Effectiveness Evaluation Method Using System of Systems Architecture Description of Aircraft Health Management in Aircraft Maintenance Program

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ABSTRACT

This study proposes a system modeling method for aircraft maintenance program development that adopts condition-based maintenance using aircraft health management (AHM) based on a systems engineering approach, which considers AHM as a system of systems. The metamodel is tailored on the basis of the Unified Architecture Framework (UAF) and the NASA Systems Modeling Handbook for Systems Engineering. It is described using the modeling tool "Balus 2.0" (Levii, Inc). The applicability and effectiveness of a maintenance program adopting AHM is analyzed on the basis of the Maintenance Steering Group-3 (MSG-3), and its effectiveness is evaluated using the proposed system modeling method. The proposed method considers the uncertainty of the aircraft maintenance environment related to airline operations in addition to the uncertainty of the aircraft system. The effectiveness of the proposed system is investigated through a sample problem that considers a tire system using a pressure monitoring system as AHM based on the MSG-3 approach. Finally, the limitations of the proposed method are discussed.

1. INTRODUCTION

To maintain the continuous airworthiness of an aircraft, a maintenance program is required. The definition of the requirement considers the effect of system failure on safety, operation, and cost. The maintenance program is one of the major factors affecting the total maintenance cost and aircraft availability. Increased maintenance requirements will increase maintenance costs, and unsatisfactory requirements will affect aircraft safety margins and availability. In assessing the potential impact of (un)availability, operators have 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 manufacturer prepares a maintenance program for each aircraft type and obtains approval from lead airline customers and the regulatory authority, because airlines need to prepare their maintenance programs according to the manufacture's maintenance requirements to avoid deviations. Maintenance Steering Group-3 (MSG-3; A4A, 2018) is considered the standard method for developing and optimizing maintenance programs. The MSG-3 method has been refined by manufacturers, airlines, and regulatory authorities since the 1960s and is currently maintained by the International Maintenance Review Board Policy Board (IMRBPB) and Maintenance Programs Industry Group. The approach to maintenance programs has been changed from overhaul to hard time, on condition, and condition monitoring (A4A, 2018). Finally, condition-based maintenance has been introduced as an optional method for more efficient aircraft operation and maintenance since 2018 as an agreed method (IMRBPB, 2018).

Condition-based maintenance can be considered as one of the aircraft health management (AHM) functions. According to the International Air Transport Association (IATA) definition, AHM is a unified capability that controls the scheduling of necessary maintenance actions for aircraft by monitoring the health condition of the aircraft structure and systems, including the propulsion system. This capability can be applied to the process stages of sense, acquire, transfer, analyze, and act (IATA, 2022). AHM optimizes aircraft operation and maintenance by providing functions to utilize fleet health data, indicate the appropriate time for maintenance before actual failures occurs, and promptly share failure data with maintenance on the ground. These functions influence the development of a maintenance

https://doi.org/10.36001/IJPHM.2024.v15i3.3847

program. According to the IATA report (IATA, 2022), predictive maintenance using health monitoring mechanisms is estimated to enable airlines to save approximately $3B per year in maintenance costs.

A number of prognostics and health management (PHM) researches have been conducted in the aircraft industry. Data-driven aerospace engineering to reframe the industry with machine learning has been reported (Brunton et al., 2021), leveraging data and providing significant opportunities to improve and optimize aircraft maintenance. Kordestani et al. (Kordestani et al., 2023) reported various approaches to failure prognostics of aircraft systems, such as data-driven, model-based, and knowledge-based approaches. An economic evaluation of an automated condition monitoring system for aircraft has been reported using the case of A320 tire pressure monitoring system (Meisser, Meyer, & Wicke, 2021). Their study presented a methodology for estimating the implications of maintenance operations for scheduled maintenance tasks considering AHM technology maturation. A life-cycle maintenance cost analysis framework considering time-dependent false and missed alarms has been reported (Yoon, J., et al., 2019). It proposed a method to estimate life-cycle maintenance costs considering various uncertainties, such as health degradation and health restoration through maintenance. A prescriptive maintenance strategy in the aviation industry for post-prognostic decision-making showing the expected benefits for airline operations with the given technological maturity has been reported (Meissner, Rahn, & Wicke, 2021). It was concluded that the evaluation of additional stakeholders for the maintenance decision-making process is required to allow holistic optimization. The critical issues in PHM design, development, and decision have been reported (Hu et al., 2022). It has been reported that the PHM design is driven by the original requirements rather than enabler/solution technologies. To evaluate the requirements for PHM, PHM systems architecture frameworks have been reported (Kunche, Chen, & Pecht, 2012), where PHM is considered as a system of interest. These studies focus on the “sensing” and “analyzing” processes of AHM as a system. However, AHM covers “sensing,” “acquiring,” “transferring,” “analyzing,” and “acting” functions, which may require a system-of-systems (SoS) approach.

Although AHM is considered a more effective approach, major initiatives require agreement from all stakeholders, including multiple airlines, regulatory authorities, and aircraft manufacturers. This is because AHM affects safety, operation, and economics, and the benefit depends on each airline’s operation and business strategy, operations, and resources. The other reason for the difficulty in achieving the most effective scope and architecture of AHM is its supposed undesired outcome, which is related to its complexity, uncertainty, cost, and airline competitiveness. To solve these problems, the AHM architecture needs to be described at the SoS level, and its functional allocation should be considered in collaboration with the airline, aircraft manufacturer, and other parties based on the quantified effective analysis.

The purpose of this study is to provide system models for evaluating the effect of AHM on aircraft operation and maintenance to perform a trade-off study on how to incorporate AHM into airline operations and maintenance. First, we present system models for describing the system architecture with respect to maintenance program development and airline operation and maintenance. Second, we present models for describing the updated architecture by applying AHM. The aircraft maintenance program and AHM can be considered components of the SoS to optimize aircraft fleet operations and maintenance. Third, we propose an approach for evaluating the effect of AHM on the aircraft maintenance program using proposed system models. Finally, we perform sample analysis of the maintenance programs adopting AHM based on the MSG-3 approach and the proposed evaluation method. A tire system that adopts a pressure monitoring system as AHM is used as a sample case.

As a model-based systems engineering method, we adopt the “Systeming” approach (Miura et al., 2022) (Nambu et al., 2019), which efficiently describes the system model. All system models in this study are described using the modeling tool "Balus 2.0" (Levii, Inc). The metamodel is tailored on the basis of the Unified Architecture Framework (UAF, OMG, 2022) (Martine, & O’Nel, 2021) and the NASA systems modeling handbook for systems engineering (NASA, 2022).

SysML is a general-purpose graphical modeling language for model-based systems engineering to describe system architecture. It was developed by OMG and was also published as ISO/IEC 19514:2017 (NASA, 2022). The UAF intends to develop architectural descriptions for commercial industries, federal governments, and military organizations. It is capable of describing SoS architecture and has various use cases from Enterprise as a System and SoS and cyber system engineering to an enabler for digital transformation plans. It was developed by OMG and published also as ISO/IEC 19540:1 and ISO/IEC 19540:2 (OMG, 2023).

2. MAINTENANCE DEVELOPMENT METHOD USING MSG-3

This section explains the MSG-3 method (A4A, 2018) and its general effect on aircraft operation. The MSG-3 method is categorized as a systems engineering approach for developing maintenance programs for transport-category aircraft. Since the publication of MSG-1 in 1968, guidelines 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. These results have made civil aircraft operations safer, more efficient, and more economical (A4A, 2018). Anderson (Anderson, 1999) reported that the FedEx DC-10 reduced the number of routine scheduled tasks by 24% by converting from MSG-2 to MSG-3. The IMRBPB agreed on a policy for maintenance programs that applied the condition-based method in conjunction with AHM and published Issue Paper 180 in 2018 (IMRBPB, 2018). The specific analysis methods are included in the 2023 revision of MSG-3. MSG-3 allows the selection of an AHM task as an alternative or a hybrid task with a traditional task if it meets the criteria of applicability and effectiveness. The selected task type can be categorized as failure prevention, failure detection, potential failure detection, or failure avoidance. To determine the interval of these tasks, different types of considerations are required, as described in Table 1. It is assumed that most of the parameters used to determine the task interval depend on the type of data obtained from the AHM system, such as the usage rate, deterioration characteristic, failure rate, potential to failure interval, and identifiable age at which significant degradation begins. Based on the typical use of conventional scheduled maintenance tasks for all aircraft systems (i.e., including propulsion systems), up to 90% of these tasks result in "no finding" (IATA, 2022). For more details on the civil aircraft maintenance program development method, please refer to the following paper (Koizumi, 2023).

Task type	Interval consideration
Lubrication, /Servicing (Failure prevention)	Usage rate, storage capacity, and deterioration characteristics of consumables
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 an underbar can be obtained using AHM

Table 1. Maintenance task type and interval considerations

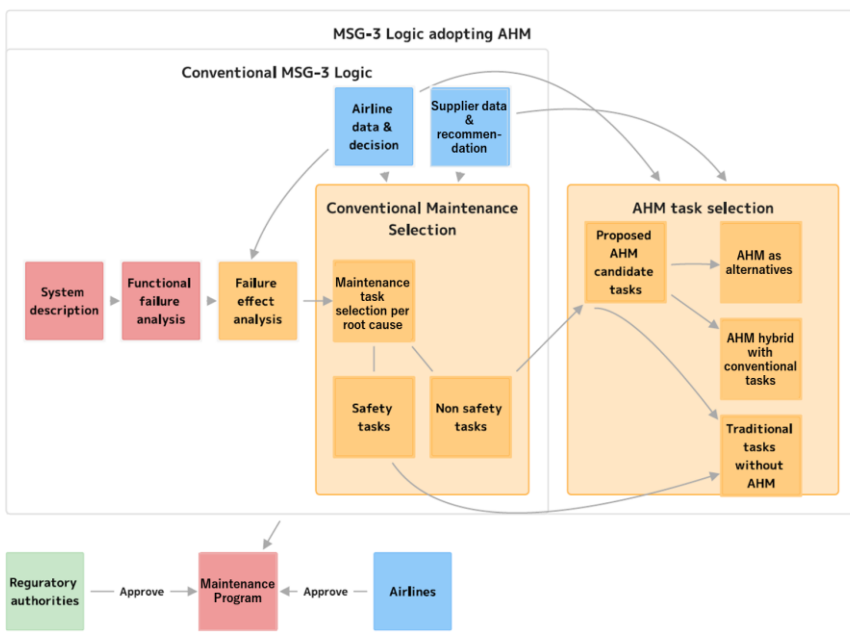

Figure 1. Maintenance program development process

3. OVERVIEW OF SYSTEM MODELING

This section explains the objective of the system model, the metamodel, and the views used to create the operation models in this study.

3.1. Objective of System Model

The objective of system modeling is to evaluate the effectiveness of AHM by describing the relationships between stakeholders regarding a maintenance program that uses AHM. The maintenance program was developed using the MSG-3 method based on the condition-based maintenance enabled by AHM. The system model is based on the UAF and SysML metamodels and is described using the MBSE tool of Balus 2.0 (Levii Inc). The overall system modeling is shown in Figure 2. The model clarifies the following aspects.

- Value produced by AHM and the benefit of each stakeholder

- Function allocated to each stakeholder to implement AHM capabilities
- Interfaces between stakeholders
- Negative concerns of each stakeholder
- Involvement of uncertainty

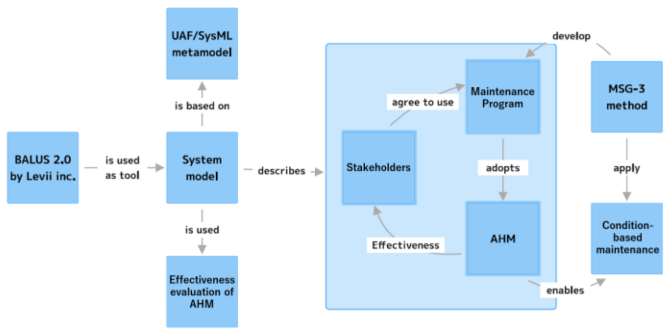

Figure 2. Overall system modeling for AHM evaluation

3.2. Metamodel and Type of View

The system model consists of system and SoS elements, which are referenced from SysML (NASA, 2022) and the UAF metamodel (OMG, 2022). Figure 3 shows the metamodel and the relationships among the elements. The system elements include "Stakeholder," "Function," "Resource," and "MOP" (measure of performance). The SoS elements include "Effect" desired by "Capability" and "MOE" (measure of effectiveness). We exclude the "Capability" element and begin to describe the "Effect" element, assuming that "Capability" is described using the metamodel of the UAF strategic domain. Figure 3 also shows the model view type. There are five types of views, "Context of stakeholders," "Functional flow," "Stakeholder resources," "Value flow," and "Taxonomy of effectiveness," which are described as follows.

- The "context of stakeholders" view describes the relationships between stakeholders and items to be exchanged. This refers to UAF's operational connectivity view describing operational performers (OMG, 2022) and SysML's internal block diagram describing the relationships between the system and the external system (NASA, 2022).
- The "functional flow" view describes the functional flow and items to be exchanged. It also describes functional allocation to stakeholders. This refers to UAF's resource process view describing functions (OMG, 2022) and SysML's activity diagram describing functional behavior (NASA, 2022).
- The "stakeholder resources" view describes resources owned by stakeholders and items exchanged between resources. This refers to UAF's resource structure view, which describes multiple types of resources (OMG, 2022), and SysML's internal block diagram, which describes the relationships between subsystems (NASA, 2022).
- The "value flow" view describes the relationships between the MOP values and stakeholders, which relate to the customer value and stakeholder benefit.
- The "taxonomy of effectiveness" view describes MOE values that are categorized by "benefit," which is considered the desired outcome, and "cost" or "risk," which is considered an undesired outcome. This refers to the UAF's resource process view, which describes functions (OMG, 2022).

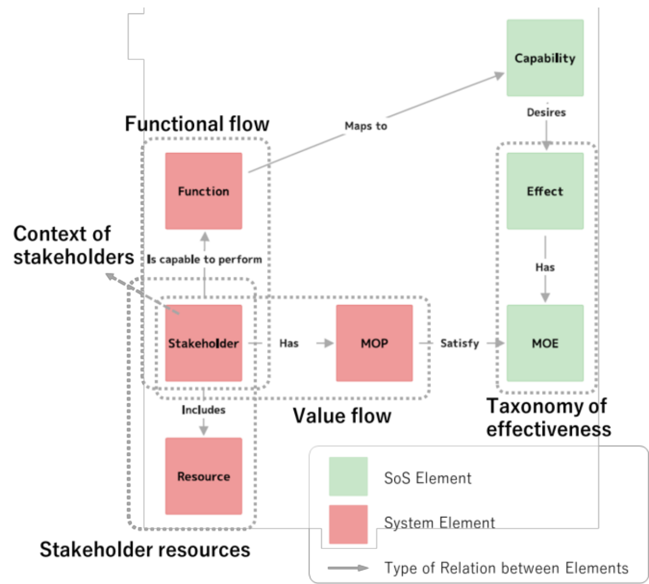

Figure 3. System modeling metamodel and view type

3.3. Relationship between Views (View Model)

The view model defines the relationships between views to understand what types of views are required and what relationships need to be considered to solve problems (Miura et al., 2022). Figure 4 shows the view model showing the flow of how the system models are created on the basis of the metamodel and view described in Sub-section 3.2. The modeling steps are summarized as follows:

1. Description of the context of stakeholders in the aircraft operation and maintenance stage, which mainly includes the maintenance program and AHM.
2. Description of the resources of the stakeholders, capturing their conventional maintenance activities based on the context of the stakeholders. This view details the relationships described in the context of stakeholders.
3. Description of the functional flow allocated to the stakeholders, capturing the conventional maintenance

activities of the stakeholders based on the context of the stakeholders and resources. Description of the functional flow of the maintenance activity adopting AHM.

4. Description of the value flow between stakeholders, capturing the MOP from the exchange items between stakeholders' functions and resources. Description of the value flow of maintenance activity adopting AHM.
5. Description of the taxonomy of desired and undesired effectiveness related to AHM. The MOE is linked to the MOP identified in the value flow.

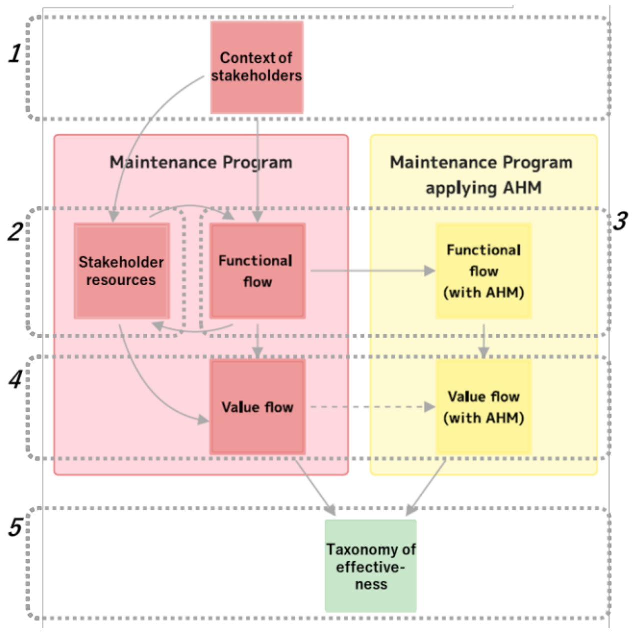

Figure 4. View model showing relationships between views

4. SYSTEM MODELS

This section shows the actual system models created to describe the maintenance program adopting AHM based on the metamodel and the views described in Section 3.

4.1. Context of Stakeholders

This Sub-section presents a system model for describing stakeholders regarding aircraft operation and maintenance, which mainly includes the maintenance program and AHM.

The lifecycle of an aircraft can be divided into seven stages from concept to retirement, as shown in Figure 5. The maintenance stage comes after the aircraft has been operated to maintain its airworthiness. During the operation and maintenance stages, airlines receive services from aircraft manufacturers. The use case of the maintenance stage consists of planned and unplanned maintenance, where the quality of planned maintenance affects the quality of unplanned maintenance.

The context of the stakeholders in the operation and maintenance stages is described in Figure 6. Airlines operate aircraft to provide transportation for passengers and shippers. Aircraft manufacturers provide requirements and procedures for operating and maintaining aircraft. Regulatory authorities approve operation and maintenance proposals from airlines and manufacturers. A maintenance program is a part of the requirements that an aircraft manufacturer provides to airlines. The operational environment, such as air route networks and the natural environment, is also related to airline operations. The supplier has a direct relationship with both the aircraft manufacturer and the airline.

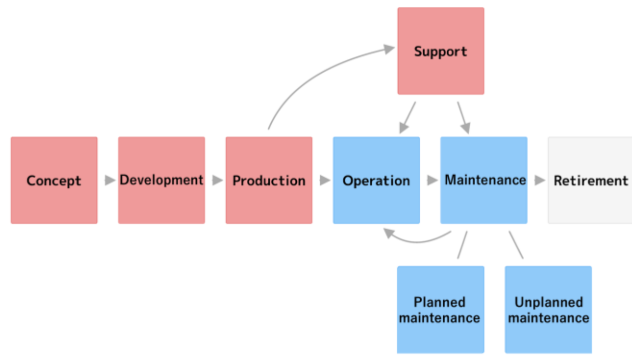

Figure 5. Lifecycle of aircraft

4.2. Stakeholder Resources

This Sub-section presents a system model for describing the resources of stakeholders, capturing the conventional maintenance operation of stakeholders based on the context of the stakeholders. The stakeholder resources related to a maintenance program are described in Figure 7. The maintenance program (by the manufacturer) is issued using aircraft design data, airline field data, and supplier design and reliability data. Once the maintenance program is approved by the airline and regulatory authorities, it is delivered to the airline for its controlling maintenance program. Typically, supplier reliability is based on field data from part logistics to the airlines. The airline maintenance crew maintains the aircraft fleet using the maintenance program and manual, which provide maintenance procedures. The airline operating crew operates the aircraft maintained by the maintenance crew. When maintenance is required, the maintenance crew recovers the aircraft for operation. Finally, the transportation is provided to passengers and shippers.

4.3. Functional Flow

This Sub-section presents a system model for describing the functional flow allocated to stakeholders, capturing the conventional maintenance operation of stakeholders based on the context of stakeholders and resources. It also describes the functional flow of a maintenance program that adopts AHM.

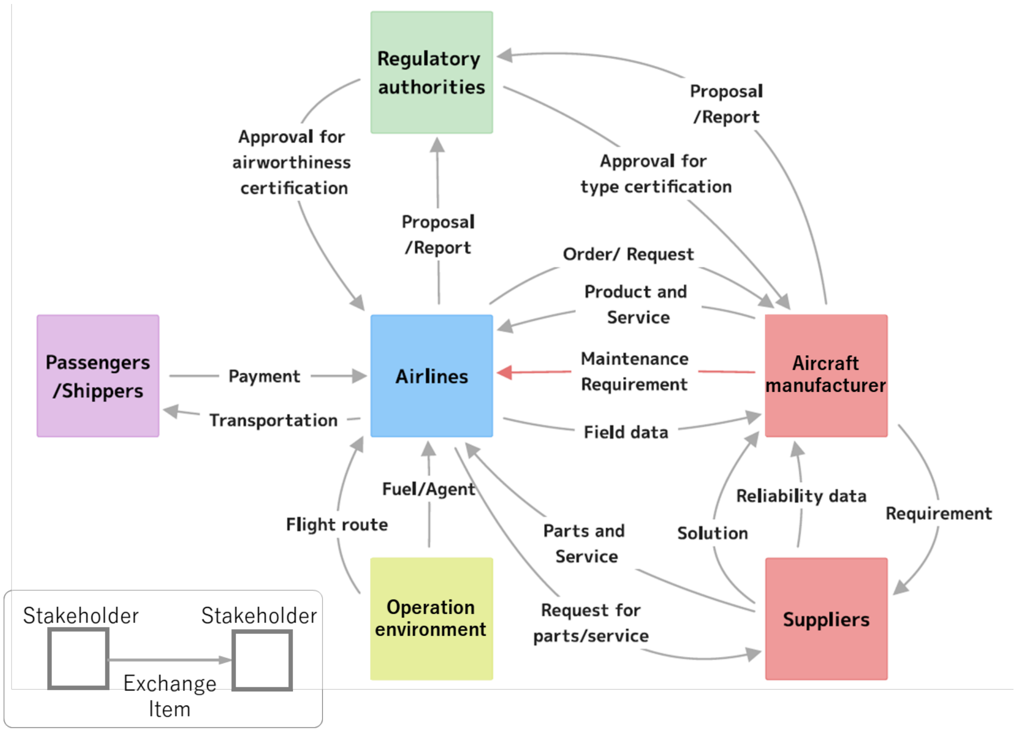

Figure 6. Context of stakeholders (aircraft maintenance and operation stages)

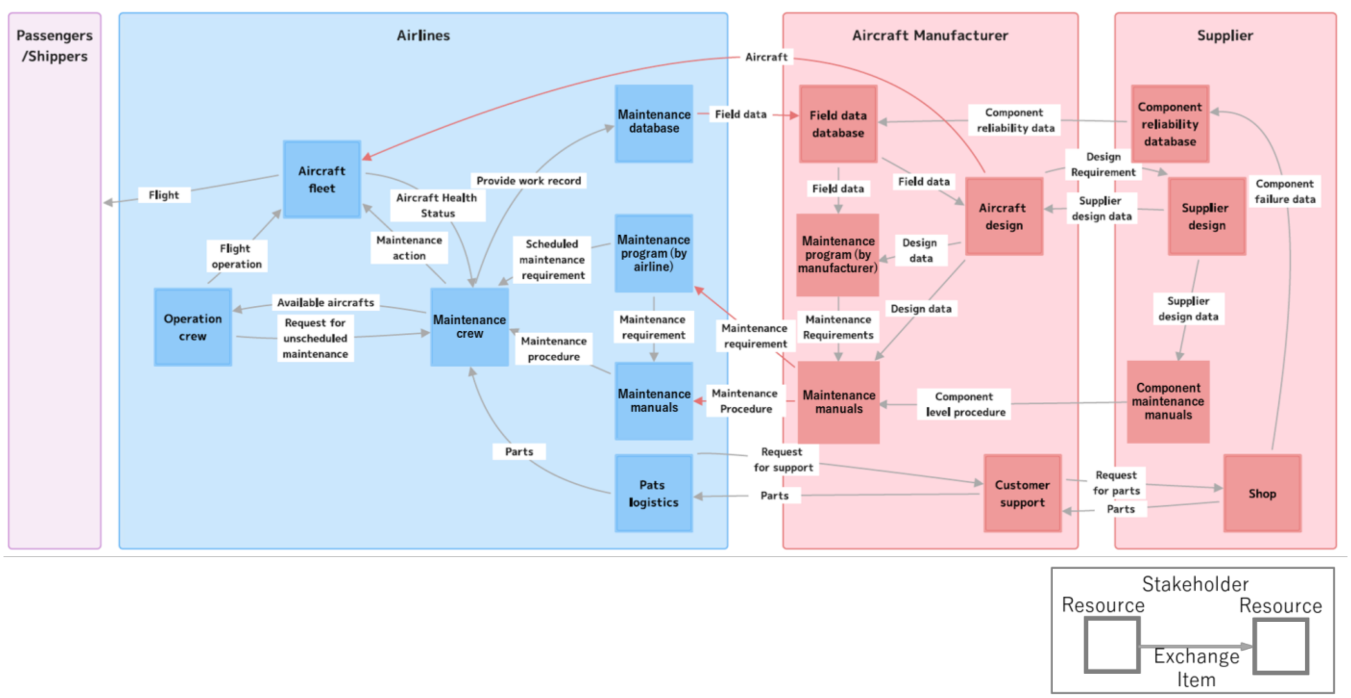

Figure 7. Stakeholder resources related to maintenance program

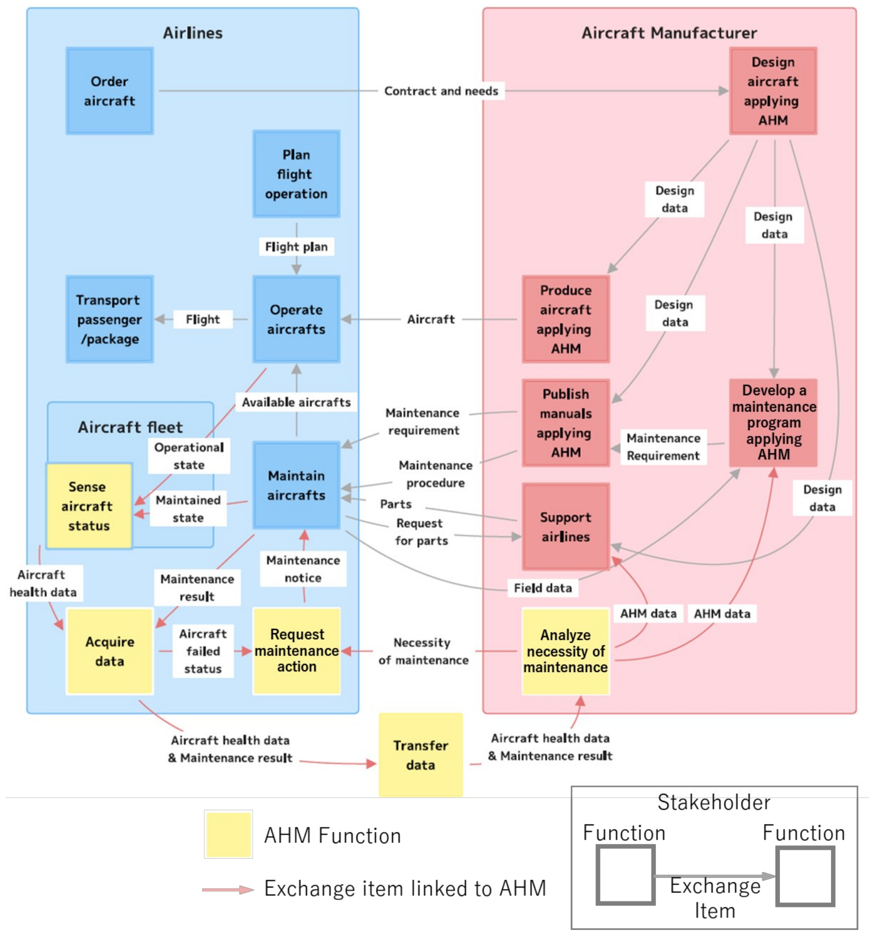

Figure 8. Functional flow related to maintenance programs that adopt AHM

Figure 8 shows the functional flow related to a maintenance program that adopts AHM. Airlines order aircraft. Aircraft manufacturers design aircraft and develop maintenance programs that contain maintenance requirements and are published as maintenance manuals. An airline maintains the aircraft using the manufacturer's manual and operates the aircraft to transport passengers and packages.

AHM senses the aircraft health, acquires the health status, transfers the data, and analyzes the maintenance schedule. Then, AHM issues a maintenance request to the maintenance crew and provides the AHM database to the aircraft manufacturer to develop a maintenance program and support airlines. The AHM function of "sense aircraft status" has input from the functions "operate aircraft" and "maintain aircraft," which are mainly implemented by human activities. Uncertainty will exist under operation and maintenance conditions, which are inputs to the AHM function. The aircraft manufacturers' functions of "produce aircraft," "publish manuals," and "develop maintenance program" should be updated to implement AHM capability. For example, an airline's preventive maintenance can affect the monitored aircraft health data. Additional maintenance affects the monitored failure rate and deterioration trend. As another example, parts may be replaced during troubleshooting regardless of their failure, which also affects the AHM data.

The assignment of the AHM functional allocation to the airline and aircraft manufacturer in Figure 6 can be reconsidered according to the process described in Section 5. The AHM functions of "transfer" can be considered as the IT infrastructure of AHM, which is considered as another stakeholder.

4.4. Value Flow between Stakeholders

This Sub-section presents a system model for describing the value flow between stakeholders, capturing the MOP from the exchange items between stakeholders' functions and resources. It also describes the value flow of the maintenance operation adopting AHM.

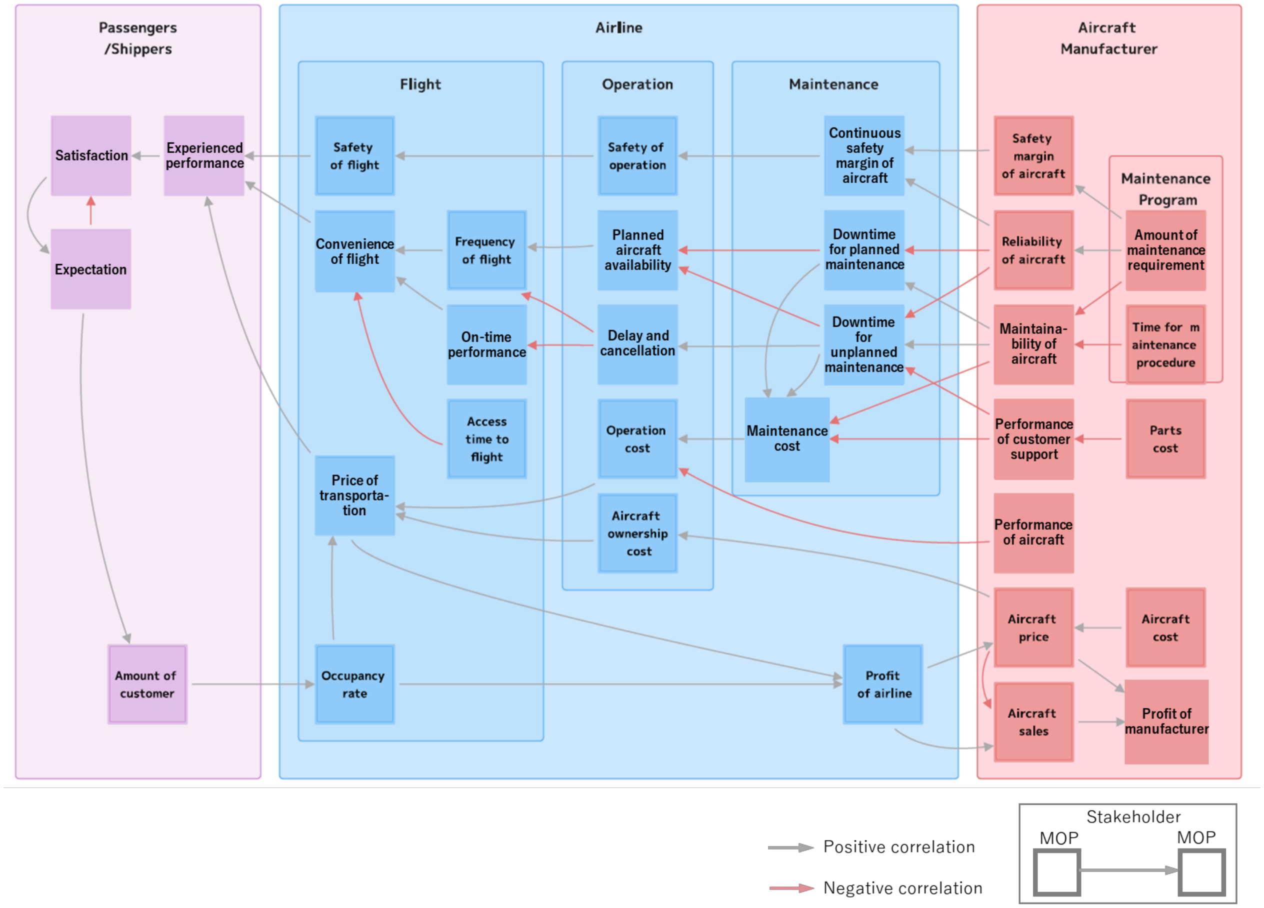

Figure 9. Value flow of maintenance program

Figure 9 shows the value flow of the maintenance program. The goal of the value is passenger/shipper satisfaction, which is influenced by the experience and expectations of passengers/shippers. Higher expectations, combined with high satisfaction, will increase the number of airline customers and profits. This increases the aircraft sale price, which increases the profit of the aircraft manufacturer. The maintenance program values passengers' and shippers' experience by providing transportation that meets their needs for safety, convenience, and affordability. Convenience can be satisfied by on-time performance, frequency of flights, and access time to the flight. Before the value comes to the final benefit of passengers and shippers, the maintenance program contributes to the continued airworthiness of the aircraft, the downtime for planned and unplanned maintenance, and the maintenance cost of the airline. This contributes to the safety of operations, planned aircraft availability, delay and cancelation rates, and operational costs.

Figure 10 shows the value flow of the maintenance program adopting AHM. The MOP values affected by AHM are extracted from Figure 10. AHM contributes to the MOP of both the airline and the aircraft manufacturer by alternating conventional planned maintenance, providing additional preparation time by issuing a maintenance request to the maintenance crew before the aircraft lands, and increasing the remaining life of the parts. The entire operation of AHM is recorded as an AHM database and can be used to improve the requirements and performance of the customer support of aircraft manufacturers. Conversely, AHM increases the part and aircraft costs and requires the airline to pay the cost for AHM operation. These costs increase the airline maintenance cost, whereas the other AHM MOP values decrease them. Uncertainty in AHM data decreases the continuous safety margin of aircraft and increases the downtime for unplanned maintenance and maintenance cost due to unnecessary maintenance.

4.5. Taxonomy of Effectiveness

This Sub-section presents a system model for describing the taxonomy of desired and undesired effectiveness related to AHM.

The effect of AHM is composed of desired and undesired outcomes. MOE values are generalized to benefits considered desired outcomes or costs and risks considered undesired outcomes. The MOE is listed with reference to value flow and industrial common sense. The MOE can be validated by defining the capability based on the UAF's strategic domain, which is not included in this study.

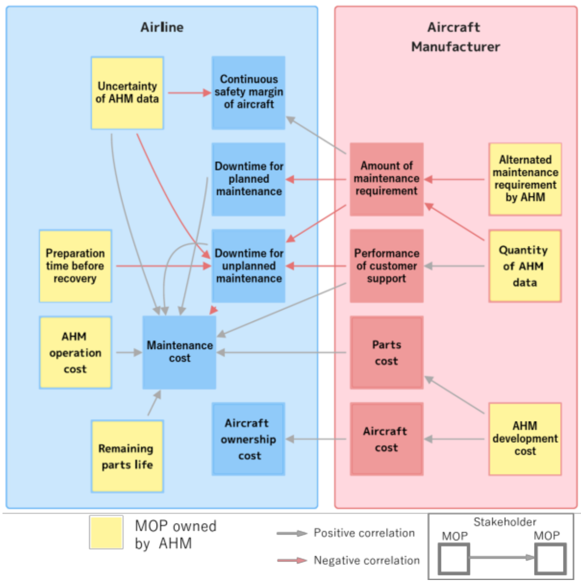

Figure 10. Value flow of maintenance program adopting AHM

In addition to the benefits of AHM, the costs and risks associated with it need to be evaluated. Therefore, the stakeholders of AHM are required to search for the most effective scope and architecture of AHM. The following description explains the background and examples of some MOE values that need to be carefully controlled to obtain stakeholder agreement.

AHM system complexity and uncertainty

An AHM system is complex because the required functions are allocated both to the aircraft and outside of the aircraft, including the airline organization and IT infrastructure, which includes human activities as a part of SoS. Furthermore, the AHM result can be affected by the uncertainty of the airline maintenance crew and the maintenance program in addition to the uncertainty of aircraft deterioration and the operating environment. The uncertainty of AHM affects safety, operational, and economic risks.

Airline competitiveness

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

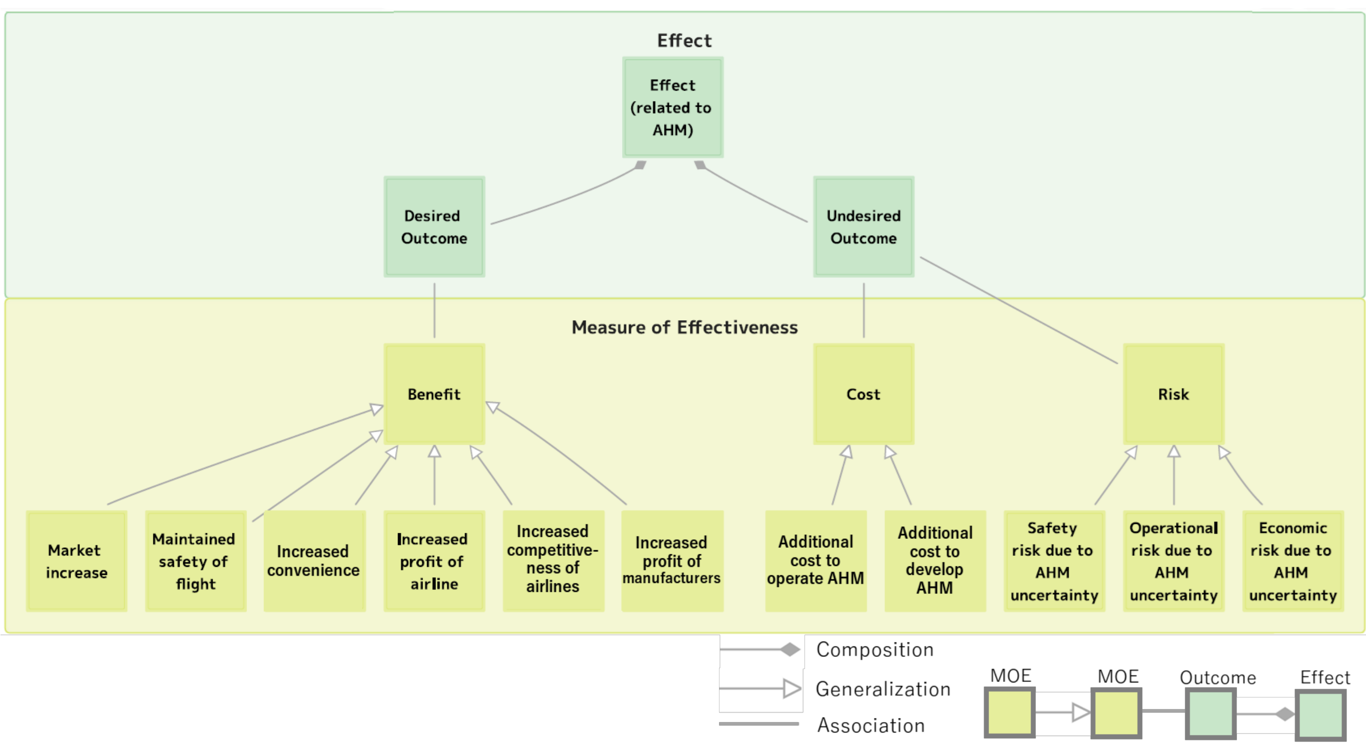

Figure 11. Taxonomy of AHM effectiveness

Cost of AHM development and operation

When any software functions are implemented in aircraft, they must be certified by regulatory authorities, and their development costs must be considered. If the system is used for safety-critical applications, it will be more expensive. In addition, the certification of the AHM function outside the aircraft system is unclear, and it should be more complex because they should consider AHM as a SoS.

5. PROPOSED APPROACH TO EVALUATE AHM APPLICATION

This section proposes an approach to assess the effectiveness of AHM on aircraft maintenance programs using the system models described in Section 4.

Step 1: Propose a candidate system that adopts AHM.

Describe the architecture of the candidate system adopting AHM for evaluation. The dedicated AHM function and structure of the system are related to the functional flow described in Figure 8 and the stakeholder resource described in Figure 7.

Step 2: Analyze the candidate system using the MSG-3 method.

Analyze the candidate system using the MSG-3 (A4A, 2018) method explained in Section 2. Traditional maintenance without AHM and candidate AHM maintenance to alternate the traditional task are the outputs. The task and its interval are selected considering the applicability and effectiveness of AHM. The effectiveness is evaluated through steps 3 and 4.

Step 3: Evaluate the effectiveness (benefits and costs) of AHM.

Define and describe the MOP of AHM for the airline, aircraft manufacturer, and other parties. Use the relationships of the MOP defined in the value flow of the maintenance program adopting AHM described in Figures 9 and 10. Next, we link the MOP to the MOE defined in the taxonomy of MOE described in Figure 11. The analysis result of MSG-3 can be used to evaluate the MOP in terms of safety, availability, on-time dispatch reliability, and cost.

Step 4: Identify the risk of AHM due to uncertainty.

First, we define uncertainty in terms of aircraft deterioration (including components), maintenance and operational activity, or IT infrastructure flexibility. The functional flow created on the basis of Figure 8 can be used for assessment. Next, we evaluate the MOP values affected by the uncertainty and link them to the MOE categorized as risk in the same way as in step 3.

Step 5: Agree on the AHM architecture by SoS stakeholders

The AHM functional allocation to the aircraft, organization, and infrastructure needs to be agreed upon by the stakeholders who own the functions of the SoS. The adoption of AHM to the maintenance program will be agreed upon by the airlines and regulatory authorities through the MSG-3 process shown in Figure 1 using the effectiveness evaluation results from steps 3 and 4.

6. SAMPLE ANALYSIS USING THE PROPOSED APPROACH

This section presents a sample analysis of the maintenance program adopting AHM based on the MSG-3 approach and the proposed evaluation method. A tire system in which a pressure monitoring system is employed as an AHM is used as an example.

6.1. Sample System (Step 1)

The resource structure of the tire system with pressure monitoring as an AHM is shown in Figure 12. The tire system is considered as a subsystem of the landing gear, which is hierarchically a subsystem of the aircraft system. The following system description is created referring to Aircraft tire care and maintenance (Goodyear, 2020) and A320 tire pressure indication system (Meisser, Meyer, & Wicke, 2021).

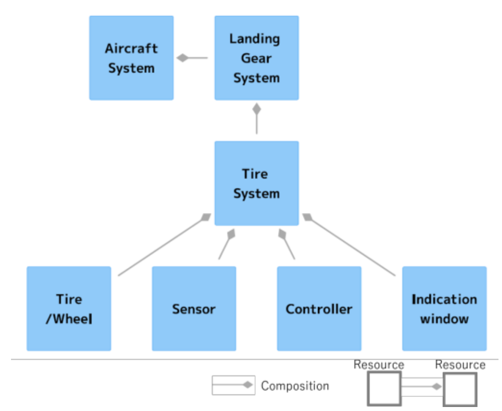

Figure 12. Resource structure of tire system

The controller electronically determines the tire pressure status on the basis of pressure and temperature monitoring data for each tire. Tire pressure information is displayed on the landing gear indication display window for each tire. The data are available both on and off the aircraft via the indication window. In addition to pressure, the pressure decreasing rate is analyzed and reported as a leak indication. The tire pressure is measured while the aircraft is on the ground because the tire temperature should be stable.

There are four main functions of the tire system and one AHM function as part of the aircraft system. In addition to the aircraft function, the AHM functions are assumed to be allocated to the airline and aircraft manufacturer. Figure 13 shows the assumed functional allocation related to the tire system adopting AHM for the analysis.

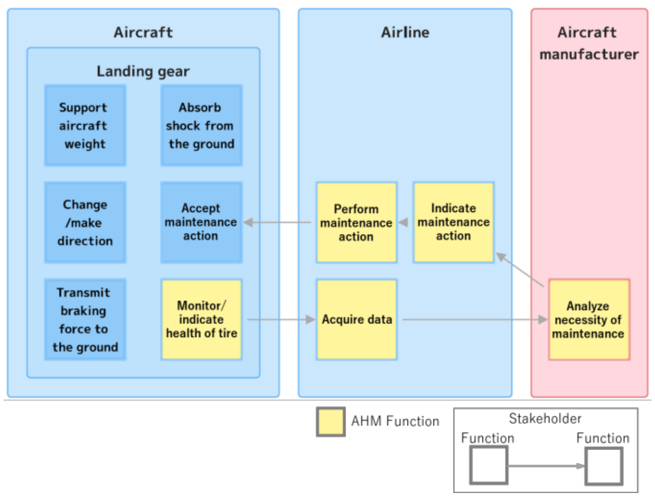

Figure 13. Assumed functional allocation of tire system that adopts AHM

Type	Function	Failure effect	Failure cause	Mainte-nance task
Main func-tion	To support aircraft weight	CAT 9	Tire (flat / low pressure)	Selected (Ref: task summary)
	To transmit braking force to the ground	CAT 9	Tire (flat / low pressure)	
	To change/make the direction	CAT 9	Tire (flat / low pressure)	
	To absorb shock from the ground	CAT 9	Tire (flat / low pressure)	
AHM func-tion	To monitor/ indicate the condition of the tire pressure	CAT 6	Sensor / Controller	Not task selected

*CAT 9: Failure is hidden to the operating crew and does not have a safety effect.

*CAT 6: Failure is evident to the operating crew and does not have a safety effect.

Table 2. MSG-3 analysis summary of tire system adopting AHM

6.2. Summary of MSG-3 Analysis (Step 2)

The tire system adopting AHM was analyzed according to the MSG-3 method (A4A, 2018) with reference to the analysis samples explained in the IMRBPB Issue Paper, IP180 (IATA, 2018). Table 2 shows the MSG-3 analysis summary of the tire system adopting AHM. Maintenance tasks are selected on the basis of the function and its failure effect. Maintenance tasks are selected in two ways: traditional maintenance without and with AHM. The selected tasks are summarized in Table 3.

Type	Maintenance task	Interval	Man hour
Task without AHM	(1) Inspect tire surface for damage	3 days	0.1 hour, 1 person
	(2) Check/Service tire pressure	3 days	0.1 hour, 1 person
Task with AHM	(1) Inspect tire surface for damage	3 days	0.1 hour, 1 person
	(3) Analyze tire pressure limit alert (AHM)	AHM	Not applicable

Table 3. MSG-3 maintenance task summary of tire system adopting AHM

6.3. Summary of AHM Effectiveness Evaluation (Step 3)

Tables 4 and 5 show an effectiveness evaluation summary of the tire system adopting AHM for MOP of AHM and MOP of airline, respectively. The MOP values of AHM and the airline shown in Figure 10 are evaluated in terms of how they are affected by the AHM function. As shown in Figure 11, the affected MOE is identified when MOP is affected by adopting AHM. AHM increases the profit of the airline by reducing maintenance costs because a maintenance requirement is alternated by AHM. Conversely, there is an impact on the additional costs to develop AHM. In this case, because both traditional and AHM maintenance checks and related maintenance, such as tire replacement, are performed during night parking, there is no effect on availability and convenience.

6.4. Summary of Risk Identification due to Uncertainty (Step 4)

Table 6 shows the risk identification summary of the tire system adopting AHM. First, the event causing uncertainty is identified using the functional flow shown in Figure 8 by applying the function of the tire system adopting AHM defined in Figure 13. Second, the actual effect of the uncertainty event is identified. The type of uncertainty is selected on the basis of the uncertainty matrix of reality and perception, which is defined in the white paper on AHM (IATA, 2022). This white paper states that considering that a health indicator is positive when indicating a failure, the resulting errors in diagnosing the system/component emerge as a false positive or a false negative, and AHM with robust predictive capability performance will generate a "TRUE" result following a successfully executed diagnosis (IATA, 2022). Finally, the associated MOP and its risk implications are evaluated.

MOP of AHM	Impact by AHM	Affected MOE
Alternated maintenance requirement by AHM	One maintenance task is alternated by AHM task and reduces man hour for the task	Increased profit of the airline
Quantity of AHM data	No effect	None
Preparation time before recovery	No effect	None
Remaining parts life	No effect	None
AHM development cost	Increase to develop AHM function of aircraft.	Additional cost to develop the AHM
AHM introduction cost	Minor	None

Table 4. Effectiveness evaluation summary of tire system adopting AHM (MOP of AHM)

MOP of airline	Impact by AHM	Affected MOE
Continuous safety margin of aircraft	Same level as without AHM	None
Downtime for planned maintenance	No effect because the maintenance is performed during night parking.	None
Downtime for unplanned maintenance	No effect because the maintenance will be required during night parking.	None
Maintenance cost	Reduces maintenance cost due to the reduction of maintenance task performed by a maintenance crew. Increase parts replacement cost which are added for AHM function.	Increased profit of the airline Additional cost to operate the AHM
Aircraft ownership cost	Increase due to the AHM parts installed to the aircraft.	Additional cost to develop the AHM

Table 5. Effectiveness evaluation summary of tire system adopting AHM (MOP of Airline)

Event to cause uncertainty	Effect	Affected MOP	Affected MOE (risk)
Unplanned servicing by maintenance crew	Pressure leak may not be detected	Continuous safety margin of aircraft	Safety Risk: Benefit brought by AHM is reduced.
Erroneous indication to request maintenance	Unnecessary servicing and tire replacement is required.	Maintenance cost	Economic Risk: Maintenance cost increases due to unnecessary maintenance.
No indication to request maintenance	Predicted state is healthy but real state is failed.	Continuous safety margin of aircraft	Safety Risk: The risk of tire damaged increases but maintained by the redundancy.
		Maintenance cost	Economic Risk: Maintenance cost increased due to additional tire replacement.

Table 6. Risk identification summary of tire system adopting AHM

Type of MOE	MOE
Benefit	Increased profit of the airline
Cost	Additional cost to develop the AHM
	Additional cost to operate the AHM
Risk	Safety risk due to AHM uncertainty
	Economic risk due to AHM uncertainty

Tabe 7. Summary of MOE affected by AHM

6.5. Examination of AHM Effectiveness Evaluation for SoS Stakeholder Agreement (Step 5)

Table 7 shows the MOE that is affected by the adoption of AHM. This MOE needs to be quantified. This study excludes a quantitative evaluation of MOP and MOE.

Using these evaluated MOE values, the AHM functional allocation identified in Figure 13 will be used to be agreed upon by the stakeholders who own the functions of the SoS. The adoption of AHM into the maintenance program will be then agreed upon by airlines and regulatory authorities while considering the identified benefits and costs, and all risks are mitigated to a level acceptable to all stakeholders.

7. DISCUSSION

In this section, three topics , are discussed: a comparison with existing methodologies applying detailed case studies, the relationship with AHM tools, and the extension of this methodology to evaluate interoperability and collaboration between different systems and stakeholders.

7.1. Comparison with existing methodologies and applying more detailed case studies

The conventional MSG-3 method uses an airline-centric effectiveness-based logic to determine the application of AHM. In contrast, this study focuses on proposing a holistic evaluation method for the effectiveness of AHM, which is necessary for multiple stakeholders in the SoS to agree on the goal, individual roles, and functions that they collaborate.

In the logic of MSG-3, the maintenance tasks are determined by considering the applicability and effectiveness of the task. For operational and economic effectiveness, only parameters that are important for the airline, such as the probability of downtime for unplanned maintenance and maintenance costs, were evaluated. This approach was appropriate when they determined the maintenance task after the aircraft manufacturers already had defined the aircraft system architecture. On the other hand, to apply AHM to practical use, it is necessary to agree on the functional allocation at the SoS layer, considering such as changes in the airline maintenance system, and establishing an IT environment, before or in parallel with the aircraft design definition. To solve such problems, this study proposes an evaluation process of the holistic stakeholders effectiveness (shown in Fig. 9) to optimize the entire system and satisfy the needs of each stakeholder.

In this paper, we applied a tire monitoring system to the proposed system model which is written in the SoS layer, as a case study. But the case was a very limited. As tire maintenance is the most frequent type of aircraft maintenance, the scope of the effectiveness of the AHM application was expected to be various. However, the results of the study concluded that the only benefit was an increase in airline revenue due to reduced maintenance costs.

The effectiveness of the AHM depends on the use case and it will be such as increasing the number of flights by reducing planned maintenance, improving passenger convenience by reducing delays through the reduction of unplanned maintenance or reducing prices to passengers by improving aircraft utilization rates and reducing operating costs as shown in Figs. 10 and 11. Because the effectiveness of the applied case study was limited in scope, the results did not fully demonstrate the superiority of this method, which can consider the effectiveness of all stakeholders in the AHM, compared to the conventional MSG-3 analysis method. In addition, since the analysis in this study does not include quantitative evaluation, it is not possible to show the trade-off between the airline's benefits and the AHM's operational and development costs and risks.

In the future, we will validate the effectiveness of our method by comparing the results with real cases and views based on real cases. In the validation process, we need to quantify the results of the analysis using data from actual cases and apply sample cases of the AHM system which affects various types of effectiveness.

7.2. Relationship with real-time data analytics and advanced prognostic tools

This study proposes a descriptive model of the AHM system, in which the AHM functions are expressed as Sense, Acquire, Transfer, Analyze, and Act.

In this model, technologies such as real-time data analytics and advanced prognostic tools are represented as means to perform these functions. The value and effectiveness of real-time fault prediction using sophisticated data processing techniques applied to AHMs in unplanned maintenance can also be evaluated using this method.

On the other hand, the proposed method is intended to be applied in the maintenance program development using the MSG-3 framework (Fig. 1), whose use cases are for planned maintenance. We consider that, by adding a decision logic to Fig. 1, the method can be also used for the standalone unplanned maintenance apart from the planned maintenance determination.

When AHM is applied to planned maintenance, the main objective is to ensure that failures are detected within a certain exposure time from the viewpoints of safety, operability, and economy. Therefore, the adoption of AHM is often conservative because sufficient countermeasures are needed to address the risk that the detected health is Healthy and the actual condition is Failed. On the other hand, the main purpose of using AHM in unplanned maintenance is to provide the earliest possible notice of failures and potential failures from the standpoint of operational and economic efficiency. Therefore, AHM can be considered to be more progressively applied in this environment because it can be operated with a greater emphasis on benefits.

7.3. Interoperability and collaboration between different systems and stakeholders

AHM infrastructure systems of today tend to manage not only a single aircraft or a single component but also multiple aircraft types and components in a centralized manner. To analyze these relationships, it is necessary to consider multiple aircraft manufacturers and IT vendors in addition to multiple airlines as stakeholders in AHM as SoS. In addition, additional considerations for integrating different aircraft types and systems will be appearing. (e.g., AHM standards, communication data standards, etc.).

In this study, while the AHM is described as a system model of the SoS layer, we analyzed a single subject, a tire monitoring system, to evaluate the conceptual validity of the evaluation method. We consider that the proposed system model can be a basic model and it can be extended by focusing on the interactions among more stakeholders at higher layers to evaluate more complex interests from a holistic perspective.

8. CONCLUSION

This study proposed a higher-level system model of AHM based on a systems engineering approach while referring to the UAF and SysML metamodels. Furthermore, an approach to evaluate the effectiveness of AHM on aircraft maintenance programs was proposed. The proposed approach was divided into five steps, and we emphasized that the risk caused by the uncertainty of AHM should be evaluated in addition to the benefits and costs of AHM. As a case study, an aircraft tire system adopting AHM was evaluated. The results show that MOE affected by the adoption of AHM is identified considering the uncertainty examined from the functional flow between stakeholders. We demonstrate that a SoS approach aids in reaching a consensus among stakeholders who own AHM functions.

Three topics are discussed regarding the limitations of the proposed method. First, we applied a tire monitoring system as a sample case, which was a very limited object, while AHM was described as a system model at the layer of SoS. As a result, we were not able to fully demonstrate the superiority of our method compared to the conventional MSG-3 method because of the limited variation of MOEs affected by the sample case. Second, the proposed method was limited to the use case of planned maintenance determination while the proposed AHM system model covers both planned and unplanned maintenance. We consider that by applying the proposed method also to unplanned maintenance, the effectiveness of AHM can be analyzed for more realistic use cases. Third, it was pointed out that the proposed method can be extended to apply higher layers of stakeholders to capture more complex relationships from a holistic perspective considering the recent AHM. The AHM infrastructure tends to handle not only a single aircraft type or component but also multiple models and components in a centralized manner.

As a future problem, MOE should be quantified for the actual agreement process. In addition, the uncertainty of aircraft maintenance activities should be investigated through actual field practice. To solve these problems, the proposed model will be described using the concept of a robust optimization method to quantify MOE and MOP. In addition, for the validation of the method, it is necessary to apply the proposed method to several existing cases including unplanned maintenance in addition to planned maintenance. Then we will be able to demonstrate the validity and usefulness of the analysis result by interviewing airlines that utilize AHM. Furthermore, it would be useful to extend the scope of the system model to evaluate higher-level concepts and more complex stakeholders' concerns including multiple aircraft types and airlines.

ACKNOWLEDGMENT

The authors thank Levii Inc. for providing the MBSE tool, Balus 2.0 (Miura et al., 2022).

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