inventory levels for LRUs are only temporary, because of continuous changes to flight schedules and market conditions. Frequent planning cycles are necessary.

New methods are required in order to handle multi-echelon supply chains as well as temporary cost optimums. Current methods of inventory planning fail to give consideration to the characteristics of the MRO providers’ supply chain.

3. Literature review

Economical spare parts management is important for MRO suppliers. Wagner and Lindemann have conducted a survey of various companies working in spare-parts management in the engineering industry. Shrinking margins for primary products can and must be compensated by providing service engineering for the machines sold [2]. For the companies questioned, spare parts and aftersales services contribute 25 % to revenues and 40 % to 50 % to profits. Sherbrooke is the first author to model repairable item inventory systems in a multi-echelon setting. The restrictive assumptions make adaption of his model to commercial airlines spare parts management very difficult [3]. Cavalieri et al. propose a step-wise decision-making path for managing spare parts inventory [4]. The planning process for spare parts inventory is divided up into different steps. Part demand is low and time intervals between two different spare part requests may be as long as several years. Chunxun and Hongguang have studied inventory strategies for recyclable components of aviation materials, finding that parts amounting to 70-80 % of the tied capital in stock are recyclable [5]. They have developed a mathematical model for determining order quantities. Gross improves Sherbrooke's model and introduces limited repair capacity in the repair shop [6]. His finding is that inventory level estimates generated by the computational models are too low, when ample capacity is assumed in the repair shop. Tracht, Mederer, and Schneider extend this analysis to the case of seasonal demand and simulate queuing lines in the repair shops of the closed-loop supply chain [7]. Enlarging repair shop capacity to handle seasonal peaks reduces total costs significantly.
Investigations show that forecasting of MRO expenditures and spare parts demand are subject to uncertainty. Inventory planning approaches adopted in other applications such as optimization of stock for in-house production [8] condition monitoring [9] or methods for determining required quantities of products in assembly lines [10] cannot be transferred to MRO providers.

Current planning methods used by MRO providers and research findings published to date fail to give consideration to the requirements of the commercial aviation industry. Some initial findings have been published within the scope of research activities for new MRO planning concepts. Analyzing the spare parts array of an MRO supplier in terms of seasonal demand, Tracht, Schuh, and Weikert find that seasonal effects cannot be identified when considering the spare parts array as a whole [11]. Tracht, Schneider, and Schuh model the supply chain as a feedback control system with a flow of information and materials [12]. By introducing track points for information flow they are able to enhance supply chain performance and lower costs.

Due to the lack of adequate methods an applied repairable item planning method has been developed for forecasting LRU demand and calculating necessary stock levels for the inventory management requirements of an MRO supplier. Another important aspect when introducing improved inventory systems is the behavior of employees affected by the change. In the application presented a change management processes accompanied the entire development and introduction process of the repairable item inventory planning. Current change management models deal with the introduction of newly developed systems and methods for replacement of existing ones. The experience of users of the existing system is not taken into account or even seen as profitable for the repairable item inventory planning method’s development [13-15]. A change management model is developed simultaneously to the planning method. During the development, experiences of current users are taken into account. Further details will be provided below.

4. Applied repairable inventory planning

The applied repairable item inventory planning method has been designed for strategic and tactical planning in MRO provider environments. Its key features are optimization of total costs, consideration of the two echelon supply chain, and consideration of constraints. Simultaneously all relevant input parameters are taken into account to determine inventory levels of LRUs that are mostly electronic devices. Regular recalculations are conducted to adapt inventory levels to frequent input parameter changes. The results of various calculation runs are utilized for scenario analyses.

4.1. Features

4.1.1. Cost optimization

Total costs − which are the sum of inventory costs and shortage costs − are optimized using the applied repairable item planning method (eq. 1). Inventory costs \( c_{\text{inv},i} \) depend on the number of LRUs in stock \( n_i \), their average procurement price \( c_{\text{proc},i} \) and the rate of annual depreciation \( d \) (eq. 2). The subscript \( i \) denotes the spare part \( i \). Shortage costs are incurred if the assigned warehouse is unable to fulfill a LRU request (eq 3). \( \text{Prob}(x) \) denotes the probability for a stock-out situation. The loan costs that are incurred through a loan from a competitor account for the largest proportion of the shortage costs \( c_{\text{shortage}} \). Loan costs consist of an initial fee that arises at the beginning of each loan \( c_{\text{initial}} \) and a daily rent \( c_{\text{rent}} \), thus increasing loan costs according to the duration of the loan. The shortage costs also include the expenses associated with increased process complexity and additional shipping and handling costs \( c_{\text{process}} \). Inventory levels for the depot and each base in the supply chain are calculated independently from each other in order to achieve the optimal total cost.

\[
\text{Min}(c_{\text{total},i}) = \text{Min}(c_{\text{inv},i} + c_{\text{shortage},i}) \quad (1)
\]

with

\[
c_{\text{inv},i} = c_{\text{proc},i} \cdot d_i \cdot n_i \quad (2)
\]

and

\[
c_{\text{shortage}} = \text{Prob}(x) \cdot (c_{\text{initial}} + c_{\text{rent}} + c_{\text{process}}) \quad (3)
\]

4.1.2. Constraints

Input and output parameters can be limited by setting constraints because input parameters often fail to give consideration to all applicable external factors.

![Fig. 2 Input and output parameters.](image)

If a minimum service level is guaranteed in a contract with an individual customer, for instance, the planner can set a minimum service level as a calculation constraint. The calculated result shows the optimal total costs subject to the minimum service level constraint. Maximum procurement costs, maximum inventory costs and a minimum or maximum inventory level are other examples of constraints.

4.2. Input parameters

For calculation of minimum inventory levels in different warehouses, the repairable item inventory forecasting method uses the input parameters displayed in Figure 2.

A part failure in an aircraft requires a change and triggers a request at the warehouse assigned to the airport where the
aircraft is located. The probability for a failure of an LRU follows a Poisson distribution, shown in equation (4):

\[ P(k) = \frac{\lambda^k e^{-\lambda}}{k!} \]  

(4)

A denotes the expected number of failures in a given time interval and k denotes the number of failures for which the probability is computed.

The failure/change rate is predicted by means of standard methods of inventory forecasting. An increase in demand or economic effects on airlines' flight hours can be taken into consideration by adapting the number of changes used as an input for the calculation.

Transportation times are considered for the distances covered from the depot to the bases, from a warehouse to the customer, from the customer to the repair shop and from the repair shop to the depot.

The repair times measure the time which the LRUs spend in the repair shop and include queuing times. Repair times vary in reality but are assumed to be constant for the purpose of the calculation. Repair shop capacity is taken to be ample for all the LRUs arriving, automatically enhancing shop capacity in case of increased demand. As research has shown, in case of strong seasonal demand this assumption leads to longer queues and increased costs [7, 12].

Shortage costs arise when the assigned warehouse is unable to deliver the requested LRU. They include costs associated with increased process complexity as well as loan costs (see Fig. 2).

The scrap rates equal the percentage of LRUs that cannot be repaired out of all the LRUs arriving at the repair shop. Irreparable LRUs are scrapped. Replacements have to be ordered from the original equipment manufacturer and entail procurement times.

The procurement time is the time that elapses between the order of a new LRU from the original equipment manufacturer and its arrival at the depot. LRUs subject to high scrap rates or long procurement times have to be ordered in advance in order to maintain sufficient inventory levels. The procurement time may be up to several months.

The average procurement costs are used in order to calculate capital costs. Procurement costs may vary for different orders of the same LRU, due to bulk discounts for example. A variation in the average procurement costs for the LRUs in stock may change the cost-optimal inventory level: if procurement costs are below the average costs then the average procurement costs for LRUs in stock will decrease. This will enhance the probability of an increase in the inventory level because purchasing costs of new LRUs and corresponding inventory costs are lower.

4.3. Output parameters

The output parameters for the applied repairable item inventory forecasting method are the inventory levels at the depot and each base. Procurement and exclusion of LRUs are assumed on the basis of the difference between current and calculated inventory levels. The method also accounts for total costs and the service level according to inventory levels. The service level is the percentage of requests which are directly fulfilled by the assigned base. The service level will fall in case of a stock-out situation at the assigned base and if the LRU has to be provided from the depot or obtained by means of a loan.

4.4. Validation

Extensive sensitivity analyses have been conducted in order to test the planning method and its assumptions. For further validation a supply chain simulation model involving repairable LRUs has been built. The simulation model uses the calculated inventory levels for each warehouse and the requested LRUs at each warehouse as input parameters. Its service level and total costs output parameters are compared with the values obtained by means of the planning method. If these values are similar, the calculated planning parameters can be considered to be validated and accurate. The development of the simulation model for the supply chain has been completed and validation of the output parameters of the planning method was successful.

Two samples of the validation analyses are presented in the following. Table 1 shows the input parameters used for the scenario analyses. The scrap rate is set to zero to prevent an impact of the procurement process on the inventory management system. Thus all the input parameters of the procurement process are set to zero. The inventory and shortage costs are considered in the model, but cannot be disclosed because of confidentiality.

| Input Parameter       | Value       |
|-----------------------|-------------|
| change rate           | 0.66 changes/day |
| transportation time   | 5 days      |
| repair time           | 10 days     |
| scrap rate            | 0 %         |
| procurement time      | 0 days      |
| procurement costs     | 0 €         |

Fig. 3 shows the results of scenario one, in which all of the inventory pieces are stored in the central depot and none at the bases. The applied planning method calculates the total costs, comprising inventory costs and loan costs for different inventory levels. Due to confidentiality the costs are normalized to a scale of a hundred. In this scenario the pooling effect of the spare parts is maximized, because they are all stored in the central depot. Inventory costs rise, when adding an extra spare part to the system, whereas the loan costs decrease. The lowest total costs arise at 22 spare parts in the central warehouse. Adding more than 22 spare parts, only increases inventory costs and does not lower the loan costs further.
Fig. 3. Results scenario one.

Fig. 4 shows the results of scenario two, in which the inventory is stored at the central depot and each of the four bases holds one part. Compared to scenario one the total costs are lower but more spare parts are needed to reach the cost optimum. Lowest total costs are achieved at an inventory level of 27 pieces. Because transportation times to the customers are shorter, fewer parts have to be loaned to cover the transportation times. The decrease of the loan cost compensates the higher inventory costs. The lower costs of scenario 2 show that the use of a two-echelon inventory system compared to a one-echelon system is reasonable.

5. Change management

The introduction of the applied repairable item planning method to a MRO-provider requires profound preparation. The processes and assumptions are different to conventional planning tools and need to be subject of staff training. A change management is required to reduce users’ fear and raise acceptance of the planning method.

The following section shows a brief introduction to the new change management process. For further details see [15]. The model comprises the four phases of the change management process, which was developed simultaneously to the dynamic LRU planning. Before entering the phase model the management sets goals and requirements the repairable item method must fulfill, when launched. Examples of requirements are lowering of costs, the increase of system reliability or lowering global inventory levels. The phases of the change management process are as follows.

5.1. Conception

The main task of the conception phase is the transition of requirements and expectations to a desirable future state. The requirements developed in the phase before give a rough idea only and need to be specified more clearly. Hence, the development team specifies the functionality, taking into account the future environment of the system.

5.2. System Design

During the system design phase the team develops mathematical formulations of the system’s functions. The team implements the algorithms into a prototype.

5.3. Validation and user integration

During validation and user integration phase the development team evaluates, whether the planning method fulfills the expectations. Future users of system test the functions in order to detect errors and suggest improvements. As the first prototype usually contains a lot of errors and does not work stable, only key users should undertake these tests in order to prevent insecurity and disapproval of the future’s using team. Other users can join the testing at a later stage of the prototype’s development, when its operation is more stable.

By involving future users during the development of the applied repairable item method they can contribute their ideas and their experience. Resistance will be a lot lower when introducing the planning method, because the users took part in the development and are aware of the advantages.

In the case of the MRO-provider the most challenging part when introducing the new system is altering the user’s way of thinking, when planning inventory levels. The goal of the conventional system was to meet predefined service levels. Without regarding costs, 90 % of the requests had to be fulfilled from stock. Utilizing the dynamic inventory planning method the crucial parameter is total costs – which are the sum of inventory costs and shortage costs.

5.4. Feedback Loop

Redesign of concepts during research projects is common. The feedback loop feeds criticism of the users, detected errors and suggested improvements back to the conception phase.

5.5. Conservation

Results approved during validation are conserved. The training for future users on the conserved parts of the new system can be started. When starting training at an early stage of the development process, future users can learn about the new system step-by-step and will not be frustrated by too much information about the system’s entire functionalities.
6. Conclusion

Current inventory planning for the supply of LRUs in the aviation industry fails to give consideration to all applicable external factors. An applied repairable item planning method has been developed in order to handle the characteristics of an LRU supply chain in this industry.

The key features of the applied repairable item planning method are calculation of minimum total costs, consideration of a multi-echelon supply chain and consideration of constraints. Using the planning method, inventory levels for various warehouses are provided that lead to minimal total costs. As cost optimums are temporary and change rapidly, regular recalculations are conducted in order to approximate the theoretical cost optimum over the entire time period. Loaning LRUs is part of the supply strategy in order to achieve minimal costs.

Consideration of two echelons of the supply chain represents an important improvement in inventory forecasting in the commercial aviation industry. The applied repairable item planning method's calculation of inventory levels for all the warehouses guarantees minimal total cost.

Employees’ experience and ability to anticipate market changes – e.g. due to financial crisis – may enable an improvement in supply chain performance. The planner is able to set constraints in terms of input and output parameters for consideration of external factors in the calculation. Examples of constraints include a maximum procurement price due to budget limitations, a minimum service level because of contracts with customers or minimum inventory levels on account of a predicted increase in demand.

The planning method is validated with calculated inventory levels generated by a discrete-event simulation model of the supply chain. The early involvement of all employees affected by the developed planning method within a scientific change management process guarantees a high accuracy of the method's forecasted inventory levels and great user acceptance.

The promising results of the work completed to date show potential for further commercial exploitation. Following implementation in the aviation industry the applied repairable item inventory planning method will also be usable in other industries that maintain multi-echelon supply chains for the supply of spare parts.

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