Maintenance Planning Optimization Based on PHM Information and Spare Parts Availability

Leonardo Ramos Rodrigues[1] and Takashi Yoneyama[2]

[1] *EMBRAER S.A., São José dos Campos, São Paulo, 12227-901, Brazil*
leonardo.ramos@embraer.com.br

[2] *ITA – Instituto Tecnológico de Aeronáutica, São José dos Campos, São Paulo, 12228-900, Brazil*
takashi@ita.br

ABSTRACT

Maintenance planning plays an important role in assets management because it directly affects assets availability. In the aviation industry, maintenance planning becomes even more important due to the high availability expectations from aircraft operators and the high costs incurred when an aircraft becomes out of service. Gathering and combining all the relevant information to generate an optimized maintenance planning is not a simple task because the number of variables to be considered is high. The aim of this paper is to present a new model to plan maintenance interventions, using RUL (Remaining Useful Life) estimations obtained from a PHM (Prognostics and Health Monitoring) system. This information is used to verify whether spare parts will be available when the next failures are expected to occur. Since spare parts are finite resources, the goal of the proposed model is to reduce the probability that multiple similar components will fail in a short period of time because, when it happens, there is not enough time to repair all failed components and fleet availability is penalized. To avoid this situation, the model suggests the anticipation of some replacements. This paper presents a simulation comparing a situation in which PHM information is not available with the proposed model in terms of fleet availability and investment in spare parts. Life cycle cost considering a time horizon of 15 years was also computed in simulations. The results showed that the proposed model allowed an increase in fleet availability and a reduction in the lifecycle cost.

1. INTRODUCTION

In a previous work, the authors presented an algorithm that uses PHM information for non-repairable items spare parts inventory control (Rodrigues & Yoneyama, 2012). In this paper, repairable items are addressed. Mathematical models for optimizing the performance of repairable components based on maintenance interventions have been widely discussed in the literature. Dekker (1996) presented an overview of many maintenance models for repairable items.

Planning maintenance interventions can be a complex task because there are many variables involved. An efficient maintenance plan must take into account information obtained from different sources. Gathering and combining all this information to generate an optimized maintenance planning is a challenge faced by maintenance planners.

This work presents a maintenance planning algorithm to support maintenance planning optimization. The proposed algorithm combines PHM information and spare parts availability estimations in order to schedule maintenance intervention with minimum impact on fleet availability.

2. SPARE PARTS INVENTORY SYSTEM FOR REPAIRABLE ITEMS

Repairable items are components or assets that, after a failure, are submitted to a repair cycle to be used again instead of been discarded (Fritzsche & Lasch, 2012; Lee, Chew, Teng & Chen, 2008). It implies that a repairable item spare part inventory system must have a repair shop where failed components are repaired, as well as a warehouse where spare parts are stocked (Perlman & Levner, 2010). An example of a typical spare parts inventory system for repairable item is shown in Figure 1.

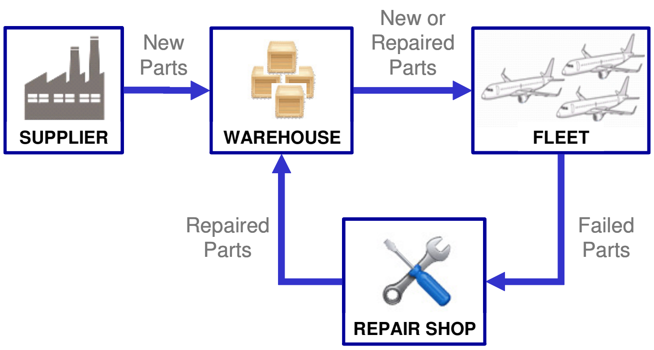

Figure 1. Spare parts inventory system for repairable items

In this inventory system, it is considered that spare parts are always bought from the same supplier and delivered at a single warehouse. When a component installed on an aircraft fails, it is removed and sent to the repair shop to be repaired. The faulty component is replaced by a new one from the warehouse. If there is no spare part in the warehouse, we assume that the aircraft is grounded until a new part is provided.

Once a faulty component arrives in the repair shop, it is submitted to the repair process. If limitation on repair shop capacity is considered, then a priority policy must be established. When the repair process ends, the repaired component is sent to the warehouse and stays there until a new failure occurs in the field. The repair process can be considered to be perfect (if repaired components returns to an "as good as new" condition) or imperfect (if repaired components keep a residual degradation). Imperfect repair models were presented by Do Van, Voisin, Levrat & Iung (2012) and Doyen & Gaudoin (2004). In this work, we consider that the repair shop has infinite capacity and that the repair process is perfect. We also consider that no degradation occurs to spare parts while they are in the warehouse.

2.1. Investment in Spare Parts versus Fleet Availability

One important decision to be made by inventory managers is related to the number of spare parts that will be bought in order to support fleet operation. In most real applications, the inventory system comprises multiple items, and the number of spare parts of each component must be defined.

The determination of how many spare parts of each component shall be bought must consider two conflicting variables: investment in spare parts and fleet availability.

Sherbrooke (2004) described a methodology called marginal analysis that can be used in order to determine the optimum sequence of spare parts to be bought in order to maximize the expected fleet availability.

3. Maintenance Planning

As a general rule, all assets demand maintenance interventions during their operational life. Maintenance planning plays an important role in assets management because it helps maintenance planners to schedule maintenance interventions with minimum impact in operation.

3.1. PHM Information

In order to identify the best moment to perform maintenance tasks, monitoring the health condition of assets can provide valuable information about how long an asset can operate before a failure occurs (Sandborn & Wilkinson, 2007).

PHM (Prognostics and Health Monitoring) is the ability of assessing the health state, predicting impending failures and forecasting the expected RUL (Remaining Useful Life) of a component or system based on a set of measurements collected from the aircraft systems (Vachtsevanos, Lewis, Roemer, Hess & Wu, 2006).

Based on measurements collected from the aircraft, a PHM system estimates the degradation level of monitored components. The degradation index is zero when the monitored component is new. During operation, degradation process starts and the degradation index increases. If the degradation index threshold that defines the failure is known, it is possible to extrapolate the curve generated by the evolution of the degradation index over time and estimate a time interval in which the failure is likely to occur (Leão, Yoneyama, Rocha & Fitzgibbon, 2008). This estimation is usually represented as a probability density function, as shown in Figure 2.

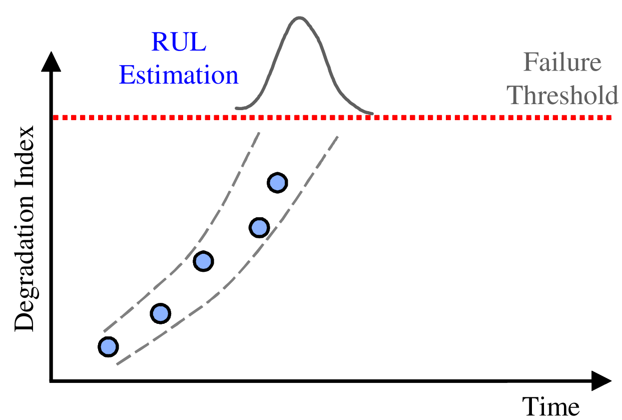

Figure 2. RUL estimation

3.2. Spare Parts Availability

In order to plan maintenance interventions, maintenance planners must verify the availability of all required resources such as technicians, spare parts, tools, etc. In this work, PHM information will be used to estimate the availability of spare parts. We consider that all maintenance interventions require a spare part. We also consider that all other resources are always available.

Spare parts in the repair shop are unavailable and can not be installed in an aircraft. They become available when the repair process ends and they are sent to the warehouse. Fleet availability is affected when a failure occurs and there are no spare parts in the warehouse.

Suppose S_X is the number of spare parts of component X and $R_X(t)$ is the number of components X in the repair shop at instant t. The number of aircraft grounded waiting for a component X at instant t, $G_X(t)$, can be calculated as a function of $R_X(t)$ and S_X as follows (Sherbrooke, 2004).

$$G_X(t) = \begin{cases} 0 & ; R_X(t) \le S_X \\ R_X(t) - S_X & ; R_X(t) > S_X \end{cases} \qquad (1)$$

In Eq. (1), we can observe that fleet availability is affected by component X only when there are more than S_X components simultaneously in the repair shop.

4. Proposed Model

In the proposed model, PHM information is used to estimate when failures are likely to occur. Using the RUL estimations for the monitored components and their MTTR (Mean Time to Repair), it is possible to build an expected repair shop time schedule for each component type, as illustrated in Figure 3.

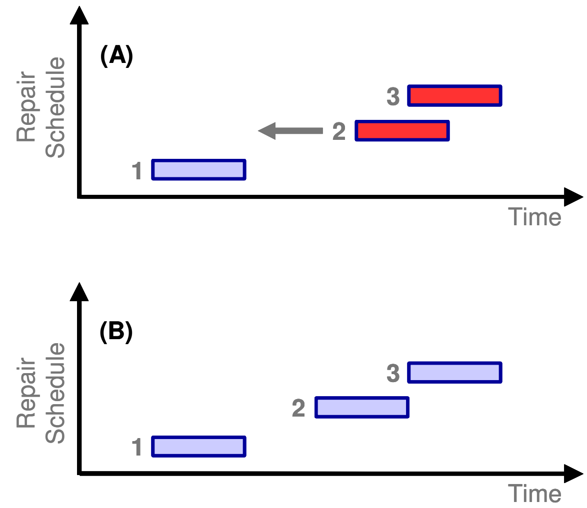

Figure 3. Repair shop time schedule estimation

Figure 3(A) shows an example of a repair shop time schedule for component X. Each bar in Figure 3 represents the repair cycle of one component. Let's assume that the number of spare parts for component X, S_X, is 1. PHM information is used to determine when a failure is expected to occur and, consequently, when a faulty component is expected to be sent to the repair shop. MTTR is used to determine how long the faulty components will stay in the repair shop.

We can observe in Figure 3(A) that the third component is expected to arrive in the repair shop while the second component is still being repaired. In this situation, there will be two components simultaneously in the repair shop. During this time, $R_X(t)$ is 2, and according to Eq. (1), $G_X(t)$ is 1. In other words, there will be one aircraft grounded waiting for a component X.

In order to reduce the probability that multiple similar components will be simultaneously in the repair shop, some components can be replaced earlier. When some replacements are anticipated, the period of time in which aircraft are grounded can be reduced or even eliminated. In the example illustrated in Figure 3(A), if the replacement of component 2 is anticipated, we generate a new time schedule in which the maximum number of components in the repair shop never exceeds 1. This new time scheduled is shown in Figure 3(B).

The identification of concentrations of failure events, as well as the preventive anticipation of maintenance interventions, is possible only when PHM information is available. In a situation without PHM, the effects of the concentrations of failure events can not be reduced.

5. Numerical Example

In order to analyze the potential increase in fleet availability provided by the anticipation of some replacements to avoid the concentration of similar components in the repair shop at the same time, a set of simulations were run. The spare parts inventory system shown in Figure 1 was used in this example.

Two identical fleets were simulated. In the simulation of the first fleet, PHM information was not used. In the simulation of the second fleet, PHM information and spare parts availability estimations were used to anticipate maintenance tasks whenever a high concentration of similar spare parts in the repair shop was detected.

Four LRUs (Line Replaced Units) were considered in the simulation. Table 1 shows the price and the reliability data for each LRU. It is considered that an aircraft is available only if all its components are working properly. In other words, a failure of any LRU puts the aircraft to an AOG (Aircraft on Ground) condition.

Table 1. LRU data

LRU	A	B	C	D
Price [Monetary Units]	400	250	150	100
MTTF [days]	300	150	200	120
MTTR [days]	30	20	25	25

The decision of anticipating a maintenance task or not is made based on a cost criteria. The cost parameters used in the simulation are shown in Table 2.

Table 2. Cost data

Parameter	Value
Holding Cost	30% of component price per year
Repair Cost	30% of component price per repair
Stockout Cost	3.3 M.U. per day per aircraft

The PHM system estimates the RUL for all components installed in the fleet. The estimated RUL for each component is given as a normal distribution. In other words, for each component the PHM system informs the estimated RUL and a standard deviation. Table 3 shows the maximum and the minimum values for the error in the RUL estimation and for the standard deviation used in the simulation.

Table 3. PHM system data

Parameter	Value
Minimum RUL Error [days]	0
Maximum RUL Error [days]	20
Minimum RUL Standard Deviation [days]	5
Maximum RUL Standard Deviation [days]	20

Figure 4 illustrates the relation between the date of failure and the RUL estimation provided by the PHM system.

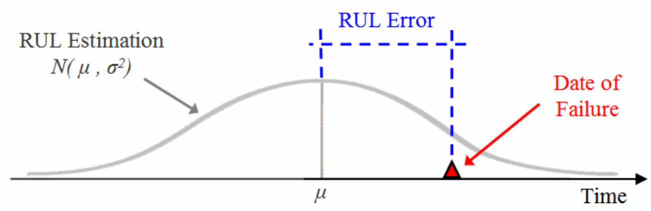

Figure 4. Failure date and RUL estimation

5.1. Scenario Description

The spare parts inventory system shown in Figure 1 is used in this example. The two identical fleets simulated will be compared in terms of investment in spare parts and expected fleet availability.

A spare part list must be defined in the beginning of each simulation. Once defined, we consider that all spare parts are bought from the supplier and are stored at the warehouse in the beginning of the simulation. When a failure occurs, a spare part is sent from the warehouse to replace the failed component, which is sent to the repair shop to be repaired. Once repaired, the component is sent to the warehouse and stays there until a new failure occurs in the field. In this work, we consider that components can always be repaired, and that repaired components are as good as new.

Sherbrooke (2004) developed a methodology to determine the optimum sequence of spare parts to be added to the spare parts list in order to maximize the expected fleet availability. We applied this methodology and defined the sequence of spare part to be bought. For each new spare part list, we repeated the simulation. Table 4 shows the optimum sequence of spare parts. PHM information is not necessary to calculate the optimum sequence of spare parts to be acquired.

The sequence of spare parts shown in Table 4 indicates that, for the group of LRUs considered in this example, if the inventory manager decided to support fleet operation with only one spare part, the best choice would be to have a spare part of LRU D. Another example: if inventory manager decides to invest 1,500 monetary units in spare parts, the optimum choice would be to buy the first eight spare parts listed in Table 4 (1 spare part of LRU A, 2 spare parts of LRU B, 2 spare parts of LRU C and 3 spare parts of LRU D).

Table 4. Optimum spare parts acquisition sequence

Spare Part	LRU	Cumulative Investment	Spare Part	LRU	Cumulative Investment
1st	D	100	9th	D	1,600
2nd	D	200	10th	C	1,750
3rd	C	350	11th	A	2,150
4th	B	600	12th	B	2,400
5th	D	700	13th	D	2,500
6th	C	850	14th	C	2,650
7th	A	1,250	15th	A	3,050
8th	B	1,500	16th	B	3,300

5.2. Simulation Results

After defining the optimum sequence of spare parts to be bought, a set of simulations without using PHM information were run, considering a fleet of 10 aircraft. The time horizon for each simulation was 15 years.

First of all, fleet operation was simulated with no spare parts at all. In this simulation, every time a component failed, the aircraft stayed out of service until the repair was completed. After that, the spare part list was incremented, following the sequence presented in Table 4. For each spare part list, 20 repetitions of the simulation were run. Figure 5 shows the average fleet availability obtained with each spare part list, including the first set of simulations with no spare parts.

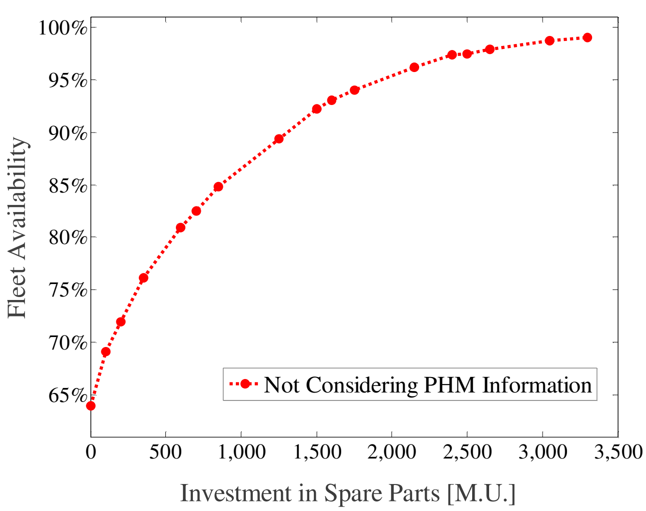

Figure 5. Average fleet availability versus investment in spare parts not considering PHM information

PHM information was then introduced in the simulation. The procedure of increasing the spare parts list according to Table 4 was repeated. Again, 20 repetitions of the simulation were run for each spare parts list. Figure 6 shows the average fleet availability obtained with each spare part list using PHM information and spare part availability (solid blue). For comparison purposes, the fleet availability curve obtained without PHM information – shown in Figure 5 – was also plotted in Figure 6 (dotted red).

Cost information presented in Table 2 was used in each simulation to calculate the expected maintenance life cycle cost. Since fleet availability and operational cost are conflicting variables, the purpose of this simulation was to investigate whether the increase in fleet availability obtained by the use of PHM information did not cause an increase in the maintenance life cycle cost.

Figure 7 shows the average life cycle cost computed during simulations. The investment in spare parts is shown in the horizontal axis, following the sequence presented in Table 4. For each spare part list, the bar on the left is the life cycle cost obtained without using PHM data, while the bar on the right is the life cycle cost obtained considering PHM information. In Figure 7, total life cycle cost is broken into four terms: investment in spare parts (black), holding cost (dark gray), repair cost (light gray) and stockout cost (white).

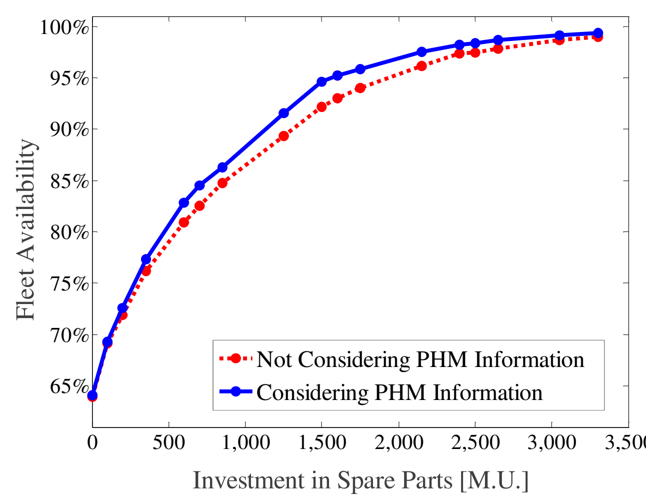

Figure 6. Increase in fleet availability when PHM information and spare parts availability is considered

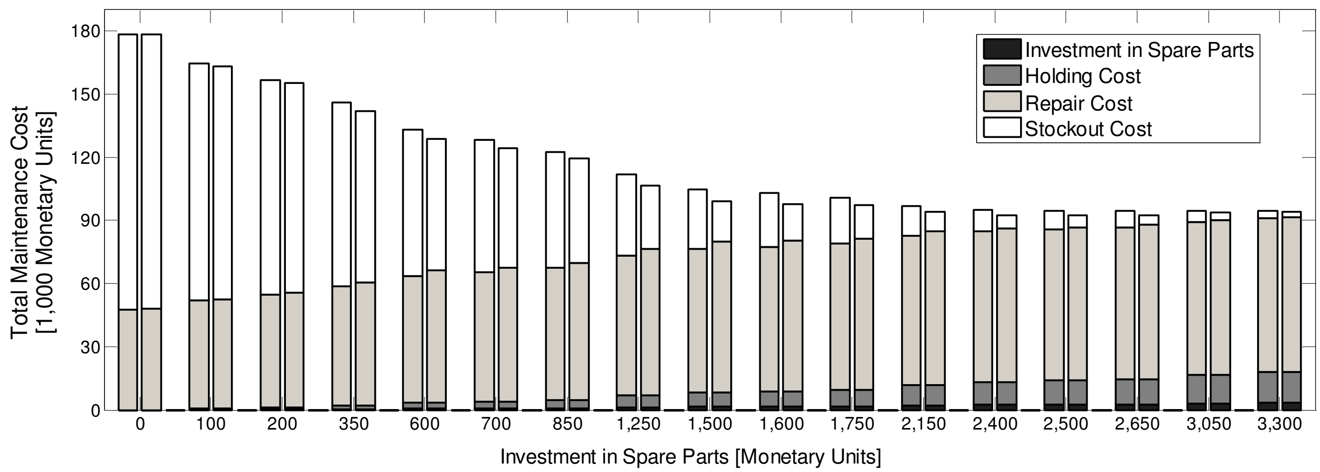

Figure 7. Average life cycle cost breakdown

6. CONCLUSIONS

We found that combining PHM data and spare parts availability estimations allowed us to improve fleet availability without additional investments in spare parts. RUL estimations provided by the PHM system were used in order to anticipate some maintenance actions. It avoided multiple similar components of being simultaneously in the repair shop and caused an increase in fleet availability.

The proposed model presented the best results when the expected fleet availability was around 92%. In this situation, the proposed model allowed and increase of 2.4 percentage points (from 92.2% to 94.6%). In all other situations, the proposed model allowed to achieve a better fleet availability in comparison with the situation in which PHM data are not used.

When maintenance tasks are anticipated, the number of maintenance interventions performed during fleet operational life is higher, and an increase in repair cost is expected. The computation of life cycle cost confirmed this expectation. However, the increase in fleet availability reduced the stockout cost, compensating the increase in repair cost.

Although the numerical increase in the availability achieved by using PHM information is small, the result is relevant considering that in the aviation industry the cost of an AOG event is usually very high. Intangible aspects associated to AOG events such as company reputation and damage to customer relationship are also relevant for aircraft operators.

Future research may extend the proposed model by considering the limitations associated with other resources such as technicians and tools.

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BIOGRAPHIES

Leonardo Ramos Rodrigues holds a bachelor's degree in Electrical Engineering from Universidade Federal do Espírito Santo (UFES, 2003), Brazil, and a Master Degree in Aeronautical Engineering from Instituto Tecnológico de Aeronáutica (ITA, 2008), Brazil. He is currently pursuing his doctorate in Aeronautical Engineering at ITA. He is with EMBRAER S.A. since 2006. His current research interests are the application of health monitoring techniques for electronic components and the usage of PHM information for inventory optimization.

Takashi Yoneyama is a Professor of Control Theory with the Electronic Engineering Department of ITA. He received the bachelor's degree in electronic engineering from Instituto Tecnológico de Aeronáutica (ITA), Brazil, the M.D. degree in medicine from Universidade de Taubaté, Brazil, and the Ph.D. degree in electrical engineering from the University of London, U.K. (1983). He has more than 250 published papers, has written four books, and has supervised more than 50 theses. His research is concerned mainly with stochastic optimal control theory. Prof. Yoneyama served as the President of the Brazilian Automatics Society in the period 2004-2006.