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An innovative method to optimize the maintenance policies in an aircraft: General framework and case study

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A B S T R A C T

Maintenance policies applied to aircrafts are governed by a mix of airworthiness authorities' regulations and choices of suppliers and users. This allows airlines to use different strategies to minimize the total costs of maintenance. In this paper, a new approach that integrates the failure and reparation processes, such as modelling, optimization algorithms, and simulation methods, is proposed to define the best maintenance strategies for complex systems.

A case study of an airline carrier is presented. In particular, several critical components for the A320 aircraft family are considered. The impact of the spare parts inventory management is discussed. Different preventive maintenance policies are tested and simulated. With the new policies, the average availability of the aircraft is satisfactory and the total annual cost is reduced to a value of approximately 20% in comparison with the previous policies adopted by the company.

1. Introduction

Maintenance costs represent on average of 14% of the variable costs incurred by airlines (Sriram and Haghani, 2003; Ferrari et al., 2002). Global competition forces airlines to improve flying hours as well as the availability of their aircrafts with adequate maintenance costs.

An aircraft maintenance program must ensure the realization of the inherent safety and reliability levels of the equipment at a minimum total cost, including maintenance costs and the costs of resulting failures.

The target must be the optimization of the technical total cost of service of an aircraft due to two elements: the maintenance costs (e.g., in terms of labour, spare parts purchase, logistics, etc.) and aircraft downtimes (e.g., in terms of repair and inspection time, waiting time for missing spare parts, etc.). For an aircraft's components, the two cited costs usually have a countertrend, and the goal must be to find the best mix of maintenance policies in agreement with the minimization of the total cost of service. The three-step method proposed pursues this optimization.

Aircraft maintenance is highly regulated. There are various airworthiness authorities around the world (i.e., the European Aviation Safety Agency (EASA), Europe; the Federal Aviation Administration (FAA), the United States; and others). Manufacturers and users (e.g., airlines) of aircrafts are important actors in defining effective maintenance policies after licensing by authorities.

The initial maintenance policies schedule follows the well-known Maintenance Steering Group-3 (MSG-3) process. The MSG-3 process was defined by the participation and combined efforts of the Federal Aviation Administration (FAA), Civil Aviation Authority (CAA/UK), Aircraft Electronics Association (AEA), U.S. and European aircraft and engine manufacturers, U.S. and foreign airlines, and the U.S. Navy.

This process outlines the general organization and decision processes for determining scheduled maintenance requirements initially projected for the life of the aircraft (Life Data Analysis Reference Book, 1993). The initial scheduled maintenance program has been specified in Maintenance Review Board (MRB) Reports. The MRB development process is also discussed in different Advisory Circulars of the FAA (i.e., AC No: 121-22A (1997), 121-22B (2010), 121-22C (2012)).

All of these documents become the basis for the first issue of each airline's maintenance requirements to govern its initial maintenance policy. Adjustments may be necessary to address

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Nomenclature

C_{tot} Total cost of maintenance policies (for each analysed component)
C_{CM} Cost of Corrective Maintenance (CM) policy
C_{PM} Cost of Preventive Maintenance (PM) policy
C_{IM} Cost of Inspection (IM) policy
C_{STOCK} Cost of spare parts stock management
$C_{CREW_{CM}}$ Cost of crew (CM)
$C_{PARTS_{CM}}$ Cost of spare parts (CM) due to part acquisition from the company warehouse or from the supplier (cost of item plus cost of logistics in normal/emergency provisions)
$C_{LOSS_{CM}}$ Cost of loss of service (CM)
$C_{I_{CM}}$ Cost of CM interventions (linked to maintainability function in RPM analysis)
$C_{TE_{CM}}$ Cost of travel expenses of maintenance crew for CM interventions. The airplane can be stopped in a random airport of the network, considering the regional focus of the network. In the proposed case study, the analysed fleet of A-320 works only in southern Europe, and then $C_{TE_{CM}}$ is assumed as the average value coming from the study of 2009–2012 CM past interventions.
$C_{FH_{CM}}$ Cost due to the loss of flight hours. This term considers the mean time to failure (MTTF) originating from the FPM analysis and the average values of flight delays and cancelled flights. In the case study, data comes from the study of 2009–2012 CM past interventions.
$C_{RP_{CM}}$ Cost of passengers rerouting. In the case study, the average value coming from the study of 2009–2012 CM past interventions is considered.
$C_{CREW_{PM}}$ Cost of crew (PM)
$C_{PARTS_{PM}}$ Cost of spare parts (PM) due to part acquisition from the Company warehouse or from the supplier (cost of item plus cost of logistics in normal provisions)
$C_{LOSS_{PM}}$ Cost of loss of service (PM)
$C_{I_{PM}}$ Cost of PM interventions
$C_{TE_{PM}}$ Cost of travel expenses of maintenance crew for PM interventions. In general, the PM interventions can be realized in different airports of the network. In the case study, considering the regional focus of the network (the analysed fleet of A-320 works only in southern Europe), the $C_{TE_{PM}}$ is assumed as the average value coming from the study of 2009–2012 PM past interventions. A significant fraction of PM actions are realized in the repair station without travel expenses.
$C_{FH_{PM}}$ Cost due to the loss of flight hours. PM interventions are realized over-night or during weekend stops (i.e., no flight hours losses), but a delay in the interventions can cause a loss of service. In the case study, the data originated from the study of 2009–2012 PM past interventions.
$C_{CREW_{IM}}$ Cost of crew (IM)
$C_{LOSS_{IM}}$ Cost of loss of service (IM)
$C_{I_{IM}}$ Cost of IM interventions
$C_{TE_{IM}}$ Cost of travel expenses of maintenance crew for IM interventions. In general, the IM interventions can be realized in different airports of the network. In the case study, considering the regional focus of the network (the analysed fleet of A-320 works only in southern Europe), the $C_{TE_{IM}}$ is assumed as the average value coming from the study of 2009–2012 IM past interventions. A significant fraction of IM actions are realized in the repair station without travel expenses.
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C_{STOCK} Cost of the stock and the management of spare parts in the warehousing centre

operational and/or environmental conditions unique to the operator. As operating experience is accumulated, additional adjustments may be made by the operator to maintain an efficient maintenance program. For example, AC 121-22C provides the Statistical Analysis Tasking Optimization (SATO) procedure that describes an original equipment-customized program for the optimization of scheduled maintenance.

The MSG-3 logic was task-oriented, and generally, there are two groups of tasks: scheduled tasks to be accomplished at specified intervals (i.e., Lubrication/Servicing (LU/SV), Operational/Visual Check (OP/VC), Inspection/Functional Check (IN/FC), Restoration (RS), Discard (DS)), and non-scheduled tasks (i.e., corrective measures deriving from malfunctions, usually generated by the operating crew reports).

For an aircraft, the inspection/replacement interventions are the most relevant in terms of effort and costs. For this reason, this paper is focused on the optimization of the preventive maintenance policy, in particular considering the on-aircraft repair operations, which are usually out of A/C planned checks.

This study discusses the optimization of maintenance policies. Often, policies are based on a manufacturer's or maintainer's experience. The initial MRB for any new aircraft is developed in the absence of actual in-service experience. As a result, the tendency is to be conservative in the decision-making process. However, as service experience is accumulated, task intervals should be adjusted to reflect the results of a professional analysis of actual in-service data. However, intervals of intervention/replacement are often not seriously based on the actual system reliability. This causes maintenance costs to be higher than the optimum. The authors show how it is possible to achieve significant improvements in terms of availability and reduction of maintenance costs using a systematic procedure of data analysis based on RAM (Reliability, Availability, Maintainability) principles. The proposed method is applied in a real case involving an important airline carrier. Different maintenance strategies, including corrective (CM) and preventive (PM) maintenance policies, are compared. The choice of the best maintenance policy has also been linked to a study of inventory management strategies to identify the most effective one from an operational point of view. Both studies are related to the economic impact assessment.

This paper is organized as follows. The next section presents the literature review with regard to the problem. Section 3 explains the new proposed method. An exhaustive case study of an airline carrier is discussed in Section 4. Finally, conclusions are given in Section 5.

2. Literature review

The growing importance of maintenance has generated increasing interest in the development and implementation of optimal maintenance strategies for improving system reliability, preventing the occurrence of system failures, and reducing maintenance costs.

An effective maintenance policies plan not only reduces operating costs but can ensure greater aviation safety and punctuality. Although a variety of management strategies have been proposed that address the airline crew scheduling problem (Yang et al., 2003; El Moudani and Mora-Camino, 2000), little research has stressed maintenance policies and strategies.

The determination of an effective set of maintenance policies requires an effective failure and reparation process investigation normally based on non-trivial knowledge about the past performance of components or systems, in particular in terms of failure times.

A robust modelling of the reliability performance of a complex system permits the application of robust models minimizing the total relative cost of the equipment and/or maximizing the system availability.

Preventive maintenance is a popular issue for most researchers. Since Barlow and Hunter gave the minimal repair model (Barlow, 1960), many preventive strategies have been developed and implemented. These models support the determination of the proper maintenance intervention intervals, the optimization of the spare parts consumption, and the best management of related operating costs (Wang, 2002).

In the case of complex systems, the reliability performance of the system is studied by following the Failure Process Modelling (FPM) analysis (Regattieri et al., 2010; Battini et al., 2005, 2009, 2013).

However, to date, the aforementioned models have not been significantly applied in the aviation industry. The analysis of the costs of major air carriers by Wu and Caves (2000) and Thiassou et al. (2013) quantifies the effects of maintenance on aircraft availability and variable costs. Sachon and Pate'-Cornell (2000) have developed a systematic method to quantify the effect of the maintenance policy on delays, cancellations, and flight safety. The method is based on a probabilistic analysis. A study of costs and intervention intervals has been proposed by Wolde and Ghobbar (2013). However, this study is applied to railway carriers.

Several authors have developed studies based on a prognostic approach, well described by Janasak and Beshears (2007). In particular, Benedettini et al. (2009) discuss the evolution of prognostic systems in the Integrated Vehicle Health management (IVHM). This approach provides continuous monitoring and real-time assessment of vehicle functional health, predicts remaining useful life of faulty or near failure components, and uses this information to improve operational decisions. In brief, the goal is the definition of a prognostic health management (PHM) system. PHM is now considered an approach to enhance equipment availability by decreasing downtime for repair at a reduced cost.

Nicolai and Dekker (2006) categorized the Condition-Based Maintenance strategies for PHM in corrective and preventive maintenance over a finite (dynamic) and an infinite (stationary) prognostic horizon. The finite models are dynamic because these models can generate dynamic decisions that may change over the planning horizon. Fritzsche et al. (2014) implement a PHM system based on the optimal prognostic distance (PD) to minimize maintenance cost.

The preventive maintenance strategies in the aviation system are also investigated by the introduction of the maintenance free operation period (MFOP). MFOP is a metric, alternative to MTBF, used by the Royal Air Force, similar to a warranty that esteems the probability of not having unscheduled maintenance for a definite interval of time (Kumar et al., 1999).

The MFOP concept combined with an adequate preventive maintenance strategy leads to a downward adjustment of the failure rate.Kumar et al. (1999) and Crocker and Kumar (2000) develop several interesting mathematical models.

Fritzsche (2012) extends existing models by implementing a dynamic failure rate using the operational learning effect of Duffey and Saull (2003) integrated into the MFOP concept with the objective of enhancing the availability of aircrafts and reducing costs due to aircrafts on the ground.

Furthermore, inspection intervals are mainly related to the detection of damage. The FAA regulations specify the nature and frequency of maintenance of some critical components. Some studies – Clarke et al. (1996) and Sriram and Haghani (2003) – tried to improve aircraft operation based on such constraints. The approaches presented concerned components subject to regulation.

Cobb (1995) models repair times, including relation to the stocks level, to compare different maintenance vendors.

The spare parts management in the aviation sector is another very relevant issue. Spare parts service is a critical factor to the success of a company. Sherbrooke (1968) was the first to analyse a multi-echelon inventory model for repairable items. He developed an approximate technique (METRIC) to calculate the stock levels at each echelon. Cohen et al. (1997) performed a benchmark study of service parts logistics (SPL) systems for technologically complex high-value products. They provided a detailed introduction to SPL and reported the industrial practices and trends. Muckstadt (2005) collected his and others' research results on SPL systems. Alfredsson and Verrijdt (1999) considered a two-echelon inventory system where the demands at facilities were not backordered but satisfied through emergency lateral trans-shipments (ELT), a direct delivery from a central warehouse, or a direct delivery from a manufacturing facility. Kutanoglu and Mahajan (2009) modify their model by assuming that the central warehouse has infinite capacity and minimize the total cost subject to time-based service level constraints. van der Heijden et al. (2013) develop an optimization heuristic for the cost trade-off between the standard throughput times (TPT) for repair and transportation and the spare parts inventory reduction.

Sarker and Haque (2000) demonstrate how simulation-based optimisation can help spare parts inventory policies in systems operating with block replacement. The response of the system was studied for a number of case problems. Lee et al. (2008) develop a solution framework that integrates a multi-objective evolutionary algorithm (MOEA) with the multi-objective computing budget allocation (MOCBA) method for the multi-objective simulation optimization problem applied to the aircraft spare parts allocation problem. Lendermann et al. (2012) investigate the multi-location inventory problem by quantifying synergy potential between locations. They also discuss how the total service lifecycle cost can be further reduced without increasing risk right away from the initial provisioning (IP) stage onwards by taking into account advanced logistics policies such as pro-active re-balancing of spares between stocking locations.

The forecasting of spare parts consumption is a relevant issue for an effective application of the previous optimization models. Ghobbar and Friend (2002, 2004), Regattieri et al. (2005) and Lolli et al. (2001) discuss the methods for forecasting the demand of spare parts. Manzini et al. (2009), Faccio et al. (2010) and Basten et al. (2012) have developed innovative methods and an algorithm for the management of spare parts in industrial systems, which have not yet been applied in the aviation sector.

The determination of an effective set of maintenance policies based on a systematic and robust approach, and in particular its application in the aviation sector, is an important issue in the literature. For this reason, the authors propose an original methodology and its application in a real case.

3. Proposed method

The authors propose a method to optimize the maintenance policies for aircraft components based on three steps. Fig. 1 shows a framework of these three steps. It is important to note that in the aircraft sector, there are several interventions defined in terms of time interval by airworthiness authorities. However, the major part of maintenance activities is governed by suppliers and users. Clearly, the proposed method is applicable only to this second group of components. The first step addresses the failure process modelling – FPM (reliability analysis) of each single critical component (Manzini et al., 2010). Critical components are usually a small part of the total number of components of an aircraft and are usually selected with a Pareto analysis on a multi-criteria function considering the number of past failures, the magnitude and the costs of these failures, and the impact on the safety of flight and others.

The failure process modelling is realized by the procedure discussed in Regattieri et al. (2010). The target is the determination of statistical functions representing the failure rate λ(t) and the Reliability R(t) of the components that are useful for both non-repairable and repairable components, characterized by stationary or non-stationary failure times, which also consider censored data.

Specialized maintenance software can allow users to automatically process statistical distributions that approximate reliability functions. In the real case discussed in the following sections, the reliability analysis is performed using the software Weibull++® suite of ReliaSoft®. In the aircraft scenario, the application of the well-known Weibull and Gamma distributions can be useful.

The expressions of the reliability R(t) and of the probability density function of time to failure f(t) of the Weibull-3 parameters (Weibull 3P) distribution are:

$$R(t) = e^{\left[-\left(\frac{t-\gamma}{\eta}\right)^{\beta}\right]} \quad (1)$$

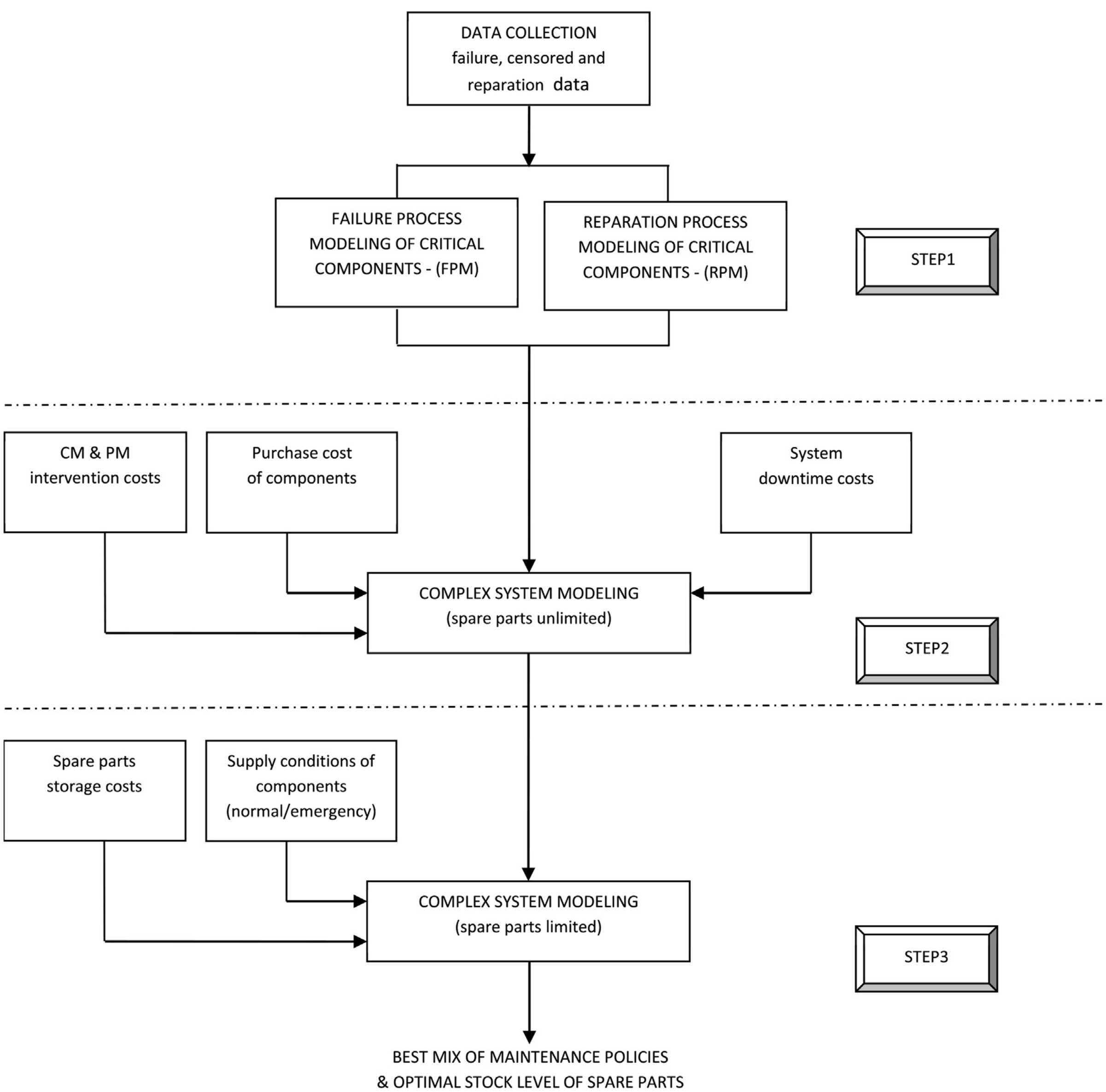

Fig. 1. Proposed method for the determination of the maintenance policy and the best inventory management strategy.

$$f(t)=\frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1}e^{\left[-\left(\frac{t-\gamma}{\eta}\right)^{\beta}\right]} \quad (2)$$

where η is the scale parameter ($\eta > 0$), β is the shape parameter ($\beta > 0$), and γ is the location parameter ($\gamma \in \mathbb{R}$).

The generalized Gamma distribution is a distribution described by the scale parameter ($\theta > 0$) and by the shape parameters ($\beta > 0$) and ($k > 0$). The probability density function in this case is given by:

$$f(t)=\frac{\beta}{\Gamma(k)\cdot\theta}\left(\frac{t}{\theta}\right)^{k\beta-1}e^{-\left(\frac{t}{\theta}\right)^{\beta}} \quad (3)$$

The same approach is also applied for the modelling of the maintenance intervention after a failure of each critical component. The target is the determination of the mathematical distributions for the probability density function and for the cumulative function representing the probability of the end of the maintenance intervention. Normal, Weibull, and Gamma distributions are the distributions often used. This process can be called Reparation Process Modelling (RPM).

The second step of the proposed general methodology addresses the modellisation of the entire aircraft (combining the models of the single critical components in step 1) and the research of the best maintenance policy by using a simulative approach.

The reliability functions describing the different critical components are combined using the reliability theory (i.e., components in series, in parallel with or without redundancy, etc.) to achieve the reliability modellisation for the entire aircraft (Ebeling, 2005; Manzini et al., 2009).

Additionally, this analysis can be supported by commercial software. In the real case discussed in the following sections, the software BlockSim® suite of ReliaSoft is used.

Using the reliability modellisation of the aircraft is made possible by a simulative approach to analyse different scenarios characterized by different maintenance policies, particularly in terms of components managed by corrective or preventive policies and, in this last case, in terms of time intervals between preventive interventions.

The simulative analysis involves both the reliability parameters with regard to failures and reparation behaviours of all of the components and the costs, in particular, of the maintenance crew and spare parts, as well as due to the loss of flight hours and the rerouting of passengers.

The cost function used in the simulative model considers four main factors for each analysed component, including:

$$C_{tot}=C_{CM}+C_{PM}+C_{IM}+C_{STOCK} \quad (4)$$

where

$$C_{CM}=C_{CREW_{CM}}+C_{PARTS_{CM}}+C_{LOSS_{CM}}$$

$$C_{CREW_{CM}}=C_{I_{CM}}+C_{TE_{CM}}$$

$$C_{LOSS_{CM}}=C_{FH_{CM}}+C_{RP_{CM}}$$

$$C_{PM}=C_{CREW_{PM}}+C_{PARTS_{PM}}+C_{LOSS_{PM}}$$

$$C_{CREW_{PM}}=C_{I_{PM}}+C_{TE_{PM}}$$

$$C_{LOSS_{PM}}=C_{FH_{PM}}$$

$$C_{IM}=C_{CREW_{IM}}+C_{LOSS_{IM}}$$

$$C_{CREW_{IM}}=C_{I_{IM}}+C_{TE_{IM}}$$

$$C_{LOSS_{IM}}=C_{FH_{IM}}$$

The simulative model developed considers several other assumptions, in particular:

- The network discussed is a single echelon system with one spare parts warehousing centre due to the regional character of the analysed problem;
- The spare parts inventory strategy is based on the Reorder Point model (ROP). Spare parts stock must face the requests caused by corrective maintenance. Inspections can generate unexpected parts requirements, and the spare parts demand coming from the scheduled PM interventions often is not clear, for example, because of the time shifting between scheduled and realized interventions over the network;
- Preventive maintenance (PM) and inspections (IM) are scheduled over-night or in the weekend stops;
- An inspection can generate immediate preventive actions (the model considers a parametric average ratio of IM resulting in a PM).

The authors suggest a progressive tuning of the set of maintenance policies by a trial-and-error procedure starting with a reference scenario derived from the application of several mathematical approaches dealing with the optimization of the preventive interventions (i.e., Duffuaa, et al., 1999) or the inspections (Taghipour and Banjevic, 2011). The primary goal is the minimization of the above-mentioned cost function C_{tot}.

In step 2, required spare parts are always available in the company warehouse; this represents a type of technical optimization based only on the reliability performance of the aircraft system.

In step 3 of the proposed methodology, the inventory management of spare parts is introduced and managed by inserting the simulative model of supply costs in normal conditions and in

Table 1
A summary of the available information.

Component	Number of times to failure	Number of censored times	Number of PM reparation times	Number of CM reparation times
A	115	10	21	98
B	106	10	15	76
C	20	0	6	13
D	36	10	11	28
E	29	6	5	19
F	37	0	12	27

Table 2
Statistical distributions parameters for the failure process.

Component	Distribution	Parameters		
A	G-Gamma	μ(h) = 8781	σ = 0.391	λ = 1044
B	G-Gamma	μ(h) = 8016	σ = 0.287	λ = 1029
C	Weibull 3P	β = 1738	η(h) = 4036,042	γ(h) = 1993,52
D	G-Gamma	μ (h) = 9013	σ = 0.256	λ = 2308
E	Log-Normal	LogMean(h) = 8058	LogStd = 0.515	
F	G-Gamma	μ (h) = 7545	σ = 0.348	λ = 0.694

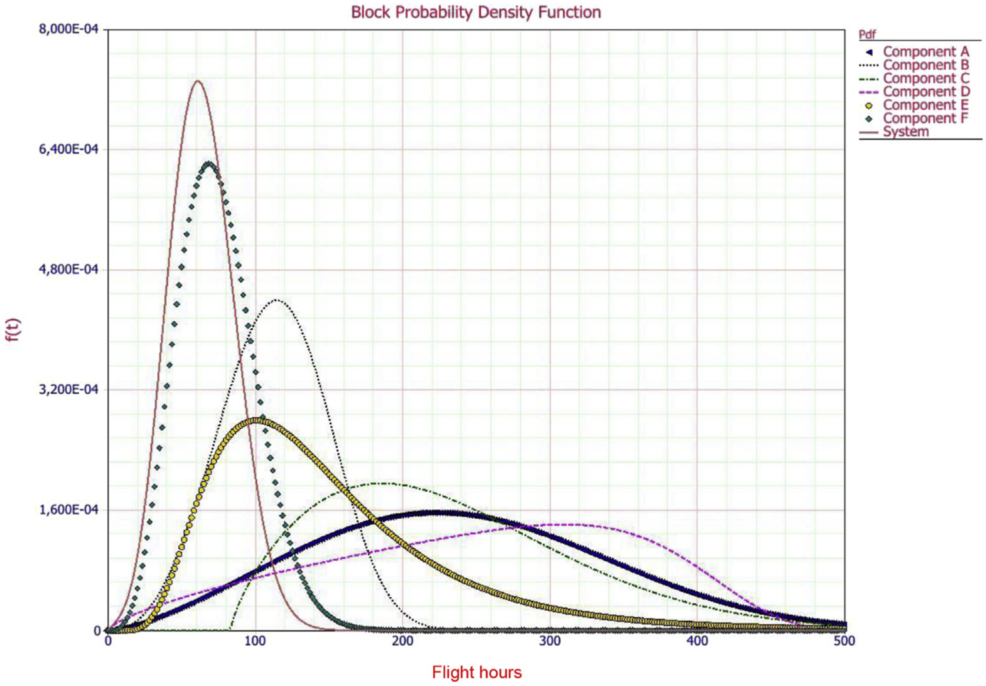

Fig. 2. Probability density functions f(t) of components.

emergency conditions of lead times and storage costs of the components.

In this final analysis, a complete optimization, which also considers the logistics impact of spare parts in terms of the availability or non-availability of spare parts in the local warehouse, is performed. The results are a set of maintenance policies for the critical components of the aircraft optimizing the principal costs of a commercial aircraft.

The proposed method considers a single echelon spare parts network due to the regional characteristics of the fleet considered in this study. Aircraft system components are stocked in a single location and are managed using the Reorder Point (ROP) system, which considers an inventory target level. This means that in the case of a fault at an outstation, a replacement would have to be shipped from the central warehouse.

Several authors (e.g., Lendermann et al., 2012; Simao and

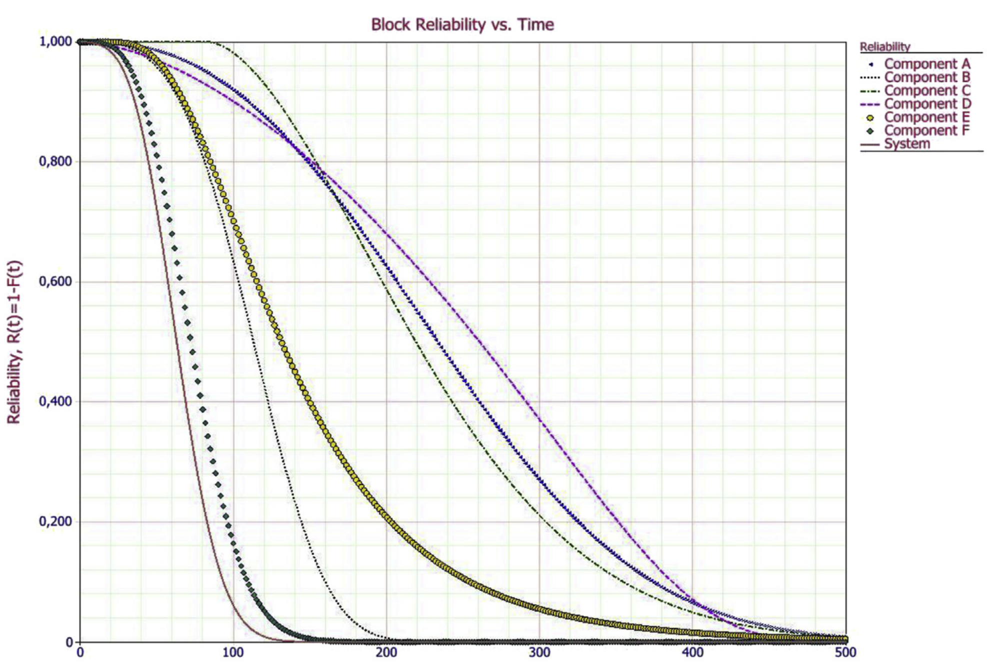

Fig. 3. Block reliability R(t) vs. flight hours.

Table 3
Statistical distributions parameters for the reparation process.

Component	Corrective		Preventive	
	μ (min)	σ (min)	μ (min)	σ (min)
A	345,1	32,1	276,2	25,6
B	210,3	45,5	189,1	40,5
C	650,6	67,3	650,7	67,0
D	37,3	8,9	18,5	4,1
E	738,2	121,2	590,4	96,8
F	276,6	45,1	193,2	31,5

Table 4
Purchase costs and supply conditions of components.

Component	Purchase cost (normal condition) (US$/item)	Purchase cost (emergency condition) (US$/item)	Lead time (normal condition) (dd.)	Lead time (Emergency condition) (dd.)	Storage cost (US$/year)
A	165,6	187,5	40	10	21,5
B	1557,1	2125,0	20	5	203,9
C	667,5	1125,0	10	1	86,8
D	289,4	289,4	10	1	37,6
E	6736,3	10625,0	40	5	875,7
F	427,5	875,0	5	1	55,6

Powell, 2009; Lye and Chan, 2007 and MacDonnel and Clegg, 2007) propose high performance computing simulation approaches for the spare optimization in flight networks (i.e., D-Simpair, Vari-metric, Opus10 and others) based on the MRP approach. These systems use sophisticated optimization procedures and consider a large number of decision variables, and they also require a complete and up-to-date set of data that is not always available and robust (e.g., the known demand coming from preventive maintenance interventions that will actually be made, an up-to-date version of the bill of material (BOM) of aircrafts and a continuous maintenance of these documents, and an estimation of incoming failures).

Due to this difficulty, these forecasting tools are not widely used within the airline community at the moment. Considering the survey by Tysselan and Halskau (2007), of 175 respondents, 152 use ROP and only 23 were using an MRP-based system.

For these reasons, and for the current step of the research, the authors consider a spare parts management system based on the ROP system and on inventory target levels for components.

The authors applied the proposed methodology in several real cases, and the results were very encouraging. In the next section, a real case is discussed.

4. Case study

The real case concerns the Airbus A-320 family fleet of an important Italian carrier. The analysed fleet works for a regional network centred in southern Europe.

The company collected reliability data of all failures and maintenance interventions since 2001. The proposed approaches are applied to more than 100 critical components.

In this paper, a simplified application involving six critical components (named A to F) is discussed.

For each component, we collected time to failures, suspended (censored) times, and times to repair both in corrective and preventive interventions Table 1.

By the application of the failure process modelling, namely FPM (Regattieri et al. [12]) provided in step 1, the best distribution of the reliability function for each component is calculated.

Table 2 shows the best distribution and corresponding parameters for the failure process. All distributions fit the real data with a goodness of fit parameter (correlation index) higher than 0.97.

Figs. 2 and 3 show the probability density functions f(t) and the reliability functions of components derived from the FPM approach, respectively.

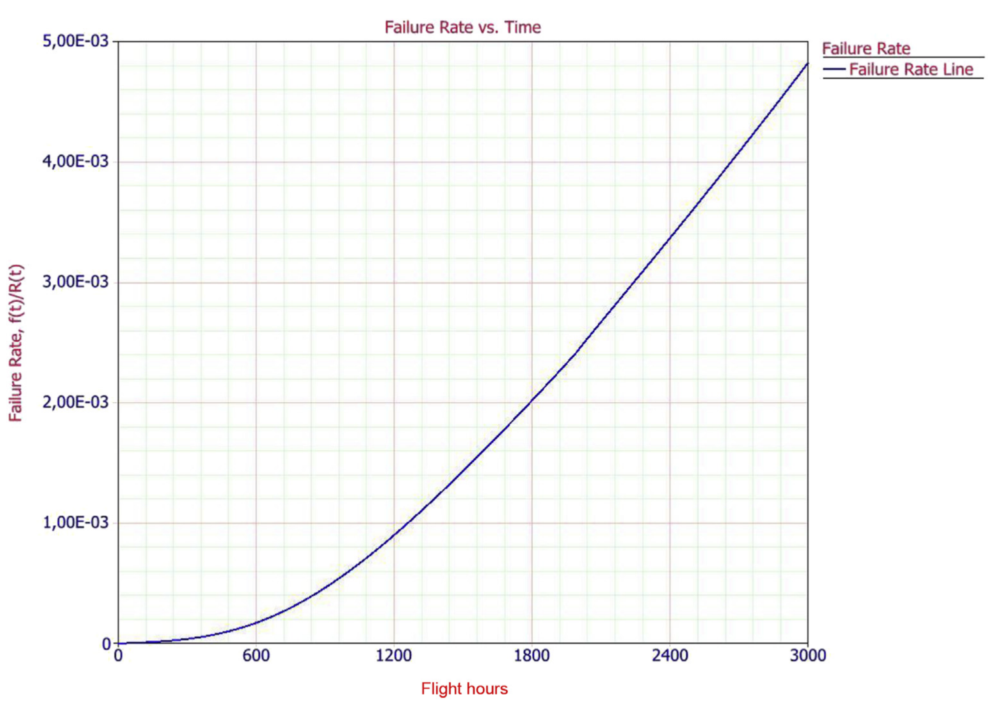

Fig. 4. System failure rate λ(t) vs. flight hours.

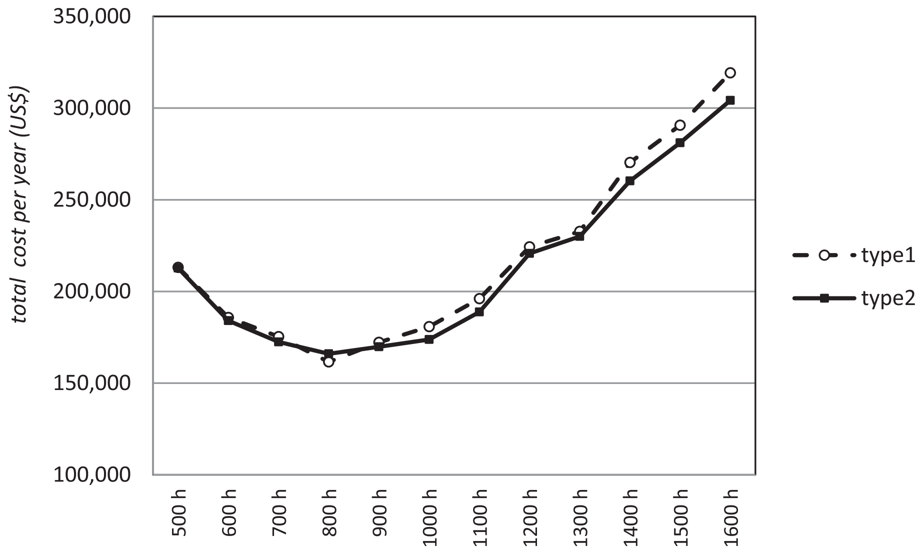

Fig. 5. Average value of total maintenance cost (Type 1 and Type 2 methods).

Table 5
Average availability (A) and average total cost for the different maintenance policies (A/cost).

Time horizon (years)	CM only	PM type 1 (ΔT = 800 h)	PM type 2 (ΔT = 800 h)
1	0.991/US$ 1.013.330	0.986/US$ 161.593	0.987/US$ 165.987
3	0.991/US$ 3.426.023	0.982/US$ 520.648	0.986/US$ 515.693
5	0.991/US$ 5.831.325	0.981/US$ 869.778	0.986/US$ 871.476

By the application of the reparation process modelling, namely RPM provided in step 1, the best distribution of maintainability function for each component is calculated. A set of times to repair both in corrective and in preventive interventions is available for each component.

The normal distribution is used to describe the reparation process; the goodness of fit value (correlation index) for all components is higher than 0.90.

Table 3 summarizes the parameters' mean values (μ) and standard deviations (σ) of the normal distributions for the reparation process of each component.

The reliability and probability of reparation functions that characterize the different critical components are combined using the reliability theory to achieve the model for the entire aircraft.

In particular, considering that a failure of only one of the components causes the grounding of an aircraft, the components are configured as a pattern series. This allows a reliability model for the entire aircraft to be built. With this model, it is possible to calculate all of the reliability functions of the entire system (i.e., reliability,

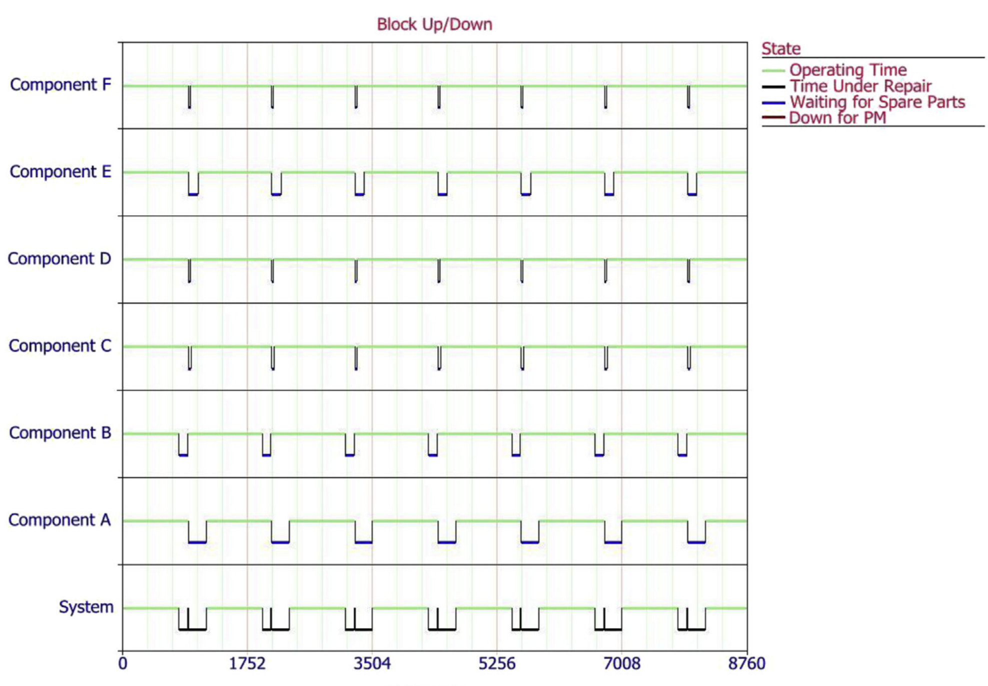

Fig. 6. Up/down patterns (no spare parts in stock).

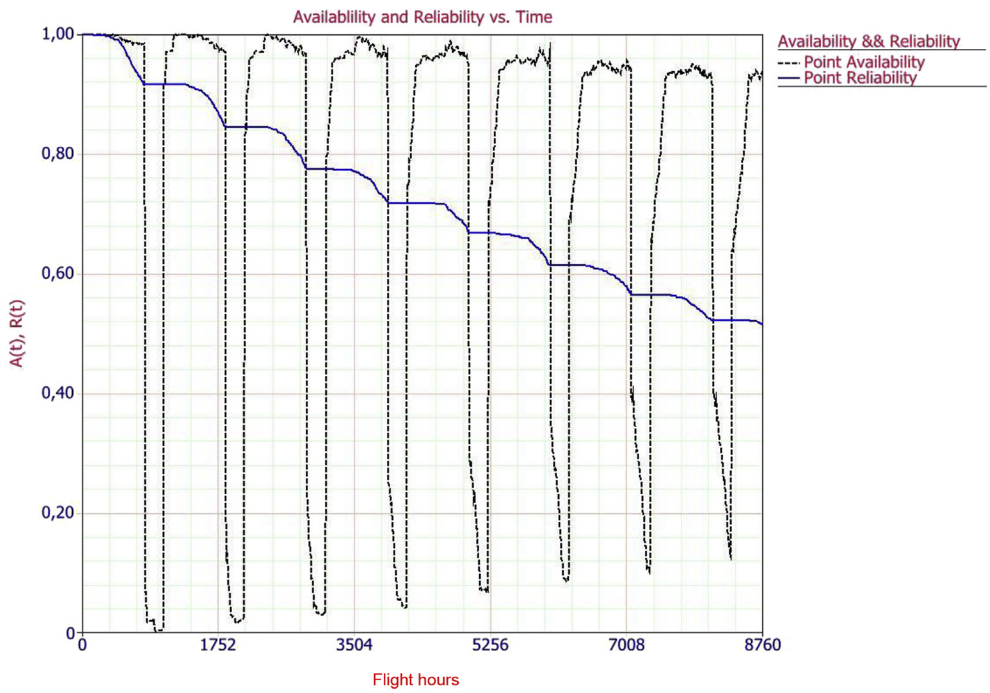

Fig. 7. System availability and reliability (no spare parts in stock).

maintainability, availability).

For example, Fig. 4 shows the failure rate of the entire system.

Using the modellisation of the aircraft, it is possible, via a simulative approach, to analyse different scenarios characterized by different maintenance policies in terms of components managed by corrective or preventive policies and, in this last case, in terms of time intervals between preventive interventions.

The simulative analysis involves both the reliability parameters with regard to failures and reparation parameters of all components and costs. Specifically, it considers the cost of personnel and spare parts and the cost due to the loss of flight hours and the rerouting of passengers.

Table 4 summarizes these parameters.

The aircraft downtime cost is 13.125 US$/flight h, according to data supplied by the company based on the Liebeck approach (1995). The cost of the maintainers is 60 US$/h. Maintainers can be

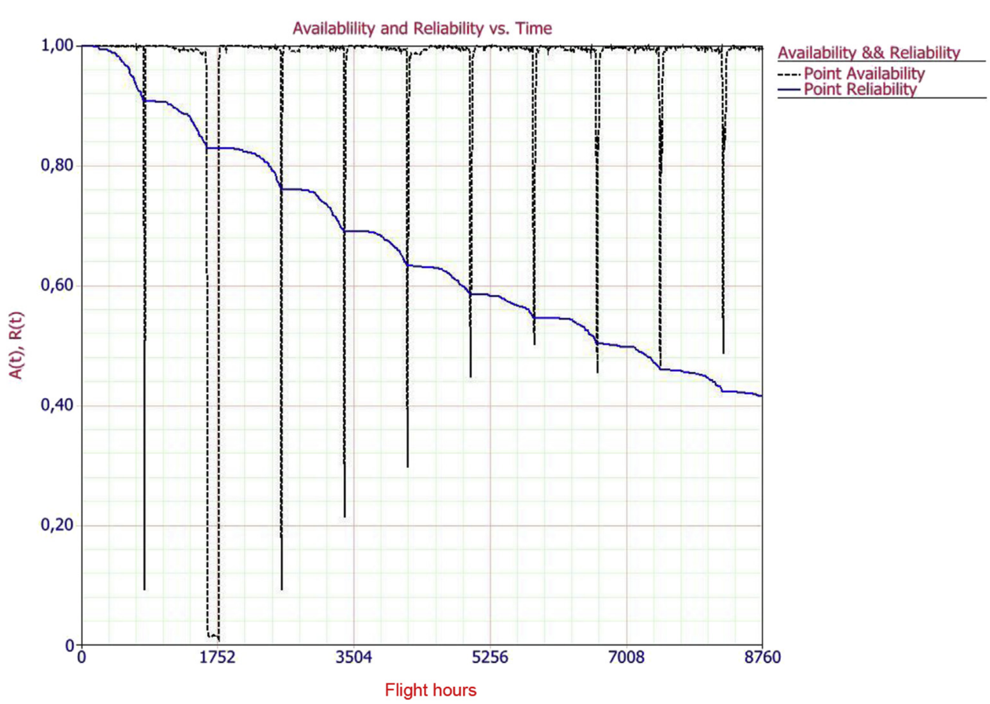

Fig. 8. Availability and reliability (spare parts in stock = 1, ROP = 0).

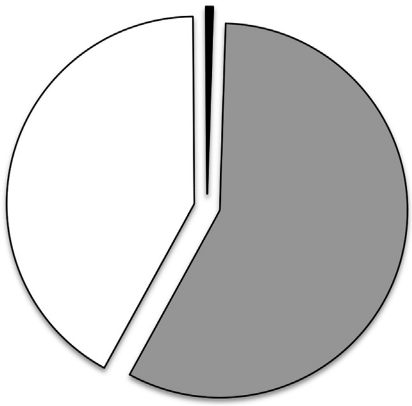

Fig. 9. Cost break down (spare parts in stock = 1, ROP = 0).

considered always available. Therefore, there are no call costs.

4.1. Determination of maintenance policies with infinite stock of spare parts

The authors suggest a progressive tuning of the set of maintenance policies by a trial-and-error procedure starting with a reference scenario characterized by the "only corrective" policy for all of the components.

This policy is the one used before this study by the carrier for the six analysed components.

It is assumed that the spare parts are always available in stock (i.e., infinite spare parts condition). The costs of spare parts are considered only when components are used.

The simulations are realized using three different time horizons: 1 year, 3 years, and 5 years.

A second scenario investigated addresses the introduction of a preventive policy for components.

For the sake of simplicity, only one time interval between preventive interventions is used for all six components. This hypothesis is realistic because each preventive intervention on an aircraft usually groups many PMs on single components. However, it is possible to consider different time intervals for the different components.

The age-based replacement strategy (type 1) and the constant interval replacement strategy (type 2) (Duffua et al., 1999) are both developed in the simulative model.

By simulation, in particular 1000 runs for each scenario, different time intervals of preventive interventions are analysed. For both of these models, the optimal time interval is approximately 800 h Fig. 5 shows the average value of the total maintenance cost (corrective plus preventive) linked to the time interval of interventions (called ΔT).

The effect of the introduction of the preventive strategy on the availability of the aircraft and then on total costs is very significant. Table 5 shows the results of the simulations (also 1000 runs for each scenario in this case).

The yearly average cost obtained by simulation in the only corrective strategy is very close to the real value sustained by the company.

4.2. Maintenance policies with a finite stock of spare parts

The availability of spare parts assumes a relevant role for the optimization of the maintenance policies. For this reason, step 3 of the proposed methodology addresses the analysis of the system availability considering a preventive policy and a finite level of the stock of spare parts.

In the proposed case study, the first group of simulations for step 3 is realized considering the type 1 preventive policy with no spare parts in stock. In this case, the purchase orders are always performed under emergency conditions. The downtimes of the system are very significant. The average value of availability is 0.763, and the average total annual cost of this policy is US$ 895.180.

Fig. 6 presents the up/down pattern of each component and the up/down pattern of the entire system.

The system has very significant downtimes due, in particular, to the continuous procurement under emergency conditions of the

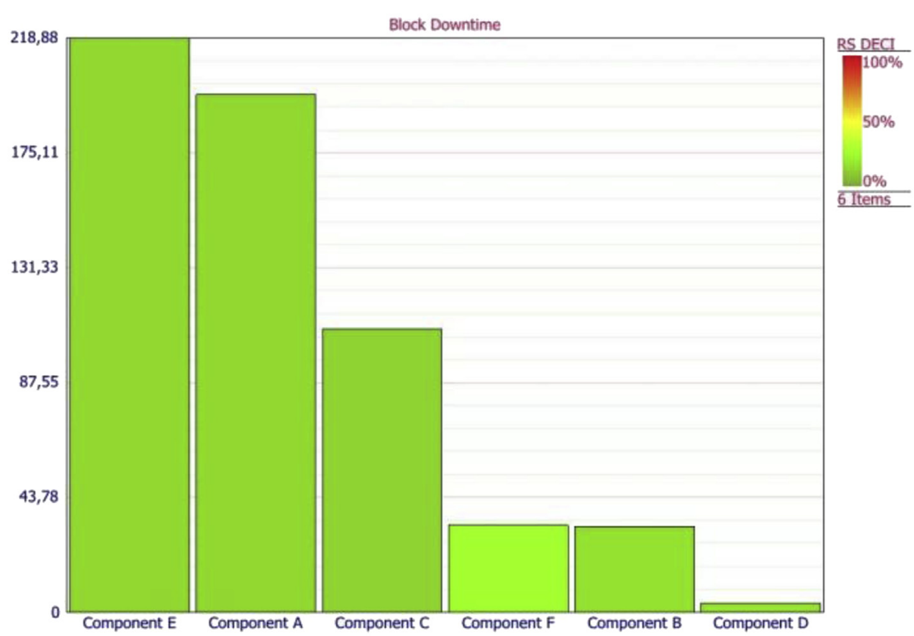

Fig. 10. Downtimes of components (spare parts in stock = 1, ROP = 0).

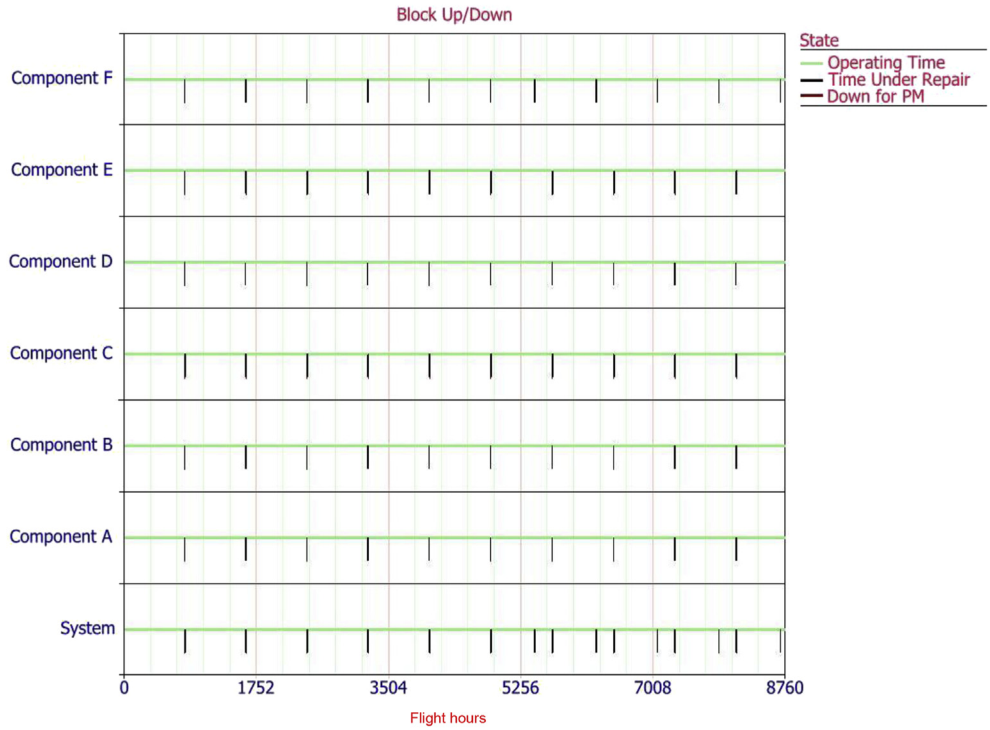

Fig. 11. Up/down patterns (two spare parts for A and E and one spare part for the others).

components. Fig. 7 presents the availability and the reliability of the aircraft in this condition.

The presence of components in stock reduces the waiting time. For this reason, the authors investigated a scenario with one spare part for each component in stock. The re-order point (ROP) is fixed at zero.

The availability of the system grows significantly (Fig. 8); its average value is approximately 0.960, and the average annual total cost decreases to 238.048 US$.

In this scenario, the cost of corrective maintenance (CM) is low, but the cost of downtimes remains very significant. Fig. 9 shows the cost breakdown.

The cost of downtimes is mainly due to the downtimes of components A and E (Fig. 10).

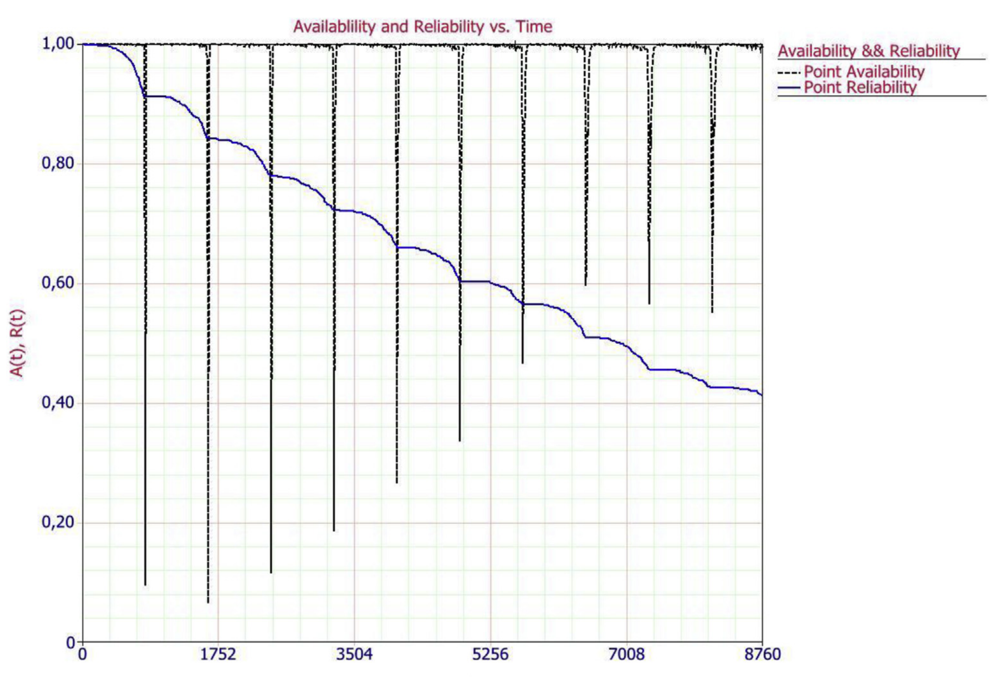

Fig. 12. Availability and reliability (two spare parts for A and E and one spare part for the others).

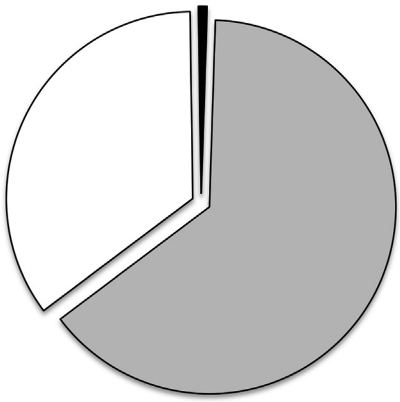

Fig. 13. Cost breakdown (two spare parts for A and E and one spare part for the others).

Table 6
Availability and average annual cost of different maintenance strategies.

Maintenance strategies	Average availability	Annual average cost (US$)
Corrective only	0.991	1.013.330
Corrective + preventive (type1) No spare parts in stock	0.763	895.180
Corrective + preventive (type1) Spare parts in stock = 1, ROP = 0	0.960	238.048
Corrective + preventive (type1) Two spare parts for A and E and one spare part for the others	0.980	181.995

The application of the proposed method allows for a total cost reduction of approximately 80% more than the previous applied maintenance policy.

Considering the effect of components A and E, a new scenario is investigated: two spare parts in stock for components A and E (ROP = 1) and one spare part in stock for the other components (ROP = 0).

The simulation of this scenario (1000 runs) results in an average annual total cost equal to 181.995 US$. This maintenance strategy (i.e., type 1, time interval = 800 h) with two spare parts for A and E (ROP = 1) and one spare part for the others reduces downtimes (Fig. 11), increases availability (Fig. 12) and decreases costs (Fig. 13). The average value of availability is approximately 0.980.

Adopting the last strategy, the waiting times due to the supply of components are null (including components A and E). Thus, it is not considered appropriate to continue further increasing the stock.

In brief, it is possible to summarize the results of the analysed case study (Table 6).

5. Conclusion and further research

The definition of an effective maintenance policy plays a fundamental role in the availability and total cost of complex systems (machines, equipment, etc.).

The authors developed a three-step methodology based on Failure Process Modelling FPM/Reparation Process Modelling RPM to define an optimal maintenance policy based on preventive and corrective approaches.

The method combines the use of mathematical models and simulation. The simulative approach permits a fine tuning of the policies, which are set by analytical models.

The method also considers the effect of the inventory management of spare parts; their impact on total cost is very significant.

The case study developed in an airline carrier, and in particular on a set of critical components, shows that a correct definition of the maintenance policies is a very critical issue and requires effort often not sufficiently focused on by engineers.

The maintenance policies applied to aircrafts are governed by a mix of airworthiness authorities' regulations and choices by suppliers and users. This allows airlines to use different strategies to minimize the total costs of maintenance.

The widespread application of the redundancy in the components and subsystems of aircrafts often results in an intensive use of corrective policy.

However, the cost of downtimes represents the most important element of the total cost. Therefore, their reduction is necessary by the application of effective preventive strategies.

The developed methodologies exploit Failure Process Modelling for a robust application of preventive mathematical models. The results are tuned by a simulative approach, which also considers the logistic impact of spare parts.

The results are very interesting. Considering only six critical components for the A320 aircraft family, the total annual cost is reduced to a value of approximately 20% of the previous amount. The average availability of the aircraft remains close to high values.

As demonstrated by this study, a preventive policy can play a fundamental role in the optimization of the total cost of maintenance for complex systems. Many mathematical models are available in the literature. Several models can be integrated into the proposed method. The authors consider this subject very important for further research.

The extension of the proposed approach to the multi-echelon networks and the introduction of spare parts inventory strategies linked to the MRP system, which are then based on the known demand coming from the preventive interventions, are also very interesting areas for further studies.

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