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Efficient aircraft spare parts inventory management under demand uncertainty

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A B S T R A C T

In airline industries, the aircraft maintenance cost takes up about 13% of the total operating cost. It can be reduced by a good planning. Spare parts inventories exist to serve the maintenance planning. Compared with commonly used reorder point system (ROP) and forecasting methods which only consider historical data, this paper presents two non-linear programming models which predict impending demands based on installed parts failure distribution. The optimal order time and order quantity can be found by minimizing total cost. The first basic mathematical model assumes shortage period starts from mean time to failure (MTTF). An iteration method and GAMS are used to solve this model. The second improved mathematical model takes into account accurate shortage time. Due to its complexity, only GAMS is applied in solution methodology. Both models can be proved effective in cost reduction through revised numerical examples and their results. Comparisons of the two models are also discussed.

1. Introduction

In airline industries, an operator has to deal with two types of issues: the aircraft operating cost and customer satisfaction. Aircraft maintenance planning plays a major role in both of them. On the one hand, based on an analysis in 2012 conducted by the International Air Transport Association (IATA)'s Maintenance Cost Task Force (MCTF, 2012), the maintenance cost takes up about 13% of the total operating cost, and it can be reduced by a good planning. On the other hand, an excellent maintenance program can effectively avoid flight delays and cancellations, thus improve customer satisfaction and competitiveness in the industry. Spare parts inventories exist to serve the maintenance planning. An excess of spare parts inventory leads to a high holding cost and impedes cash flows, whereas inadequate spare parts can result in costly flight cancellations or delays with a negative impact on airline performance. Since the airline industry involves with a large number of parts and some of them are quite expensive, it is important to find an appropriate inventory model to achieve a right balance.

Compared with other industries, the airline industry is unique due to a combination of four market characteristics: global need for parts, demand unpredictability, traceability of parts for safety reasons, and high cost of not having a part. Traditionally, spare parts are generally classified into four groups: Rotables, Repairables, Expendables and Consumables, which are listed in Table 1. For different categories, different replenishment policies are used. Rotables and Repairables are mainly based on predicted failures estimated by manufacturers, and the planning parameters are finished as management decision. As to Expendables and Consumables, the reorder point system (ROP) is used and input comes from historical demand with estimated changes. However, this kind of inventory management is typically subjective and imprecise, thus is not an ideal policy. From a survey conducted by Ghobbar and Friend (2004), 152 out of 175 respondents were using the ROP system and about half were dissatisfied and considering implementing new systems.

Our research was motivated by creating an efficient spare parts inventory model in order to provide better service for maintenance needs. When aircraft parts fail, they generate demand for spare parts, and are supplied from spare parts inventory. Under ideal situation, those parts should be in stock and in turn replenished by further activities such as purchasing or repairing. Demands will be satisfied immediately, and aircraft maintenance work can take place on schedule. However, if required spare parts are not available at that time, even purchase orders can be accepted by suppliers at once, delivery time is still a big issue that cannot be ignored. Postponed troubleshooting due to spare parts shortage will probably lead to flight delay or cancellation which will incur huge extra cost. Unfortunately, the second situation is hard to avoid because of

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Table 1
Definitions of Rotables, Repairables, Expendables and Consumables.

Rotables	Complex components Normally unlimited number of repairs Normally no scrap is expected Controlled by individual serial number Exchange during maintenance
Repairables	Components which can be technically and economically repaired: Under normal conditions, a follow up of each individual serial number is not necessary. Have limited number of repairs and also have a possibility of scrap
Expendables	Cannot be repaired and will be scrapped after removal and inspection result is unserviceable 100% replacement items Items which cannot be repaired (not economical to be repaired) Standard parts
Consumables	any materials used only once Raw material Chemical material Items which merge on production with new product and cannot be removed

uncertain parts failures, large number of parts, limit budget and warehouse space, etc. We try to establish an efficient spare parts inventory model that use minimum expense to achieve maximum productivity. Unlike the previous inventory models that just address the problem of determining the amount of parts to be purchased, our efficient inventory model satisfies spare parts demands from two perspectives: quantity and time. Therefore, it can better improve service level and control the total costs which generally include purchasing cost, holding cost, and shortage cost.

In the context of our model, the installed parts failure distribution is introduced. We assume failures can be predicted based on maintenance data or manufacturer's manual, and maintenance activities are the key drivers of spare parts demand. Advance orders are triggered to reduce downtime caused by parts delivery time. In our analysis, we examine the parts failure distribution to find optimal order time and order quantity by considering that the lifetime and quantity of installed parts failure distribution may influence the duration and numbers of spare parts shortage or overstock, thus result to total cost fluctuation. A non-linear programming (NLP) model is presented with the objective of minimizing air carriers' expected cost in spare parts. Numerical and iteration methods and GAMS are employed to solve the model.

This paper is organized as follows. In the next section, we give a brief literature review. Section 3 presents a basic mathematical model considering shortage period starts from mean time to failure (MTTF). Numerical and iteration methods as well as GAMS can be used to solve this model. We also develop an improved mathematical model, which takes into account exact shortage time, and its solution methodology in Section 4. Section 5 illustrates the value of our models in cost reduction by numerical examples and their results. Sensitivity analysis and models comparison is conducted in the following section. Finally, Section 7 provides the conclusions and suggestions for future research.

2. Literature review

Over the past few decades, great efforts have been made to improve spare parts inventory management. Some research did demand forecast based on spare parts consumption in the past years. Among those work, Ghobbar and Friend (2003) discussed the forecasting of intermittent demand in relation to these primary maintenance processes, and compared the experimental results of thirteen forecasting methods. Regattieri et al. (2005) analyzed the behavior of forecasting techniques when dealing with lumpy demand, and made a comparison for twenty forecasting techniques. Both papers found that the best approaches for intermittent demand are weighted moving average, Holt and Croston methods.

In some other research, flying hours was considered as a critical factor in demand forecast. This is due to the fact that long flying hours may cause aging or wearout which closely relates to part failure or demand. Campbell (1963) examined demand data from the United State Air Force's maintenance records, and explored relationships between demand and operational variables. He concluded that demand seemed to be related to flying hours and sorties flown, with flying hours having a stronger relationship. Ghobbar and Friend (2002) investigated the source of demand lumpiness, and proposed an assumption that demand is strictly linearly to flying hours/landings. Today, more companies are considering flying hours as the major factor in their forecasting of demand calculation and using the mean time between removal/overhaul (MTBR/O) to forecast a failure rate. Thus preventive maintenance (PM) is widely used especially for some critical components that directly affect flight safety.

Many papers are presented to address spare parts and failure-based maintenance actions or spare parts with either an age or block-based replacement policy. The earliest papers can be traced to Natarajan (1968) who proposed a reliability problem with spares and Allen and D'esopo (1968) who studied an ordering policy for repairable stock items. Armstrong and Atkins (1996) and de Smidt-Destombes et al. (2007) described the joint optimization of spare parts inventory and age or block-based replacement policies. Vaughan (2005) proposed a failure replacement and PM spare parts ordering policy. Wang (2012) presents a model to optimize the order quantity, order intervals, and PM intervals jointly under a two-stage failure process.

The aforesaid papers mainly address the problem either from an inventory point of view based on the past spare parts usages to forecast the future demand, or from a maintenance point of view to find an optimal order quantity and PM interval considering the correlation between flying hours and failures. To the author's best knowledge, limited research handles failure-based procurement inventory management which is very common in practice. One the one hand, when demand is triggered by failures, the demand forecast result based on past consumption may not be accurate. For example, past low demand in many periods may indicate significant parts aging and therefore high impending demands, but the traditional replenishment system will scale back replenishment which is counter to the actual requirement. One the other hand, PM inventory management is different from failure-based inventory management. As the spare parts demand is uncertain, and sometimes the part delivery time may be very long, it could lead significant loss if a critical part fails but there is no spare to replace it.

Deshpande et al. (2006) explored this issue. To improve the performance of aircraft service parts supply chain in the United States Coast Guard (USCG), they used mathematical programming tools to link the demand transactions to a corresponding maintenance activity. Subsequently, they developed an approach to use part-age data to make inventory decisions. It sets an age threshold and observes the number of installed parts whose age is greater than the threshold, thereby deciding the advance order quantity in the end of the observation period. This approach tries to synchronize the inventory of good parts with demand distributions, and replenish the inventory just as anticipated demands arrive. It has great advantages compared with traditional inventory policies. However, one important operational problem is not mentioned-when is the best time to issue orders? Ordering at the beginning of period will result in high holding cost, whereas replenishing at the end of period may lead to extensive shortage cost, both tend to