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A sustainable approach to Aircraft Engine Maintenance

S. KEIVANPOUR *, D. AIT KADI **

* Département de génie mécanique,Pavillon Adrien Pouliot, ,1065, avenue de la Médecine
Université Laval, Québec (Québec), G1V 0A6, (e-mail: samira.keivanpour.1@ulaval.ca)

** Département de génie mécanique,Pavillon Adrien Pouliot, ,1065, avenue de la Médecine
Université Laval, Québec (Québec), G1V 0A6, (e-mail: Daoud.AitKadi@gmc.ulaval.ca)

Abstract:

This paper proposes a conceptual framework in order to integrate simultaneously reliability, economic, environmental and social performance of aircraft engine maintenance activities. A practical guideline for application of this framework for an aircraft engine is illustrated. After studying the available scientific literature on the problem, we highlight the main contributions of past research and the existing gap of considering a sustainability approach to aircraft engine maintenance operations. We uncover the main areas which provide insights for researchers and manufacturers.

Keywords: **Aircraft Maintenance, Engine maintenance, Sustainable development,**

1. INTRODUCTION

Maintenance activities have essential environmental impacts including wastes and end-of-life (EOL) parts. According to life cycle assessment (LCA) of commercial aircrafts, the environmental impact of the maintenance phase is significant and cannot be neglected (Chester, 2008 & Fernandes Lopes, 2010). Corporate social responsibility forces aircraft manufacturers take into account these impacts and develop some solutions in order to minimize the environmental impacts of the maintenance phase. Moreover, maintenance steering groups (MSG) highlight the importance of considering safety and reliability as well as economic benefits in developing the maintenance tasks. Therefore, the aircraft manufacturers need to develop efficient and practical solutions to meet the requirements of safety and reliability. But at the same time, they need to minimize life cycle costs while preventing or limiting harmful impacts to the environment. This goal can be achieved by defining objectives including making longer life parts (prevention of part replacements) and limiting harmful impacts to the environment (wastes and EOL parts) during maintenance operations without any adverse effects on safety and performance. Furthermore, considering the social impacts as the result of maintenance actions are also essential in order to achieve the sustainable development. In this paper, we propose a framework for improvement of engine maintenance operations considering, economic, environmental, reliability and social performance. This paper is organized as follows: section 2 provides a background and literature review, section 3 illustrates the framework for engine maintenance in the sustainable development context, section 4 introduces the proposed integrated framework and finally section 5 concludes with some remarks and the challenges.

2. BACKGROUND

2.1. Aircraft Maintenance & Life cycle Impact of maintenance Phase

According to Nowlan & Heap (1978), in aircraft maintenance, only 11 percent of aircraft components would benefit from setting interval checking with respect to their wear out conditions (Fig 1). The failure rate for these items can be predicted and scheduled maintenance is a good solution in order to prevent the failures for these items. But for the other 89 percent of items, as the failures occur, the scheduled maintenance or preventive maintenance cannot be applied and un-scheduled maintenance is required to correct the problems (Kinnison, 2004).

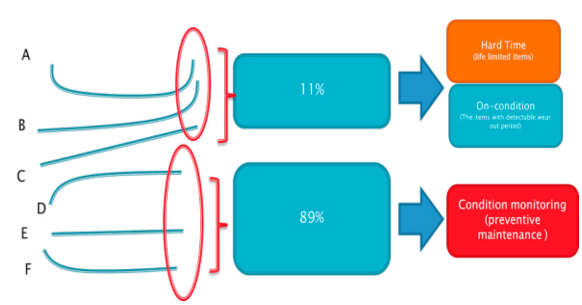

Fig 1: Failure rate patterns for different aircraft items (adapted from Kinnison, 2004)

In this part, we provide a review of the environmental impact of the maintenance operations and the LCA. According to EPA/310-R-97-001, aircraft maintenance is the function of three factors: hours of flight time, number of landing and take-off cycles and calendar length of time from prior maintenance (EPA website). This EPA document provides a list of maintenance operations and the potential impacts of

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these operations on the environment. Chester (2008) studied of the life cycle environment inventory of passenger transportation in the US. The author used EPA/310-R-97-001 category, in order to evaluate the impact of the maintenance phase. According to the study outcomes, the impact of vehicle maintenance is comparable with vehicle manufacturing and is not negligible. However, the result of this study is based on the costs of different maintenance operations and the effect of part replacement has not been considered. In the vehicle and passenger car, the maintenance phase in the LCA is considered in different approaches. For example, a study of environmental improvement of passenger cars by Nermy et al., 2008 considers the manufacturing of spare parts such as oil, tire and battery as well as the maintenance and repairing operations. According to the report of product sustainability index of Ford (Ford Product sustainability index), three parts in maintenance operations are considered: maintenance material production, waste and other maintenance processes. However, the effect of oil and the other sections have been excluded from the study due to the lack of information. In the study of analyzing the life-cycle of new automobile technologies, it has been specified that "Maintenance energy encompasses all energy that is used to replace vehicle parts or liquids, throughout the entire vehicle life. As there is virtually no information available, we have neglected this stage of energy use and emissions. However, the associated error should be small, as energy use and emissions are likely significantly smaller than material production and vehicle assembly" (Weiss et al., 2000). Therefore, according to existing literature, there is not a unique approach to considering the impact of maintenance phase in life cycle assessment. And, it seems that parts and components replacement, repairing operations and waste during maintenance operations are three important categories of maintenance and repairing phase in order to be considered as the environmental impacts.

2.2. Related research works

According to Dekker, & Scarf, 1998, engineers and mathematicians have considered the maintenance optimization area because it's an interesting area for modeling and exploiting their analysis. However, as the result of the complexity of these models and lacking of data, application is limited. The papers which address maintenance optimization in aerospace context can be classified into two categories. The first category of studies is related to optimization of overhaul planning and manpower planning that usually utilizes job scheduling and planning methods (Gray (1992), Dijkstra, et al., (1994) & Van Rijn et al., (1992)) cited in (Dekker, & Scarf, 1998). The second category considers maintenance optimization at design stage which is also limited. Tanaka et al, (2003 focuses on the large engine maintenance techniques and proposes some solutions in order to decrease the maintenance costs. The solutions are classified into two categories of planning and developing new techniques. In planning, they explained that how setting time and range of engine maintenance can lead to reducing the engine maintenance cost. In developing techniques, they demonstrated some parts repair techniques which lead to part repair costs and saving parts which were bound to be scrapped. An optimization model using the genetic algorithm is developed in order to support maintenance infrastructure (Saranga & Kumar, 2006). The objective of this model is optimization of maintenance and maintainability during the design stage of the equipment for minimum life cycle cost (LCC) or minimum total cost of ownership (TCO). They developed the model based on the modular and multi-echelon perspective.

2.3. Stakeholders outlook

A manufacturer with sustainable organization culture requires identifying not only the stakeholders and their expectations but also interdependencies and synergies in stakeholder's network to maximize the value considering environmental, economic and social requirements (Wheeler et al., 2003). Thus, for sustainable eco-design strategy, in addition to considering the value outcomes of implementation an eco-design technique, its impact on stakeholders network is also needed to be taken into account. In order to have a sustainable approach to maintenance in aerospace context, we need to identify the stakeholders, their needs and expectation and interaction among them. Considering the life cycle of the aircraft, aircraft manufacturer, suppliers (particularly Tier 1 & 2), operators, MRO (Maintenance, repair and operation), aerospace authorization body, local and international actors and society are stakeholders involved in the maintenance operations.

3. ENGINE MAINTENANCE & STRATEGIES FOR SUSTAINABLE IMPROVEMENT

The engine maintenance covers 30% of the total cost of the aircraft maintenance. Moreover, reduction of shop maintenance cost is important for the reduction of the operational cost of an aircraft because it would be approximately 50-60% of the total cost (Tanaka et al, 2003). Hence considering the different aspects of engine maintenance at design stage is crucial. The complex equipment has modular design (multi indenture design) and maintenance is carried out at multiple echelons (Saranga & Kumar, 2006). The modular structure of aircraft engine has three levels: line replaceable unit level, shop replicable unit and part. Saranga & Kumar, 2006 used engine (LRU) case study including 10 modules (SRU) with 22 parts spread between these modules in order to optimize Level of Repair Analysis (LORA). The process of engine maintenance is consisted of disassembly, cleaning, repair, assembly and test (Tanaka et al, 2003). In each part of this process, there is a potential for optimization particularly at design stage. In the disassembly and assembly phases, design for maintainability, in the cleaning and inspection, information provision or providing manual, in the repair phase, choosing techniques, level of operation and decision regarding part destination (reusing, remanufacturing or disposal) and finally for the testing phase, providing information can be considered as the areas for improvement.

3.1. Design for maintainability

Maintainability is the degree to which a product allows safe, quick and easy replacement of its component parts. It is embodied in the design of the product. At the conceptual design stage, optimizing future aircraft considering environmental and operating performance needs an integrated approach that identifies the multidisciplinary nature of aircrafts, and can take into account simultaneously variables and constraints from related disciplines (Antoine & Kroo, 2004). In the case of optimization of engine maintenance, we need to identify the design for maintainability parameters, the associated cost performance, risk, reliability and environmental performance. With knowing the current parameters and improvement options considering these disciplines, we can develop the optimization model.

3.2. Scheduled maintenance & Un-Scheduled maintenance

There are several studies which address the optimization of maintenance interval. For example, Tsai et al, (2001) proposes a periodic preventive maintenance of a system with deteriorated components. Two activities, simple preventive maintenance, and preventive replacement, are simultaneously considered to arrange the preventive maintenance schedule for a system. Regarding the engine maintenance, we need to consider the scheduled maintenance tasks related to each part and identify the cost performance, environmental impact, reliability and risk of these tasks. The optimization of un-scheduled maintenance should be done regarding reparable items and non-repairable items. Saranga & Kumar (2006) defined three decisions regarding parts; replacing, repairing or discarding. Moreover, the authors addressed the level of operations. In addition, using special techniques can lead to increasing the part life span and reducing the parts scrap rate (Tanaka et al, 2003). Therefore, with integration of these essential decisions, we can develop a holistic optimization.

3.3. Providing information and manuals

The required information which can be provided by manufacturers include disassembly and recycling information such as material composition, hazardous material type, and design for disassembly level, recycling category and disposal consideration such as related regulation. For the procedure, related directives for each task, best practices, and checklist can also be considered. In order to have a manual demonstrating an effective and practical means of preventing or limiting harmful impacts to the environment during maintenance activities, reviewing literature can bring some insights. In this part, we reviewed some related works. The first study is a guideline for the Vehicle Dismantling and Recycling, this guideline was prepared by Ministry of Environment of Canada /Environmental Protection Division, in order to assist vehicle dismantlers and recyclers in meeting the requirements of the regulation (Guideline for the Vehicle Dismantling and Recycling). All regulation related to waste management of ozone depleting substances and other halocarbons; oils, brake fluids, solvents, fuels and other hydrocarbons; antifreeze; lead and lead-acid batteries; waste tires; mercury switches; and windshield washer fluids have been addressed in this document. In each category, the legal requirement, operational checklist and best practices with respect to dismantling, storage, transportation and recycling have been explained in this document. The second study is Environmental best practices for highway maintenance Activities which has been prepared by Ministry of transportation and infrastructure of Canada (MoT) (Environmental best practices for highway maintenance Activities). The MoT contracts the maintenance of British Columbia's provincial highways to privatized Road and Bridge Maintenance Contractors. These contractors play an essential role in meeting the Ministry's mandate to provide safe transportation and to carry out all works in an environmentally responsible manner. The Ministry has developed this manual of Environmental Best Management Practices for Highway Maintenance Activities. These standardized practices and protocols are designed to be applicable to the province and to serve as a practical and cost effective means for contractors to meet regulatory agency requirements and public expectations for environmental protection. In this document, sixteen environmental best practices have been developed for 9 maintenance categories, and covering 35 specific maintenance activities. This document is organized into three main segments: key environmental concerns, legislative requirements and performance standards and environmental best practices. Therefore, an appropriate maintenance manual with objectives addressing environmental concerns, addressing environmental impact of maintenance activities, addressing the relevant policy and regulation requirement and standards (provincial, federal , etc.) applicable to maintenance activities, addressing the relevant best practices , can be provided by manufacturers to preventing or limiting harmful impacts to the environment during maintenance activities.

4. THE INTEGRATED FRAMEWORK

4.1. The key aspects of the framework

Recently, extensive attention to sustainable development has started becoming an essential aspect of the aviation industry. Aircraft manufacturers have reacted to this situation and recognized the importance of focusing their efforts to integrate sustainable development policies into their core business strategies. However, the effectiveness and the efficiency of such efforts have been in question because systematic approaches to support such activities are limited (Morimoto & Agouridas, 2009). Design for environment (DfE) or Eco design strategy is one of these efforts in order to integrate the environmental considerations into product and process design. There are different techniques and practices which can be used by manufacturers for DfE. Material substitution, design for disassembly, design for recyclability, design for reusability are some of these practices (Keivanpour et al., 2014). Based on literature reviews, DfE tools and methodologies are required to be more developed (Handfield, et al., 2001). Furthermore, the stakeholders, life cycle approach, and multi-criteria decision analysis are needed to be considered in an integrated eco-design approach (Bovea & Pérez-Belis, 2012). Based on this existing gap, a holistic approach to integration sustainable development into engine maintenance is introduced (Fig 2). In the next sub-sections, the essential parts of this framework will be explained.

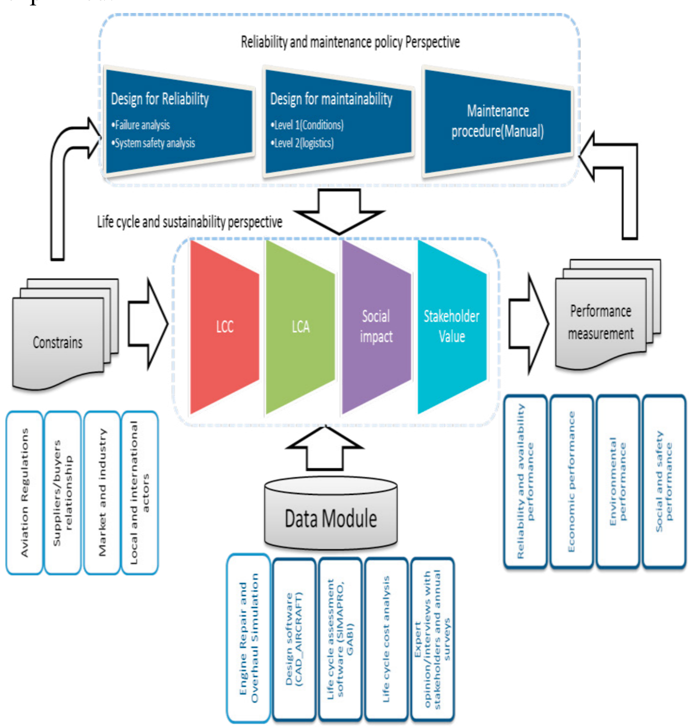

Fig 2: The integrated framework for sustainable engine maintenance design and policy

4.2. Reliability and maintenance policy perspective

According to (Kumar & Cracker, 2003), the major cause of engine failure is age related issues. However, there are other three sources: foreign object damage, inadequate training of the personnel and quality control. In addition, the authors emphasize that considering the difficulty of part inspection in situ; the opportunistic maintenance plays an essential role in engine reliability. In opportunistic maintenance, the corrective activities on failed parts can be joined with preventive activities performed on other parts. Opportunistic maintenance is a valuable strategy for an aircraft engine considering multiple components, high costs of shop visits and safety importance. When a down-time opportunity is created by service, maintenance team may perform preventive maintenance on the other parts. Kumar & Cracker, (2003) explained the minimum issue life (MISL) and soft life as two important parameters in engine and its components maintenance policies. According to authors, "The issue life is the number of hours/cycles that a component still has remaining before it is due for a scheduled replacement when refitted with a module/ engine. A low MISL would result in fewer parts being replaced before they reach their hard life than would be the case for a higher MISL. A soft life, on the other hand, is not related to a hard life. A component that has exceeded its soft life would be reconditioned/replaced the next time the engine, in which it is installed, is removed for maintenance" (p.387). The change in each of these parameters leads to some variations in LCC. However, the associated environmental and social impacts during the life cycle of the aircraft also need to be taken into account.

4.3. Life cycle and the Sustainability perspective

In order to clarify the life cycle perspective of maintenance operations, in this section we provide an example. Engine consists of three levels: LRU level or line replacement unites SRU level or shop replacement unit and Part level (Fig3). For simplicity of calculation, we suppose that we have 2 SRU and 5 parts as illustrated in Fig 4. The specification of the parts described in Tab 1.

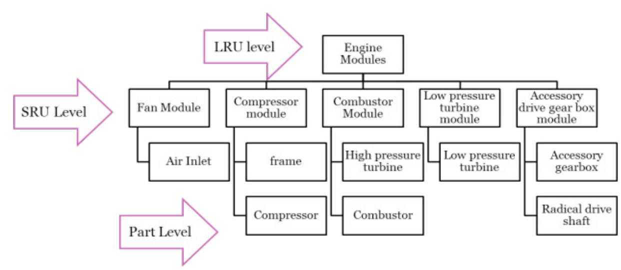

Fig 3: Three levels of parts and components

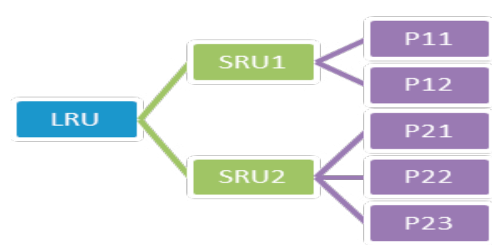

Fig 4: The example with 5 parts

Tab 1: The specification of the parts

	LRU				
	SRU1		SRU2		
	P1.1	P1.2	P2.1	P2.2	P2.3
MTBF	NA	2500	1500	NA	9500
Scheduled maintenance Interval	600	NA	NA	12000	NA
Repairable /Non-repairable/Discard	D	NR	NR	D	NR
Materials composition (Mass)	X(0,4),K(0,6)	X(0,2),Y(0,3),Z(0,6)	Y(0,15),Z(0,4)	X(0,2),K(0,3)	X(0,15),Z(0,4),K(0,6)

In this example, we suppose that P1.1 and P2.2 are life limited items that should be replaced during scheduled maintenance intervals. The other three parts are non-reparable items with specific MTBF (Mean time between failures). Four types of materials are considered for this example. Materials X and Y are recyclable and materials Z and K are non-recyclable. Moreover, material Z is in the category of hazardous material. The mass of each type in the material composition of the part is also shown in Tab 1. The unit of MTBF for non-repairable parts and scheduled maintenance interval for life limited items are based on (FH: Flight Hour). Now, if we suppose that the life cycle of the aircraft is 100,000 FH, and then based on the number of replacements during the life cycle, the following results will be obtained (Fig 5). For example, for P2.1 with MTBF, 1500 FH, (100,000/1500) =66.67 times replacement need to be considered during aircraft life cycle. As the item is non-repairable, we assumed that it can be re-used by 0.67 FH in the other aircraft; hence we considered the re-using option for its material. Non-recyclable items should be landfilled. Thus, the costs of landfilling Z and K considering the hazardous contains in Z would be different. Moreover, safety consideration for maintenance staff should be considered during the maintenance operations.

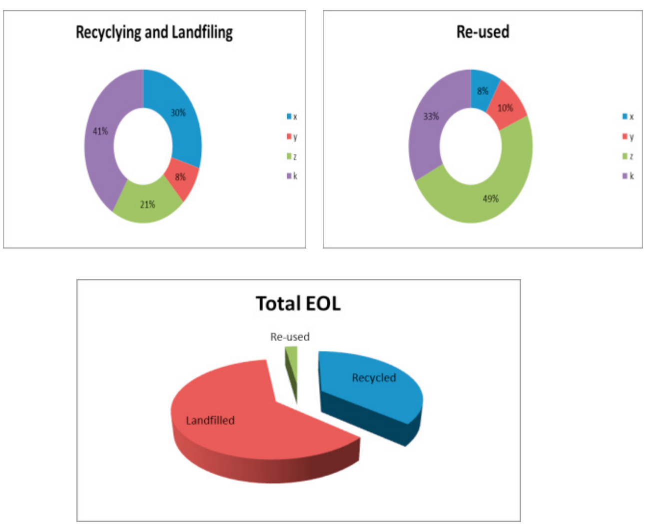

Fig 5: The parts replacements impacts

In addition to reliability features, the first level of design for maintainability also includes the information related to level of repair, accessibility of the parts and components during the maintenance activities, the final decision regarding the parts (discarding, repairing or remanufacturing) and the quality audit. These characteristics are directly related to the environmental and social aspects. For example, Tab 2 shows this relationship.

Tab 2: The relations between design for maintainability features and sustainability aspects

	Environmental impacts			Social impacts		
Level of repair	Noise	Solid wastes	Air emission	Safety	Employment	Risk to emplyment
Local						
Srvice center	*		*	*		*
Mnaufacturer						
Accebility and modularization						
Visibility						
Human factor						
Interchangeability						
Simplicity		*		*	*	*
Decesion						
Repairing						
Reconditioning						
Replacing		*	*	*	*	*
Quality control						
				*		

The second level of design for maintainability contains the information related to logistics elements. Human resources, organization and management for maintenance staffs, the required tools and equipment, skills level, facilities, and software have also direct impacts on sustainability indexes. Not only LCA, LCC, and social impacts but also stakeholder's value analysis should be performed to shed the light regarding the impacts of policy making on different players involved in engine maintenance operations. Keivanpour et al., (2014) introduced a novel approach in order to compare different Eco-design practices considering the value network of stakeholders. This decision tool helps manufactures in early stage of design to select a portfolio of eco-design techniques to maximize the value perceived by all stakeholders in a dual life cycle approach including the business product life cycle as well as physical life cycle. Based on the guideline proposed by the authors, in the first step, the green strategy should be identified by engine manufacturers. In the second step, sustainable design for maintainability practices (which are feasible) should be determined and relevant features and characteristics of these practices should be addressed. Step 3 is mapping stakeholder's network, including identifying the key stakeholders and their relationship, needs, and expectations as well as the network structure as the result of applying the green policies. The next step includes linking the design for maintainability features and stakeholder's needs and finally finding the best practices based on the maximum value for all stakeholders (see Keivanpour et al., 2014 for more details).

Data module plays an important role. The source of data could be the simulation and design software (such as CAD_AIRCARFT, Engine Repair and Overhaul Simulation, LCA and LCC tools (such as GABI or SIMAPRO) or in some cases expert opinions. As the first priority is safety, thus complying with the aviation regulations and standards is crucial. The other constraints include the collaboration challenges with suppliers, market and industry context and the local authorities.

5. DISCUSSION & CONCLUSION

There is a growing demand as well as interest in considering social and environmental impacts of the product during the life cycle. Therefore, manufacturers need to have a sustainable approach to optimizing products characteristics at the design stage. Airplanes are amongst the most expensive industrial systems which at the same time have the highest reliability and safety requirements. The aerospace industry, with complex and expensive products and need for high requirements of safety and reliability, face more challenges in order to have a sustainable approach at the design stage. The maintenance operation is an essential phase in the life cycle of the aircraft considering the environmental impacts and costs of operations. In this paper, we proposed a framework for improvement of aircraft maintenance in a framework of sustainable development. Working on a detailed case study can be proposed as future research. However, there are still some challenges. Considering of the highest reliability and safety requirements in the aviation industry, there is a little scope for improving maintenance outside the manufacturer.

In order to have a multi-objective optimization, it is needed to have detailed information about the LCA and LCC. As the maintenance phase occurs in the scope of operation, access to this level of information is difficult or sometime impossible. For example, the main issue in order to calculate the impact of part replacement during maintenance operations is the way to estimate the frequency of failure rate of the components and sub-parts. It is a challenging issue due to the different approaches and considering the probabilistic nature of the failure rate of components. Overhaul and shop operations are other concerns because these activities are included in restoration task, but the detailed information regarding these activities is not available. Therefore, integrated optimization should be done with collaboration of all parties. Resolving a distributed decision-making framework with collaboration of key players is a challenging task which needs to be addressed in an organized way.

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