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Effect of Aircraft Health Management on Aircraft Maintenance Program Development by Aircraft Manufacturer

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ABSTRACT

The objective of the research is to propose a system modeling method for aircraft maintenance program development applying the condition-based maintenance using AHM (Aircraft Health Management) from the viewpoint of aircraft manufacturer. The proposed model based on the MSG-3 (Maintenance Steering Group - 3) considers the uncertainty of aircraft maintenance environment related to the airline operation and assumed system degradation levels. Then, the proposed model is formulated by using the concept of a robust optimization method.

1. INTRODUCTION

The aircraft maintenance program is the requirement to maintain the continuing airworthiness of the aircraft. The requirement is defined by considering the system failure and its effect on safety, operation and cost. The maintenance program is the one of major factors of total maintenance cost and aircraft availability. Increased maintenance requirements will increase maintenance costs and unsatisfactory requirements will affect aircraft safety and availability. In assessing the potential impact of (un)availability, operators stated that aircraft dispatch delays can cost more than $10K per hour with flight cancellations imposing a financial penalty of $100K (and more) per instance. (IATA, 2022)

An aircraft manufacture prepares maintenance program for each aircraft type and obtains approval from lead airline customers in addition to the regulatory authority, because airlines need to prepare the airline maintenance program within its requirement avoiding deviations from it. MSG-3 (Maintenance Steering Group - 3) (A4A, 2018) is considered as the standard method to develop and optimize the maintenance program. The MSG-3 method has been improved by manufactures, airlines, and regulatory authorities since 1960's and is currently maintained by the IMRBPB (International Maintenance Review Board Policy Board) and MPIG (Maintenance Programs Industry Group). The maintenance program approach has been changed from overhaul to hard time, on condition and condition monitoring (A4A, 2018). Then finally, condition-based maintenance is introduced as an optional method of the aircraft for more efficient operation and maintenance since 2018 as an agreed method (IMRBPB, 2018).

The condition-based maintenance can be considered as one of the Aircraft Health Management (AHM) functions. AHM is the method to optimize aircraft operation and maintenance by providing the function to utilize fleet health data, to indicate appropriate time for maintenance before the actual failures, and to share failure data with maintenance on ground lively. All these functions will influence the development of the maintenance program. According to the IATA (International Air Transport Association) report (IATA, 2022), the predictive maintenance using health monitoring mechanisms is estimated to enable airlines to save about $3B per year in maintenance costs.

A lot of PHM researches have been conducted in the aircraft industry. The data-driven aerospace engineering to reframe the industry with machine learning was reported (Brunton et al., 2021) that leveraging data is significant opportunities to improve and optimize aircraft maintenance. Kordestani et al. (Kordestani et al., 2023) reported the various approaches of failure prognostics of aircraft systems such as data-driven, model-based, and knowledge-based approaches. Many of them focus on the field of "sense" and "analyze" process of AHM while AHM covers from sense, acquire, transfer, analyze and act.

Although AHM is considered as more effective approach, not all airlines are willing to adopt all AHM functions and aircraft

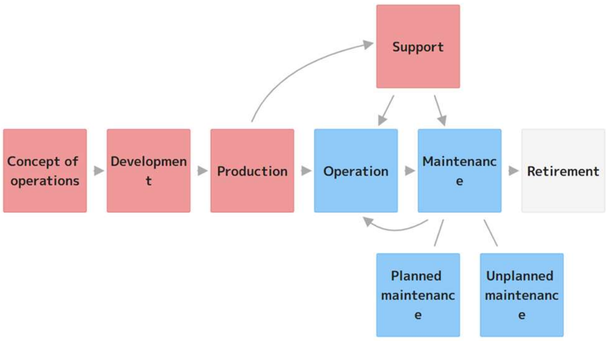

Figure 1. Lifecycle of civil aircraft

manufacturers are looking for the most effective scope and architecture of AHM considering the supposed undesired outcome from AHM which are related to its complexity, uncertainty, cost and airline competitiveness. To solve these types of problems, AHM needs to be described at system of systems (SoS) level and its functional allocation should be considered in collaboration with the airline, aircraft manufacturer and other parties.

The purpose of this research is to provide model to evaluate AHM effect on aircraft operation and maintenance to perform trade-off study how to incorporate AHM to the airline operation and maintenance. Firstly, it provides system models to show the relationships between maintenance program and airline operation and maintenance. Second, it provides models to show the relationships between AHM, maintenance program and airline operation and maintenance. Aircraft maintenance program and AHM can be considered as the component system of SoS to provide the optimized aircraft fleet operation and maintenance. Finally, it proposes an approach to evaluate the effect of AHM on the aircraft maintenance program using the proposed system models.

As a model-based systems engineering method, this study adopts the "Systeming" approach [Miura et al., 2022], which efficiently describes the system model. All system models in this manuscript are described by using the modeling tool, "Balus 2.0" developed by Levii, Inc.

2. Aircraft Maintenance Program

2.1. Context of Maintenance Program

This section shows system models to explain the aircraft maintenance program and its relationship to airline operations and maintenance.

The lifecycle of an aircraft can be divided into seven stages from ConOps (concept of operations) to retirement as shown in Figure 1. The maintenance stage comes after the aircraft has been operated to maintain the airworthiness of the aircraft. During the operation and maintenance stages, airlines have received services from aircraft manufacturers. The use case of the maintenance stage consists of planned and unplanned maintenance, where the quality of the planned maintenance affects the quality of unplanned maintenance.

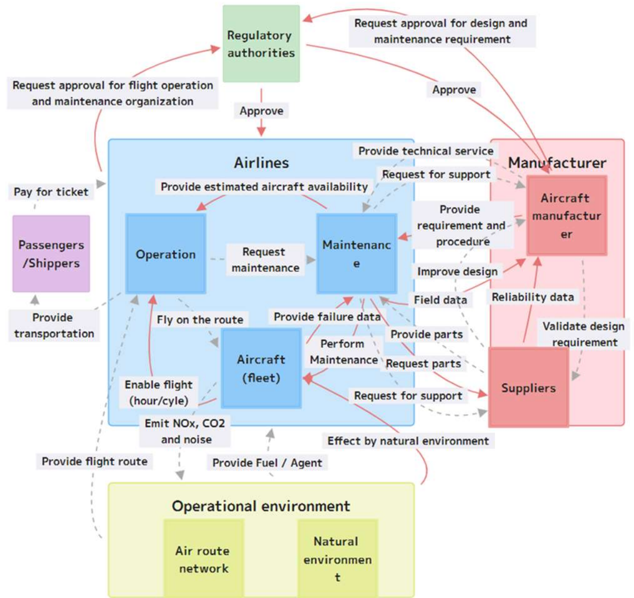

Figure 2. Context of stakeholders in the operation/maintenance stage

The context of stakeholders in the operation and maintenance stage is shown in Figure 2. Airlines operate aircrafts to provide transportation for passengers and shippers, and aircraft manufacturers provide requirements and procedures to operate and maintain aircrafts. Regulatory authorities approve operation and maintenance proposals from airlines and manufacturer. The maintenance program is part of the requirements which the aircraft manufacturer provides to the airline. The operational environments such as air route networks and natural environments are also related to the airline operations. The supplier has a direct relation with both the aircraft manufacturer and the airline.

The maintenance program values passengers and shippers ultimately by providing transportation that meets their needs for safety, convenience, and an affordable ticket price. The convenience can be satisfied by on-time performance, frequent flights and easy access. Figure 3 shows the value of the maintenance program at the aircraft operation and maintenance stage. Before the value comes to the final beneficiary of passengers and shippers, the maintenance program directly contributes to continuous airworthiness of the aircraft, less planned maintenance, and less unplanned maintenance. Then it contributes to operational safety, higher planned aircraft availability, fewer delay and cancellations, and lower operational cost.

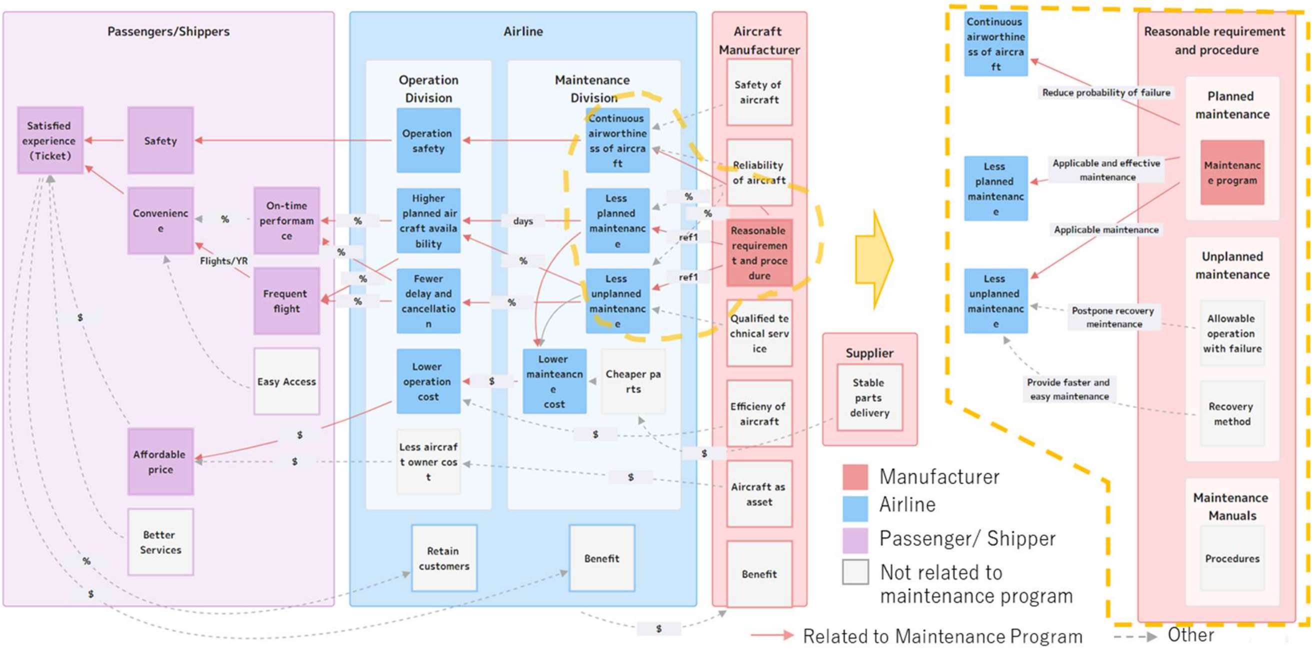

Figure 3. Maintenance program value in the aircraft operation/maintenance stages

2.2. Method of maintenance program development

The MSG-3 method is categorized as a systems engineering approach to the development of the maintenance program in the transport category aircraft. Since the publication of MSG-1 in 1968, the guideline for the development of modern maintenance programs have been refined by both the public and private sectors. The MSG-3 analysis method has matured into an international standard for the development of maintenance programs. The results have made civil aircraft operations safer, more efficient, and more economical (A4A, 2018). As an example, Anderson (Anderson, 1999) reported that the FedEx DC-10 reduced the number of routine scheduled tasks by 24% by converting from MSG-2 to 3. The IMRBPB agreed on a policy for maintenance programs applying the condition-based method in conjunction with AHM maintenance and published Issue Paper 180 in 2018 (IMRBPB, 2018). The specific analysis methods will be included in the next revision of MSG-3. This may result in a change of name from MSG-3 to MSG-4 (IATA, 2022).

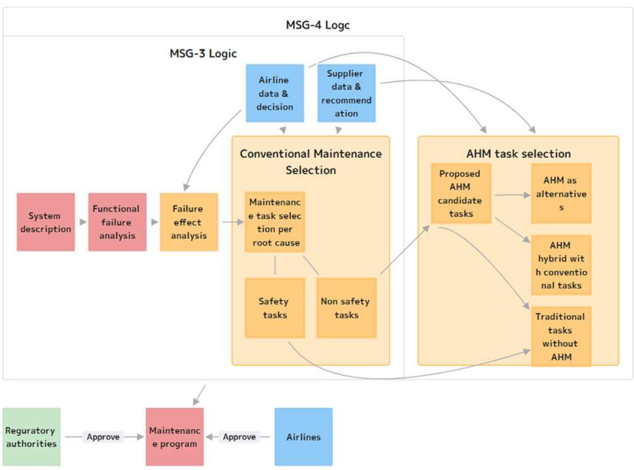

Figure 4. Maintenance program development process using MSG-3 and MSG-4

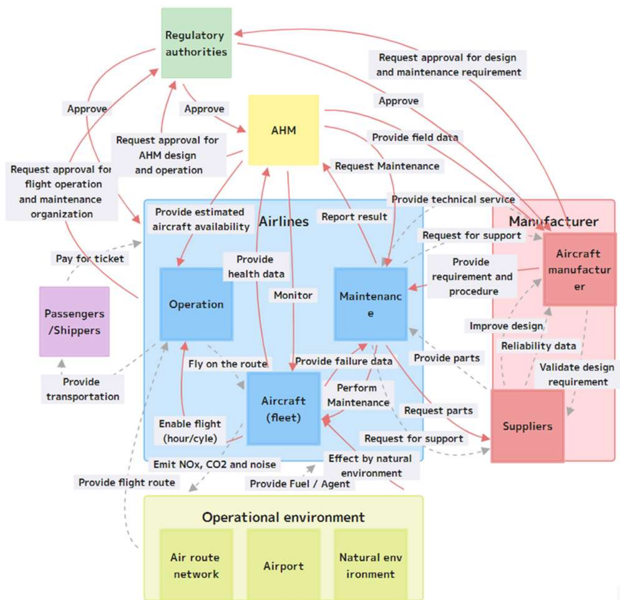

Figure 5. Context of AHM in the operation/maintenance stages

Table 1 Maintenance task type and its interval consideration

Task type	Interval considerations
Lubrication, servicing (Failure prevention)	Usage rate, storage capacity and deterioration characteristic of consumable
Check (Failure detection)	Allowable exposure time of hidden failure and failure rate
Visual inspection functional test (Potential failure detection)	Practical interval between detectable potential failure to the actual failure.
Restoration discard (Failure avoidance)	"Identifiable age" when significant degradation begins and where the conditional probability of failure increases significantly.

* Parameters with underbar could be obtained by AHM

The maintenance program development method using MSG-3 and MSG-4 is shown in Figure 4. The MSG-3 method is considered as a top-down approach starting from the system level for the function identification, instead of a bottom-up approach starting from the component level. Then, the functional failure effect is evaluated whether the failures are categorized as hidden/evident, safety, operational, or economic category. Based on the failure effect category, the maintenance task to prevent or detect the root cause failure is selected or not selected. The maintenance task interval is also determined for each task. Dibsdale (Dibsdale, 2020) reported that approximately 89% of the functional failures in a complex machine such as an aircraft occur according to a random deterioration model.

The newly proposed MSG-4 method allows to select AHM task as alternates, or hybrid task with traditional task if it meets the criteria of applicability and effectiveness.

The analysis results of MSG-3 and MSG-4 are considered as the maintenance program to define the planned maintenance. The selected task type can be categorized by failure prevention, failure detection, potential failure detection and failure avoidance. To determine the interval of these tasks, different types of considerations are required as described in Table 1. It is assumed that many of parameters to determine the task interval depend on type of data obtained from the AHM system, such as usage rate, deterioration characteristic, failure rate, potential to failure interval, and identifiable age when significant degradation begins. It is reported that, based on the typical use of conventional scheduled maintenance tasks for all aircraft systems (i.e., including propulsion systems), it is claimed that up to 90% of these tasks result in "no finding" (IATA, 2022). For more details on the civil aircraft maintenance program development method, refer to the following paper (Koizumi, 2023).

3. Aircraft Health Management

3.1. Context of AHM

The relationship of AHM to the operation and maintenance stages is shown in Figure 5. AHM interfaces with aircraft, airline operations, maintenance, aircraft manufacturers, and regulatory authorities. The aircraft provides health data to the AHM, which requests maintenance to the airline maintenance instead of the airline operation, if necessary. AHM provides the estimated aircraft availability to the airline operations for the commercial flight. AHM then provides field data to the aircraft manufacturer for the optimized maintenance requirements to the airline. In addition, AHM requires certification for its usage in the airline operation/maintenance and the aircraft development.

From the IATA definition, AHM is the unified capability using health monitoring of aircraft structure and systems (including propulsion system) to control the scheduling of aircraft needed maintenance actions, which could be resumed to the process stages of sense, acquire, transfer, analyze and

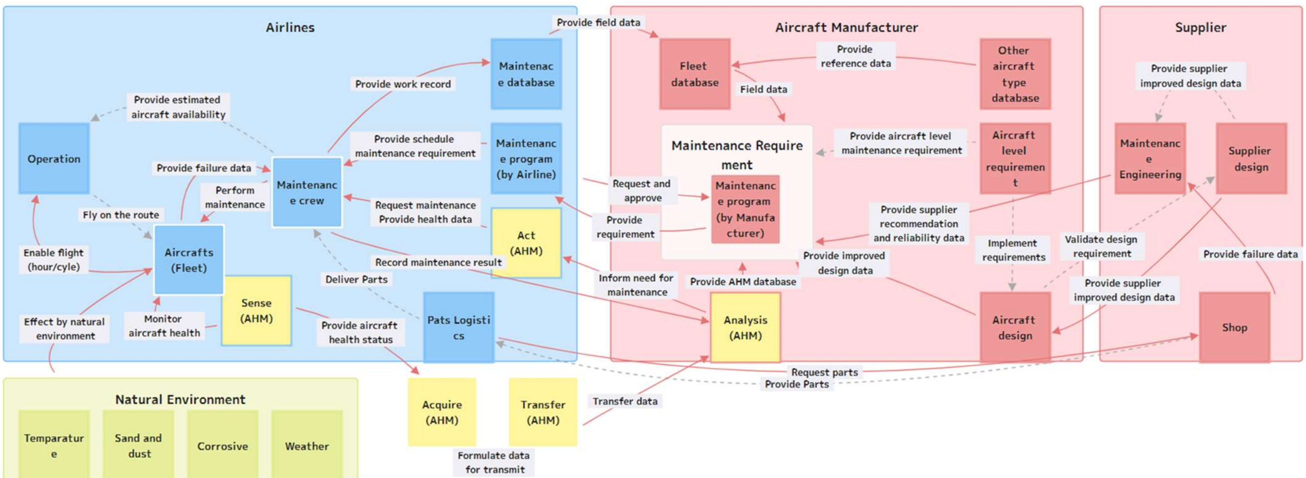

Figure 6. Context of AHM and maintenance program in aircraft maintenance stage. * Not including regulatory authorities

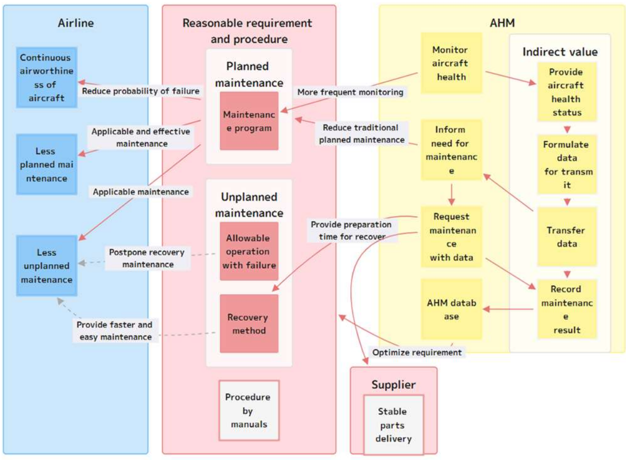

Figure 7. AHM value in the aircraft operation/maintenance stages

act (IATA, 2022). Figure 6 shows the context of AHM and maintenance program in aircraft maintenance stage, which is detailed from Figure 5. The maintenance program (by the manufacturer) is conventionally issued by using the aircraft design data, the airline field data/ requirements, and the supplier recommendation/reliability data. Once the maintenance program is approved by the airline and regulatory authorities, it is delivered to the airline for their controlling maintenance program. Usually, supplier reliability is based on field data through parts logistics to the airlines. AHM senses aircraft health, acquires it, transfers it as data, and analyzes the maintenance timing. Then AHM requests the maintenance to the maintenance crew and provides the AHM database to the aircraft manufacturer to improve the design and maintenance programs. The assignment of the AHM function to the airline and aircraft manufacturer in Figure 6 could be reconsidered in Section 4.

The AHM value in the aircraft operation/maintenance stages is shown in Figure 7 which is updated from Figure 3. AHM directly contributes to both planned and unplanned maintenance before the final value is delivered to passengers and shippers. AHM allows more frequent monitoring for maintenance program optimization, reduces conventional planned maintenance by informing the need for maintenance, and provides more preparation time by requesting maintenance to the maintenance crew with health data before landing. The entire activity of AHM is recorded as AHM database and can be used to improve requirements and procedures. The AHM functions related to acquisition, transference and recording have no direct value relation to the aircraft manufacture and airline. They can be considered as IT infrastructure of AHM, although they could take much cost to develop.

Table 2 Supposed undesired outcome from AHM

Category	Supposed undesired outcome from AHM
Safety	● Unexpected event due to the error (lower DAL) or failure of AHM system ● Unexpected data due to uncertainly of airline maintenance
Airline business	● Loosing competitive maintenance capability ● Strength competitors (other airlines) by providing data ● Higher cost for maintenance digitalization
Aircraft manufacturer business	● Additional development cost for AHM ● Complex certification for AHM system including outside system of the aircraft

DAL: Development assurance level

3.2. Issue to architect AHM system as part of SoS

The value of AHM is obvious as described in Section 3.1. But in the actual aircraft operation field, not all airlines want to adopt AHM for their operation. Therefore, the aircraft manufacturer is required to search for the most effective scope and architecture of AHM considering its undesired outcome from AHM as shown in Table 2. Those undesired outcomes are summarized as the following three issues.

AHM system complexity and uncertainty

The AHM system will be complex because the required functions will be allocated to both the aircraft and outside of the aircraft including airline organization and IT infrastructure which can be considered as part of SOS. Also, the AHM result can be affected by the uncertainty of the airline maintenance crew and the maintenance program in addition to the uncertainty of the aircraft deterioration and the operating environment. For example, the airline's own preventive maintenance can affect the monitored aircraft health data. The additional maintenance affect monitored failure rate and deterioration trend. For another example, parts may be replaced during troubleshooting regardless of their fault that also affects AHM data.

Airline competitiveness

For some airlines, the benefits of AHM may not be cost effective or may conflict with their strategy to maintain their competitive capability of the maintenance engineering function. In addition, the airlines may also be unwilling to share their effective and/or unique maintenance to other parties.

Cost of AHM development and implementation

When any software functions are implemented in an aircraft, they must be certified by regulatory authorities, and their development cost must be considered. If the system will be used for safety critical applications, it will be more expensive. Also, the certification of AHM function outside the aircraft system is not clear and it should be more complex because they need to consider AHM as SoS.

4. Proposed Approach

This section proposes an approach to assess the effectiveness of AHM on the aircraft maintenance program using the system models described in Sections 2 and 3.

Step 1: Propose candidate AHM system.

Describe the candidate AHM system architecture for evaluation.

Step 2: Define and formulate the effectiveness of AHM.

Define and formulate the measure of effectiveness (MOE) of AHM for airline, the aircraft manufacturer and other parties. MOE could be related to safety availability, on-time dispatch reliability, costs, and competitiveness of airline capability. Figures 3 and 7 can be used for evaluation.

Step 3: Define interface of AHM and their uncertainty.

Define interface with aircraft, airline functions and IT infrastructures. Uncertainty could be in the aircraft (including components) deterioration tendency, customized maintenance, or IT infrastructure flexibility. Figure 6 can be used for assessment. Then, the model including the uncertainty can be formulated by using the concept of a robust optimization method.

Step 4: Evaluate effectiveness of AHM system

Evaluate the measure of effectiveness defined by the step 2 for the airline, the aircraft manufacturer and other parties considering the uncertainty defined by the step 3. In addition to the value from the AHM, the undesired outcome need to be considered, which are described in the section 3.2.

Step 5: Agreement on AHM functional allocation

The result of the functional allocation to the aircraft, organization, infrastructure, and maintenance program needs to be agreed by stakeholders as they are considered as SoS. The process shown in Figure 4 can be used to implement AHM into the maintenance program.

5. Conclusion and Future Problems

This research proposed AHM model in higher level and the approach to evaluate the effect of AHM on the aircraft maintenance program. The proposed approach to evaluate the effect is divided by five steps and is emphasized that the uncertainty of the AHM interfaces such as aircraft maintenance activities must be considered in addition to the uncertainty of technical failure and deterioration. It is also clarified that a SoS approach is required to implement the AHM function.

As future problems, the uncertainty of aircraft maintenance activities needs to be investigated through the actual field practice. Then, limitation or improvement of the proposed approach will be considered.

As a next action to solve the problems, proposed or actual cases of AHM system and uncertainty model of its related maintenance actions are required. To proceed the action, the modeling tool, "Balus 2.0" developed by Levii, Inc. is useful to work collaboratively with airline. Airline involvement is important to evaluate proposed or actual cases of AHM system considering expected value and undesired outcome. The subject of the research should be such as type of uncertainty, impact, frequency, necessity, and intention. Specially, the airline whose dispatch reliability performance is significant, is assumed to perform much more effective intended unique maintenance. Their maintenance best practices may have great potential to architect AHM system more effective.

Acknowledgments

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