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IMPACTS OF A PROGNOSTICS AND HEALTH MANAGEMENT SYSTEM ON AIRCRAFT FLEET OPERATING COST DURING CONCEPTUAL DESIGN PHASE BY USING PARAMETRIC ESTIMATION

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ABSTRACT

The scope of the study is to analyse the operating cost of an aircraft fleet, during conceptual design phase, when installing a Prognostics and Health Management (PHM) system. Part of the work is devoted to the process and related methodologies aimed at estimating the cost and the fleet operative behaviour in a very preliminary phase of the product life cycle. The cost estimation is carried out using a commercial and proprietary parametric cost estimation software in order to quantify the impact of a PHM system in terms of additional costs related to the installation of the new system (i.e. PHM system) and the benefits due to its use. These benefits are related to the reduction of maintenance hours necessary to carry out hard structural inspection and to the increment of aircraft availability. To correctly estimate the impact of these benefits, a fleet simulation model, which employs Monte Carlo methodology, has been developed within this research.

NOMENCLATURE

BITE	Built-In Test
CBM	Condition Based Maintenance
CMC	Central Maintenance Computer
COTS	Commercial Off The Shelf
DMC	Direct Maintenance Cost [$]
DOC	Direct Operating Cost [$]
FH	Flight Hour [h]
FY	Fiscal Year
GSE	Ground Support Equipment
HUMS	Health and Usage Monitoring System
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IVHM	Integrated Vehicle Health Management Systems
LCC	Life Cycle Cost [$]
MFD	Multi Function Display
N.A.	Not Applicable
PBS	Product Breakdown Structure
PHM	Prognostics and Health Management

RUL	Remaining Useful Life
SHM	Structure Health Monitoring
TOC	Total Operating Cost [$]

1 INTRODUCTION

The Prognostics and Health Management (PHM) system is considered an additional aircraft on-board equipment able to predict the remaining useful life (RUL) of the main aircraft components with the aim of reducing their maintenance cost and increasing aircraft availability and safety. In rotorcraft aerospace segment, the Health and Usage Monitoring System (HUMS), which is a variety of PHM, proved to be useful in facilitating Condition Based Maintenance (CBM) [1] and hence in reducing operating cost [2]. In aircraft sector, from some decades, these kinds of systems have been implemented on some main aircraft components such as avionic equipment, in the form of Built In Test (BITE), and on engines, which are among the most expensive ones. Lately, airframers are studying the installation of another prognostic system specifically developed to monitor and extend the life of the aircraft structure, which represents another remarkable cost item. The Structure Health Monitoring (SHM) should be able to reduce considerably the time necessary to inspect the airframe during maintenance checks C and D [3], hence reducing maintenance cost and increasing structure reliability and safety.
Since PHM systems used for avionics and engine are already successfully implemented on aircraft reducing maintenance expenses, in the present work, the analysis has been focused on the possible benefit due to the introduction of the SHM system. The software tools and methodologies employed to quantify the effect of the SHM on a complex system, such as a commercial transport aircraft, required a relative small amount of data which are available during the early aircraft design phase.
SHM system, as the other aircraft on-board systems, could introduce additional maintenance cost (even the SHM system sensors and computer may have a fault) and sometimes it may notice false positive detections determining unnecessary maintenance actions. On the other hand, SHM could be able to: extend the aircraft components service life, reduce the number of necessary spare parts, lessen the repair time (maintainers are aware of the failure location) and optimize the maintenance activities also increasing the aircraft availability. For a commercial transport aircraft, more availability means more flights and revenue. Since, the more availability is more difficult to quantify for military aircraft, the present work takes into account a civil aircraft fleet as a test case.
Moreover, examining a complete aircraft fleet it is necessary to properly estimate the effect of the maintenance optimization. This is suitable considering that maintenance teams, maintenance management and aircraft operations are subjects designed for a fleet instead of the single aircraft. To better calculate aircraft fleet parameters, it was necessary to develop an environment in which the fleet operation is simulated. Moreover, to obtain actual operating parameters, the model has to include Monte-Carlo methodology [4], [5] in which some important variables, such as failures, repair time etc., should be simulated using a stochastic approach. The description of this fleet simulation environment and its results are reported in the paper.
From the cost estimation point of view, to evaluate the effect of the PHM system, it is essential to include each item of the Life Cycle Cost (LCC). The tools used [6],[7] has to evaluate the cost during preliminary design phase. Spares and maintenance labour cost are directly affected by PHM system, however considering maintenance optimization issues, also fuel and spares management have to be taken into account. Other important cost items are related to the number of flight (i.e. aircraft availability) and the reduction of flight delay and cancellation due to unscheduled maintenance action.
A final comparison based on LCC has been made between aircraft fleets in a configuration with and without the PHM system, to show the results and the main differences.

2 MAIN ASSUMPTIONS AND REFERENCE AIRCRAFT FLEET

The installation of PHM system on aircraft produces effect for both military and civil fleet. In view of this fact, both these categories of aircraft should be investigated. The authors opted for civil aircraft fleet since the greater availability of cost data, the more uniform mission profile and the greater ease of turning the PHM benefit into economic value. In particular, for civil aviation, many organizations such as ICAO (International Civil Aviation Organization), IATA (International Air Transport Association), Eurocontrol, etc. regularly publish analyses on liner operating cost giving a detailed and reliable estimation of the worth of the different cost items. In this way, it is possible to calibrate the cost model with these data estimating the impact of the PHM system and avoiding evaluation error due to an uncalibrated cost model. Moreover, the regular mission profile and utilization of civil fleet help in estimating the benefit of prognostic system. Conversely, military aircraft are very often characterized by variable mission profiles especially when they are used for training or for war operations. Additionally, in civil aviation, all aircraft characteristics and operative performances can be assessed in terms of cost or profit. Features like aircraft availability or operational readiness are easily evaluated respectively as an increment of earnings and reduction of delay cost. These considerations, for the same operational characteristics, would be less evident for military aircraft.

Another assumption is to focus the analysis on the impact of PHM system for structure (i.e. SHM system) not considering PHM for the other aircraft components such as avionics and engine. This was decided considering that PHM system for these two aircraft components have already been implemented in the modern civil jet-liner. As reference, the Integrated Vehicle Health Management Systems (IVHM) installed on Boeing 777 aircraft in conjunction with the implementation of the Central Maintenance Computer (CMC) helps to reduce from 50% to 80% the maintenance cost [8]. Therefore, their influence it is already taken into account in present aircraft maintenance expenses, which is used, in this study, as reference.

Concerning the aircraft fleet case study, a fleet composed by 44 aircraft was selected. The fleet is made up of the same aircraft typology, a twin jet-engine regional airliner with 150 seats, which is comparable with Airbus 320 and Boeing 737. The hypothesized number of aircraft and homogeneity of the fleet is quite different from the current airlines that could have more than 100 aircraft belonging to different categories. Notwithstanding, these choices are a best compromise between having fleet reliable results and the level of complexity of the simulation model. In particular, a fleet of 44 aircraft, monitored for 5 years, is considered relevant to evaluate SHM benefit in terms of maintenance and fleet number reduction.

The airframe DMC, when SHM is installed, has been reduced to consider the save in maintenance cost due to the unnecessary airframe inspections and failure identification. The fraction of these maintenance tasks is not easily quantifiable; hence it is assumed a reduction range from 16% (Case A) to 30% (Case B) of the entire structure DMC. Since the scheduled maintenance checks are about 16% of the structure DMC [9], therefore, the minimum reduction signifies the elimination of the scheduled inspection. The maximum value (i.e. 30%) takes into account the time reduction, given by SHM, necessary to identify the failure and to perform special inspection.

3 STOCHASTIC SIMULATION MODEL

In order to perform an evaluation of the impact of PHM systems on a fleet of civil aircraft, several aspects related to logistics and maintenance should be taken into account. Many of these processes, involved in such a complex system, are deeply affected by levels of uncertainties. To overcome this problem, stochastic models have been considered useful and among the most common probabilistic forecasting methods, Monte Carlo Simulation was selected. Moreover, in order to create a tool able to represent all

the features of the system and their mutual relationships, an object-oriented software has been selected as platform to build the model (SIMIO®). Once the software and the stochastic method have been selected, each important element of the system has been studied in depth, paying a relevant attention to those characteristics that would have a direct impact on the system effectiveness. Then, the model has been implemented in SIMIO® and some detailed scenarios have been selected.
Considering a real operative and logistic support system and its most relevant activities, a model with the following features has been developed.

- A certain number of airports geographically located (latitude, longitude and altitude)
- Each airport contains a certain numbers of logistics and maintenance infrastructures depending on the function it has to perform.
- Each airport is characterized by a scheduled departures plan with a clear association between aircraft and missions.
- Each airport is equipped to perform line checks with a daily frequency. During this type of maintenance activity, visual inspections, fluid levels check, tyre and brakes and emergency equipment checks are carried out.
- Each airport hosts A-level maintenance activities during which routine light maintenance and engine inspections are performed.
- In case of old aircraft, B-check could be required (with actions similar to A-checks but with different tasks). It could be performed either at the gate or in a separate hangar.
- Those airports that are also designated as maintenance bases, should allow both C-checks and D-checks.
  - C-checks are usually carried out with a frequency of 20-24 months requiring from one to two weeks of activities. In this period of time structural inspections of the airframe opening access panels are performed. Moreover run-in tests and both routine and non-routine maintenance actions are performed [10].
  - D-checks are usually expected with an average frequency of 6 years requiring up to two months of activities. During this kind of maintenance, several actions are performed: major structural inspection of airframe after paint removal; engines, landing gear and flaps removal; instruments, electronic and electrical equipment removal, interior fittings (seats and panels) removal; hydraulic and pneumatic components removal [10].

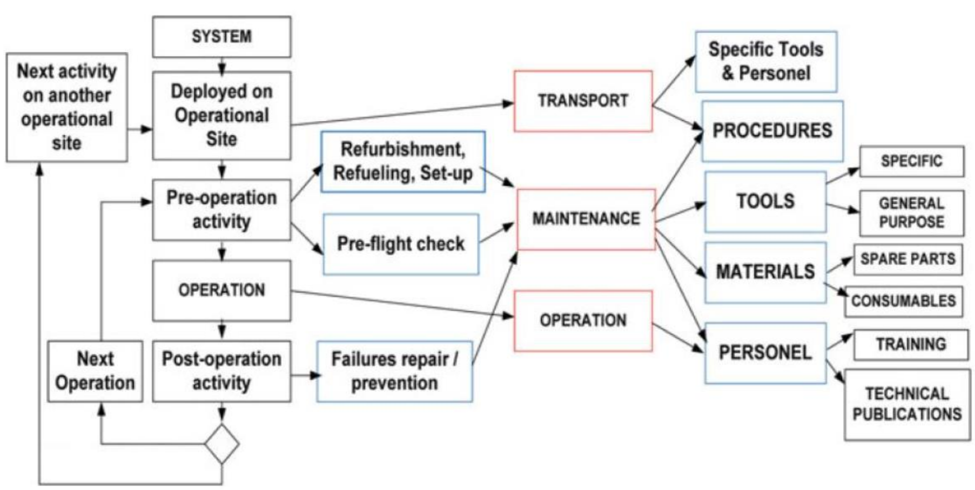

Figure 1 Operative and Logistic support for a civil airlines

The high level of complexity of this system (see Figure 1) implies stochastic models to be exploited. Indeed, the system is deeply affected by uncertainties in many areas. In particular, maintenance activities should be analysed in detail because characterized by several unpredictability:

- Number of occurrences
- duration of maintenance actions
- number of operators involved
- tools required
- severity
- …

In order to allow the aircraft to be operative, the model, like the real system, should be composed of different kinds of logistic and maintenance infrastructures with related tools and personnel. Moreover, in order to evaluate the impact of health monitoring systems on a fleet a great variety of elements shall be taken into account. In particular, in order to make the system operative, the following analyses shall be carried out:

- Proper fleet sizing
- Aircraft performance refinement
- Operative bases sizing
- Maintenance infrastructure and personnel sizing

With the aim of performing such activities, a high number of relationships among the different involved elements and the noticeable level of uncertainties requires specific simulations techniques.
In order to overcome this problem, stochastic models have been considered and among the most common probabilistic forecasting methods, Monte Carlo simulation was selected. Moreover, in order to create a tool able to represent all the features of the system and their mutual relationships, an object-oriented software has been selected as platform to build the model (SIMIO®). This choice, performed at the beginning of the first stage of the research, revealed to be a proper one during the second stage (phase at which this document refers to). Indeed, it has been possible to recover the basic structure of the model and improve it aiming at fulfilling the new requirements.

3.1 Model description

Each airport is modelled in a way through several logical blocks able to perform different functions:

- A logical block aimed at managing the missions
- A logical block aimed at managing the logistics
- A logical block able to simulate pre-flight check activity
- A logical block aimed at

These blocks are connected using paths (connectors that allow information and data to be transferred). When two or more paths are intersecting, a decisional node is used in order to select the path through which sending the information. Examples of these objects are:

- Decisional node to select between scheduled and unscheduled maintenance actions
- Decisional node to check the flight hours to verify whether scheduled maintenance is required.

The Figure 2 shows the logical process followed by each mission from the beginning to the end of the mission.

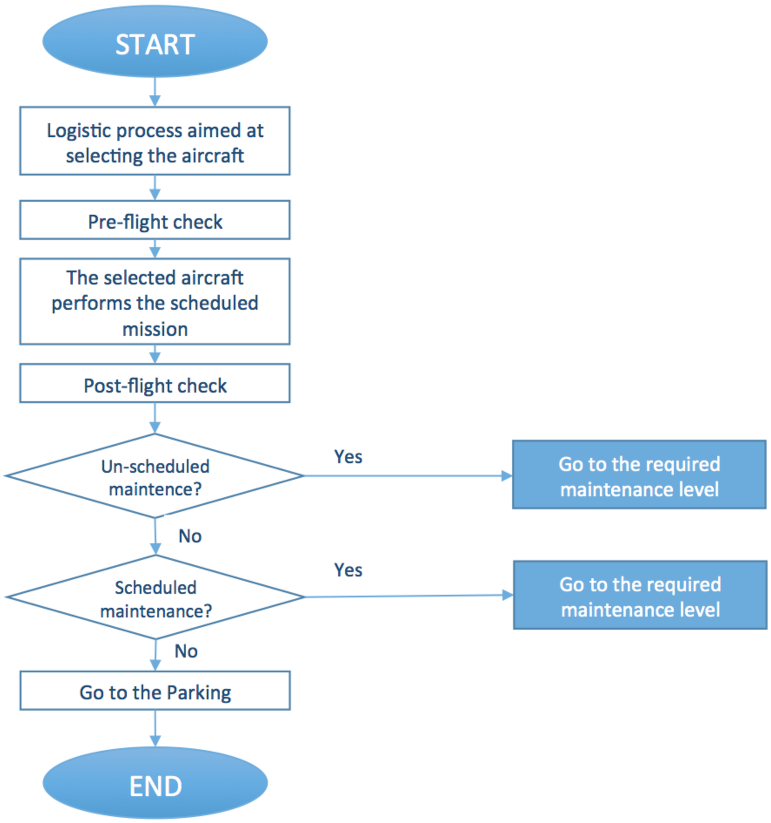

Figure 2 Flow-chart describing the sequence of main activities performed during each single mission

At the beginning of the simulation, the list of scheduled missions for a selecting period of time (repeatable) is loaded for each airport. Figure 3 offers a screenshot of the planned departures from Athens Airport. Each scheduled mission is characterized by the name of the destination airport, the scheduled time and the identification code of the flight.
Figure 4 shows an example of the table used to characterize the fleet, defining the airport which the aircraft belongs to and other variables such as flight hours, maintenance, availability and the date of the last maintenance check. These variables shall be updated during the entire simulation and are exploited to perform other evaluations.

Airports | Turin Airport | Amsterdam Airport | Athens Airport

	To	Sched	Flight
1	AMSTERDAM	10,75	AM1
2	PARIS	10,76	PA4
3	ROME	14,55	RO4
4	LONDON	16	LO5
5	AMSTERDAM	23,25	AM1
6	PARIS	23,26	PA4
*			

Figure 3 Example of departures plan from Athens airport

Athens Airport | Barcelona Airport | Berlin Airport | Brussels Airport | Bucharest Airport | Frankfurt Airport

	Flight	Flight Hours	Maintenance	Availability	Last_B_Check_Month
1	AM1	FlightHours[1]	MaintenanceFlag[1]	Availability[1]	0
2	AM2	FlightHours[2]	MaintenanceFlag[2]	Availability[2]	0
3	AM3	FlightHours[3]	MaintenanceFlag[3]	Availability[3]	0
4	AM4	FlightHours[4]	MaintenanceFlag[4]	Availability[4]	0
5	AM5	FlightHours[5]	MaintenanceFlag[5]	Availability[5]	0
6	LO1	FlightHours[6]	MaintenanceFlag[6]	Availability[6]	0
7	LO2	FlightHours[7]	MaintenanceFlag[7]	Availability[7]	0
8	LO3	FlightHours[8]	MaintenanceFlag[8]	Availability[8]	0
9	LO4	FlightHours[9]	MaintenanceFlag[9]	Availability[9]	0
10	LO5	FlightHours[10]	MaintenanceFlag[10]	Availability[10]	0
11	PA1	FlightHours[11]	MaintenanceFlag[11]	Availability[11]	0
12	PA2	FlightHours[12]	MaintenanceFlag[12]	Availability[12]	0
13	PA3	FlightHours[13]	MaintenanceFlag[13]	Availability[13]	0
14	PA4	FlightHours[14]	MaintenanceFlag[14]	Availability[14]	0
15	PA5	FlightHours[15]	MaintenanceFlag[15]	Availability[15]	0
16	RO1	FlightHours[16]	MaintenanceFlag[16]	Availability[16]	0
17	RO2	FlightHours[17]	MaintenanceFlag[17]	Availability[17]	0
18	RO3	FlightHours[18]	MaintenanceFlag[18]	Availability[18]	0
19	RO4	FlightHours[19]	MaintenanceFlag[19]	Availability[19]	0

Figure 4 Fleet definition

3.2 Outputs of the simulation model

The simulation model has been exploited to perform several iterations in order to gather useful information to be used as input in the cost model, as shown in the following sub-sections. SIMIO® allows the users to trace all the variables defined during the creation of the model during the entire period of the simulation. Moreover, it is possible to gather data about some pre-defined variables that are intrinsic within each logistic block or element used to build the model. The standard output suite offered by the program can record and show the minimum, the maximum and the average value of a certain variable considering the overall simulation period. In is also important to notice that in view of the fact that the model exploits the Monte Carlo simulation approach, several repetitions of the same scenario are required to obtain reasonable results. In this way it is also possible to evaluate the effects of some deterministic or stochastic parameters with respect to the number of repetitions.

Considering the case addressed in this paper, it has been important to record and analyse all those data required as input for the cost model. In particular:

- The total amount of flight hours for the fleet and for each single aircraft employed.
- The total amount of maintenance hours for the fleet and for each single aircraft. In this case it has been very useful to obtain data for the different types of maintenance actions and on their frequency.
- Number of maintenance bases per each type

It is worth to notice that the results reported in this section refers to a set of 5 years simulation of the above-described scenario and the hypotheses reported in Table 1.

Considering the results reported in Table 2 (only case A results are listed for shake of simplicity), it is clear that the introduction of a SHM system allows enhancing the efficiency of the overall airlines. Indeed, requiring a reduced number of maintenance activities, the level of availability of each single aircraft is increased and thus the number of completed missions.

Table 1 Hypotheses of the simulations

	Frequency [10]	**Duration [hour] (mean value) without SHM** [10]	**Advantages of SHM [%] (Case A)**	**Advantages of SHM [%] (Case B)**
A-Check	600 FH	10	0%	0%
C-Check	6000 FH	216	-16%	-30%
D-Check	22000 FH	840	-16%	-30%
Unscheduled Maintenance	Random (10% of total maintenance activity)	10	0%	0%

Table 2 Comparisons of the two scenarios in terms of missions completed and missions lost (Case A)

	1st scenario: without SHM [5 years simulation]			**2nd scenario: with SHM [5 years simulation]**		
Airport	**Missions completed**	**Missions lost**	**Inefficiency [%]**	**Missions completed**	**Missions lost**	**Inefficiency [%]**
Amsterdam	34685	557	2%	34921	439	1%
Athens	12814	543	4%	12994	371	3%
Barcelona	15428	159	1%	15476	164	1%
Berlin	13347	230	2%	13416	185	1%
Brussels	3939	85	2%	3940	77	2%
Bucharest	5653	168	3%	5666	151	3%
Frankfurt	9538	234	2%	9583	155	2%
Istanbul	5689	180	3%	5721	137	2%
London	35281	611	2%	35433	439	1%
Madrid	3943	126	3%	3959	93	2%
Moskow	9608	207	2%	9669	150	2%
Münich	1676	210	11%	1750	127	7%
Paris	43341	1220	3%	43741	817	2%
Prague	9417	285	3%	9505	160	2%
Rome	39551	796	2%	39792	536	1%
Turin	5622	210	4%	5655	143	2%
Warsaw	5648	145	3%	5676	111	2%

Table 3 Simulation results summary

	1st scenario: without SHM	**2nd scenario: with SHM (Case A)**	**2nd scenario: with SHM (Case B)**	**Delta**
Mission performed	255345	257057	258765	1712 ÷ 3420
Mission lost	5966	4255	3546	-1711 ÷ -2420
Mission lost [%]	2.28%	1.63%	1.35%	-0.65% ÷ -0.93%
Flight hours	659969	664057	668143	4087 ÷ 8174

Table 3 summarizes the main results obtained for a set of 5-years simulations, with the above-mentioned hypotheses. It stresses again the benefit in terms of missions completed but it reports the overall fleet flight hours for the two scenarios and two different cases. As expressed by the last column of the same table, the fleet of 44 aircraft equipped with SHM is able to fly from 4087 to 8174 extra hours with respect to the first scenario. This means that each aircraft of the fleet with SHM can be exploited every year for additional 19 ÷ 37 hours. This is an important result that will be exploited as input for the computation of the economic benefits of the system.

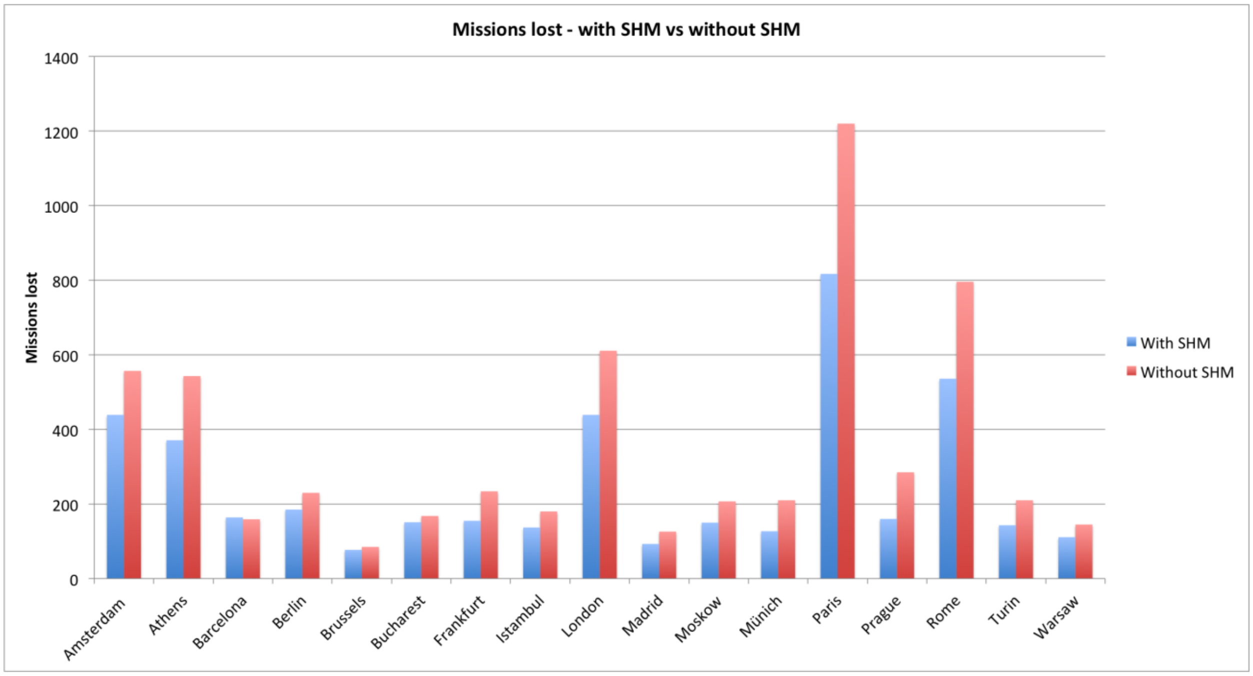

Figure 5 Histogram comparing missions lost in the two scenarios for each airport (Case A)

4 ASSESSMENT OF THE IMPACT OF SHM SYSTEM ON AIRCRAFT LCC

4.1 Parametric Cost Model Set-up and Calibration

After evaluating the benefit of SHM system on fleet operational parameters, this paragraph describes the cost model used to perform the cost-benefit analysis. The cost model has been developed within Price TruePlanning® [7] environment, integrated with a proprietary cost model [6]. The aim of this study is also to evaluate the order-of-magnitude of the acquisition cost of the SHM system in addition to understand its influence on operating cost. The first step to obtain the cost estimation on TruePlanning® environment is to define a detailed Product Breakdown Structure (PBS) of the aircraft and the SHM system. It is essential to include the aircraft in the cost model since some cost items such as SHM integration and assembly are assessed correctly only when the overall system complexity (aircraft and SHM) is well defined. Therefore, considering only SHM in the cost model, the SHM development and production cost might be underestimated.
Figure 6 shows a part of PBS that is detailed enough to perform reliable assessment, nevertheless, the typology and quantity of data can be easily obtained during preliminary design phase. The cost model is

defined by around 50 cost objects and the SHM system has been defined by the following components: hundreds of sensors, one acquisition system, one processing unit, one data storage unit and a new tab of the Multi Function Display (MFD) and the software necessary to read the data from sensors and to elaborate and manage them. The PBS of the SHM considered in the analysis is in line with what is expected by other authors [8] and summarized in Figure 7.

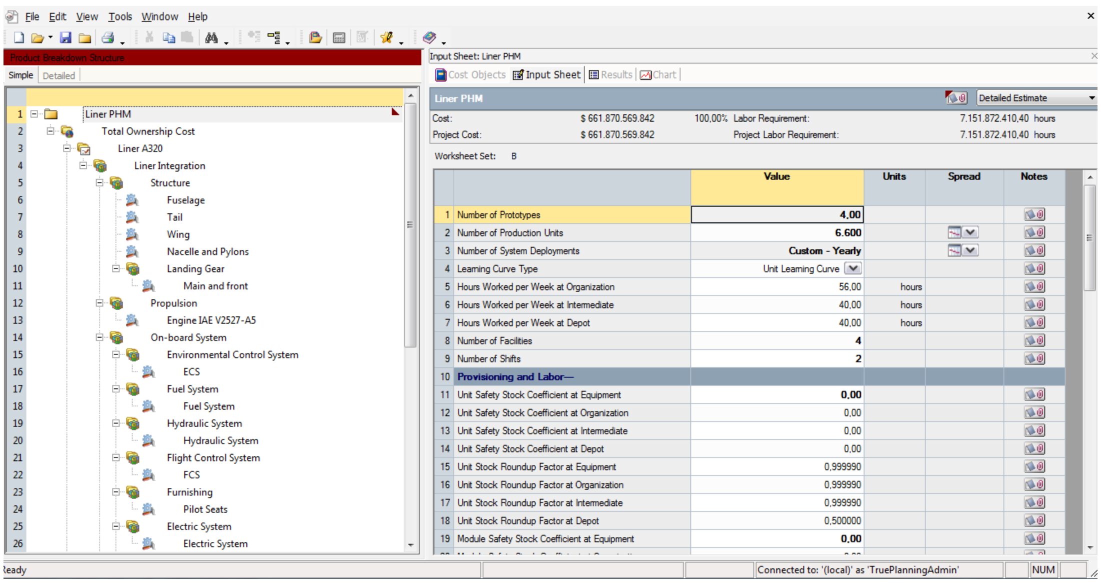

Figure 6 PBS definition on Price TruePlanning® environment.

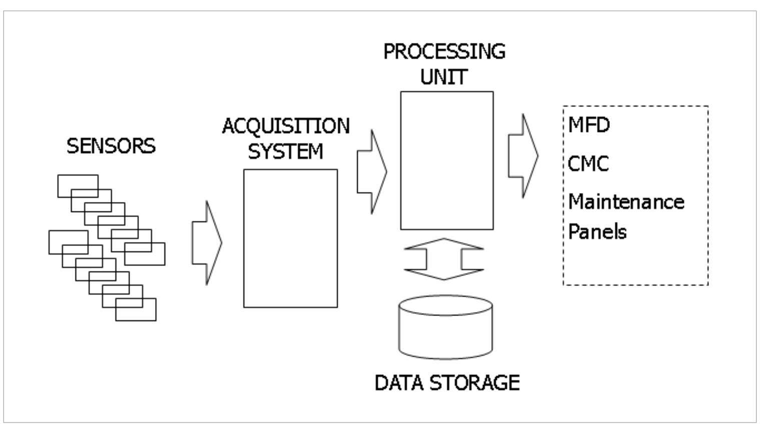

Figure 7 SHM system schematic

Some SHM Commercial Off The Shelf (COTS) components have been considered since they use state-of-the-art technologies. Conversely, the software is influenced by airframe characteristics and usage hence it is deemed as new part of the system.Moreover, considering the large amount of data, which the SHM should process, in the PBS system a Ground Support Equipment (GSE) is also included. It could be

necessary to elaborate in more detail the data acquired during flight. On PBS system the GSE is outlined as a standard computer with specific software.
Before obtaining the first results, it was necessary to specify some main characteristics of the airplane and system component. All data such as component weight, volume and complexity has been calculated using aircraft preliminary design model [11],[12].
The final step is the model calibration and validation, i.e. the model results are compared with reliable external data. Usually, cost data, such as aircraft acquisition cost and operating cost, are not always available. However, for the jet-liner segment some reliable cost data can be found. The first data used for model validation is the aircraft acquisition cost. The average price of a 150 seats jet-liner is around 97 M$ (Airbus A320) [13]. Other important available data are in terms of direct operating cost (DOC) and total operating cost (TOC) and are described hereafter in this section.

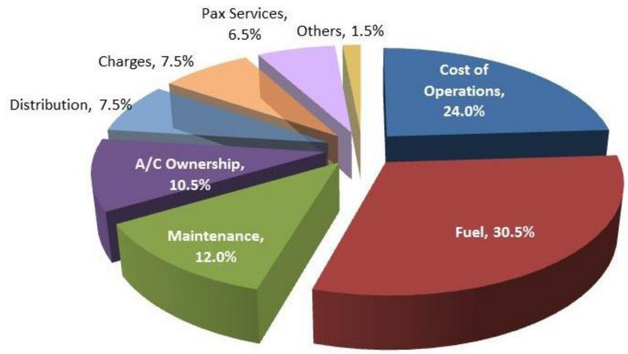

Figure 8 Airline Operational Cost breakdown (FY 2011). Source: IATA [14]

Figure 8 reports the breakdown of the TOC of an airline. Among these cost items, it is possible to identify the major contributors for DOC (i.e. the operating cost directly related to single aircraft operation). They are:

- Fuel cost
- Cost of operations (crew, station on ground and general & administrative)
- Maintenance cost (labour, material and overhead)

The fluctuation of fuel price certainly produces some variations in the percentages shown on the Figure 8, however, the aircraft DMC (Direct Maintenance Cost) is usually a value included between 12% and 18% [8],[10] of the TOC for modern aircraft.

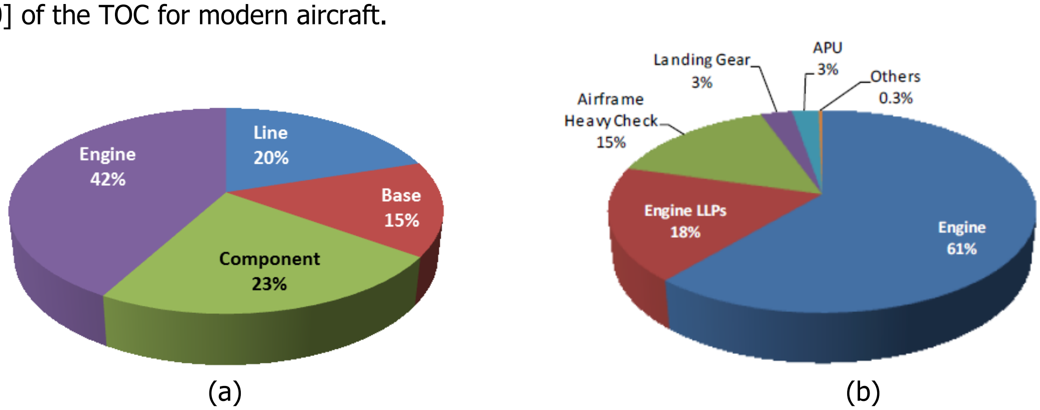

Figure 9 Direct Maintenance Cost breakdown. Source: IATA [15]

In Figure 9a the breakdown of the DMC is reported. It shows that the engine maintenance is the main expensive maintenance activity. Figure 9b represents the breakdown of the maintenance reserves, i.e. the reserves accumulated by airliners to cover future heavy maintenance. These reserves represent the amount of the expenses for the maintenance of the main valuable aircraft components. It is worth noting that the reserves for airframe heavy inspections represent only 15 % of the total reserves [15]. This highlights the fact that the merely reduction in maintenance hour, due to airframe inspections and failure identification removals, could not be enough to facilitate the introduction of SHM system.
Another important reference used to calibrate and validate the cost model is the aircraft maintenance cost per flight hour which is a value, for our test case, between 690 - 924 $/FH [10], [15].

4.2 SHM Cost Results

The results concerning the development cost (see Table 4) should be considered an order-of-magnitude estimation since some important cost drivers such as number of software LOC (Line of Code), SHM components weight and complexity are not readily available. The main cost item is the software development, which includes the development of the prognostic and health management model and the software design, test and qualification. The second cost item is related to the engineering activities necessary to modify COTS components for SHM application. The total development cost takes also into account: the design of the GSE software, the modification of the GSE hardware components considered as COTS and 3 SHM system prototypes.

Table 4 SHM system development cost

Development cost	Project management , quality assurance and documentation	≈ 100 k$
	SHM system integration	≈ 50 k$
	SHM hardware component development	≈ 950 k$
	SHM model and software development	≈ 3600 k$
Total		≈ 4700 k$

The production cost breakdown of the SHM system is reported in Table 5. The calculation is carried out for 6000 products and it considers the learning curve effect. The results are reported in terms of mean unit production cost. The main cost item is the production of the modified hardware components of the system. Considering the reference jet-liner price, the SHM represent a 0.26 % of the total aircraft production cost.

Table 5 SHM system unit production cost

Production cost	Production management and quality assurance	≈ 5 k$
	Production engineering	≈ 8 k$
	Production manufacturing and COTS acquisition	≈ 240 k$
Total		≈ 253 k$

Table 6 shows the reference aircraft DMC and the benefit using SHM system. The global value of maintenance cost is obtained using TruePlanning® software as well as for SHM system DMC. The maintenance cost of each aircraft main component is obtained using proprietary cost estimating software [6]. Both scheduled and unscheduled maintenance are included in the DMC figures.

Table 6 Maintenance cost comparison

	Reference Jet-liner	Jet-liner with SHM (Case A)	Ref. Jet-liner with SHM (Case B)
Aircraft PBS	Unit DMC [$/FH]	Unit DMC [$/FH]	Unit DMC [$/FH]
Flight Control	17.38	17.38	17.38
Hydraulic	29.48	29.48	29.48
Secondary Power	5.29	5.29	5.29
Gear	91.45	91.45	91.45
ECS/Pneumatic/Anti-ice	34.01	34.01	34.01
Fuel	46.86	46.86	46.86
Electric	27.21	27.21	27.21
Avionics	187.43	187.43	187.43
Engines	210.86	210.86	210.86
Airframe	34.77	29.20	24.34
Furniture	47.61	47.61	47.61
Other	23.43	23.43	23.43
SHM	N.A.	1.49	1.49
Total DMC	755.78	751.71	746.84

Both in case A and B the save in maintenance cost is small: respectively -4.1 $/FH and -8.9 $/FH.
As result of the simulation model, another possible benefit is the increment in annual flight hours (from 19 to 37 FH) due to increased aircraft availability. The greater availability could produce a rise in airliner revenue and a reduction of flight cancelation events and their related cost. Focusing on the increase in airliner revenue a realistic value is estimated considering a profit per passenger of 4.13 $ [15]. The benefit obtained is then divided by the aircraft annual flight hours (i.e. 3000 FH) in order to compare it with the above maintenance reduction. Global cost reduction and benefit is listed in Table 7.

Table 7 SHM cost reduction and benefit

	Reference Jet-liner	Jet-liner with SHM (Case A)	Ref. Jet-liner with SHM (Case B)
DMC reduction [$/FH]	-	4.1	8.9
Revenue increment [$/FH]	-	3.9	7.6
TOTAL benefit [$/FH]		8.0	16.5

5 FINAL REMARKS

The PHM systems are well-known in modern aircraft segment in particular for engine and avionic systems that are some of the most important maintenance cost items. These PHM applications gave important reduction in terms of aircraft operative cost. PHM technologies (i.e. SHM for structure) did not have been exploited by airliners to reduce airframe DMC, which is a significant cost item. The integration of a SHM system on a jet-liner aircraft proved to have positive effect in reducing the operative cost and increasing revenue. The save in maintenance expenses are small if compared with the aircraft TOC, but some issue such as maintenance optimization, reduction of aircraft assurance, the increase of safety and a possible aircraft life extension have not yet been quantified. The SHM development and production cost are relatively small in comparison to the global aircraft cost. Finally the fleet simulation and cost estimating model gave results in good accordance with reliable references and they will be further developed for future works to assess in more detail the impact of the SHM system.

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