Airline Fleet Maintenance:

Trade-off Analysis of Alternate Aircraft Maintenance Approaches

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Abstract **– Airline maintenance is a significant contributor to the overall operating costs of airlines, making up 11% of the total operating costs. In fact, the cost of airline maintenance has steadily increased in recent years. An improvement in the approach airlines take to maintain aircraft is needed to reverse this trend.**

Currently, aircraft operators use a preventative maintenance approach, where parts are replaced on a schedule. The purpose of this project is to examine the effectiveness of utilizing a condition-based approach, which considers the actual physical condition of the parts onboard the aircraft to dictate the time at which they are replaced. This additional information would allow parts to be replaced when they near the end of their actual usable life, thus reducing unnecessary replacements.

These two approaches of maintenance were decomposed into three alternatives. The first alternative uses a preventative approach whereas the other two alternatives are condition-based. The preventative alternative involves the transmission of maintenance data to maintenance personnel when the aircraft is out of service. The second alternative, Condition-Based with Flight Line Transfer, involves the transmission of part condition information in between flights. The third alternative, Condition-Based with Airborne Transfer, provides a near real-time condition monitoring system during flight operations.

The three design alternatives were compared in a discrete event simulation, using ARENA®, to determine the overall benefits of each maintenance approach. They were then evaluated using a utility function to determine their overall value to the system's stakeholders.

Based on the results from the simulation, the Flight Line alternative ranked first out of the three considered alternatives. However, the aircraft operators could realize the most benefit by applying the condition-based process to parts with a high infant mortality failure pattern with low mean times between failure given that the other costs (shipping, storage, ordering, etc.) remain the same. The preventative alternative, though it had a very low implementation cost, resulted in more total replaced parts and a lower percentage of parts replaced with notification. While the Airborne alternative provided nearly perfect notification for part replacements, the high implementation and operating costs greatly offset its overall value to the stakeholders.

Keywords-a*ircraft*, *maintenance engineering, fault detection;*

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I. INTRODUCTION

The airline industry is a business of significant risk; for airlines to be profitable, companies must maximize passenger and cargo traffic flow, minimize expenses, and remain a viable competitor against competing airlines. There are several factors that affect the profitability of airlines, including direct and indirect maintenance costs, increasing complexity of aircraft, and regulatory pressure imposed on airlines from governing bodies.

The profitability of airlines is the difference of the revenue earned by the airline and the costs incurred by the airline company. If the total revenue gained is greater than the cost of flight operation, then the airline earns profit; otherwise, the airline loses money.

While there are many costs an airline incurs during operation, 11% of those costs come from direct aircraft maintenance. Direct aircraft maintenance costs include labor, materials, and the repair and replacement of parts on the aircraft [1]. Figure 1, below, shows the direct costs of aircraft maintenance per flight hour [2]. These costs were adjusted for inflation by multiplying the cost of maintenance in a given quarter by the ratio of the current consumer price index to the consumer price index at that quarter [3]. Beginning around the year 2003, the direct costs of maintenance have been increasing over time. The slope of the trend-line represents an increase in the cost of direct maintenance per flight hour by approximately $2.09 (USD) per quarter.

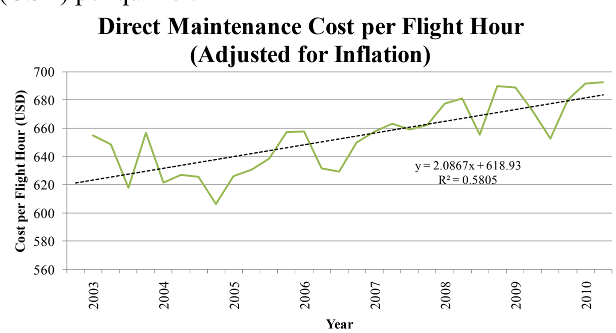

Fig. 1. Direct Maintenance Costs per Flight Hour

Alongside the increasing trend of direct maintenance costs, airlines also have indirect costs associated with maintenance. While an aircraft is in service, it is producing revenue by transporting passengers and/or cargo. When the aircraft leaves operation to go out for maintenance, the airline is not only incurring the cost of performing the maintenance action, but it is also faced with the opportunity cost of no longer producing revenue for the time required for aircraft maintenance. Airline companies are now faced with the task of finding an effective way to reverse the increasing trend of maintenance costs in order to increase their profitability.

II. Problem Definition

1. Stakeholder Analysis

A variety of stakeholders are affected by adjustments to the process of maintaining aircraft. These stakeholders exist at 3 levels: aircraft, workshop, and enterprise.

The aircraft level of the system is concerned with operational changes of personnel and equipment on each aircraft. The primary stakeholder affected on this level is the aircraft flight crew.

Secondly, the workshop level of the system refers to changes in infrastructure, operations, and equipment that occur in the maintenance facility, both at the work site where maintenance actions are performed and at the office where administrative or managerial duties are performed for the maintenance personnel. The primary stakeholders affected on this level are Maintenance, Repair, and Overhaul (MRO) personnel.

Thirdly, the enterprise level of the system refers to changes that affect airline fleet management and its interaction with the general public. This includes communications or data infrastructures, and maintenance or schedule tracking systems that may be implemented or altered. The primary stakeholders affected on this level are the fleet owner, the fleet operator, and the aircraft manufacturer.

2. Need Statement

Given that the direct maintenance costs per flight hour are increasing over time, airline companies need an effective way to reverse this trend and reduce the overall costs of maintenance. The airlines must also consider the effects of indirect maintenance costs when choosing a maintenance approach.

3. Problem Approach

In order to address the need of the airline companies, alternate maintenance approaches will be designed and then analyzed to determine the most effective method to reduce the overall maintenance costs.

In this project, direct maintenance costs are proportional to the number of times a given part onboard an aircraft is replaced. Similarly, the indirect maintenance costs are relative to the amount of lead-time that maintenance personnel are given prior to replacing the given part. This lead-time refers to a part replacement where maintenance personnel had prior knowledge of a part replacement and had sufficient time to prepare and conduct any maintenance work that could be done before the aircraft arrives in the hangar.

4. Scope

There are certain elements of airline maintenance that will not be addressed in this project. The elements that will not be considered are phased maintenance schedules, fluctuating demand and ticket prices, non-maintenance related operating costs, the time spent in the maintenance facility, and outsourced maintenance.

The scope of the project revolves around the frequency of part replacement; the number of maintenance actions performed on the aircraft; part condition tracking; and the aircraft, workshop, and enterprise levels as discussed in the Stakeholder Analysis section of this paper.

5. Assumptions

The primary assumptions of the maintenance system model are listed below.

1. Outsourced maintenance is not modeled or factored into cost calculations.
2. The maintenance system will work as advertised, so safety of the new system will not be modeled.
3. The cost of maintenance labor hours is constant regardless of time of day or day of the week.
4. The aging effect of aircraft is not modeled.
5. Maintenance facilities and personnel will be available when maintenance is required.
6. The labor time associated with part replacement will not be modeled.

III. Design Alternatives

There are three design alternatives considered in this project. The first alternative is a preventative-based approach, which means that parts are replaced on a predetermined schedule. This alternative is considered to be the current maintenance approach used by airline companies today. The other two alternatives are condition-based approaches. Condition-based maintenance (CBM) is based on the reliability of the part, which is based on statistical analyses of key factors that indicate a reduction of reliability of the part or the system as a whole. These factors can include exceeding oil temperature thresholds, voltage spikes, and other faults that are determined to be significant using failure mode analysis. The primary distinction between the alternatives in the model is the time at which maintenance information is made available to maintenance personnel and the frequency at which maintenance updates are provided.

1. Preventative Maintenance

   The preventative maintenance option will schedule parts to be replaced based on the expected life span of the part. This alternative is assumed to be the base-line of this project. Replacing parts on a regular schedule allows maintenance personnel to accomplish preparatory work for those parts that are scheduled for replacement. For parts that require replacement prior to their scheduled time, maintenance personnel are not given prior notification, which increases the indirect maintenance costs.

   The preventative-based alternative utilizes sensors already onboard the aircraft. The maintenance information is transferred to the maintenance personnel in the maintenance bay. Since the aircraft is already in the maintenance bay when the information is transferred, the airline is not producing revenue from the aircraft, and maintenance personnel have no prior notification of parts needing replacement that are not scheduled to be replaced at that maintenance trip.

2. Condition-Based with Flight Line Transfer

   Flight Line Transfer is a condition-based maintenance approach. Flight Line Transfer also utilizes existing sensors onboard the aircraft to monitor the condition of select parts, but additional communication infrastructure is required to transfer the information collected by the sensors to the maintenance personnel. The maintenance information for this alternative is transferred every time the aircraft arrives at the terminal to load or offload passengers and cargo. This transfer allows system health tracking for enterprise level stakeholders, and also allows maintenance personnel to expect part replacements and perform preparatory work prior to the aircraft's arrival at the maintenance facility.

3. Condition-Based with Airborne Transfer

   Similar to the Flight Line Transfer alternative, Airborne Transfer is also a CBM approach. The maintenance information for this alternative is transferred while the aircraft is in flight, giving maintenance personnel lead-time to perform preparatory work, as well as providing live tracking for the enterprise level stakeholders.

IV. METHOD OF ANALYSIS

The three design alternatives will be evaluated based on a utility function that will be determined using a value hierarchy, shown in Figure 2.

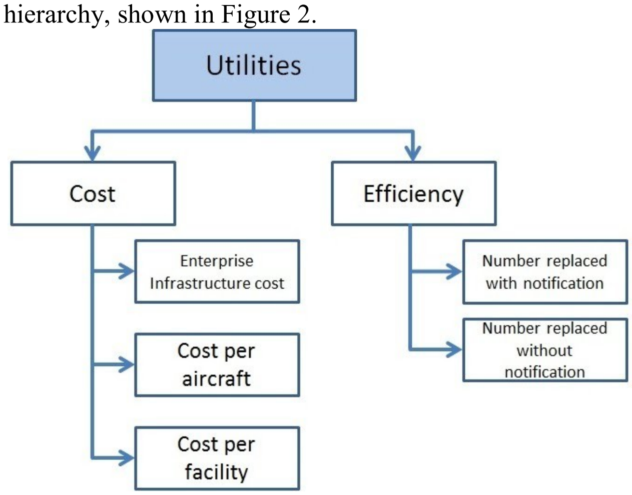

Fig. 2. Aircraft Maintenance System Value Hierarchy

This value hierarchy represents the decomposition of the efficiency associated with the airline maintenance system. The efficiency of the alternative is determined by the number of parts replaced with notification over the life of the aircraft and the number of parts replaced without notification over the life of the aircraft. The sum of these two values is the total number of parts replaced over the life of the aircraft, which addresses the direct cost of maintenance. The notification of part replacement addresses the indirect cost of maintenance.

The efficiency of the maintenance system will then be compared against the cost of that system for recommendation purposes.

V. SYSTEM MODEL AND SIMULATION

A discrete event simulation, using ARENA®, was used to model the various maintenance approaches. The simulation modeled a Boeing 737 aircraft entity, which had an associated age, measured in flight hours, that was calculated based on flight length. The flight lengths were generated using a lognormal distribution with a mean of 2.05 hours and a standard deviation of 1.31 hours, which was based on ramp-to-ramp times of Boeing 737 aircraft from the Bureau of Transportation Statistics [4]. The aircraft also had representative critical parts: 15 parts with a high infant mortality, 15 parts with a constant rate of failure, and 15 parts with an aging effect. Figure 3 shows a simplified depiction of the process flow used in the ARENA® simulation.

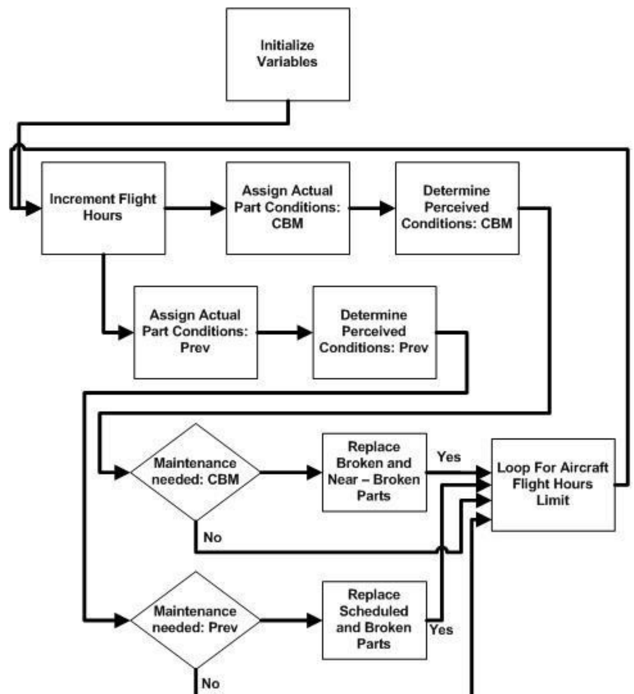

Fig. 3. Process Flow of ARENA® Simulation

The simulation consisted of loops, where each iteration of the simulation represented a flight taken by the aircraft. The age added to the aircraft each time it passed through the loop was calculated based on the aforementioned lognormal distribution. The simulation terminated when the aircraft reached an appropriate age to retire.

The critical parts that were modeled had several characteristics. The first characteristic was the expected life of the part, measured in flight hours. The parts also had a condition, which was a "green", "yellow", or "red" assignment. A "green" assignment referred to a part that was healthy and did not need to be replaced; a "yellow" assignment referred to a part that needed to be replaced, but immediate action was not necessary; and a "red" assignment referred to a part that needed to be replaced at the aircraft's next landing. Alongside the expected life and the condition of the part, the part also had an attribute that recorded whether or not there was prior notification to the maintenance personnel that the part needed to be replaced.

Three different categories of critical parts were modeled: 1) parts with a high infant mortality rate, 2) parts with a constant rate of failure, and 3) parts with an increasing rate of failure as time goes on. The distributions used in the simulations for each of these three categories were based on data retrieved from the FAA's Service Difficulty Reporting Site as well as previous analysis of failure patterns of aircraft parts [5].

A Weibull distribution was used to replicate the three failure patterns. In a Weibull distribution, the α parameter refers to the shape of the curve, and the β parameter refers to the scale. The α parameters for the Weibull distributions for the high infant mortality, constant rate of failure, and aging effect failure patterns were α = 0.5, α = 1.0, and α = 1.5 respectively. Each failure pattern was also given three individual β parameters of 10000, 20000, and 40000 to represent parts that have different average part lives. These parameters are shown in Table I.

TABLE I
ALPHA AND BETA PARAMETERS FOR WEIBULL DISTRIBUTION

			Scale Parameter		
			Low Rate of Failure (Lower Quartile) β=10000	Average Rate of Failure (Average) β=20000	High Rate of Failure (Upper Quartile) β=40000
Behavior Parameter	High Infant Mortality	α= 0.5	α= 0.5, β=10000	α= 0.5, β=20000	α= 0.5, β=40000
	Constant Rate of Failure	α= 1.0	α= 1.0, β=10000	α= 1.0, β=20000	α= 1.0, β=40000
	Aging Effect	α= 1.5	α= 1.5, β=10000	α= 1.5, β=20000	α= 1.5, β=40000

1. Model Inputs

The inputs to the aircraft maintenance simulation were:

1. Maximum Number of "Yellow" Parts

   The maximum number of "yellow" parts refers to a threshold of "yellow" parts on board the aircraft. If at any time during the simulation, the aircraft reaches this threshold, it will require maintenance at the next landing.
2. Predicted Life of Part

   The predicted life of the part is the time that a part should be replaced based on the expected life of the part, not its condition.
3. Probability of Part Failure

   The probability of part failure allows the simulation to assign health states to the part in question, triggering a diagnosis or maintenance action. This value was calculated based on analysis of data available from the Federal Aviation Administration (FAA) Service Difficulty Reporting Site located at [5].

2. Model Outputs

The outputs to the aircraft maintenance simulation were:

1. Number of Parts Replaced

   The number of parts replaced counts the total number of parts that are replaced during the simulation.
2. Number of Parts Replaced With or Without Notification

   The number of parts replaced with or without notification counts the number of parts that are replaced with prior notification (lead-time) versus the number of parts replaced without notification.

VI. Simulation Results

The following graph, Figure 4, shows the output of the simulation. Along the horizontal axis are the different alternatives with associated Weibull β (scale) parameters, and along the vertical axis is the average number of times a part was replaced over the life of an aircraft. The condition-based alternatives are both represented as CBM in the figure as they replaced parts the same number of times throughout the simulation; the only distinguishing result between the two CBM approaches was the number of parts replaced with notification. The Weibull α (shape) parameters are represented by the different shapes, where the diamond represents α = 0.5 (high infant mortality), the square represents α = 1.0 (constant rate of failure), and the triangle represents α = 1.5 (failure due to an aging effect).

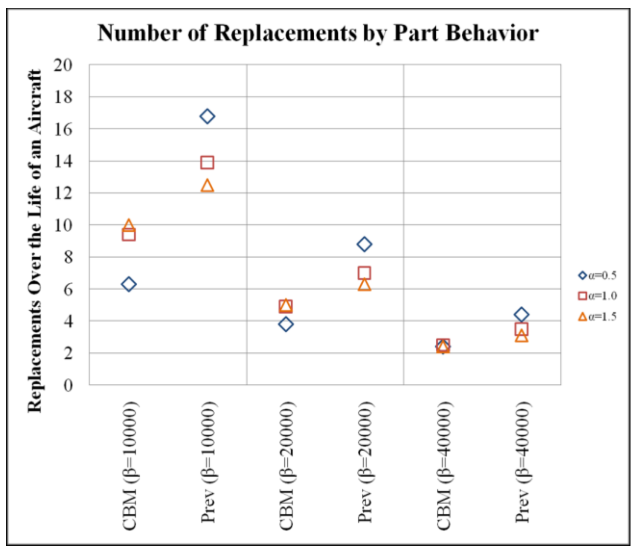

Fig. 4. Simulation Results

From Figure 4, it can be concluded that parts with a smaller β parameter are replaced more frequently than those parts with a larger β parameter as expected. Overall, the condition based alternatives replaced parts a fewer number of times than the preventative alternative.

The three design alternatives were scored using the weighted model in (1).

$$V(x) = \sum_{i=1}^{n} v(x_i) * w_i \quad (1)$$

$V(x)$ represents the overall value, of the alternative, w_i is the associated weight of criterion i as determined by stakeholder input, and $v(x_i)$ is the measured value of alternative x for criterion i.

The measures for each alternative for performance were:

1) the number of parts replaced with prior notification over the life of the aircraft

2) the number of parts replaced without prior notification over the life of the aircraft

The number of parts replaced for each alternative was weighted to represent typical part behavior mixtures identified in [6]. The values for these measures were normalized to a linear scale between 0 and 1 by interpolating the values from a scale of 0 parts (best expected) to 8.1 parts (worst expected). The value of each alternative, $v(x_i)$, was determined for parts replaced with notification and without notification respectively using (2) and (3). MPR refers to the maximum number of times the average part is replaced over the lifespan of the aircraft. The # Replaced With and Without Notification refers to the average number of parts replaced over the lifespan of the aircraft that had or did not have an associated notification.

$$v(x_i) = \left[\frac{MPR - \#\ Replaced\ With\ Notification}{MPR}\right] \quad (2)$$

$$v(x_i) = \left[\frac{MPR - \#\ Replaced\ Without\ Notification}{MPR}\right] \quad (3)$$

The values for the alternatives were then compared against their costs of implementation. To represent the total cost of implementation for each of the alternatives, a notional fleet size of 15 aircraft and 4 maintenance facilities was used to in the total cost calculation. Costs for operation, installation on the aircraft, and installation at the ground station were estimated based on input from representatives from The Boeing Company and Rockwell Collins. Table II shows the total costs for each of the alternatives.

TABLE II
TOTAL COSTS

Alternatives	Cost of Operation (USD)	Cost of Installation per Aircraft (USD)	Cost of Installation per Ground Station (USD)	Total Cost (USD)
Preventative	$0	$0	$0	$0
Flight-Line Transfer	$0	$5,000	$50,000	$275,000
Airborne Transfer	$1.50 per Message Transmission	$50,000	$0 (Included with Aircraft Installation)	$750,000 + ($1.50) x (Number of Parts Replaced)

Figure 5, below, shows the local weights used to evaluate the efficiency and cost of each alternative. The "# Without Notification" weight is higher than the "# With Notification" weight because aircraft operators are more concerned about the parts replaced without prior notification as they cost more to replace than those with prior notification. The additional cost is due to the lack of ability to do preparatory work prior to the aircraft's arrival in the hangar, or through equipment acquisition such as ordering required parts before replacement can occur.

The combination of these measures address the direct and indirect costs associated with the alternatives, while "Total Cost" addresses the cost of implementation of the alternatives.

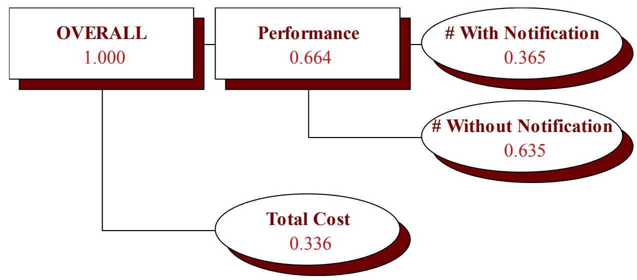

Fig. 5. Weights Hierarchy

Based on the weights hierarchy above, the alternatives were ranked according to their utility. The overall values for each of the alternatives are shown in Figure 6.

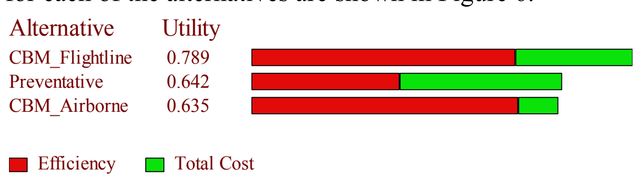

Fig. 6. Value Ranking

The results indicate the Condition-Based with Flight Line Transfer alternative had the highest overall value based on the combination of Efficiency and Total Cost. In contrast, the preventative alternative had a low implementation cost but poor Efficiency due to many parts being replaced both with and without notification. The Airborne Transfer alternative had similar total part replacements with Flight Line but with a higher rate of prior notification, but the value was offset by the high implementation and operating costs.

VII. SENSITIVITY ANALYSIS

Since the costs of part replacement and the modeled parts are unknown due to their proprietary nature, a sensitivity analysis was conducted to see how changes in the weights of cost and efficiency affect which alternative is recommended. Figure 7 shows the results from the sensitivity analysis using Logical Decisions for Windows.

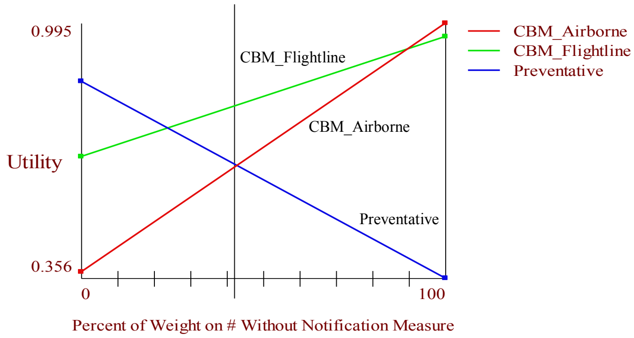

Fig. 7. Sensitivity Analysis

From the graph, it is evident that as the weight on the parts replaced without notification increases and the weight on the cost of the system decreases, the overall value of the preventative approach decreases while the values of the condition-based approaches increase. The overall value of using the Airborne alternative is consistently lower than the values of the other two alternatives due to its relatively high cost of implementation and operation.

VIII. Conclusion

While the highest ranking alternative was Flight Line Transfer, not every part on a given aircraft would be monitored in such a system due to cost and weight restrictions. From the simulation results, parts with different failure patterns should be monitored using different approaches. Thus, it is important for airlines and aircraft manufacturers to consider the failure patterns of the parts on the airframes that they operate when deciding on a maintenance approach. The most benefit from the CBM approaches was realized in parts with a high infant mortality rate. For those parts with an aging effect, the additional benefit from using a CBM approach compared to a preventative approach was less pronounced. Also, parts that generally fail more often (modeled with a smaller β parameter in the Weibull distribution) realized a greater benefit from using a CBM approach than those parts that fail less often.

IX. Future Work

This project could be expanded to encompass improvements to tailor this project to specific airline configurations. These improvements could be any or a combination of the following: 1) refining the cost estimates to more accurately reflect the implementation and operating costs, 2) obtaining more detailed information about the failure behaviors of certain parts to more accurately model the behavior of those parts, 3) including fault and redundancy analysis to ensure the safety of aircraft using a particular alternative, 4) including a human factors analysis on how changing a maintenance approach affects the aforementioned stakeholders, and 5) including further analysis on the expenses associated with scaling the system.

Acknowledgements

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