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Affiliée à l'Université de Montréal

**Future-Proofing Sustainable Aircraft Maintenance: A Novel Aircraft
Maintenance Sustainability Assessment Method and Investigating Green
Maintenance Repair Overhaul**

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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présenté par **Seyed Hadi ALAVI**

en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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DEDICATION

To my dearest wife, Molood, whose unwavering love and support have been my guiding light through every challenge, and to my wonderful son, Mahan, whose presence fills my life with joy and serves as a daily reminder of the importance of perseverance and hope.

You are my compass, guiding me through the toughest times!

&

To my mother and my family, for their endless encouragement, love, and support, I am forever grateful.

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Lastly, a special thanks goes to my wife, Molood, and my son, Mahan, for their patience, understanding, and unwavering support during the time I dedicated to this research and thesis writing.

RÉSUMÉ

L'industrie aéronautique joue un rôle crucial dans le développement durable en connectant les personnes, les entreprises et les communautés à travers le monde. Comme le déclare le Air Transport Action Group : "Un transport aérien sûr, fiable, efficace et abordable est essentiel pour une stratégie de mobilité globale visant à atteindre les Objectifs de Développement Durable 2030 des Nations Unies". Cependant, en 2018, l'industrie du transport aérien était responsable de 2,5 % des émissions totales de gaz à effet de serre (GES), un chiffre qui pourrait atteindre 22 % d'ici 2050 si des mesures ne sont pas prises. En réponse, l'industrie de l'aviation s'est fixé un objectif ambitieux de zéro émission nette d'ici 2050. Cet objectif nécessite des avancées technologiques, notamment le développement d'avions plus économes en carburant et des améliorations des flottes existantes. Par conséquent, les systèmes d'avions deviennent de plus en plus complexes sur le plan technique et exigeants en termes de maintenance, positionnant la maintenance des avions comme un élément clé dans la transition vers la neutralité carbone. L'exploitation et la maintenance des avions représentent environ 80 à 85 % du coût total du cycle de vie (LCC) de la plupart des avions. Les coûts de maintenance directs (DMC) peuvent à eux seuls représenter 10 à 20 % des coûts d'exploitation directe (DOC), en fonction de la taille, du type, de la portée, de l'âge et de l'utilisation de la flotte. Compte tenu de ces coûts significatifs, l'amélioration de la durabilité et de l'efficacité des systèmes de maintenance est essentielle pour réduire les coûts du cycle de vie et améliorer la disponibilité des avions. La maintenance a également un impact direct sur la sécurité des vols, la rentabilité et la compétitivité dans l'industrie aérienne, représentant environ 11 % de la main-d'œuvre d'une compagnie aérienne. Cela souligne l'importance de l'industrie de la maintenance des avions dans les dimensions économique, environnementale et sociale de la durabilité de l'aviation. Les recherches et la littérature existantes se concentrent principalement sur l'éco-conception des produits aéronautiques, la circularité et la gestion de fin de vie, tandis qu'il n'y a pas ou peu d'études sur la durabilité de la maintenance des avions.

Cette étude considère la maintenance comme l'élément clé de la durabilité dans l'industrie du transport aérien. Elle explore et aborde la durabilité de la maintenance des avions à la fois du point de vue du produit et du processus opérationnel.

Contributions :

La première contribution - Article de journal évalue la performance de durabilité de la phase de maintenance des avions d'un point de vue produit. Elle examine les fondements du développement des programmes de maintenance des avions, la méthodologie et les processus, ainsi que l'évaluation de la durabilité dans le paysage de l'industrie de la maintenance, en vue de développer un cadre pour mesurer le score de performance de la durabilité de la maintenance des avions (MSPS). Cette étude vise à promouvoir l'éco-maintenance dans une perspective de développement de produit et propose une approche novatrice potentielle pour réintroduire la performance de durabilité de la maintenance dans les pratiques de développement d'éco-conception futures. Le cadre proposé vise à fournir une mesure cohérente et comparable pour évaluer l'impact de la durabilité des exigences de maintenance des avions, des systèmes et des sous-systèmes. Avoir un tel cadre offrirait une visibilité accrue sur l'impact de la durabilité au cours de la durée de vie des avions, en tant qu'outil de benchmarking précieux pour le développement futur d'avions plus durables. Cela aide également les opérateurs aériens et les bailleurs d'avions à prendre des décisions plus éclairées et durables concernant leurs acquisitions et investissements futurs.

La deuxième contribution - Chapitre de livre : Elle présente une étude exploratoire complète sur la durabilité de la maintenance des avions d'une perspective Maintenance, Réparation et Révision (MRO). Elle examine le rôle de la maintenance dans l'atteinte de l'objectif zéro carbone net d'ici 2050. Elle découvre le rôle de la maintenance aéronautique dans les mesures d'atténuation et d'adaptation au changement climatique. Elle explore la mise en œuvre et l'intégration potentielles d'un ensemble multidisciplinaire de technologies de l'industrie 4.0, d'outils lean et verts, vers des pratiques MRO plus durables. Ensemble, les deux contributions présentent des informations nouvelles et perspicaces sur les défis et les opportunités vers une maintenance plus durable de la flotte mondiale existante ainsi que sur le développement futur d'avions plus durables.

ABSTRACT

The Aviation industry plays a crucial role in sustainable development by connecting people, businesses, and communities worldwide. As the Air Transport Action Group states, "safe, reliable, efficient, and affordable air transport is essential for a comprehensive mobility strategy to achieve the United Nations' 2030 Sustainable Development Goals." However, by 2018, the air transport industry was responsible for 2.5% of total greenhouse gas (GHG) emissions, which could rise to 22% by 2050 if not addressed. In response, the aviation industry has set an ambitious goal to achieve net-zero emissions by 2050. This goal requires technological advancements, including developing more fuel-efficient aircraft and improvements in existing fleets. As a result, aircraft systems are becoming more technically complex and maintenance-intensive, positioning aircraft maintenance as a key enabler in the journey toward carbon neutrality. Aircraft operation and maintenance account for approximately 80-85% of the total life cycle cost (LCC) of most aircraft. Direct maintenance costs (DMC) alone can comprise 10-20% of direct operating costs (DOC), depending on fleet size, type, range, age, and utilization. Given these significant costs, enhancing the sustainability and efficiency of maintenance systems is vital for reducing life cycle costs and improving aircraft availability. Maintenance also directly impacts flight safety, profitability, and competitiveness in the airline industry, representing about 11% of an airline's workforce. This underscores the importance of the aircraft maintenance industry in the economic, environmental, and social dimensions of aviation sustainability. Existing research and literature were found mainly focused on aviation product eco-design, circularity, and end-of-life handling while there is no or limited scope study on aircraft maintenance sustainability.

This study regards maintenance as the key enabler of sustainability in the air transport industry. It explores and approaches aircraft maintenance sustainability from both product and process operation perspectives.

Contributions:

The 1st Contribution-Journal paper assesses the aircraft maintenance phase sustainability performance from a product perspective. It delves into the aircraft maintenance program development fundamentals, methodology and processes also reviews the sustainability assessment in the maintenance industry landscape towards developing a framework to measure the aircraft Maintenance Sustainability Performance Score (MSPS). This study aims toward eco-maintenance

from a product development perspective and a potential novel approach toward circling back maintenance suitability performance to future-proof future eco-design development practices. The proposed framework aims to provide a consistent and comparable measurement to assess the aircraft, systems, and subsystems' maintenance requirement sustainability impacts. Having such would provide enhanced visibility over aircraft service life sustainability impact as a valuable benchmarking tool for future aircraft more sustainable development. It also helps air operators and aircraft lessors make more informed and sustainable decisions regarding their future aircraft acquisitions and investments.

The 2nd Contribution-Book Chapter: It Presents a comprehensive exploratory study on aircraft maintenance sustainability from a Maintenance, Repair, Overhaul perspective. It delves into the role of maintenance in achieving the 2050 Net-Zero Carbon goal. Discovers the role of aviation maintenance on climate change mitigations and adaptation measures. It investigates the potential implementation and integration of a multidisciplinary set of Industry 4.0 technologies, lean and green tools, toward more sustainable Maintenance, Repair, and Overhaul (MRO) practices. Together both contributions present novel and insightful information on the challenges and opportunities toward more sustainably maintaining existing global fleet as well as more sustainable future aircraft development.

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LIST OF SYMBOLS AND ABBREVIATIONS

AD	Airworthiness Directive
AHM	Aircraft Health Management
ALS	Airworthiness Limitation Section
AM	Aircraft Maintenance
ASK	Available Seat Kilometer
ATA	Air Transport Association
ATK	Available Tone Kilometer
BFE	Buyer Furnishing Equipment
BER	Beyond Economic Repair
CM	Condition Monitoring
CMM	Component Maintenance Manual
CSR	Corporate Social Sustainability Report
DET	Detailed Inspection
DMC	Direct Maintenance Cost
DOC	Direct Operating Cost
EASA	European Union Aviation Safety Agency
ESG	Environmental Social Governance
FAA	Federal Aviation Administration
FC	Flight Cycle
FEC	Failure Effect Category
FH	Flight Hour
GRI	Global Reporting Initiative
GVI	General Visual Inspection
HT	Hard-Time
ICAO	International Civil Aviation Organization
LCA	Life Cycle Analysis

LCSA	Life Cycle Sustainability Analysis
LTAG	Long-Term Aspirational Goal
MPD	Maintenance Planning Document
MRBR	Maintenance Review Board Report
MRO	Maintenance Repair Overhaul
MSG-3	Maintenance Steering Group 3 rd -Task Force
MSP	Maintenance Sustainability Performance
OC	On Condition
OEM	Original Equipment Manufacturer
OTP	On-Time-Performance
RCM	Reliability-Centered Maintenance
RUL	Remaining Useful Life
SB	Service Bulletin
SDI	Special Detailed Inspection
SM	Sustainable Maintenance
SRM	Structural Repair Manual
TOW	Time-On-Wing

CHAPTER 1 INTRODUCTION

1.1 Context

Aviation contributes significantly to the sustainability of modern society; however, it also poses its environmental impact. It is been estimated as of 2018 prior to pandemic disruptions, the air transport sector was responsible for 3.5% of global greenhouse gas (GHG) emissions[2]. For the next twenty years, Boeing's 2023 Commercial Market outlook (CMO) forecasted 42,600 new commercial airplanes, which is closely aligned with the 40,850 new aircraft deliveries projected by Airbus's 2023 Global Market Forecast (GMF) for the same period [4],[5].

Given the aviation industry's rapid growth outlook ,if it remains unmitigated, it could account for 22% of global GHG emissions by 2050[2]. Considering the significant environmental impact of air transport industry, the International Civil Aviation Organization (ICAO) has established an initiative known as "Long-Term Aspirational Goal" (LTAG) of achieving net-zero carbon emissions by 2050. In line with industry LTAG objective, some technological and operational measures are defined, in which maintenance plays a key role on existing global fleet's performance improvements as well as in adaptation to new emerging technologies. A prior study on the maintenance needs of a hydrogen-powered aircraft found that aircrafts systems are likely to become more complex and challenging to maintain. Furthermore, the shift from kerosene to hydrogen fuel is expected to lead to higher maintenance costs and stricter regulatory compliance needs [6].

Studies indicated that a substantial portion, up to 85 %, of an aircraft's Life Cycle Cost (LCC) is attributed to its operation and maintenance phase. Based on estimates provided by airline companies, maintenance costs typically account for 10 to 20% of the aircraft's Direct Operating Cost (DOC), depending on factors such as age, utilization, and size of fleet. In the airline industry where coemption is fierce, maintaining low DOC can provide significant competitive edge for the air operator [1],[7]. Furthermore, in addition to maintenance direct impacts, other studies on maintenance optimization estimated a significant indirect impact of maintenance in reducing fuel consumption and greenhouse gas (GHG) emissions [8], [9].

All these underscores maintenance as a key enabler of sustainability in air transport industry. Maintenance practices significantly impact all aspects of sustainability performance, affecting the environment, society, and economic profit. The impacts of maintenance are not only limited to technical aspects like productivity, reliability, and availability but also sustainability issues such as

safety, environmental damage, and resource consumption [10]. An increasing number of research and initiatives are aiming to explore the environmental, economical, and social sustainability indicators of the maintenance industry. A research conducted was comprehensively investigating the key performance indicators for sustainable maintenance, aiming to balance environmental, social, and economic impacts in industrial settings [11]. Effective maintenance planning and execution is crucial for ensuring safe flight operations. It also has a significant impact on the On-Time Performance (OTP) of airline's operations which is the key factor to the customer satisfaction and airline perceived reputation [1].

Aircraft maintenance is defined as the necessary actions needed to ensure that aircraft's systems consistently performing their "intended functions" at their designed level of reliability and safety [12]. The Reliability Centered Maintenance (RCM) and Maintenance Steering Group 3rd task force (MSG-3) are both structured methodologies that focused on maintaining system functionality by identifying critical failure modes and determining the most effective maintenance tasks to prevent them. While RCM is a broader approach applied across various industries, MSG-3 is a more aviation-specific implementation of similar principles, tailored to aircraft systems and their maintenance needs [13]. Aircraft maintenance program effectivity is identified as a critical issue in aircraft performance reliability, availability, maintenance related Life Cycle Cost (LCC) and generated wastes [1]. Therefore, the effectiveness of the maintenance program can be considered a crucial factor in aircraft maintenance sustainability performance.

1.2 Thesis outline

Chapter 2 presents the exploratory literature review in regard to Aviation maintenance sustainability context. It also highlights the identified gap in the research literature. Chapter 3 is about the thesis organization. Chapter 4 presents the 1st contribution which is a Journal paper titled as "Toward Future proof Eco-design; A novel approach to assessing aircraft maintenance sustainability performance;". Chapter 5 presents the 2nd contribution which is a book chapter titled "The potential integration of Lean and Green, and Industry X.0 tools in more Sustainable Maintenance Repair and Overhaul (MRO) practices". Chapter 6 is about the research findings, recommendations, limitation, and future research.

CHAPTER 2 LITERATURE REVIEW

This literature review highlights relevant research linked to the Maintenance sustainability performance assessment of aircraft from “Equipment Perspective” and sustainable aviation maintenance from maintenance “Process and practices perspective”.

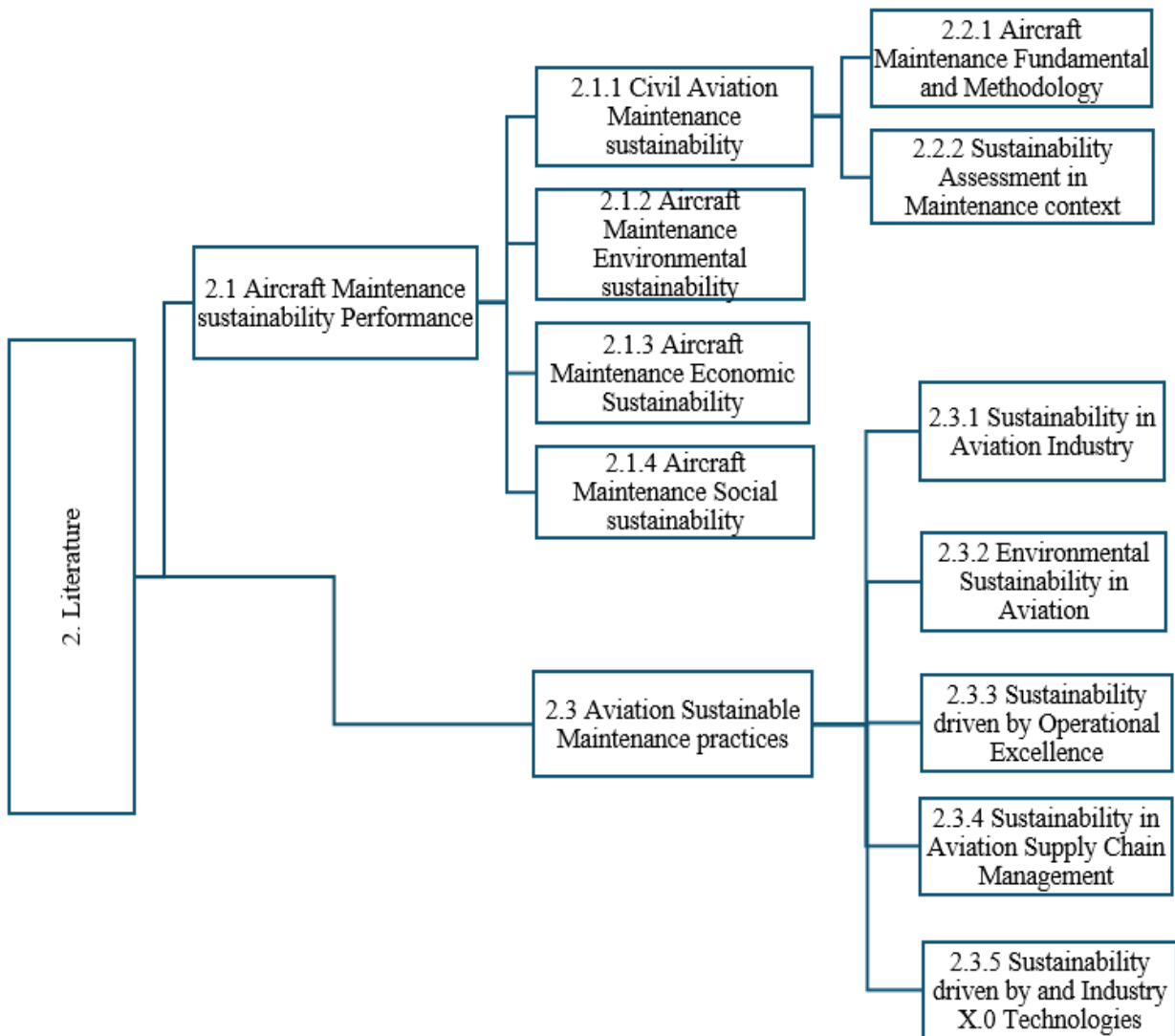


Figure 2-1:Literature review structure

2.1 Aircraft Maintenance Sustainability Performance

2.1.1 Civil Aviation maintenance Sustainability

A recent study on aircraft service life sustainability suggests integrating estimated maintenance costs with environmental factors to evaluate the overall sustainability of aircraft throughout their service life. The study introduces a "green index" to help identify the most sustainable design solutions by balancing economic and environmental impacts [14]. However, the proposed model approximates the life cycle impact and estimates the maintenance cost of a new aircraft based solely on its geometrical shape and functional similarities to an older reference aircraft. This approach found too rough, not incorporating other technological dimensions, and likely differences in their corresponding maintenance requirements. It also found not extendable to aircraft's systems. Another research on composite component circularity indicates that the use phase dominates the entire life cycles impacts which it is mainly driven by component weight not embodied emissions[15], however it did not address the maintenance impacts during the use phase. A comprehensive sustainability index (SI), utilizing Multi-Criteria Decision Making (MCDM), has been proposed to integrate technological, environmental, economic, and circularity factors during the early design phase of aircraft composite components. This approach aims to optimize composite component design while balancing various sustainability objectives [16]. This method does not addresses the components' use phase maintenance impacts.

2.1.2 Aircraft maintenance Environmental Sustainability

Air transport industry is committed to reduce its environmental footprint in order to meet 2050 aviation decarbonization goal set forth by International Civil Aviation Organization [2]. A report by the U.S. Environmental Protection Agency highlights that the aircraft maintenance environmental impact is comparable to that of the manufacturing process. As a result, aircraft maintenance should be regarded as an important environmental concern [17]. The most critical areas requiring efficient management due to their substantial environmental impacts include maintenance operations, parts replacement, and waste generated during these processes [17],[18].

Current literature found primarily addressing the environmental impacts of aircraft manufacturing, flight operations, aircraft End-of-life stages but the ecological impacts of aircraft maintenance have not been thoroughly explored. This could be because maintenance is perceived as having a

relatively insignificant environmental impact within the aircraft maintenance life cycle, hence not grabbed enough attention [19]. While an assessment on the life cycle assessment of passenger aircraft revealed that, maintenance phase significantly impacts the environment, accounting for 5 - 10% of the total greenhouse gas (GHG) emissions throughout the aircraft's service life [17],[20]. There are different methods and tools available for conducting environmental assessments. A well-recognized approach is the conventional Life Cycle Assessment (LCA), which serves as a comprehensive analytical method for evaluating and comparing the environmental impacts of both existing and emerging technologies or materials across their entire life cycle [21],[22]. Notably, LCA is recognized to be data-intensive and involves complex modeling and interpretation. Another widely adopted method is the aggregation of the indicators and Sustainability indexing (SI) which offers straightforward, clear, easy to understand , and comparable metrics for monitoring environmental impacts [23],[24]. Most frequently used environmental assessment methods are provided in Table 2-1.

Table 2-1: Environmental Assessment Tools

Most Frequently Used Environmental Assessment Methods					
Method	Scope	Complexity	Ease of use	Customization	Reference
Life Cycle Analysis- LCA	Holistic (cradle-to-grave analysis)	High (data-intensive analysis), Modeling	Requires expertise and tools	High (can be tailored to any system)	[21],[22]
Life Cycle Impact Analysis- LCIA - ReCiPe	Midpoint and endpoint LCIA categories	Moderate (simplifies data into midpoint and endpoint categories)	User-friendly with clear outputs	Moderate (based on standard impact categories)	[25]
Aggregation- Indexing	Focuses on selected metrics and indicators	Low (produces a single index or set of indices)	Easy, straight forward, Comparable	High (tailored to specific needs or sectors)	[23],[24]

2.1.3 Aircraft maintenance Economical Sustainability

An aircraft life cycle typically is divided into four stages, including Design and Development, Manufacturing, Use and End-of-Life phases. The Use phase involves the operation and required maintenance of the aircraft to maintain its designed level of reliability and performance. Research indicates that the use phase is the most costly part of an aircraft's entire life cycle [26],[27]. Commercial air transport is a highly competitive industry and maintaining low Direct Operating Costs (DOC) is essential for profitability. Based on estimates provided by airline companies, maintenance expenses generally account for 10 to 20% of aircraft-related DOC, hence low aircraft maintenance cost is the key to economical sustainability [13]. Airlines recognize the competitive edge that effective aircraft maintenance can offer. Aircraft maintenance has a key role in ensuring high levels of aircraft availability, safety, and cost-efficiency, therefore it should be regarded as a critical component of the air transport business, supporting and enabling the flight production [13].

Some studies found to analyse the aircraft maintenance cost based on the aircraft major functional units like Airframe, engine, APU, landing gear , and components while some others found focused on maintenance sustainability from the points where maintenance events are taking place such as line, base and shop maintenances [28],[19]. Another study approaches aircraft maintenance cost reduction by optimizing line maintenance scheduling and more efficient use of available maintenance opportunities [29]. The aircraft maintenance costs analysis and their driving factors were explored, which found aircraft utilization and more specifically flight hours is the most significant maintenance cost driver [26]. Current literature is found to focus primarily on the specific aspects of aircraft maintenance costs mainly from maintenance processes perspective, with no or little attention on a comparable economical sustainability assessment of aircraft's and aircraft systems' maintenance from product perspective. However, in line with 2050 decarbonization efforts, technological advancements and fleet improvements might shift environmental and economic burdens to the maintenance phase, rather than eliminating them. Hence assessing aircraft maintenance sustainability performance is crucial to provide insights and supporting data into eco-design practices, ensuring that maintenance aligns with broader sustainability goals.

2.1.4 Aircraft maintenance Social Sustainability

Sustainable air transportation refers to the ongoing development of the aviation sector, aimed at generating economic benefits while simultaneously mitigating its negative social and environmental impacts [17]. Conventional maintenance practices are mainly driven by economic and technical factors, with no or little consideration on environmental and social dimensions. Recently environmental considerations have gained more traction in industry and researches but social aspects are less addressed and inadequately considered [30]. This is mainly because of social dimension data scarcity, lack of standardized indicators and challenges with social impacts accurate measurement. Social Life Cycle Assessment (S-LCA) is a thorough method for social impacts assessment which was developed by the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC). It enables the evaluation of both positive and negative social impacts throughout the entire life cycle of a product/process, using social indicators that highlight key social attributes and themes [31].

Global Reporting Initiative (GRI) is a multistakeholder initiative that is developed to be used mainly as sustainability reporting standardized framework at organizational level [2]. Both GRI and S-LCA can be deployed as complimentary tools, where a maintenance firm can use GRI framework for sustainability reporting by incorporating S-LCA results to provide a more quantified and interpretable view of their social sustainability performance. A recent research found delving into Maintenance, Repair, Overhaul (MRO) companies' Environmental, Social, Governance (ESG) reporting of aircraft major MRO providers aiming to explore the social, environmental sustainability focus areas as a basis for "sustainable MRO" definition [17]. However, GRI and ESG social topics and indicators found to be used mainly at organizational level, hence more specific set of suitable and relevant social metrics and indicators might need to be selected, analyzed, when assessing aircraft maintenance sustainability performance from "Processes" or and "Equipment" perspectives.

2.2.1 Aircraft maintenance fundamentals and Methodology

Aircraft Maintenance Decision Logic

In the early stages of aviation, there was not a systematic approach toward maintenance program and aircraft's required maintenance were mainly defined and developed by mechanics and pilots [3]. Given the complexity of the modern passenger aircraft's, the maintenance program are continuously developed and evolved ,aiming to maintain aircrafts systems' reliability and airworthiness to perform their intended functions consistently. The Reliability Centered maintenance (RCM), which was developed by Society of Automotive Engineers (SAE) is a widely adopted decision logic used in broader industrial context. It focuses on maintaining system functionality by analyzing potential failure modes and determining the most effective maintenance strategy [32]. Based on similar decision logic concept, Maintenance Steering Group (MSG) methodology was formed to be used in specific for commercial aircraft scheduled maintenance program development [12],[1].

ATA Systems

Aircraft systems are classified and known as ATA Spec 100, which divides aircraft systems into chapters whereas each chapter is assigned to a specific area/function. ATA 100 provides a uniform structure for aircraft manufacturers, operators, and maintenance personnel to create, distribute, and reference maintenance manuals and technical documents. ATA chapters are classified based on FAA Joint Aircraft System and Component (JASC) code [33]. The chapters are universally standardized, allowing maintenance personnel to navigate documentation consistently, regardless of the aircraft manufacturer.

MSG-3 Decision Logic

The Maintenance Steering Group- 3rd taskforce (MSG-3) Logic is the most recent and widely adopted systematic maintenance strategy which it has been collaboratively developed by aviation industry key stakeholders. It is a top-down approach to develop aircraft maintenance schedule by focusing at the systems' level function preservation which is driven by systems' failure consequence analysis [34]. It aims to improve aircraft safety and reliability by avoiding unnecessary and intensive maintenance tasks, thereby reducing aircraft downtime, costs, and waste generation.

MSG-3 analysis outlines the general process and decision logic to identify all the required scheduled tasks, and their intervals based on operational capabilities of the certificated aircraft [13],[12].The analysis includes:

1. Identification of Maintenance-Significant Items (MSI Selection);
2. Analysis of the MSI to identify their functions, functional failures, failure consequence, and causes.

MSG-3 Failure Effect Categories (FEC) are defined in five class as failures with: Evident Safety, Evident Operational, Evident Economic, Hidden Safety, and Hidden Non-Safety effects.

3. To select the required maintenance actions (Tasks & Intervals) by using decision logic based on:
 - MSG3- Level 1 analysis: Evaluation of Failure Effect Category (FEC)
 - MSG3- Level 2 analysis: Selection of the maintenance task required to address the identified functional failure.

As per FAA Advisory Circular AC-121-22A, the most up-to-date MSG analytical process must be applied when developing scheduled maintenance tasks for any new or derivative aircraft. Therefore, aircraft manufacturers are using MSG-3 process to develop a Maintenance Planning Document (MPD) for each aircraft as the foundation of the operators' maintenance program. This program is then adjusted by air operators based on their operating profile, exposed operational environment, utilization, technical reliability targets to serve as their approved maintenance program [1].

Initial scheduled maintenance program development of an aircraft has a significant impact on its lifecycle costs and available production time [34]. Therefore, it is crucial to review current practices and find ways to improve the effectiveness of maintenance program.

MSG-3 Methodology Integration with Sustainability Practices

Currently aircraft maintenance scheduled tasks are developed primarily based on the MSG-3 methodology and experts' experience with similar aircraft. While MSG-3 offers a structured approach to creating a maintenance program that meets airworthiness requirements, it lacks supporting data for being the most effective and economical justification in required maintenance tasks and schedule definition. Moreover, MSG-3 does not account for the environmental impact of

failures, nor does it consider the operational consequences of hidden failures[1]. Hence making the integration of sustainability with MSG methodology a significant research area and a potential new paradigm to be developed and adopted.

Maintenance Planning Document

The maintenance tasks selected through the MSG-3 process are documented by aircraft manufacturers which is the Type Certificate (TC) holder in their applicable Airworthiness Authority (FAA, EASA, TCCA) approved report which is known as the Maintenance Review Board Report (MRBR) [12]. It contains the airframer's initial proposed scheduled tasks for the subjected aircraft types, which must be reviewed, and approved by MRB organization.

Then airframers will use the MRBR approved report and Airworthiness Limitation Sections' (ALS) documents which are derived from individually approved design data to develop and publish a document which is called Maintenance Planning Data (MPD) at Boeing, and at Airbus called Maintenance Planning Document [12],[1]. The MPD includes all the MRB and ALS mandatory scheduled maintenance requirements, providing all details on the defined tasks, thresholds, repeat intervals, and the average Manhour to perform each task (Boeing and AIRBUS MPDs). MPD serves as the foundation of air operators approved maintenance program (AMPD) which outlines a customized maintenance program for performing different required scheduled operational and letter checks.

Aircraft Maintenance Activities

Civil aircrafts maintenance involves activities in Line, Base, and Shop stations[12],[19].

Line Maintenance: Refers to the necessary inspection and maintenance tasks performed on aircraft to ensure their airworthiness and safe daily operation. These tasks include daily checks, transit checks, Light letter checks (A & B), troubleshooting, defect resolution, and minor repairs based on Aircraft Maintenance Manual (AMM) that do not require extensive disassembly and significant downtime. Line maintenance is typically conducted on the ramp, at the gate, or in nearby terminal line stations.

Base Maintenance: It refers to more heavy and comprehensive scheduled maintenance activities that requires aircraft to be out of service for an extended period of time. It often includes thorough

inspection and disassembly of airframe systems and structures for required detailed inspections, repairs, retrofits, modifications, and implementing heavy letter checks (C & D).

Shop Maintenance: It refers to the maintenance activities performed off-wings on the removed aircraft engines and components in a workshop space. It involves, special inspections, repairs, overhauls, and testing based on the Component Maintenance Manual (CMM).

Table 2-2 demonstrates, an example of various aircraft maintenance checks.

Table 2-2:Aircraft Maintenance Checks adapted from [35]

Check Type	Tasks	Interval	Labor Required
Line Maintenance Checks			
Service Check	Inspection of wheel, brakes, fluid levels...	Every 48-72 Hours (Mostly Overnight)	4-10 Man-Hours
A-Check	Filters replacement, Flight control inspection and lubrication, Emergency slides Inspection...	Every 3 Month or (Every 750 FH)	40-60 Man-Hours
B-Check	Full visual Inspection, Lubrication, Landing Gears alignment check and torquing.	Every Six Month or (Every 1500 FH)	NB: 100 Man-Hours & WB:200-300Man-Hours
Heavy Maintenance Checks			
C-Check	Structural components Inspection & repair, Deferred defects repairs, Landing Gear inspection, Defective Cabin interiors removal & replacement, etc.	Every 1.5- 2 years or Every (2500-300 FH)	2500-4000 Man-Hours (10 days to 2 weeks)
D-Check	It is a full overhaul of aircraft, Entire aircraft will be dismantled and then put together	Every 4 C-Checks or (Every 6 years)	Depends on Aircraft type 10,000-50,000 (6 - 8 weeks)

2.2.2 Sustainability Assessment in Maintenance Context

In maintenance context, maintenance operations, parts replacement, and waste handling, have been identified as three key activities that require careful management due to their considerable environmental impact [36]. Adoption of most suitable maintenance strategy from sustainability perspective been studied by determining most relevant indicators for each sustainability pillars and a fuzzy VIKOR method was used to rate each strategy based on sustainability factors [37]. Another research has proposed a Composite Maintenance sustainability Index (CMSI) and a decision support systems by adapting Balanced Scorecard (BSC) model and integrating it with the sustainability indicators relevant to maintenance processes [23]. A multi-stakeholder perspectives study on sustainable maintenance performance assessment was delving into the direct and indirect sustainability impacts of maintenance and evaluating the involved stakeholder's awareness on maintenance sustainability performance [38]. In this context, numbers of literature were found approaching sustainability measurement by identifying most relevant suitability indicators for each of economic, environmental and social pillars. Then proposing a framework on how to normalize, weight based on their perceived importance and priorities and finally aggregate all pillars' sub-indices into a Composite Sustainability index [39]. The Life Cycle Sustainability Analysis (LCSA) is the conventional and comprehensive approach in Life Cycle Engineering (LCE) domain to measure all sustainability impacts of a product or a service, or a process across its full life cycle; LCSA will further breakdown into Life Cycle Analysis (E-LCA) for environmental impact assessment mainly based on ISO 14040 and 14044 framework, requirements and guidelines [21],[22], Life Cycle Cost Analysis (LCCA) for economical impact assessment and Social Life Cycle [Impact] Assessment (S-LCA) [40]. However, conventional LCA is often a data-intensive approach that relies on various database and life cycle analysis software to trace, source, and calculate significant amount of life cycle data; Hence making maintenance sustainability performance measurement for the complex aircraft's systems exhaustive and difficult to assess, compare, and benchmark across different fleets. Another widely used approach for sustainability performance assessment is the selection of a set of most relevant indicators that could be aggregated and synthesized in accordance with their relevance and priorities in the subjected context [41]. A recent study proposed aggregating environmental indices and Reliability, Availability, and Maintainability (RAM) analysis to evaluate different maintenance options across various economical and environmental sustainability indicators [42].

2.3. Aviation Sustainable Maintenance Practices

2.3.1. Sustainability in Aviation industry

Numbers of literature underscoring the challenges and opportunities in aviation sustainability, Bonser et al. [43] highlighted the need for strategic management, global communication, and technological expertise to ensure the sustainable development of the global aviation system. They emphasized that addressing the environmental, economic, and social issues requires integrating global systems thinking and the perspectives of various stakeholders.

Elhmoud and Kutty [40] reviewed tools and methods for sustainability assessment in aviation, including life cycle assessment and decision support systems, which can evaluate sustainability at different levels such as aircraft, airlines, and airports. Stamoulis et al. [44] pointed out that current MRO (Maintenance, Repair, and Overhaul) practices are lagging behind advancements in aircraft design and technology, calling for data-driven, adaptive, and circular MRO approaches to create a more sustainable aviation industry.

2.3.2 Environmental Sustainability in Aviation

A growing body of research found focused on finding solutions for greener aviation, exploring areas such as operational efficiency, alternative energy sources, and the use of sustainable aviation fuels. Afonso et al. [45] reviewed various solutions to reduce aviation's environmental impact, including enhancing operational efficiency, using alternative energy sources, improving propulsion systems, optimizing aerodynamics, and developing new materials. They emphasized the need for a holistic approach to address the complex challenges of green aviation, highlighting gaps such as the lack of comprehensive life cycle assessments and uncertain future regulations.

Chiaramonti [46] discussed the potential of sustainable aviation fuels (SAFs), which can reduce greenhouse gas emissions by up to 80%. While SAFs can be produced from renewable or waste sources, they face obstacles like high costs, limited supply, and low public awareness, requiring support from various sectors to realize their full potential.

Su-Ungkavatin et al. [47] compared biofuels, electro-fuels, electric, and hydrogen fuels, recommending a systemic approach to evaluate their trade-offs and synergies. Similarly, Upham et al. [48] explored the environmental, economic, and social dimensions of sustainable aviation,

arguing that radical transformation, including both technological innovation and social change, is necessary.

Yusaf et al. [49] focused on hydrogen as a promising solution for sustainable aviation due to its high energy density, low emissions, and renewable potential. Lastly, Zhang, Butler, and Yang [50] reviewed SAFs' benefits and challenges, concluding that while SAFs offer significant environmental and economic advantages, further research and stakeholder support are crucial for their development. All in All, a combination of innovative technologies and collaborative efforts are required to achieve sustainable aviation.

2.3.3 Sustainability driven by operational Excellence

Various approaches in current literature about aviation maintenance management found exploring the ways for improving operational efficiency and sustainability. Alansari and Ziadat et al. [51] examined how implementing Enterprise Resource Planning (ERP) systems can improve logistical functions such as handling, transporting, and storing. They highlighted that standardized operational procedures enhance both safety and efficiency while reducing environmental impact and operational costs, demonstrated through PAL Aerospace Services. Ayeni et al. and Korchagin et al. [52],[53],[54],[55] focused on applying lean principles to the Maintenance, Repair, and Overhaul (MRO) industry. They argued that lean practices help streamline operations, improve service quality, and increase customer satisfaction in a highly competitive field. Similarly, Demiral et al. [56] applied lean thinking to a Turkish airline's maintenance system, showing that standardization and coordination can eliminate inefficiencies and improve sustainability.

Baluch et al. [57] explored Total Productive Maintenance (TPM) and lean maintenance, two complementary methods for boosting productivity and quality in manufacturing systems. TPM is more preventive, while lean focuses on optimizing processes to reduce waste. Bhuiyan et al. [58] presented a continuous improvement framework for aerospace companies, utilizing tools like Six Sigma and Kaizen to increase efficiency and eliminate waste.

Ajukumar and Gandhi [59] proposed an integrated approach combining life cycle assessment and analytic hierarchy process to evaluate green maintenance, applying it to a hydraulic press system. Ararsa et al. [60] reviewed green maintenance, emphasizing its importance in improving sustainability across energy efficiency, resource use, and waste management. Lastly, Jasiulewicz-

Kaczmarek [61] highlighted the complementary nature of lean and green maintenance, which together contribute to the overall sustainability of manufacturing systems. In summary, integrating lean and green strategies into maintenance processes, along with implementing an effective ERP system to manage the supply chain and other maintenance support functions, can provide a robust framework for enhancing operational efficiency and environmental sustainability.

2.3.4 Sustainability in Aviation Supply Chain Management

Sustainable supply chain management is crucial in industries like aerospace, naval, and automotive. Ramirez-Peña et al. [62] reviewed how these sectors are incorporating Industry 4.0 technologies, such as additive manufacturing, blockchain, and big data, alongside lean and green methodologies, to enhance their supply chain operations. Gopalakrishnan et al. [63] explored the sustainability practices of British Aerospace Systems, presenting a framework for improving sustainability in their supply chain. Debnath et al. [64] reviewed the role of additive manufacturing (AM) in transforming the aircraft spare part production, streamlining supply chain by integrating digital and physical processes. They explored how AM, combined with Industry 4.0 technologies, can support maintenance, offering both centralized and decentralized supply chain models. It also highlights the advantages of adopting AM for Maintenance, Repair, and Overhaul (MRO) operations and its potential to improve efficiency, reduce waste, and promote sustainability in aerospace supply chains.

Together, the adoption of these technologies can transform the aerospace maintenance industry, driving it towards more sustainable practices.

2.3.5 Sustainability driven by Industry X.0 technology

The aviation maintenance sector is undergoing a significant transformation driven by technological advancements and a growing focus on sustainability. Cortés-Leal et al. [65] introduced a framework called Maintenance 5.0, which focuses on enhancing the resilience of physical assets through human-machine collaboration, artificial intelligence, and wireless sensor networks. This approach relies on close cooperation between operators and machines, allowing workers to adjust parameters and repair faults, ultimately boosting the system's resilience.

Eschen et al. [66] explored how augmented and virtual reality (AR and VR) could support workers in aviation maintenance. They found that these technologies improve efficiency, quality, and safety by providing real-time information, guidance, and feedback. Additionally, AR and VR create

interactive training environments for technicians, enhancing learning through immersive simulations.

Meanwhile, Ahmad et al. [67] examined the role of Blockchain technology in aviation maintenance, highlighting its potential to improve data transparency, security, and traceability. By creating trustworthy maintenance records, Blockchain could help stakeholders make informed decisions, though challenges such as transaction throughput and fees remain.

Lastly, Peng et al. [68] proposed integrating augmented reality (AR) with artificial intelligence (AI) to enhance maintenance procedures. Their study found that this AI-AR system reduced human error, improved technician training, and offered a cost-effective solution to challenges in aviation maintenance. Together, these studies demonstrate how cutting-edge technologies can revolutionize maintenance processes, improving efficiency, safety, and decision-making in aviation maintenance industry.

2.3.6 Summary

The literature review was conducted in a way to thoroughly explore and investigate the sustainability in aviation maintenance context and from multiple perspectives. Numbers of literature found focusing on aircraft maintenance firms' sustainability performance evaluation at organizational level based on their published Corporate social sustainability report (CSR) or Environmental, Social, and Governance (ESG) reports. while fewer but growing number of study found addressing sustainability from MRO processes and practices perspective; Additionally, very few and limited scope study found evaluating Maintenance Sustainability of aircrafts often without a clearly defined distinction with MRO processes. Therefore, the gap was identified to address the maintenance sustainability performance of aircraft and its systems from "*Product perspective*", aiming to develop a Maintenance Sustainability Performance (MSP) assessment method to support new aircraft development eco-design practices and design trades-off decision making. Moreover, a variety of industry X.0 applications in MRO practices, tools and techniques are found in various literature. Consequently, this study aims to review and examine the integration of a multidisciplinary set of industry X.0, lean, and green tools, towards promoting more sustainable MRO practices.

CHAPTER 3 THESIS ORGANIZATION

3.1 Research Objectives

The focus of this research is to explore and investigate the concept of sustainability within the aviation maintenance industry, a sector characterized by intricate processes and multifaceted interactions among various stakeholders. The air transport maintenance ecosystem is inherently complex, involving highly regulated operations, interconnected systems, and constant focus on safety, efficiency, and environmental sustainability.

In light of these challenges, the study aims to address the following objectives in a systematic manner:

- The first objective is to investigate the aircraft maintenance requirements, maintenance strategies and methodology, maintenance programs development process and their sustainability impacts and implications. The purpose is to identify a suitable approach to develop a comparable aircraft maintenance sustainability performance assessment method from “Product” perspective.
- The second objective is to explore the fundamentals of aircraft maintenance processes, practices, key stakeholders, and their interactions. Additionally, it evaluates climate change relation to sustainability in aviation maintenance. Finally, to assess the transformational potential of Industry X.0 technologies towards achieving more Sustainable “Maintenance, Repair, Overhaul (MRO) practices”. Overall objective here is to explore the Aviation sustainable maintenance from “MRO practices” perspective.

3.2 Research Methodology

In this research, a mixed-method approach is used to comprehensively explore sustainability in aviation maintenance from different perspectives. This research methodology is based on 4 key phases:

- **Literature Review:** For the two contributions of this research, different concepts been reviewed and explored in the literature. For the First contribution Journal paper - the reviewed literatures involve “Civil Aviation industry maintenance sustainability”, “Aircraft

Maintenance (AM) Environmental sustainability assessment”, “AM Economical sustainability Assessment”, “AM social sustainability Assessment”.

For the second contribution Book-chapter, the reviewed literatures include: “Sustainability in aviation industry”, “Environmental sustainability in aviation”, “sustainability driven by lean, Green, and operational excellence”, “Sustainability in aviation supply chain management”, “Sustainability driven by industry X.0 technologies”.

- **Data Collection:** Studying and collecting data about aircraft maintenance fundamentals including maintenance methodology, decision logics, major airframers (Boeing and AIRBUS) maintenance planning document (MPD) development, Aircraft Approved maintenance Program (AMP) development methods, and identifying maintenance related sustainability indicators and metrics.
- **Framework Development:** Investigating the aircraft maintenance requirements, regulatory compliance requirement, maintenance program development methodology, processes and practices, identifying sustainability impact assessment tools, exploring relevant sustainability indicators and metrics. An assessment method, adapted from the MSG-3 maintenance methodology, is developed based on aggregation and sustainability indexing techniques. It involves selecting the most relevant and widely adopted set of metrics and indicators to evaluate the aircraft and its systems' maintenance sustainability performance score (MSPS). The proposed scoring system is designed to be consistent, comparable, and easy to implement as an assessment tool. The indexing method utilizes a weighted sum aggregation model, with weights assigned based on expert opinions regarding perceived importance and priorities. To the best of our knowledge, this is a novel approach with significant potential for adoption in the industry as a benchmarking tool for aircraft maintenance sustainability performance assessment. It also serves as a valuable tool for improving eco-design practices.
- **Case study:** A case study was conducted on two legacy single-aisle aircraft by collecting their C-check data, reviewing and analyzing all the tasks, classifying the tasks based on MSG-3 major categories, ATA chapters, and MSG-3 generic tasks, and computing sustainability indices and the proposed MSPS. The aim was to select two comparable

aircraft, preferably of the same age, with similar utilization and operating regions, to enable a comparable sustainability impact assessment for both aircraft.

3.3 Research Contributions

This study contributes to the research objectives through one book-chapter and one journal article as following:

- 1- Journal Paper: “Toward future proof Eco-design; A novel approach to assessing aircraft maintenance sustainability performance” – **Submitted-October 2024**, to the Journal of Cleaner Production

This article delves into aircraft maintenance fundamentals, decision logic and program development methodologies and offers a novel framework for assessing aircraft maintenance phase sustainability performance. The proposed framework aims toward new paradigm in aircraft and aircraft’s systems maintenance sustainability impact evaluation and benchmarking acting as maintenance feedback toward future-proof Eco-design practices.

- 2- Book-Chapter: “The Potential Integration of Lean, and Green and Industry X.0 Tools in more sustainable Maintenance Repair and Overhaul practices”- Submitted to “myTECHNIC MRO Technic Services” - Aircraft Maintenance Handbook -AMH – **Final Submission- September 2024**, currently is under peer review.

This Book Chapter investigates the potential implementation and integration of a multidisciplinary set of Lean, Green, and Industry X.0 tools in achieving more sustainable Maintenance, Repair, and Overhaul (MRO) practices. It also examines the relationship between climate change and sustainable aviation maintenance practices, while investigating a concept for a green maintenance within the Society 5.0 paradigm, Industry 4.0 technologies, and Lean and green tools.

CHAPTER 4 ARTICLE 1: TOWARD FUTURE PROOF ECO-DESIGN; A NOVEL APPROACH TO ASSESSING AIRCRAFT MAINTENANCE SUSTAINABILITY PERFORMANCE (MSP)

Submitted on 14 October 2024 to the Journal of Cleaner Production

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ABSTRACT: Air transport industry is a complex and heavily regulated sector, currently under increasing pressure to reduce its environmental footprint in line with the 2050 net-zero decarbonization goal, while maintaining unwavering standards of safety, affordability, and accessibility. The challenges are even more pronounced within the aircraft maintenance sector, which must navigate a multifaceted ecosystem characterized by supply chain uncertainties, more frequent and severe aircraft damages linked to climate change, and keeping the pace in adapting to new aircraft technologies. Despite these pressures, aircrafts must be maintained safe, airworthy, and available for continuous flight operations. Current research on aircraft sustainability primarily focuses on areas such as eco-design practices, sustainable aviation fuels, lean and green development, and end-of-life aircraft handling, there is a noticeable gap in studies addressing aircraft maintenance sustainability performance. As advancements push for more fuel-efficient aircrafts, there is a risk of inadvertently shifting the economic and environmental burdens to the maintenance phase instead of eliminating them. This highlights the critical need for aircraft's maintenance sustainability performance (MSP) assessment to provide visibility into the impacts of maintaining the existing fleet, benchmark these impacts against new developments, and feed this insight back into the eco-design practices. In response this research delves into the fundamentals of aircraft maintenance methodology, decision-making logic, and maintenance program development paradigms aiming to propose a standardized and comparable method for assessing aircraft's MSP. The proposed model presents a consistent and comparable methodology for assessing maintenance sustainability impacts of aircraft, and their systems. This approach is further illustrated through a comparable case study that evaluates a C-check maintenance sustainability impacts for two legacy aircrafts. It also suggests a potential new approach toward sustainability embedded maintenance decision logic.

Keywords: Aircraft Maintenance, Sustainability Assessment, Maintenance Planning Document, Maintenance Sustainability Performance.

4.1 Introduction

Aviation drives sustainable development by connecting people, businesses, and communities. “Safe, reliable, efficient, and affordable air transport is crucial for a comprehensive mobility strategy, to achieve the United Nations 2030 sustainable development goals” (Air Transport Action Group) [69]. Airbus has predicted a 3.5% annual growth in air transport traffic until 2042, which it requires to double the global fleet size by then [70]. By 2018, global aviation accounted for 3.5% of total GHG emissions, which if it remains unaddressed, it could account for 22% of global emissions by 2050 [71]. For most aircraft, the operation and maintenance phase constitute 80-85% of the total life cycle cost (LCC). Depending on the fleet size, type, range, age, and utilization, direct maintenance costs (DMC) make up 10-20% of direct operating costs (DOC) [1],[72]. Therefore aircraft maintenance cost can strongly affect the aircraft’s lifecycle cost and availability performance, hence critical to continually improve the efficiency and effectiveness of the maintenance programme [17]. Considering the significant portion of aircraft life cycle cost is attributed to maintenance phase and its potential direct and indirect impacts on airline performance, it should be regarded as a crucial factor for profitability and competitiveness in the airline industry. Additionally, maintenance represents approximately 11% of an airline’s workforce [1]. All of this highlights the significant importance of aviation maintenance sector in all three, economical, environmental and social aspects of aviation’s sustainability.

As industry strives toward reducing its environmental footprint, technological advancements are adopted in favor of lower emission engines, use of lighter weight, advanced materials in aircraft structure and technological advancements in aircraft systems [73],[74],[14]. A recent research has shown that future hydrogen-powered aircraft fuel systems are expected to become increasingly complex and maintenance-intensive [6]. This underscores the pivotal role of aviation maintenance in the successful adoption of new technologies.

However, technological advancements in aircraft design and development are often associated with uncertainties, with potential in-service issues leading to more frequent and intense maintenance needs which could pose higher economic, environmental, and social burden into maintenance phase. To address this issue, it is crucial to have a consistent, comparable, easy to implement aircraft’s MSP assessment framework.

Existing research and literature found primarily focused on maintenance, repair, and overhaul (MRO) service providers sustainability assessment and reporting from process perspective [17],[26],[75]. Some other researches 'found assessing aircraft maintenance limited scope environmental or and economical performance [19],[76],[14].

Given the need for a standardized, consistent and comparable aircraft MSP assessment approach, this study acknowledges the gap and proposes a novel method on assessing the aircraft's maintenance three Pillars of sustainability from "Equipment "perspective. To this end, this study will initially delve into the aircraft's conventional maintenance methodology, program development processes and practices. It proposes a consistent and comparable approach for aircraft' MSP assessment which is adapted from conventional aircraft maintenance methodology. This approach can also be extended to aircraft systems and subsystems, enabling the benchmarking of MSP across various comparable design configurations. Finally, a case study comparing two legacy aircraft C-check MSPs is presented. The major systems of both aircraft are analyzed and compared. The study highlights the potential for future research and suggests the integration of MSP into maintenance planning documentation processes

4.2 Literature Review

4.2.1 Civil Aviation industry Maintenance sustainability

Aircraft maintenance sustainability is emerging as a critical factor in the pursuit of greener aviation, requiring the integration of economic, environmental, and social considerations to optimize aircraft design and minimize its life cycle impacts.

A recent study on aircraft maintenance sustainability proposed the integration of maintenance costs and environmental parameters to assess aircraft sustainability over its service life. It introduces a "green index" to identify the most sustainable design solutions by balancing both the economic and environmental impacts [14]. However, the proposed model found approximating environmental impacts and estimating maintenance cost of a new aircraft based on its geometrical shape and similarities in function compared to an old aircraft. This approach found too rough which not considers other technological dimensions, like Aircraft systems design configurations, and the likely differences in their corresponding maintenance requirements. The integration of Life Cycle Management (LCM) with Modular design and Advanced Health Monitoring Systems (AHM) was

proposed to improve sustainability and cost-efficiency in the aircraft maintenance phase. It explores how leveraging technologies like the Internet of Things, blockchain, and artificial intelligence could transform maintenance operations, and claims a saving up to 30 % maintenance cost and 20% in asset longevity [77],[78]. Despite the efforts to replace the conventional aircraft scheduled maintenance program by AHM, it is not adopted for large commercial aircraft certification. Therefore, maintenance sustainability performance for existing global fleet and those under development yet to be addressed. However, the integration of Aircraft Health Management (AHM) with Condition Based Maintenance (CBM) concept is projected to be the future trend [79].

A research on composite component circularity indicates that the use phase dominates the entire life cycles impacts which it is mainly driven by component weight and not its embodied emissions, however it did not address the maintenance impacts during the use phase [15]. Given the complexity to integrate design objectives and somewhat conflicting sustainability goals, a comprehensive sustainability index (SI) based on Multi-Criteria Decision Making (MCDM) was proposed to balance the technological, environmental, economic, and circularity factors into early design phase of aircraft composite components aiming toward composite component design optimization [16]. This method does not address the subjected components use phase maintenance impacts in specific.

4.2.2 Aircraft maintenance Environmental sustainability assessment

Air transport industry is committed to reduce its environmental footprint in order to meet 2050 aviation decarbonization goal set forth by International Civil Aviation Organization (ICAO) [2]. A report by the U.S. Environmental Protection Agency highlights that the aircraft maintenance environmental impact is comparable to that of the manufacturing process[17]. Current literature predominantly found addressing the environmental impacts of aircraft manufacturing, flight operations, aircraft End-of-life stages but the ecological impacts of aircraft maintenance have not been thoroughly explored. This could be because maintenance is perceived as having a relatively insignificant environmental impact within the aircraft maintenance life cycle, hence not grabbed enough attention [19]. While another research on the life cycle assessment of passenger aircraft shows that the maintenance phase significantly impacts the environment, accounting for 5-10 % of the total greenhouse gas (GHG) emissions throughout the aircraft's service life [17],[20] . Hence,

aircraft maintenance should be regarded as an important environmental concern. Moreover, beyond the direct environmental impacts of maintenance, the indirect ones can also be substantial and far-reaching. For instance, research on optimizing engine maintenance washing found that engine washing to reduce fouling can remarkably decrease both fuel consumption and emissions. It is estimated that reducing fouling could decrease fuel consumption by 2,735 tons and harmful gas emissions by 8,626 tons per 100 engines (CFM56-5B) each year, saving \$10.08 million in fuel costs [9],[8]. There are various methods and tools available for conducting environmental assessments. One prominent approach is the conventional Life cycle assessment (LCA) which is a well-recognized analytical approach used to evaluate and compare the environmental impacts of current and new technologies or materials throughout their entire life cycle [21],[22]. Notably, LCA is recognized to be data-intensive and involves complex modeling and interpretation. Another widely adopted method is the aggregation of the indicators and Sustainability indexing (SI) which offers straightforward, clear, easy to understand, and comparable metrics for monitoring environmental impacts [23],[24].

4.2.3 Aircraft maintenance Economic sustainability assessment

An aircraft life cycle typically is divided into four stages, including Design and Development, Manufacturing, Use and End-of-Life phases. The Use phase involves the operation and required maintenance of the aircraft to maintain its designed level of reliability and performance. Research indicates that the use phase is the most costly part of an aircraft's entire life cycle [26],[27]. Maintenance is a crucial function for Air transport safety, organizational efficiency and profitability. According to EN13306, 2001, maintenance is defined as the "combination of all technical, administrative, and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function." [10]. For aircraft maintenance, this means ensuring that an aircraft is kept in optimal condition to guarantee safety and performance and its regulatory compliance at all times. Therefore, maintenance excellence and effective performance are the foundation for an airline to ensure the safety, efficiency, and longevity of its fleet. This, in turn, allows the airline to consistently deliver high-quality services, enhancing customer satisfaction and trust and the airline's reputation. In pursuit of achieving a sustainable maintenance system, fourteen key elements were identified in which most important ones are outlined as: Senior management commitment, strategic planning and execution, continuous improvement aiming to continually cut the wastes, delays, and unnecessary costs and

fostering the culture of innovation [17],[80]. Some studies found to analyse the aircraft maintenance cost based on the aircraft major functional units like Airframe, engine, APU, landing gear, and components while some others found focused on maintenance sustainability from the points where maintenance events are taking place such as line, base and shop maintenances [28],[19]. The aircraft maintenance costs analysis and their driving factors revealed that aircraft utilization and more specifically flight hours is the most significant maintenance cost driver [26]. Some studies have found that optimizing aircraft maintenance programs can significantly reduce airline Direct Maintenance Costs (DMC), providing a competitive advantage in the fiercely competitive airline industry [1].

4.2.4 Aircraft maintenance Social Sustainability assessment

Conventional maintenance program are mainly driven by economic and technical factors, with no or little consideration on environmental and social dimensions. Recently environmental considerations have gained more traction in industry and researches but social aspects are less addressed and inadequately considered [30]. This is mainly because of social dimension data scarcity, lack of standardized indicators and challenges with social impacts accurate measurement. Social Life Cycle Assessment (S-LCA) is a thorough method for social impacts assessment which was developed by the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC). It enables the evaluation of both positive and negative social impacts throughout the entire life cycle of a product/process, using social indicators that highlight key social attributes and themes [31].

Global Reporting Initiative (GRI) is a standardized sustainability reporting framework with primary focus on the organizational level, helping organization on their sustainability efforts also provides enhanced transparency for external stakeholders assessment and decision making [17],[81]. Both GRI and S-LCA can be deployed as complimentary tools, where a maintenance firm can use GRI framework for sustainability reporting by incorporating S-LCA results to provide a more quantified and interpretable view of their social sustainability performance. A recent research found delving into Maintenance, Repair, Overhaul (MRO) companies' Environmental, Social, Governance (ESG) reporting of aircraft major MRO providers aiming to explore the social, environmental sustainability focus areas as a basis for "sustainable MRO" definition [17]. However, GRI and ESG social topics and indicators found to be used mainly at organizational

level, hence more specific set of suitable and relevant social metrics and indicators might need to be selected, analyzed, and quantified when assessing aircraft maintenance sustainability performance from “Equipment maintenance requirement” perspective.

4.3 Research Approach

This research is based on a five-step methodology which aims to propose a comparable and practical Maintenance Sustainability Performance measurement framework for commercial aircrafts. To this end, Step 1 involves reviewing existing literature to explore the commercial aircraft maintenance’s fundamentals, structure, requirements, and processes. Step 2 is a literature review focused on sustainability performance measurement within the maintenance sector. Step 3 strives to identify and propose the most relevant sustainability indicators to be used in the proposed framework. Step 4 introduces a conceptual structure for approaching aircraft maintenance requirements sustainability measurement in a consistent and standardized way. Step 5 includes a case study for maintenance sustainability assessment of two comparable single-aisle aircrafts and analyzing the results. Figure 4-1 is presenting the research approach.

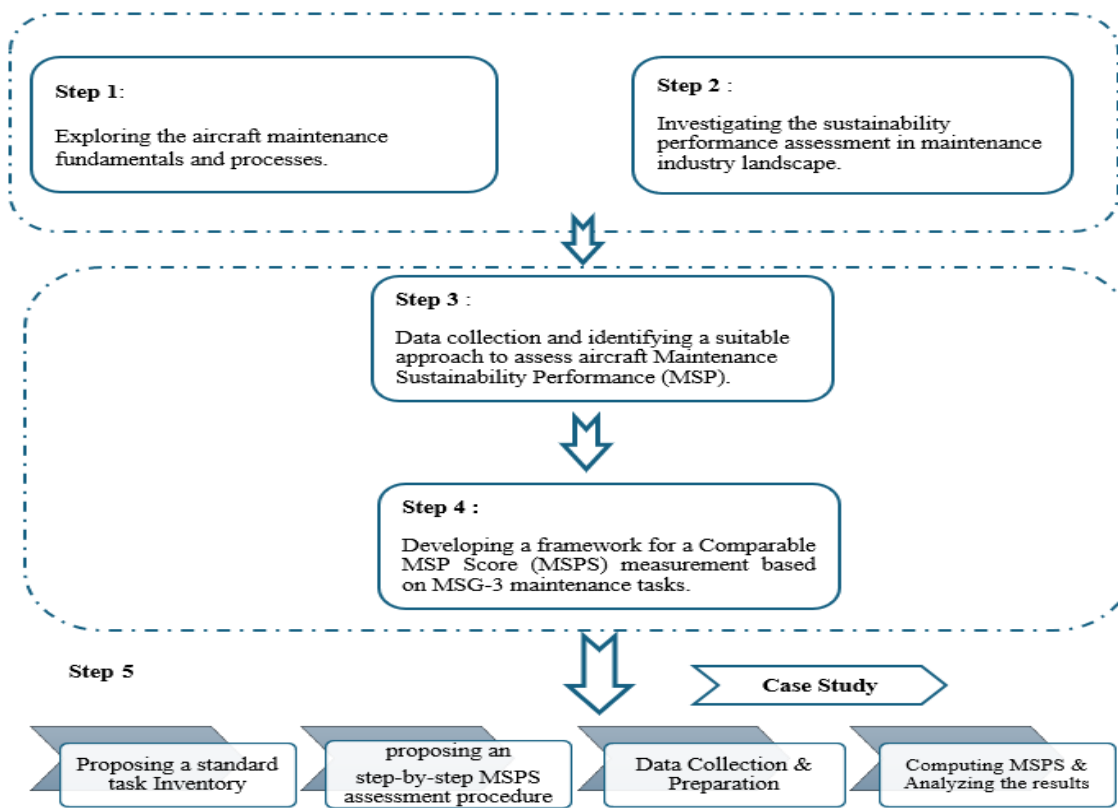


Figure 4-1: The Research Approach

4.3.1 Step 1: Aircraft Maintenance fundamentals and methodology

1. Aircraft Maintenance Requirement Decision Logic Background and Evolution

In the early stages of aviation, there was not a systematic approach toward maintenance program and aircraft's required maintenance were mainly defined and developed by mechanics and pilots [3]. In 1968, the Boeing company started a new approach toward developing a maintenance program for Boeing 747 airplane which later became the Maintenance Steering Group (MSG). The MSG-1 was a "bottom-up" approach to address the equipment failure at component level and by doing primary maintenance process such as Hard-Time (HT) replacement and On-condition (OC) as preventive maintenance [12]. Then, MSG-1 was later updated to MSG-2 in 1970 to adopt it for newer aircraft (MD-80 and DC-10) and by defining Condition-Monitoring (CM) as the third primary process. However, CM was not a preventive maintenance as it monitors the function and allows failure to happen to some limit, hence not used for the failure modes with adverse effect on safe operation [3]. Moving forward, MSG-2 logic was found quite labor and time intensive and became progressively more difficult to deal with the maintenance needs of newer and more complex aircraft like B757 and B767.

Therefore, the third ATA task force led to a new and a "task-oriented" decision tree maintenance logic which was defined as MSG-3. The third logic was aimed to "preserve function" at system level as a top-down approach instead of doing blind and intense process-oriented preventive maintenance for "failure prevention" at component level.

The Maintenance Steering Group- 3rd taskforce (MSG-3) Logic is the most recent and widely adopted systematic maintenance strategy which it has been collaboratively developed by aviation industry key stakeholders. It is a top-down approach to develop aircraft maintenance schedule by focusing at the systems' level function preservation which is driven by systems' failure consequence analysis [34]. It aims to maintain aircraft safety and reliability by avoiding unnecessary and intensive maintenance tasks, thereby reducing aircraft downtime, costs, and waste generation. As per FAA Advisory Circular AC-121-22A, the most up-to-date MSG analytical process must be applied when developing routine scheduled maintenance tasks for any new or derivative aircraft. Therefore, aircraft manufacturers are using MSG-3 process to develop a Maintenance Planning Document (MPD) for each aircraft as the foundation of the operators' maintenance program. This program is then adjusted by air operators based on their operating

profile, exposed operational environment, utilization, technical reliability targets, OEM Service Bulletins (SB), and Airworthiness Directives (ADs) to serve as their approved maintenance program [1]. Figure 4-2 demonstrates the aircraft maintenance logic evolution.

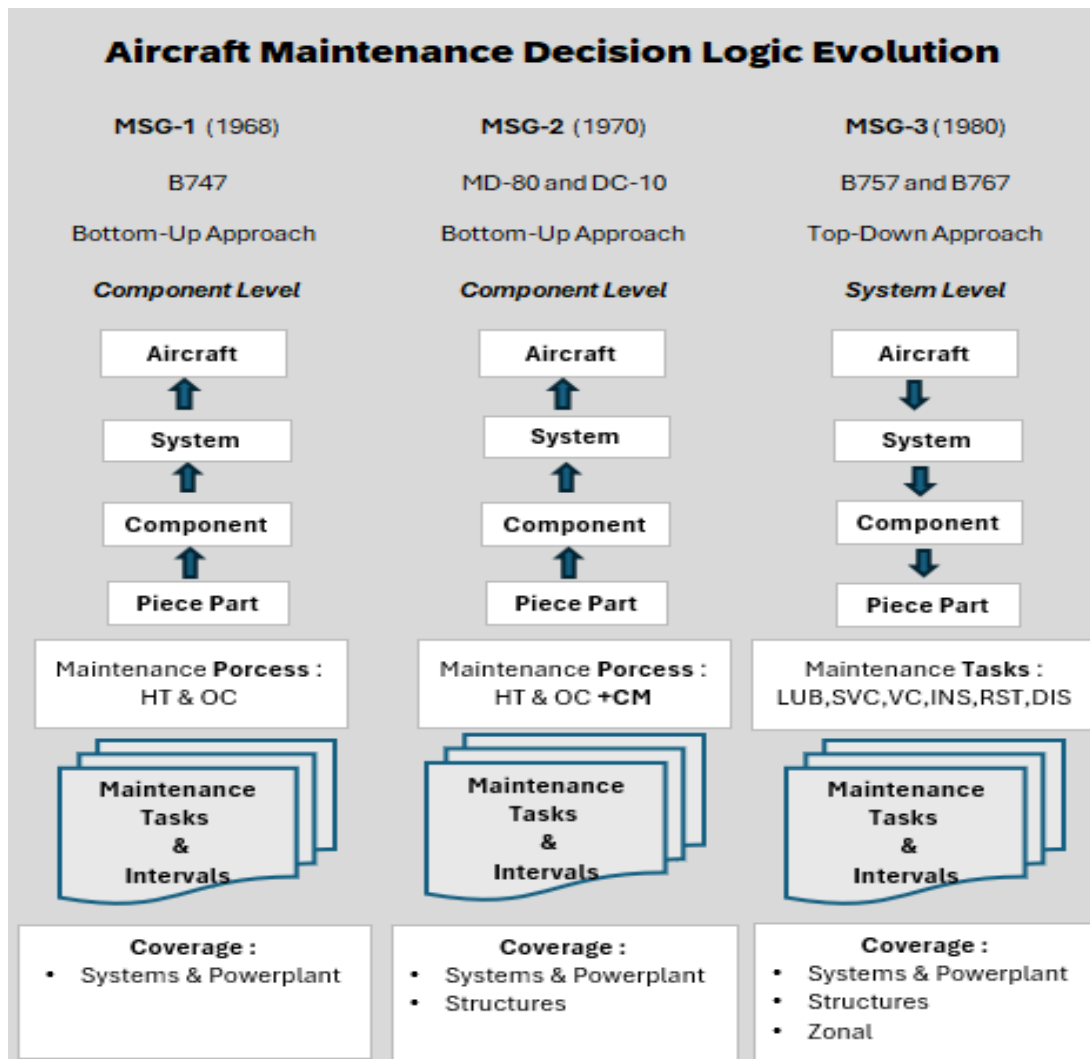


Figure 4-2: Aircraft Maintenance Logic Evolution demonstration adapted from[3]

2. Aircraft maintenance task development Based on MSG-3 Methodology

MSG-3 analysis outlines the general process and decision logic to identify all the required scheduled tasks, and their intervals based on operational capabilities of the certificated aircraft [13],[12]. The analysis includes:

1. Identification of Maintenance-Significant Items (MSI Selection).
2. Analysis of the MSI to identify their functions, functional failures, failure consequence, and causes.

3. To select the required maintenance actions (Tasks & Intervals) by using decision logic based on:

- MSG3- Level 1 analysis: Evaluation of Failure Effect Category (FEC)
- MSG3- Level 2 analysis: Selection of the maintenance task required to address the identified functional failure.

Table 4-1:MSG-3 Failure Effect Categories

Table 4-1, presents the FEC categories, in which has to be determined in every MSI level 1 analysis. Table 4-2, is showing the MSG-3 generic preventive task and their description.

FEC	MSG-3 Failure Effect Categories
5	Evident, Safety
6	Evident, Non-Safety (Operational)
7	Evident, Non-Safety (Economical)
8	Hidden, Safety
9	Hidden, Non-Safety

Table 4-2:MSG-3 Tasks as per BOEING and AIRBUS Legacy MPDs

MSG-3 Generic Task Types	
LUB	LUBRICATION - Consumable replenishment by lubricating.
SVC	SERVICING-Consumable replenishment by servicing.
OPC	OPERATIONAL CHECK - A ‘failure finding” task to determine if an item is fulfilling its intended purposes. Does not require quantitative tolerances.
VCK	VISUAL CHECK- A visual failure finding task through observation to determine if an item is fulfilling its intended purpose. Does not require quantitative tolerances.
GVI	INSPECTION - GENERAL VISUAL - A visual examination that will detect obvious unsatisfactory conditions/discrepancies.
FNC	FUNCTIONAL CHECK - A quantitative check to determine if one or more functions of an item performs within specified limits.
DET	INSPECTION - DETAILED - An intensive visual examination of a specified detail, assembly, or installation. A potential failure finding task.
RST	RESTORATION - Reworking, replacement of parts or cleaning necessary to return an item to a specific standard
SDI	INSPECTION - SPECIAL DETAILED - A thorough examination of a specific item, installation, or assembly to detect damage, failure, or irregularities. This inspection often involves the extensive use of specialized techniques and equipment like Non-Destructive Testing (NDT). It may require detailed cleaning, or, and significant access or disassembly.
DIS	DISCARD – To remove an item from service at a specified life limit.

Under MSG-3 approach, maintenance tasks are grouped into 3 main program categories as:

- Airframe systems and power plants;
- Structural tasks;
- Zonal tasks.

Airframe systems are classified and known as ATA 100, which divides aircraft systems into chapters whereas each chapter is assigned to a specific area/function. ATA 100 provides a consistent and accurate framework for maintenance documentation. ATA chapters versus MSG-3 categories tasks are depicted in Figure 4-3.

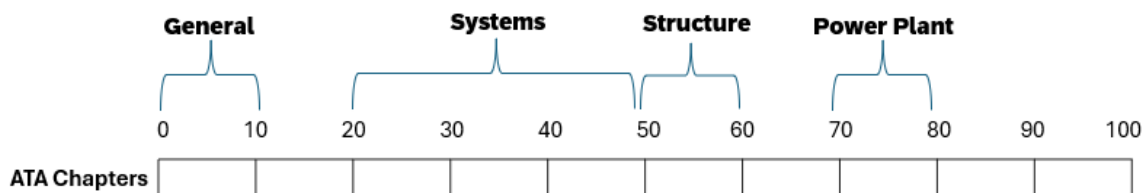


Figure 4-3: ATA 100 INDEX -Maintenance classification

3. Aircraft Maintenance Planning Document Development

The maintenance tasks selected through the MSG-3 process are documented by aircraft manufacturer which is the Type Certificate (TC) holder in their applicable Airworthiness Authority (FAA, EASA, etc.) approved report which is known as the Maintenance Review Board Report (MRBR) [12]. It contains the airframer's initial proposed scheduled tasks for the subjected aircraft types, which must be reviewed, and approved by MRB organization. Airframers use the approved MRBR and Airworthiness Limitations Section (ALS) documents, which contain design safety requirement maintenance data, to develop and publish the Maintenance Planning Document (MPD) [12],[1]. As illustrated in Figure 4-4, MPD is the practical outcome of both the type certification process and the Maintenance Review Board (MRB) process. It provides operators with a structured framework of maintenance tasks and intervals, ensuring compliance with safety regulations and the continuous airworthiness of the aircraft. MPD incorporates both the MRBR and ALS mandatory scheduled maintenance requirements, providing all details on the scheduled tasks', thresholds, repeat intervals, and the average Manhour to perform each task [82],[83]. MPD serves as the foundation of air operators approved maintenance program (OAMP) which outlines

scheduled tasks and inspections to ensure airworthiness, safety, and regulatory compliance, tailored to aircraft operators' specific operations and conditions.

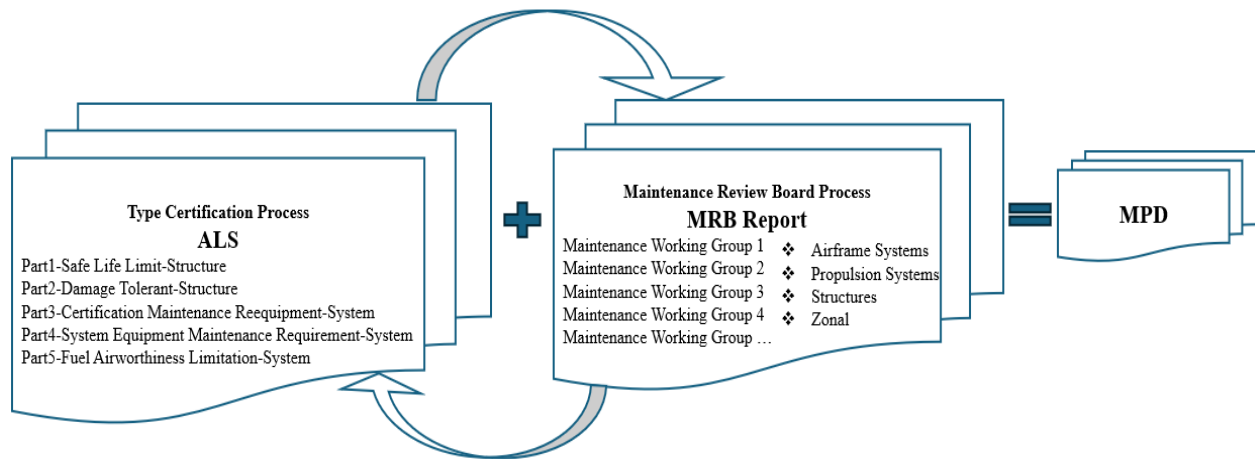


Figure 4-4: MPD Development Process based on MSG-3 Logic and MRB framework

4. Aircraft maintenance activities and tasks categories

Line Maintenance: Refers to the necessary inspection and maintenance tasks performed on aircraft to ensure their airworthiness and safe daily operation. These tasks include daily checks, transit checks, Light letter checks (A & B), troubleshooting, defect resolution, and minor repairs based on Aircraft Maintenance Manual (AMM) that do not require extensive disassembly and significant downtime. Line maintenance is typically conducted on the ramp, at the gate, or in nearby terminal line stations.

Base Maintenance: It refers to more heavy and comprehensive scheduled maintenance activities that requires aircraft to be out of service for an extended period of time. It often includes thorough inspection and disassembly of airframe systems and structures for required detailed inspections, repairs, retrofits, modifications, and implementing heavy letter checks (C & D).

Shop Maintenance: It refers to the maintenance activities performed off-wings on the removed aircraft engines and components in a workshop space. It involves, special inspections, repairs, overhauls, and testing based on the Component Maintenance Manual (CMM).

Figure 4-5 represents types of aircraft maintenance events performed at different workstations.

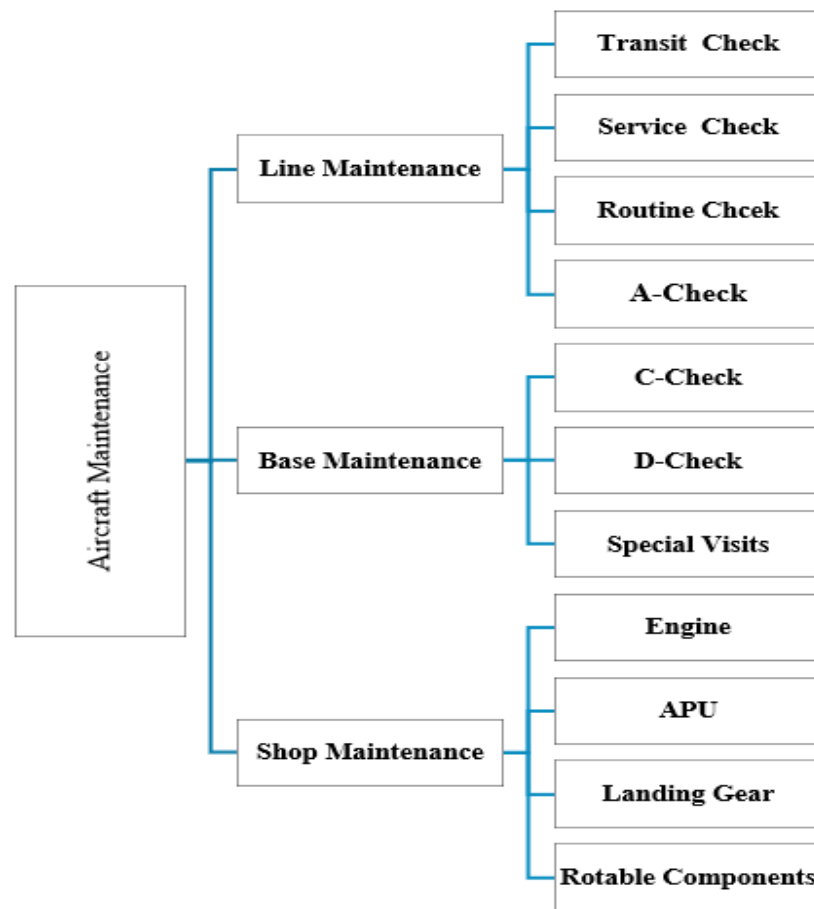


Figure 4-5: Aircraft maintenance activities

Figure 4-6, outline types of maintenance in failure management context. The preventive maintenance involves inspections and pre-determined tasks which are scheduled as per MPD at predefined intervals based on flight hours (FH), flight cycle (FC), or calendar time. Corrective maintenance addresses either unscheduled findings or the results of condition monitoring when the parts' failure can be tolerated up to some limit. The last group "Modifications" are not classified as maintenance by definition, and often conducted by service bulletins (SB), service letters (SL) and retrofit programs. Modifications are significant tasks performed by aircraft maintenance organization. Given the fact that maintenance tasks can only preserve the aircraft performance at its inherent safety and reliability level.

Therefore, if an aircraft's inherent reliability level found inadequate, then design modification is needed to improve the reliability performance (EASA, Aircraft Maintenance Program).

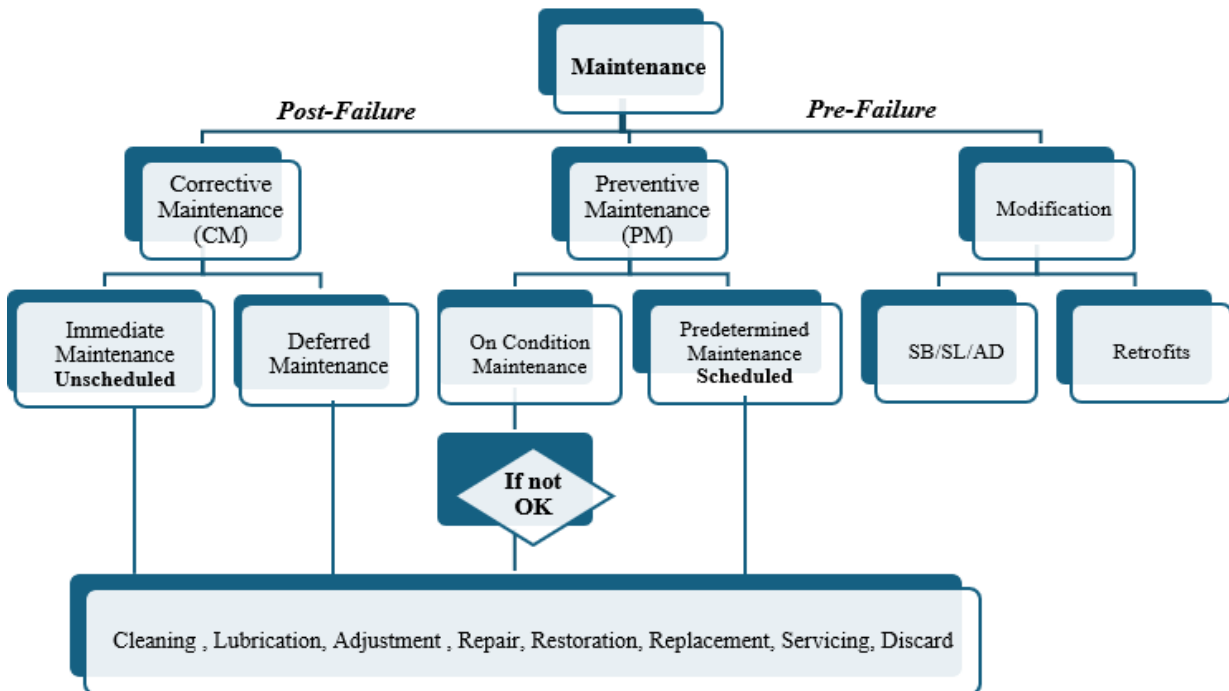


Figure 4-6: Types of Aircraft Maintenance Adapted from IEC 60300-3-14 (2004)

5. Aviation maintenance ecosystem, key stakeholders and their roles

The sustainability performance of aviation maintenance is significantly influenced by complex interplay between its stakeholders. Figure 4-7 is a demonstration of the industry key players along with their expected role toward sustainable aviation maintenance.

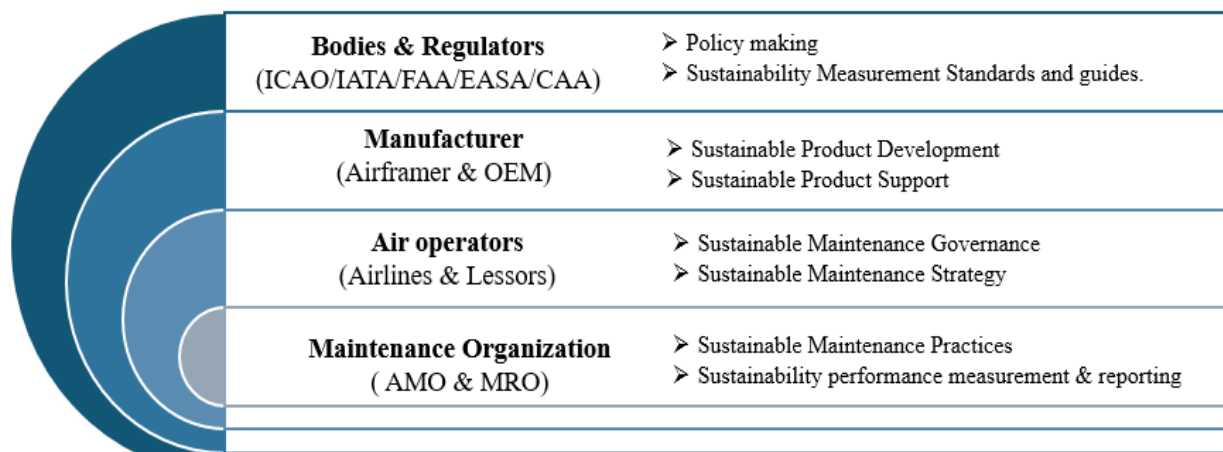


Figure 4-7: Aviation Sustainable Maintenance Key Stakeholders

Aviation Bodies and Regulators' role toward SM:

Efforts towards sustainable maintenance practices, circularity, closed loop supply chain, aircraft and component End-Of-Life (EOL) handling are often led or advised by aviation association like IATA, ICAO. Currently at aircraft maintenance organization level, there are numbers of sustainability performance indicators used in corporate ESG or CSR reporting [17] However most of these sustainability reports are at organizational level, hence providing little or no visibility over maintenance sustainability performance of aircraft itself. Establishing industry standards for assessing and reporting MSP of aircraft, aligns stakeholder efforts toward more sustainable management of the existing global fleet and provide benchmarking data for further truly sustainable aircraft development.

Aircraft and Component manufacturer role toward SM:

In alignment with industry's commitment towards 2050 decarbonization goal, aircraft manufacturers are incorporating use of advanced technologies and materials into their Eco-design product development practices. These efforts are in favor of developing more sustainable aircraft aiming for reducing the weight, lowering fuel consumption and emission, lowering maintenance needs and waste generation and eventually higher aircraft reliability and availability performance. However, not all new developments are truly sustainable throughout their entire life cycle in which some might inadvertently shift environmental or economical burdens from one to another phase of life cycle or even create some extra burdens. Therefore, aircraft's maintenance sustainability performance data must be effectively collected, evaluated, analysed, and integrated into further product development practices. This integration aims to ensure the creation of truly sustainable and future-proof eco-design aircraft products.

Airframers and OEMs have a significant role in their product aftermarket by offering "Sustainable Product Support" provisions. This is a relatively new notion in civil aviation industry. It refers to integrate sustainability aspects into the aircraft's component conventional "product support" provisions. The proposed SPS needs to support the following areas:

- ❖ Sustainable Spare part provision: offering adequate spare at reasonable price available in region/local market to avoid long lead time and prevent unnecessary shipments' emissions.

- ❖ Evolving standard repair documents like AMM, CMM, SRM, etc. and offering OEM One-off repair disposition to avoid or minimize repairable part scrapping.
- ❖ Local shop repair capability provisions to avoid unnecessary shipment cost and emissions and reduce repair Turn Around Time (TAT).
- ❖ Component End-Of-Life provisions; This can promote circularity and upcycling by reducing the need for raw material and energy by rebuilding and re-manufacturing unserviceable parts.
- ❖ Given the fact that many beyond-Economic-Repair (BER*) or and EOL components could be upcycled through the refurbishment or remanufacturing processes, OEM reverse logistic provisions are among the key sustainable product EOL supports.

Note: in aviation supply chain, BER mostly refers to a component's repair cost of more than 65% of a new identical part.

Air operators' roles toward SM:

Air operators are the key stakeholders to implement and promote sustainable maintenance practices by adopting and integrating sustainability aspects in their corporate governance [84]. Airlines can significantly contribute to more sustainable maintenance practices by leveraging green technologies, enhancing operational efficiencies, and adopting sustainable strategies in their partnerships with MROs, repair shops, and other maintenance stakeholders. Additionally, by effectively collecting, and tracking their fleet maintenance sustainability performance, they can improve their maintenance practices and take informed decision for their more sustainable future investment and aircraft acquisitions.

Maintenance organization's role toward SM:

Sustainability in Airline internal maintenance organizations, OEM maintenance shops, and MRO service providers is mainly addressed from operational efficiency perspective. Integrating digitalization and automation in their operational processes, adopting latest maintenance tools and techniques, lean maintenance process and green supply chain are the focus areas toward sustainable maintenance services.

4.3.2 Step 2: Sustainability performance measurement in Maintenance context

In maintenance context, maintenance operations, parts replacement, and waste handling, have been identified as three key activities that require careful management due to their considerable environmental impact [36]. Adoption of most suitable maintenance strategy from sustainability perspective been studied by determining most relevant indicators for each sustainability pillars and a fuzzy VIKOR method was used to rate each strategy based on sustainability factors [37]. Another research has proposed a Composite Maintenance sustainability Index (CMSI) and a decision support systems by adapting Balanced Scorecard (BSC) model and integrating it with the sustainability indicators relevant to maintenance processes [23]. A multi-stakeholder perspectives study on sustainable maintenance performance assessment was delving into the direct and indirect sustainability impacts of maintenance and evaluating the involved stakeholder's awareness on maintenance sustainability performance [38]. In this context, numbers of literature were found approaching sustainability measurement by identifying most relevant suitability indicators for each of economic, environmental and social pillars. Then proposing a framework on how to normalize, weight based on their perceived importance and priorities and finally aggregate all pillars' sub-indices into a Composite Sustainability index [39]. The Life Cycle Sustainability Analysis (LCSA) is the conventional and comprehensive approach in Life Cycle Engineering (LCE) domain to measure all sustainability impacts of a product or a service, or a process across its full life cycle; LCSA will further breakdown into Life Cycle Analysis (E-LCA) for environmental impact assessment mainly based on ISO 14040 and 14044 framework, requirements and guidelines [21],[22], Life Cycle Cost Analysis (LCCA) for economical impact assessment and Social Life Cycle [Impact] Assessment (S-LCA) [40]. However, conventional LCA is often a data-intensive approach that relies on various database and life cycle analysis software to trace ,source, and calculate significant amount of life cycle data; which could make maintenance sustainability performance measurement for the aircraft's systems, exhaustive and relatively complex to assess ,to compare ,and to benchmark across different fleets.

4.3.3 Step 3: Exploring a suitable approach for aircraft MSP

It is crucial to understand that aircraft maintenance is the process of ensuring that all aircraft systems consistently perform their intended functions at their "Designed-In" level of reliability [12]. To this end , as outlined in Step1 , aircraft manufacturers develop and publish the Maintenance

Planning Document (MPD) for each type of aircraft which serves as the basis of aircraft's operator maintenance program. Based on the MPD, and by considering factors such as the operational environment, region, and operator utilization target, the Aircraft Approved Maintenance Program (AMP) is created[13]. Therefore, it is safe to say that AMP, is governing the aircraft's "Necessary Maintenance" to consistently maintain its intended function for safe and airworthy operation at its inherent design capability and reliability. This could be the basis to define the assessment's boundary for each aircraft based on its approved maintenance program and for effectively evaluating aircraft and its major systems MSP consistently and comparably.

Current studies found primarily focused on the economical sustainability of aircraft maintenance and mainly assessed the sustainability impacts in an absolute basis. However, for a true and comparable assessment, this study proposes to assess the maintenance sustainability impacts on adjusted and as per flight inventory basis. Flight inventory terms including Available Seat Kilometer (ASK) and available Tone Kilometer (ATK) are coming from Airline industry finance but found quite useful to provide consistency and comparability in the maintenance sustainability performance assessment. Figure 4-8 presents a model for the aircraft maintenance system interfacing and boundaries with design and development (DD) and Flight Operation (FO).

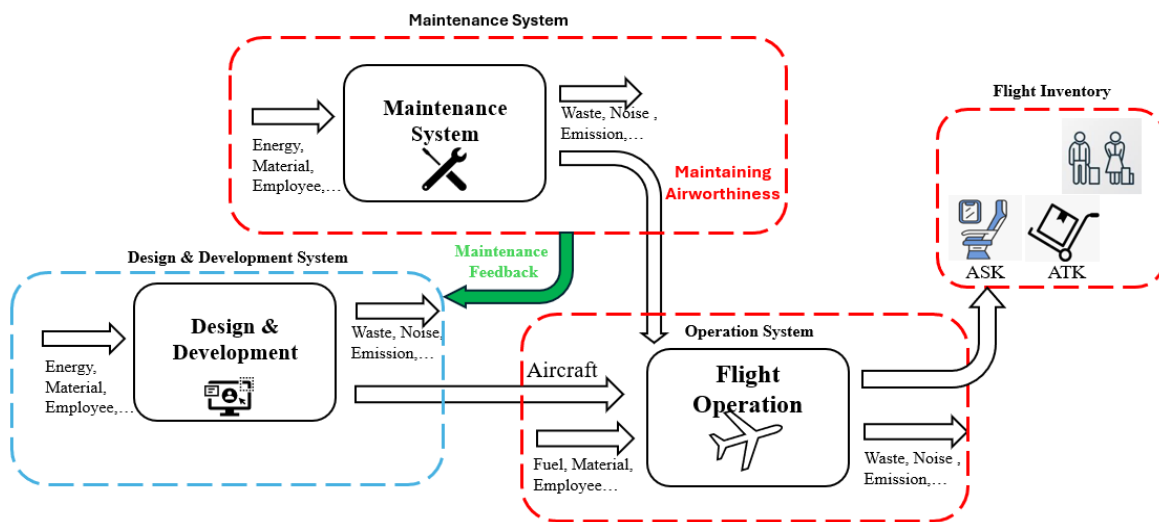


Figure 4-8: Aircraft Maintenance System Interplay with DD and FO systems

Available Seat Kilometers; $ASK = \text{Number of Seats} * \text{Distance Flown (in Kilometer)}$

Available Ton Kilometers; $ATK = \text{Total Cargo Capacity (in Tons)} * \text{Distance Flown (in Kilometer)}$

Based on the literature reviewed in Steps 1 and 2, the most relevant sustainability indicators for the economic, environmental, and social pillars have been identified and proposed, as illustrated in Table 4-3.

Table 4-3: Selected Sustainability Indicators to evaluate AM impacts

Selected Indicators in “Aircraft Maintenance Sustainability” Context				
Pillar	Indicators	Individual Metrics	Unit	References
Environmental	Resource Consumption (RC)	Energy	kWh/bbl. (Oil)/ Natural gas (M3), etc.	[17],[37],[24],[85], [42]
		Water	M3	[17],[25],[24],[85],[42]
		Material	Kg, L, M3	[17],[37],[85], [42]
	Emissions (EM)	Carbon Emissions	Kg Co2	[19],[42],[11],[86]
		Other GHG Emissions	Kg Co2-eq	[42],[11],[10]
	Pollutions (PO)	Hazardous Substance (Toxic)	Grams	[25],[85]
		Ozon depleting substance	ODP-eq value	[19],[25]
		Waste	M3 or Kg	[17],[37],[24],[85]
		Noise	db.	[24],[85], [87],[10]
Economical	Direct Maintenance Cost (DMC)	Labor	Hr.	[88],[24]
		Material (Spares +Consumables)	USD	[88],[24], [42]
	Maintenance Downtime (MDT)	Loss of Revenue	Day or USD	[23],[10]
Social	Workers Health & Safety	Risk of Injury (RI)	Rate (%)	[24],[23],[87],[10]
		Hazardous Material Exposure (HE)	Rate (%), Scale	[10],[89]
		Postural Strain (Ergonomic) (PS)	Qualitative Scale	[90]

4.3.4 Step 4: Aircraft MSP assessment framework Conceptualization

As outlined in Step 1, aircraft maintenance scheduled tasks are defined based on MSG-3 approach and categorized in three major groups as airframe System & power plant, Structures, and Zonal [12].

MSG-3 analysis is the decision logic to develop the MPD scheduled tasks and intervals. The proposed model is to leverage MSG-3 generic tasks, presented in Table 4-2 and by extending them to a more detailed set of standard tasks with a relatively consistent sustainability impact. Then for each task a qualitative Environmental Index (EnSI) and a qualitative Social Index (SoSI) can be assigned. The assigned EnSI and SoSI are then scaled by subjected task's Manhour to translate the task intensity into a quantifiable impact score. Proposed qualitative scoring is based on Likert 7 points Scale. Table 4-4 is the conversion table for the proposed qualitative scaling.

Table 4-4: Likert 7 points scale conversion table

Least Favorable	Extreme	1
	Very High (VH)	0.9
	High (H)	0.7
	Moderate (M)	0.5
	Low (L)	0.3
	Very Low (VL)	0.1
Most Favorable	N/A	0

This study acknowledges the limitations of task's impact quantification based on the manhour only and recognizes that including material consumption would provide a more accurate reflection of the environmental impacts. However, for the sake of simplicity in presenting the concept and due to limited access to material consumption details in the case study, this work focuses on manhour.

The indicators' qualitative scaling and weighting must be performed by an expert panel. An example of an expert panel with details, presented in Table 4-5.

Table 4-5: An example of Composition of the Expert Panel

Team Member	Position	Experience
Aircraft System Engineer	Subject-Matter Expert (SME)	10 Years
Aircraft Structure Engineer	Subject-Matter Expert (SME)	18 Years
Maintenance Safety, Health and Environmental Specialist	Safety & Environmental Expert	20 Years

Table 4-6, presents MSG-3 extended task inventory, proposed to be used as maintenance task building blocks for the required sustainability impacts assignment. This study acknowledges the potential of a more detailed and standardized task inventory, which could provide a more accurate assessment of sustainability impacts.

Table 4-6: MSG-3 Extended Tasks Inventory

Aircraft Maintenance Task Inventory Based on MSG-3				
MSG3-Task Category	MSG-3 Generic Task	MSG-3 Extended Task	Task Code	Task Description
Systems & Powerplants	Lubrication	Lubrication - Greasing	LUB-Gr	Lubrication by Greasing
	Servicing	Servicing -Oil Change	SVC-OC	Servicing and Oil Change
		Servicing -Oil Replenishment	SVC-OR	Servicing and topping up the Oil level. (Small amount of oil, compare to the oil change)
		Servicing - Cleaning & Fluid Change	SVC-CI	Servicing by cleaning and changing the system's liquid such as coolant fluid, De-icing fluid
	Inspection	Inspection	GVI	A General Visual examination to detect evident anomalies /discrepancies
	Visual Check	Visual Check	VCK	A visual failure finding task by observation to verify an item is fulfilling its intended purpose. (No quantitative tolerance)
	Operational Check	Operational Check	OPC	A failure finding task operational check/test to determine the fulfillment of intended purposes. (No quantitative tolerance)
	Functional Check	On-wing, Handheld Device	FNC	A quantitative check to verify an item functional integrity within specified limits
		On-wing with External Source	FNC-ES	A quantitative check to verify an item functional integrity within specified limits.

Table 4-6: MSG-3 Extended Task Inventory (Continued and End)

				This task requires External Sources of power, air or water supply pressure
	Restoration	RST- Minor Repair	RST-MR	Reworking involving Minor Repair to return an item to a specific standard
		RST-Part Replacement	RST-PR	Reworking involving Part Replacement to return an item to a specific standard
		RST-Paint touch up	RST-PT	Reworking involving Paint touch-ups to return an item to a specific standard
		RST-Cleaning	RST-CI	Reworking involving Parts Cleaning to return an item to a specific standard
	Discard	Dis-Haz	DIS-HAZ	To remove an item at specified life limit - Hazardous material (Chemical or biological contaminated items)
		Dis-Non-Haz	DIS-NHAZ	To remove an item at specified life limit - Non-Hazardous material
Structures	General Visual Inspection	General Visual Inspection	GVI	A general Visual examination to detect evident anomalies /discrepancies
	Detailed Inspection	Detailed Inspection	DET	An intensive visual examination of a specified detail, assembly, or installation. A "potential failure finding" task.
	Special Detailed Inspection	SDI-NDT (Non Radiative)	SDI-NDT	An intensive examination of a specific item(s), installation or assembly to detect damage, failure or irregularity. The examination is likely to make extensive use of specialized Inspection Techniques and/or equipment, NDT, Intricate cleaning and substantial access or disassembly procedure may be required.
Zonal	General Visual Inspection	General Visual Inspection	GVI	A general Visual examination to detect evident anomalies /discrepancies
	Detailed Visual Inspection	Detailed Visual Inspection	DET	An intensive visual examination of a specified detail, assembly, or installation. A "potential failure finding" task.

4.3.5 Step 5: Proposed aircraft MSP Scoring Step by Step Procedure

1- To select the most relevant indicators for each sustainability pillar in the context of “Aircraft Maintenance Sustainability” as presented in Table 4-3.

2- Development of a more detailed and standardized task inventory based on MSG-3 generic tasks. The proposed standardized task inventories aim to serve as building blocks to breakdown the maintenance task for the required impact assessments. An example of this concept is presented in Table 4-6.

3- To evaluate and scale every task's Environmental and Social individual metrics using 7-points Likert 7 scale and as per experts' opinion.

4- To assign weights to the selected indicators, the proposed weights in this study are based on the perceived importance and priority of experts' opinions, as presented in Table 4-10.

5- To compute the Environmental Index (EnI) and Social Index (SoI) for every MSG-3 extended task, by aggregating their weighed indicators. For the sake of simplicity and ease of interpretation, the proposed aggregations are based on Weighted Sum Linear aggregation[39] as following:

$$\text{Linear Aggregation – “Single Task” Sustainability Indexing (SI)} = \sum_{j=0}^n I_j \cdot W_j$$

$$, (\sum W_j = 1, W_j \geq 0)$$
(4.1)

$$\text{Environmental Sustainability Index (EnI)} = (RC \times W_{RC}) + (EM \times W_{EM}) + (PO \times W_{PO})$$
(4.2)

$$\text{Social Sustainability Index (SoI)} = (RI \times W_{RI}) + (HE \times W_{HE}) + (PS \times W_{PS})$$
(4.3)

$$\text{Economical Sustainability Index (EcI)} = (DMC \times W_{DMC}) + (MDT \times W_{MDT})$$
(4.4)

6- To review the subjected Maintenance Event' tasks to assign the standard MSG-3 Task, based on the developed task inventory, as outlined in Table 4-6.

Note: A combination of multiple standardized tasks may generate a new standard task, enabling a more accurate assessment of sustainability impacts. In the presented case study, the evaluated tasks were either divided into the subset standard tasks or labeled according to the task with the highest impact.

7- The tasks' sustainability impact quantification are based on task's man-hour as a scaling factor to calculate the final Environmental Impact Score (EIS) and social impact Score (SIS) as follows:

$$\text{Task Manhour} = \text{Task Elapsed time (Duration)} \times \text{Number of Person (Labor)}$$
(4.5)

$$\text{Environmental Impact Score (EIS)} = \text{Task's Environmental Index (EnI)} \times \text{Manhour}$$
(4.6)

$$\text{Social Impact Score (SIS)} = \text{Task's Social Index (EnI)} \times \text{Manhour}$$
(4.7)

By applying the man-hours of each task as a scaling factor to its environmental and social sustainability indices (EnI, SoI), the indices are translated into environmental and social impact scores.

Note: This study acknowledges that the 'Environmental Sustainability Score' evaluation accuracy could be enhanced by incorporating the Material consumption.

8- Weighting the Environmental Impact Score (EIS), Social Impact Score (SIS), and Economical Impact based on expert's opinion as presented in Table 4-10.

Note: The assigned weightings are based on experts' opinions regarding perceived importance and priorities. To ensure consistency and comparability across different fleets, the weightings must be standardized and remain fixed.

9- To compute the proposed Maintenance Sustainability Performance Score (MSPS) by aggregating all three Environmental, Social, and economical scores. Linear weighted sum aggregation is used as follows:

$$\text{MSP Score (MSPS)} = (EIS \times W_{Env}) + (SIS \times W_{Soc}) + (EcoS \times W_{Eco}) \quad (4.8)$$

Note: In this study, environmental and social indices are quantified by manhour, and economical score is based on tasks' manhour, hence all three dimensions are aggregated directly. This study suggests integrating task's material consumption in environmental and economical score measurement for enhanced accuracy. In that case, it would be necessary to normalize the sustainability indices' scores to ensure their comparability.

10- Aircraft's, their system and subsystem MSPS can be simply measured by summing all their relevant tasks MSPS.

Note: This study presents MSPS score both in an absolute and adjusted basis. The proposed adjusted score is MSPS per million Available Seat Kilometer, MSPS/MM ASK

4.4 Case Study

The case study is presenting an MSP assessment, and comparison of a C-check maintenance event for two single isle legacy aircrafts. Table 4-7 presents both aircrafts overall specifications, age, and utilization.

Table 4-7: Selected Aircrafts Specification and Yearly Utilization

Aircraft Specifications							Yearly Utilization	
Year Of Manufacturing	Type	# Seat	Engine	Length (m)	Wingspan (m)	Cruise Speed (KM/Hr)	Flight Hour (FH)	Flight Cycle (FC)
2017	A	195	CFM56-5B	44.5	34.1	833	3270	1250
2017	B	170	Leap-1B	39.5	35.9	839	3350	1330

Both aircrafts have a comparable maintenance program with equalized phased C-check in addition to transit check. Table 4-8 presents both aircrafts scheduled checks.

Table 4-8: Selected aircrafts Maintenance Checks specification

Station	Line Maintenance			Heavy Maintenance
Check	Service Check	Routine Check	A-Check	C-Check
Aircraft	Interval	Interval	Interval	Interval
A	Every 72 Hour	Every 10 Days	Every 1000 FH	Every 18 Months
B	Every 48 Hour	Every 2 Weeks	Every 1000 FH	Every 18 Months

1-Both Aircrafts' C-check Tasks been reviewed, analyzed and processed by removing accidental damage and mishap non-routine defects, then every task is classified in their relevant MSG-3 major categories and ATA Chapters. Table 4-9, Presents both aircraft C-check tasks overall statistics.

Table 4-9: Studied aircrafts' C-checks Task grouping and statistics

C-Check Duration (Day)		Aircraft A		Aircraft B	
		18		14	
Task Group	Task CAT	Task Cards Qty	Cumulative Labor (Hr)	Task Cards Qty	Cumulative Labor (Hr)
MSG-3 Major Categories	System	433	2805	348	1446
	Powerplant	110	440.5	65	226
	Structure	170	666.75	133	374
	Zonal	150	508.5	220	652.5
Operator Task	Cabin	17	300.5	28	629
Total		880	4721.5	794	3327.5

Note: The Labor hours are based on actual spent hours, including open access and closure.

2- To scale the selected environmental and social sustainability pillars' indicators for all MSG-3 extended task inventory, defined in Table 4-6, as per Likert scaling (Table 4-4), based on Experts' opinion.

3-To aggregate the social and environmental indices as described in step 5 and based on selected weighting defined per experts' opinion as their perceived relevance and priorities. Table 4-10 presents selected weightings.

Table 4-10 : Selected Weights for Sustainability Pillars and their Indicators

Pillar	Weight (%)	Indicator	Weight (%)
Environment	30	Resource Consumption	40
		Emission	30
		Pollution	30
Social	20	Risk of injury	40
		Hazardous Exposure	30
		Postural Strain	30
Economical	50	Direct Maintenance Cost	60
		Maintenance Downtime	40

Appendix A, Presents the MSG-3 extended task, with assigned environmental and social sub-indices, and the aggregated Environmental Index (EnI) and Social Index (SoI).

4- To review and assign most relevant MSG-3 task as per developed task inventory presented in Table 4-6 . Both aircrafts task inventory shares in C-check based on manhour and number of tasks are presented in Figure 4-9 and Figure 4-10.

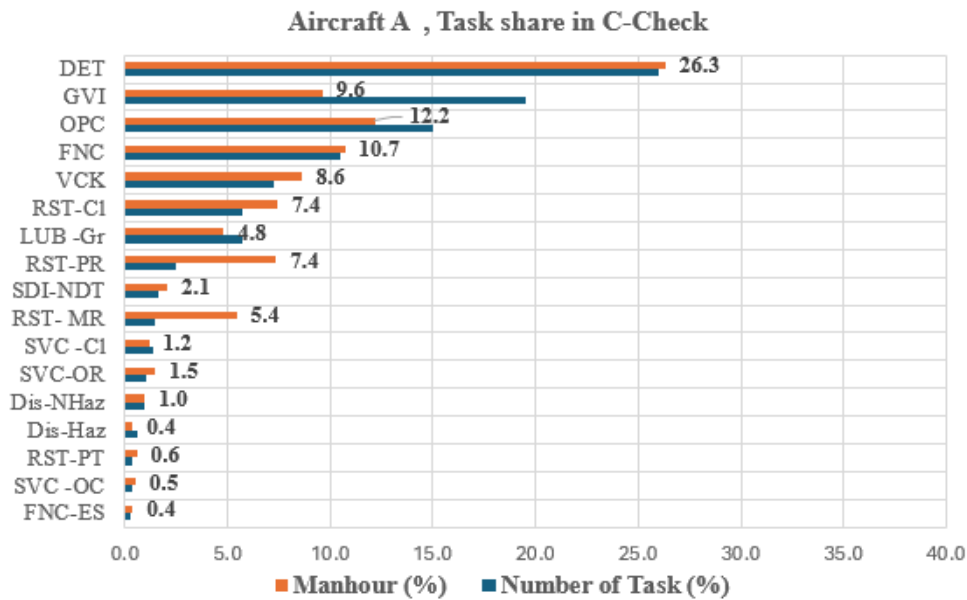


Figure 4-9: Aircraft A, Task Share in C-Check

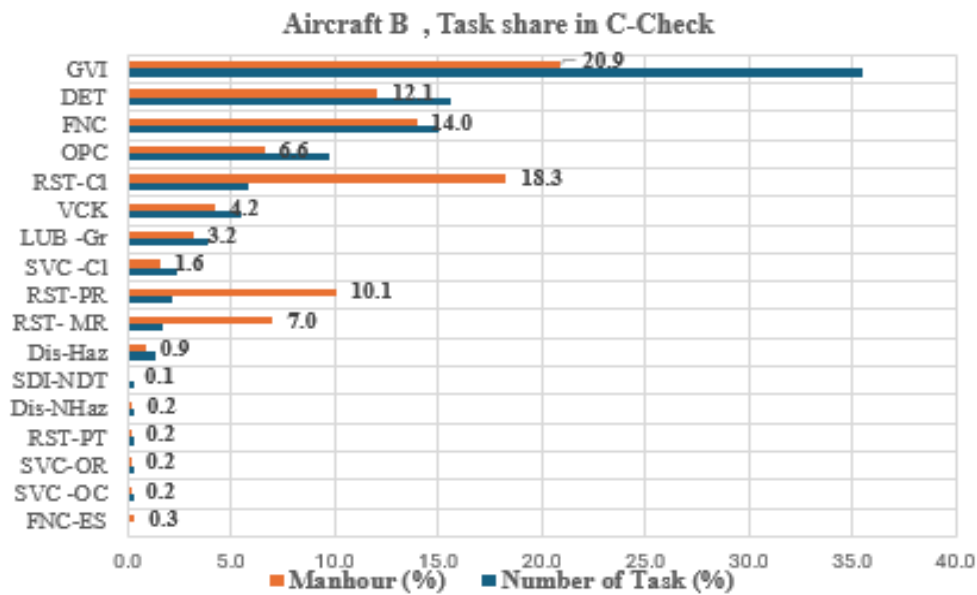


Figure 4-10: Aircraft B, Task Share in C-Check

5- To compute the Environmental Impact Score (EIS) and Social Impact Score (SIS) for each task based on their assigned Environmental and social indices and by applying labor as scaling factor.

6- To measure EIS and SIS for each MSG-3 major category by summing the subset tasks impacts. Table 4-11, presents both aircrafts measured impacts per major categories.

Note: Due to the unavailability of material consumed per task, only labor hours have been accounted for, in assessing the economic impact.

Table 4-11: Three Pillars and Overall MSPS per each Major Category

Task Category	Environmental Impact Score		Social Impact Score		Economical Impact Score (Labor)		MSPS	
	AC- A	AC- B	AC- A	AC- B	AC- A	AC- B	AC- A	AC- B
System	894.0	481.1	1418.4	719.3	2805.2	1445.8	1954.5	1011.1
Powerplant	114.6	67.8	230.6	118.2	440.5	225.7	300.8	156.8
Structure	141.9	59.1	348.9	186.2	666.7	374.1	445.7	242.0
Zonal	87.4	62.5	255.4	308.2	509.0	652.5	331.8	406.6
Cabin	102.2	410.0	163.9	368.0	300.5	628.4	213.7	510.8
Total	1340.1	1080.4	2417.3	1699.8	4721.9	3326.5	3246.4	2327.3

Appendix B is providing details on every major category measured impacts for both aircrafts. Figure 4-14, Figure 4-13, Figure 4-12, Figure 4-11 illustrate the individual impacts of the three pillars, along with the MSPS of all major categories and the total of all C-check tasks

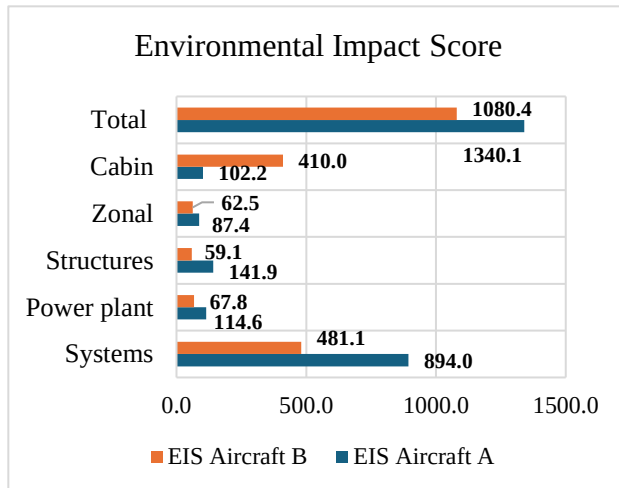


Figure 4-13: Aircraft A&B C-Check
Environmental Impact

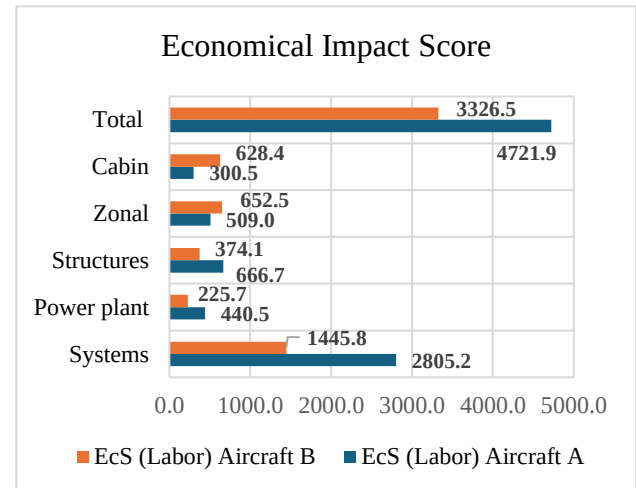


Figure 4-14: Aircraft A&B C-Check
Economical Impact

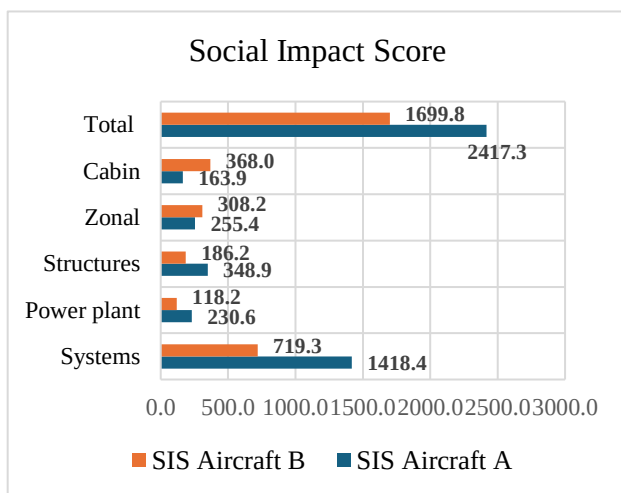


Figure 4-11: Aircraft A&B C-Check
Social Impact

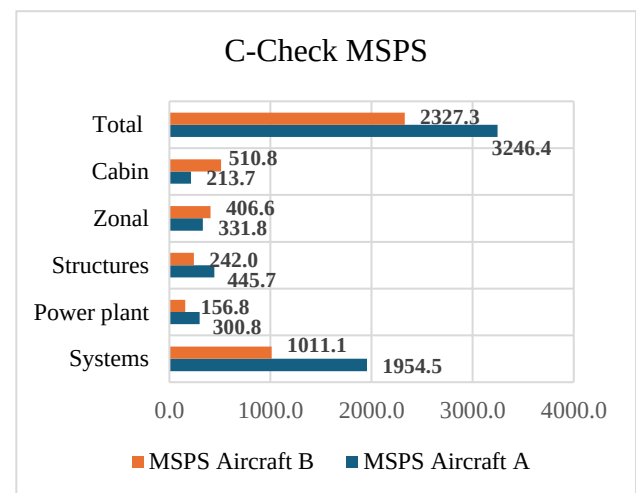


Figure 4-12: Aircraft A&B C-Check MSPS

4.4.1 Result and Discussion

The selected aircraft, A and B, are both single-aisle well-established legacy design. They were chosen to be ideally with similar flight utilization and schedule, age, and operational regions, aiming a comparable sustainability impact assessment solely from their “Maintenance requirements” perspective. The available data consisted solely of labor (man-hour) breakdown per task, along with the task description. The scores are evaluated such that lower scores indicate lower impact and more favorable performance, while higher scores reflect less favorable outcomes.

This study acknowledges that the final scaling for quantifying the intensity of the 'Environmental Sustainability Score' could be improved by integrating the material dimension. The proposed model focuses on developing an inventory of standard tasks with readily measurable sustainability impacts. These tasks serve as building blocks for deconstructing a maintenance event work package. This approach enhances visibility on the three pillars impact assessment for any group of maintenance activities, such as maintenance checks. The implemented case study has evaluated a phased C-check and was able to project the impacts based on MSG-3 major groups. The other group evaluated within C-check tasks is for the Cabin interiors. The cabin tasks found to be mainly servicing and grooming and conducted as per operator standard. It is important to note that cabin items, referred to as "Buyer Furnishing Equipment," (BFE) are selected and purchased at the discretion of the aircraft operators. Therefore, assessing the sustainability impacts of cabin interior required maintenance, could offer greater insight into existing maintenance practices, highlighting areas for improvement and facilitating more informed decision-making for future investments.

The proposed maintenance impact assessment model can be readily applied to a more detailed level as per airframe systems and sub-systems, enabling consistent comparisons of the maintenance sustainability impact across different ATA systems' design configurations, providing insight for future design improvements. Furthermore, the proposed model can be integrated within conventional LCSA approach, where the building block tasks' environmental sustainability impacts data are supported by detailed and more accurate micro assessments data instead of qualitative scoring.

As illustrated in Figure 4-8, the proposed MSP impact assessment method could serve as maintenance feedback, providing sustainability-supporting data and insights to improve Eco-design practices.

This study suggests an opportunity to enhance current Maintenance Planning Document (MPD) development practices by incorporating the proposed model, which establishes detailed, standardized tasks with measurable impacts. This approach could potentially be integrated into the MPD to facilitate aircraft's maintenance sustainability impacts' tracking and assessment.

For transparency, the downtime associated with C-check duration has not been included in the Economic Indexing but is presented in Table 4-9.

4.4.2 Findings

Based on projected C-check's MSPS results, and considering both aircraft A and B similar age, utilization, and almost similar maintenance programs for lighter checks, aircraft A shows significantly higher impacts compared to aircraft B. This disparity can be partly explained by the fact that aircraft A is slightly larger and has a higher seating capacity than B. Consequently, adjusting the MSPS per delivered flight inventory may offer a more accurate and comparable assessment.

To this end the presented C-checks' MSPS shown in Table 4-11, must be adjusted per delivered flight inventory (ASK) within the same period as C-check (18 months).

As per aircraft specifications presented in Table 4-7, ASK in 18 months period is measured and presented in Table 4-12.

Table 4-12: Measured ASK within the same period as scheduled C-checks

Aircraft	Yearly FH	Cruise Speed (KM/Hr)	# Seats	ASK/Year (Million Seat-Km)	ASK /18 Months (Million Seat-Km)
A	3270	833	195	531.16	796.7
B	3350	839	170	478.38	717.57

Based on Table 4-11, the adjusted MSPS per Million Seat-KM is presented in Table 4-13.

Table 4-13: Measured MSPS/Million ASK for the C-Check

Aircraft	C-Check MSPS	ASK /18 Months (Million Seat-Km)	MSPS/Million Seat-Km
A	3246.4	796.7	4.07
B	2327.3	716.71	3.25

Given the adjusted MSPS/ASK presented in Table 4-13, it is important to emphasize that it is limited solely to the impacts of the studied C-check. However, for a comprehensive assessment of the overall maintenance sustainability performance of both aircraft, the proposed model must be applied to all maintenance events outlined in the AMP.

As shown in Figures 4-9, 4-10, a significant percentage of the C-check tasks on both aircrafts are projected to involve GVI, DET, FNC, and OPC. While all these tasks are focused on finding

failures, the tasks like GVI and OPC are aimed to detect more obvious failures, whereas DET and FNC are aiming to capture more hidden failures.

Considering the relatively young age of the studied aircraft, no significant structural, powerplant findings were captured on the assessed categories. However, among major MSG-3 groups studies, airframe systems consistently presented the higher impacts on all three pillars and for both aircrafts.

Comparing aircraft, A, and B powerplants' impacts as illustrated in Figures 4-11, 4-12, 4-13, 4-14, Aircraft B demonstrates significantly lower impacts. This is consistent with the fact that Aircraft B is equipped with a newer and more advanced LEAP-1B engines, which are designed for lower operational costs, and reduced maintenance needs. While these results seem reasonable, it is essential to supplement them by evaluating the impacts of other maintenance events.

This study suggests using this model to benchmark legacy aircraft against newly developed aircraft with advanced technologies. This approach aims to provide enhanced visibility over new development maintenance sustainability performance, and to support necessary improvements.

4.5 Validation and Sensitivity Analysis

The presented MSPS framework is implemented on a single case study of two legacy single isle aircrafts which provides useful insights into the potential drivers of maintenance sustainability performance. However, it is important to recognize the other key factors impacting aircraft maintenance sustainability performance which need to be considered for further validation of this method;

1-Regional Specificity: The operating region significantly impacts maintenance sustainability performance. Aircraft operating in harsher environmental conditions tend to require more intensive maintenance. Therefore, regional differences must be accounted for when assessing MSPS and comparing results across various regions.

2-Age: The aircraft maintenance cost and imposed environmental burden increases along with the age of the aircraft, which is also known as the Aging effect[91]. Age related MSP impacts are mainly caused by 1) the frequency of Routine maintenance tasks that increases as the aircraft ages. 2) the deterioration of aircraft materials over time, leading to more costly repairs. 3) Airworthiness directives (ADs) and Service bulletins (SBs) that mandate the removal and replacement of certain components [26]. Therefore, performing MSP assessment and comparison while neglecting the subjected aircrafts' age could be quite misleading. However, for a given fleet performing MSP

assessment across different age aircrafts could provide insightful data and support the robustness of the proposed MSP assessment framework.

3- Utilization: Utilisation is a major driver of maintenance schedule, as maintenance intervals are tied to flight hours (FH) and flight cycles (FC). Also the failure probability increases with higher utilization rate [1].

4- Flight Schedule: The effect of flight schedule in aircraft utilization can be reflected into the FH/FC ratio. The flight schedule can significantly impact maintenance needs, as aircraft with shorter flights (more cycles relative to hours) experience different types of stress than those with longer flights. Given the fact that aircraft utilization in short-haul flights poses higher tension on engines and landing gears, compare to long-haul flights, hence requiring higher maintenance caused by increased number of take off/landings (FC).

5-Maintenance specifications and practices: Regional or organizational differences in aircraft maintenance program, standards, and practices might need to be considered when generalizing the results.

While this single case study provides valuable insights, it is crucial to acknowledge the inherent limitations of generalization in case study research. As Yin [92] notes, case studies offer "analytic generalization" where findings are compared to existing theory rather than statistically generalized to populations. Flyvbjerg [93] further argues that the strength of case studies lies in their ability to generate "context-dependent knowledge" which can be valuable for understanding specific situations and informing theory development. However, transferring findings to other contexts requires careful consideration of similarities and differences. While multiple case studies can enhance generalizability [94], it is essential to recognize that the goal is not to achieve universal laws but to develop nuanced understandings applicable to similar contexts.

4.6 Conclusion

This study introduces a novel approach to assess and score the aircraft Maintenance sustainability performance (MSP). Unlike conventional Life Cycle Assessment (LCA) which are complex and data-intensive, the proposed MSP assessment method is straightforward, easy to implement, and comparable across various fleet and aircraft systems. As industry strives toward reducing its environmental footprint, it is adopting technological advancements, including new propulsion systems and the use of lightweight, advanced materials in airframe structures and systems [73],[74],[6]. However, these advancements are often associated with increased environmental and economic burden in maintenance phase [6]. Hence, making aircraft MSP assessment critical to provide supporting data for required improvement, design trade-offs and enable future-proof eco-design practices. The presented MSP assessment framework can significantly contribute to improve existing industry practices by 1) providing comparable supporting data as maintenance feedback toward enabling “closed loop” eco-design practices. 2) enhancing visibility to prioritize in-service fleet required improvements, catalyzing the efforts in phasing out unnecessary maintenance burdens. 3) enabling MSP benchmarking across different fleets, supporting the future investment and aircraft acquisition informed decision making.

It also provides a ground for future research: 1) improving the MSPS accuracy through the integration of consumed material into the assessment and extending task inventory in more detailed level, specific per ATA systems. 2) The exciting potential of integrating the MSPS in MSG-3 decision logic and MDP development processes, aiming towards a new and sustainability embedded maintenance decision logic. All these areas are significantly relevant agenda for future research and development in academia and industry.

4.7 Funding

This research did not receive any specific funding from public, commercial, or non-profit organizations.

4.8 Data Anonymity

For confidentiality purposes, the Aircraft data provided by anonymous sources have been masked and referred to as 'Aircraft A,' 'Aircraft B,' throughout the study.

4.9 Appendix

Appendix A

MSG-3 Extended Task Inventory								
Task Code	Environmental (Qualitative Scale)				Social (Qualitative Scale)			
	RC	EM	PO	EnI	RI	HE	PS	SoI
LUB-Gr	0.6	0.7	0.6	0.63	0.7	0.8	0.7	0.73
SVC-OC	0.8	0.7	0.6	0.71	0.6	0.7	0.6	0.63
SVC-OR	0.6	0.7	0.6	0.63	0.5	0.7	0.5	0.56
SVC-CI	0.6	0.7	0.6	0.63	0.5	0.5	0.6	0.53
VCK	0	0	0	0.00	0.5	0.5	0.5	0.5
OPC	0.3	0.3	0.1	0.12	0.3	0.5	0.5	0.42
FNC	0.3	0.3	0.1	0.24	0.3	0.3	0.5	0.36
FNC-ES	0.6	0.5	0.3	0.48	0.8	0.6	0.6	0.68
RST-MR	0.5	0.6	0.7	0.59	0.6	0.6	0.6	0.6
RST-PR	0.7	0.7	0.7	0.70	0.6	0.5	0.6	0.57
RST-PT	0.7	0.6	0.7	0.67	0.6	0.7	0.5	0.6
RST-CI	0.7	0.6	0.7	0.67	0.6	0.6	0.6	0.6
DIS-HAZ	0.8	0.8	1	0.86	0.5	0.7	0.5	0.56
DIS-NHAZ	0.7	0.7	0.6	0.67	0.5	0.5	0.5	0.5
GVI	0.00	0.00	0.00	0.00	0.5	0.5	0.4	0.47
DET	0.20	0.10	0.10	0.14	0.5	0.5	0.6	0.53
SDI-NDT	0.50	0.30	0.20	0.35	0.4	0.5	0.5	0.46

Appendix B-1/3

MSG-3 Task Categories																
Task	EnI	Sol	Systems (ATA-CH 21-49)						Powerplant (ATA-CH 70-80)							
			Aircraft A			Aircraft B			Aircraft A			Aircraft B				
			Task (Qty)	Manhour	EIS	SIS	Task (Qty)	Manhour	EIS	SIS	Task (Qty)	Manhour	EIS	SIS		
LUB-Gr	0.63	0.73	19	99	62.37	72.27	27	98.2	61.866	71.686	4	24	15.12	17.52	0	0
SVC-OC	0.71	0.63	3	24	17.04	15.12	2	6	4.26	3.78			0	0	0	0
SVC-OR	0.63	0.56	7	64	40.32	35.84	2	6	3.78	3.36	2	6	3.78	3.36	0	0
SVC-CI	0.63	0.53	9	40.75	25.6725	21.5975	9	40.1	25.263	21.253	2	12	7.56	6.36	0	0
VCK	0	0.5	56	261.2	0	130.6	44	146.25	0	73.125			0	0	0	0
OPC	0.12	0.42	96	473.25	56.79	198.765	61	172.12	20.6544	72.2904	6	18	2.16	7.56	4.056	14.196
FNC	0.24	0.36	62	413.75	99.3	148.95	84	381.8	91.632	137.448	4	10	2.4	3.6	2.688	4.032
FNC-ES	0.48	0.68	2	18	8.64	12.24	1	11.2	5.376	7.616			0	0	0	0
RST-MR	0.59	0.6	7	197.5	116.525	118.5	5	32.2	18.998	19.32	4	20	11.8	12	30.975	31.5
RST-PR	0.7	0.57	12	253	177.1	144.21	8	90.7	63.49	51.699	6	35	24.5	19.95	0	0
RST-PT	0.67	0.6	1	7.25	4.8575	4.35			0	0			0	0	0	0
RST-CI	0.67	0.6	35	201.5	135.005	120.9	25	179.62	120.345	107.772			0	0	20.1	18
DIS-NHAZ	0.67	0.5	8	45.5	30.485	22.75	2	8.25	5.5275	4.125			0	0	0	0
DIS-HAZ	0.86	0.56	5	18	15.48	10.08	11	30	25.8	16.8			0	0	0	0
DET	0.14	0.53	109	650.5	91.07	344.765	67	243.4	34.076	129.002	40	208	29.12	110.24	9.968	37.736
SDI-NDT	0.35	0.46	2	38	13.3	17.48			0	0	10	52	18.2	23.92	0	0
GVI	0	0.47			0	0			0	0	32	55.5	0	26.085	0	12.69
Total			433	2805.2	893.955	1418.42	348	1445.84	481.068	719.276	110	440.5	114.64	230.595	67.787	118.154

Appendix B-2/3

MSG-3 Task Categories																					
Task	EnI	Sol	Structures ATA-CH 51-57										Zonal								
			Aircraft A					Aircraft B					Aircraft A					Aircraft B			
			Task (Qty)	Manhour	EIS	SIS	Task (Qty)	Manhour	EIS	SIS	Task (Qty)	Manhour	EIS	SIS	Task (Qty)	Manhour	EIS	SIS			
LUB-Gr	0.63	0.73	27	104	65.52	75.92	4	10.5	6.615	7.665			0	0			0	0	0		
SVC-OC	0.71	0.63			0	0			0	0			0	0			0	0	0		
SVC-OR	0.63	0.56			0	0			0	0			0	0			0	0	0		
SVC-CI	0.63	0.53	1	2.5	1.575	1.325			0	0			0	0			0	10	13.5	8.505	7.155
VCK	0	0.5			0	0			0	0			0	0			0	0	0	0	
OPC	0.12	0.42	30	83	9.96	34.86	4	21.7	2.604	9.114			0	0			0	0	0	0	
FNC	0.24	0.36	24	65.7	15.768	23.652	2	4.5	1.08	1.62	2	16	3.84	5.76	29	72	17.28	25.92			
FNC-ES	0.48	0.68			0	0			0	0			0	0			0	0	0	0	
RST-MR	0.59	0.6			0	0			0	0			0	0	1	6.7	3.953	4.02			
RST-PR	0.7	0.57			0	0	4	50.25	35.175	28.6425			0	0			0	0	0	0	
RST-PT	0.67	0.6			0	0	2	6	4.02	3.6	2	20	13.4	12			0	0	0	0	
RST-CI	0.67	0.6			0	0			0	0	12	93.5	62.645	56.1	4	39.75	26.6325	23.85			
DIS-NHAZ	0.67	0.5			0	0			0	0			0	0			0	0	0	0	
DIS-HAZ	0.86	0.56			0	0			0	0			0	0			0	0	0	0	
DET	0.14	0.53	68	330.75	46.305	175.2975	10	58.5	8.19	31.005	12	53.5	7.49	28.355	11	43.5	6.09	23.055			
SDI-NDT	0.35	0.46	2	8	2.8	3.68	2	4	1.4	1.84			0	0			0	0	0	0	
GVI	0	0.47	18	72.75	0	34.1925	105	218.62	0	102.7514	122	326	0	153.22	165	477	0	224.19			
Total			170	666.7	141.928	348.927	133	374.07	59.084	186.2379	150	509	87.975	255.435	220	652.45	62.4605	308.19			

Appendix B-3/3

Task	EnI	SoI	Operator Standard							
			Cabin							
			Aircraft A				Aircraft B			
			Task (Qty)	Manhour (hr)	EIS	SIS	Task (Qty)	Manhour (hr)	EIS	SIS
LUB-Gr	0.63	0.73			0	0			0	0
SVC-OC	0.71	0.63			0	0			0	0
SVC-OR	0.63	0.56			0	0			0	0
SVC-CI	0.63	0.53			0	0			0	0
VCK	0	0.5	8	146	0	73			0	0
OPC	0.12	0.42			0	0			0	0
FNC	0.24	0.36			0	0	2	12	2.88	4.32
FNC-ES	0.48	0.68			0	0			0	0
RST-MR	0.59	0.6	2	39	23.01	23.4	6	150.4	88.736	90.24
RST-PR	0.7	0.57	4	59.5	41.65	33.915	5	207	144.9	117.99
RST-PT	0.67	0.6			0	0			0	0
RST-CI	0.67	0.6	3	56	37.52	33.6	15	259	173.53	155.4
DIS-NHAZ	0.67	0.5			0	0			0	0
DIS-HAZ	0.86	0.56			0	0			0	0
DET	0.14	0.53			0	0			0	0
SDI-NDT	0.35	0.46			0	0			0	0
GVI	0	0.47			0	0			0	0
Total			17	300.5	102.18	163.915	28	628.4	410.046	367.95

CHAPTER 5 ARTICLE 2: BOOK-CHAPTER: THE POTENTIAL INTEGRATION OF LEAN, GREEN, AND INDUSTRY X.0 TOOLS IN MORE SUSTAINABLE MAINTENANCE REPAIR AND OVERHAUL PRACTICES

Submitted to myTECHNIC MRO Technic Services - Aircraft Maintenance Handbook - AMH

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ABSTRACT: Aviation industry plays a vital role in sustainable development by connecting people, businesses, and communities worldwide. As of 2018, air transport accounted for 3.5% of total greenhouse gas (GHG) emissions, with projections indicating this figure could increase to 22% by 2050 if it remains unmitigated. In response, the industry has set an ambitious goal of achieving net-zero carbon emissions by 2050, focusing on a range of measures such as improving the operational efficiency of existing global fleet and adopting new technologies that reduce fuel consumption and emissions. Hence aircraft maintenance sector plays a pivotal role not only to maintain the aircraft airworthy for a safe, reliable, and on-time flight operation but also by contributing toward improving existing global fleet and keeping the pace in adapting to the new aircraft technologies. Moreover, aircraft direct maintenance costs (DMC) is estimated to be between 10-20 % of total Direct Operating Cost (DOC) which highlights the importance of maintenance processes cost effectiveness in airline profitability and economy.

This chapter explores the aircraft maintenance fundamentals, processes, and practices, uncovers the impacts and interplays between climate change and aircraft maintenance practices. It introduces a green aviation maintenance concept grounded in the Society 5.0 paradigm, which integrates lean and green methodologies with advanced Industry X.0 technologies to promote operational excellence geared by digitalization, automation, and other innovative solutions. Ultimately, this approach aligns with the broader objectives of sustainable aviation, contributing to reduce emissions, pollutions and more responsible use of resources all while maintaining operational excellence and ensuring high safety standards.

Keywords: Sustainability, Aviation maintenance, Industry 4.0, Society 5.0, Green practices, Lean maintenance.

5.1 Introduction

Aviation is one of the most dynamic and multi-faceted industries in the world, facing the challenge of reducing its environmental impact while meeting the growing demand for air transport and mobility services. Sustainability is a crucial issue for this industry, as it affects all stages of aircrafts life cycle, from design and production to operation and disposal. Maintenance sustainability is one of the key aspects that can contribute to improving the environmental performance of this industry, by optimizing the use of resources, minimizing waste generation, extending product life span, and enhancing operational efficiency. However, maintenance sustainability also faces many challenges and constraints that need to be overcome by adopting innovative technologies and practices, as well as by engaging with various stakeholders. Therefore, this chapter aims to propose a conceptual framework for green aviation maintenance in the society 5.0 paradigm, which integrates the human centered and social aspects to industry 4.0 context.

There are various drivers and challenges associated with sustainable maintenance. The aviation industry faces increasing pressure from regulators, customers, and stakeholders to reduce its greenhouse gas emissions and achieve net-zero targets. This is one of the main drivers of sustainable maintenance, as it motivates industry to adopt more eco-friendly practices and technologies. Moreover, the industry also recognizes the potential benefits of adopting sustainable practices, such as cost savings, improved reputation, enhanced innovation and competitiveness, and reduced risks and liabilities. Additionally, the industry has access to various technologies and solutions that can improve the sustainability of maintenance operations, such as fuel-efficient planes, sustainable aviation fuels, electric aircraft, waste management and recycling, and digital tools and platforms.

However, the industry also faces significant technical, operational, and financial barriers to implement sustainable maintenance practices. For instance, some of the challenges include high upfront costs, lack of infrastructure and standards, regulatory uncertainty and complexity, and market volatility. Furthermore, the industry also faces human factors and organizational challenges, such as skills gaps, resistance to change, communication issues, safety culture, and stakeholder engagement. These challenges can delay the adoption of sustainable maintenance practices. Lastly, the industry needs to balance the trade-offs and synergies between different

aspects of sustainability, such as environmental, social, and economic dimensions, as well as between short-term and long-term objectives.

Hence, sustainable maintenance is a vital and complex issue for the aviation industry, which requires a holistic and collaborative approach from all actors involved. By addressing the drivers and challenges of sustainable maintenance, the industry can achieve its environmental goals while maintaining its operational excellence.

- **Section 2** provides a literature review on the most relevant topics of sustainability in aviation industry, aviation maintenance, sustainability in maintenance practices, applications of lean in maintenance, industry 4.0 technology in maintenance, and society 5.0 and new paradigms. This section aims to identify the current state of the art, the gaps and challenges, and the opportunities and benefits of applying sustainable development methods in aviation maintenance operations.
- **Section 3** explores the global civil aviation growth outlook, implications, new emerging requirements, adaptation measures and the role of sustainability in air transport maintenance.
- **Section 4** explores the aircraft maintenance program development framework, delving into the intricacies and complexities of the aviation maintenance practices. It aims to uncover the significance of a well-developed and optimized maintenance program in promoting sustainability within the aviation industry.
- **Section 5** reviews the climate change relationship with sustainability in air transport maintenance sectors, aiming to uncover the interactions and implications and to better understand and navigate current and future needs and requirements.
- **Section 6** presents the conceptual framework for green aviation maintenance in society 5.0 paradigm, which consists of four main components: vision, goals, enablers, and outcomes. This section explains the rationale and logic behind the framework, as well as the interrelationships and interactions among the components. The framework is based on the principles of lean management, industry 4.0, and society 5.0, and it reflects the vision and aspiration of creating a more sustainable and human-centric aviation maintenance industry.
- **Section 7** discusses the applications of the conceptual framework in various scenarios and contexts, using case studies and practical examples from the industry. This section

demonstrates how the framework can be implemented and adapted to different situations and challenges, as well as how it can generate positive impacts and outcomes for industry and society. The section also highlights the best practices and lessons learned from the applications, as well as the potential barriers and risks that need to be addressed.

- **Section 8** concludes the chapter by summarizing the main points and contributions of the chapter, as well as providing some recommendations and suggestions for future research and practice. This section also discusses the limitations and implications of the chapter, as well as the future trends and directions for green aviation maintenance in society 5.0 paradigm.

5.2 Literature review

5.2.1 Sustainability in Aviation Industry

Bonser et al. [43] examined the challenges and opportunities for achieving sustainable development of the global aviation system. The authors concluded that the global aviation system requires strategic management, global communication proficiency, and technological expertise to address the environmental, economic, and social issues. The global system thinking, and the perspectives of the multiple stakeholders should be integrated to address the complexity and dynamics of sustainability.

Elhmoud and Kutty. [40] performed a review of the literature on various tools, models, and methods of sustainability assessment in the aviation industry. They discussed that Sustainability assessment can be conducted at different levels, such as the aircraft, the airline, the airport, the air traffic management, and the global aviation system, using different indicators, criteria, and metrics. In addition, various tools such as life cycle assessment, eco-efficiency analysis, multi-criteria decision analysis, and decision support systems been discussed and their application to measure, compare, and optimize the sustainability performance of the aviation industry been evaluated.

According to Stamoulis et al. [44], the current MRO practices are lagging the evolutions in aircraft design, materials, and production techniques, which require new knowledge and tools to optimize and integrate MRO operations with modern aircraft systems and components. The author discusses focal areas towards smarter and more sustainable MRO, such as adaptive, digital, and circular

MRO tools, data-driven MRO, and human factors and education in MRO and examples of ongoing and future research projects and collaborations in the field of Aviation MRO, as well as recommendations for policy makers, industry stakeholders and researchers.

Summary: These studies underscore the challenges and opportunities in aviation sustainability, stressing strategic management, global communication, and technological expertise. Utilizing sustainability assessment tools aids in effective decision-making. Recognizing sustainability's importance in aviation maintenance, MRO practices require adaptation to match aircraft advancements. Smarter, sustainable MRO entails digital tools, data-driven methods, and attention to human factors.

5.2.2 Environmental Sustainability in Aviation Industry

Afonso et al. [45] reviewed the most promising solutions for reducing the environmental impact of aviation, such as improving operational efficiency, using alternative energy sources, enhancing propulsion systems, optimizing aerodynamics, and developing new materials and structures. The authors also proposed potential synergies between the different technologies to achieve green aviation. They also mentioned some gaps in the current research, such as the lack of comprehensive life cycle assessments, the uncertainty of the future demand and regulations, and the need for more interdisciplinary collaboration. Hence, a holistic approach is required to address the complex and multidimensional challenges of sustainable aviation.

Chiaromonti. [46] discussed the challenges and opportunities of producing and using sustainable aviation fuels (SAFs) to reduce the greenhouse gas emissions of the aviation sector. The authors mentioned that SAFs are alternative fuels for aviation that can lower the environmental impact and increase the social and economic benefits of flying. They can be produced from renewable or waste sources and can cut the GHG emissions by up to 80%. However, they face many challenges, such as high costs, limited supply, and low awareness. Therefore, they need the support and cooperation of various actors to overcome the obstacles and achieve their potential.

Su-Ungkavatin et al. [47] compared four types of sustainable aviation fuels: biofuels, electro fuels, electric, and hydrogen. They evaluated them based on their life cycle assessment, techno-economic analysis, and social acceptance. A systemic and holistic approach that considers the trade-offs and synergies among the different options are required to find the optimum solutions. Upham et al. [48] explored the feasibility and desirability of achieving sustainable aviation. They examined the

environmental, economic, and social dimensions of aviation, as well as the technological and institutional barriers and opportunities. They discussed that sustainable aviation requires a radical transformation of the aviation system, involving both technological innovation and social change. Yusaf et al. [49] discussed hydrogen as the future of sustainable aviation. They reviewed the status and future prospects of hydrogen production, storage, distribution, and utilization for aviation. They highlighted the advantages of hydrogen over conventional and alternative fuels, such as its high energy density, low emissions, and renewable potential. Zhang, Butler, and Yang. [50] analyzed the recent trends, opportunities, and challenges of SAF. They discussed the environmental and economic benefits of SAF, as well as the technical and regulatory hurdles. They concluded that SAF can play a significant role in reducing the carbon footprint of aviation, but it requires more research, development, and support from stakeholders.

Summary: Several studies explore solutions for greener aviation, including operational efficiency, alternative energy sources, and sustainable aviation fuels. Challenges such as cost and supply limitations accompany these efforts, requiring interdisciplinary collaboration and stakeholder support. Hydrogen emerges as a promising option for sustainable aviation, with its high energy density and low emissions. Despite hurdles, sustainable aviation fuels hold potential in significantly reducing aviation's carbon footprint, pending further research and development.

5.2.3 Sustainability driven by operational excellence

Alansari, Ziadat et al. [51] discussed the improvement of the logistical functions of a corporation that provides aviation, maintenance, and logistics services. The authors use a mixed-methods approach that involves literature review, interviews, surveys, and data analysis. They concluded that the implementation of Enterprise Resource Planning Systems can enhance the efficiency of handling, transporting, and storing. In addition, the establishment of standardized operational procedures can ensure the quality and safety of the logistics, as well as reduce the environmental impact and operational costs. The authors applied the suggested framework in the case of PAL aerospace services.

Ayeni et al. [52], [53], [54] and Korchagin et al. [55] discussed the application of lean principles and practices to the aviation maintenance, repair, and overhaul (MRO) industry, which faces various challenges such as high costs, low margins, and intense competition. They concluded that

Lean could help the MRO industry to achieve competitive advantage by improving the operational efficiency, quality, and customer satisfaction of its services. It also needs a product and service-centric approach.

Demiral et al. [56] applied lean thinking to the aircraft maintenance system of a Turkish airline company. The author assessed the challenges of the maintenance operations including inefficient, costly, and prone to errors and delays, due to the lack of standardization, coordination, and communication among the maintenance processes and personnel. Hence, lean practices can help to identify and eliminate non-added value activities and enhance the reliability and sustainability of maintenance operations.

Baluch et al. [57] reviewed the literature on TPM and lean maintenance, which are two approaches to improve the efficiency and sustainability of manufacturing systems. The authors discussed that these two approaches are complementary and enhance the productivity and quality of manufacturing as well as reducing the waste. TPM approach is more preventive for reducing the failure rates, while lean approach focuses on optimizing the maintenance activities. Both approaches require the holistic method to integrate people, processes, and technology, along with ensuring alignment among these elements.

Bhuiyan et al. [58] presented a continuous improvement methodology to achieve world-class quality in products and processes of an aerospace company. The proposed framework included a systematic approach and various tools and techniques, such as value stream mapping, 5S, six sigma, lean production, and kaizen, to identify and eliminate waste, improve efficiency.

Ajukumar and Gandhi. [59] developed a method to evaluate the environmental impact of mechanical systems at the design stage, using a combination of life cycle assessment and analytic hierarchy process. The authors apply their method to a case study of a hydraulic press system and compare three alternative designs based on their green maintenance performance. The authors proposed an integrated approach for evaluating the green maintenance aspects at the design stage with identifying the maintenance objectives and criteria, selecting the appropriate maintenance strategies and techniques, assessing the environmental impacts of the maintenance activities, and optimizing the maintenance plan to minimize the environmental impacts and maximize the performance.

Ararsa et al. [60] conducted a review on green maintenance. They found that green maintenance is a relatively new concept that has not been well defined or explored in research. It contributes to sustainability by improving energy efficiency, resource utilization, waste management, and environmental performance of manufacturing systems. It also influences all three pillars of sustainability by reducing operational costs, reducing environmental impacts, and improving safety and quality. One of the challenges is considering the whole life cycle of the product from design to EoL. Therefore, there are different tools that can be used such as LCA, TQM, lean and asset management.

Jasiulewicz-Kaczmarek. [61] reviewed the literature on lean and green maintenance, which are two approaches to improve the efficiency and sustainability of manufacturing systems. These two approaches are Lean maintenance is based on the elimination of waste and non-value-added activities, while green maintenance is based on the reduction of environmental impact and resource consumption. Both approaches are required in a sustainable maintenance context.

Summary: These studies advocate for implementing Enterprise Resource Planning Systems to enhance efficiency and standardizing operational procedures to ensure quality, safety, and environmental responsibility. Lean principles offer competitive advantages by improving operational efficiency, quality, and customer satisfaction. Lean and Total Productive Maintenance (TPM) approaches complement each other, enhancing productivity and reducing waste. Green maintenance, a newer concept, focuses on sustainability by improving energy efficiency, waste management, and environmental performance. Hence, integrating lean and green maintenance practices is vital for sustainable maintenance in the aviation industry.

5.2.4 Sustainability in Aviation Supply Chain Management

Gopalakrishnan et al. [63] examined the British Aerospace Systems sustainability in its supply chain and proposes a framework for sustainable supply chain management.

Ramirez-Peña et al. [62] reviewed the current state of sustainability in the supply chain management of three transport sectors: aerospace, naval, and automotive. They examined the existing publications on how these sectors are adapting to the industry 4.0 technologies and practices, such as Lean, digitalization, and collaboration. According to the authors, green and lean are the main supply chain driving methodology in Aerospace. The main technologies among

Industry 4.0 technologies for this industry are additive manufacturing and then, blockchain and big data.

Summary: These studies are exploring the sustainability embedded supply chain initiatives, tools, and techniques aiming to integrate social, economic, and environmental dimensions across supply chains activities to drive higher operational efficiency while reducing socio- environmental impacts.

5.2.5 Sustainability driven by Technologies and Industry X.0

Cortés-Leal et al. [65] proposed a new framework for maintenance in smart manufacturing, called Maintenance 5.0. Maintenance 5.0 aims to improve the resilience of physical assets by leveraging human-machine interaction, artificial intelligence, and wireless sensor networks. It requires the collaboration between machines and operators. They also showed that the worker in the loop can enhance the resilience of the network by adjusting the parameters and repairing the faults.

Eschen et al. [66] explored the potential of using augmented and virtual reality (AR and VR) to support human workers in inspection and maintenance processes in the aviation industry. They concluded that this technology could improve the efficiency, quality, and safety of inspection and maintenance processes by providing real-time information, guidance, and feedback to the operators. It can also help in the learning and training process by enabling interactive and immersive scenarios and simulations. The application is also explained in inspecting aircraft components, repairing engines, training technicians, and collaborating with remote experts.

Ahmad et al. [67] have explored the capabilities of Blockchain technology as the aviation maintenance data platform that could offer transparency, enhanced security, and traceability over aircraft maintenance history. Attained data trust, and visibility could help different stakeholders to take informed decision-making. For e.g. it could enable the FAA to determine an aircraft airworthiness score based on aircraft maintenance logbook records that are trustworthy and immutable. However, the authors identified, limited transaction throughput and transaction fee as some significant challenges of existing Blockchain platforms, while in contrast, private blockchain platforms are fast, reliable, trustful, and capable of handling hundreds of transactions per second as an aviation maintenance platform would require. This technology will enable a more effective maintenance data platform for enhanced visibility, better parts, and components life cycle cost

trackability resulting to more informed decision across all aircraft maintenance stakeholders. This eventually could result in higher overall maintenance performance.

Peng et al. [68] have proposed the application of using Augmented reality (AR) with artificial intelligence (AI) technology as a smart system inspections and training framework to facilitate performing maintenance procedures effectively, also to reducing human error and learning curve for the new aircraft maintenance technicians. This study concluded the AI-AR interactive software as a low cost and highly efficient solution to the recent aviation equipment maintenance problems, caused by less experienced workers and high workload. The proposed AI-AR is a more sustainable solution that would help in reducing human errors learning curve for newly hired maintenance technician, also improve the maintenance tasks performance efficiencies by means of live and intuitive work instruction.

Summary: Technological advancements such as Maintenance 5.0, augmented reality (AR), virtual reality (VR), and blockchain are among significant sustainability drivers in aviation maintenance. These innovations improve resilience, efficiency, and safety by enhancing human-machine interaction, providing real-time information and guidance, ensuring transparency and traceability in maintenance data, and reducing human error through AI-driven smart systems. Sustainability-driven technologies empower aviation maintenance with enhanced performance, reduced costs, and improved decision-making, shaping the future of Industry X.0 in the aviation sector.

All in all, in the aviation industry, factors such as safety, reliability, cost, environmental impact, and asset longevity are apparent priorities. However, beneath the surface there are many intricacies, hidden layers, and various stakeholders. Given the industry's competitiveness, stringent safety regulations, and complex maintenance programs, ensuring efficient and sustainable maintenance management is essential not only for survival but also for maintaining a competitive edge. Therefore, one sector that stands to benefit from the integration of green maintenance practices and industry 4.0 techniques is the aviation maintenance, repair, and overhaul (MRO) industry. This sector faces challenges such as high expenses, narrow profit margins, and fierce competition. The MRO industry can use green maintenance tools and techniques, such as life cycle assessment, total productive maintenance, lean and green production, asset management, and remanufacturing, to identify and eliminate waste, improve efficiency, and enhance quality in its services. The MRO

industry can also use Industry 4.0 technologies, such as augmented and virtual reality, cognitive cyber-physical systems, and internet of everything, to provide real-time information, guidance, and feedback to the workers, and to enable interactive and immersive scenarios and simulations for learning and training. By combining green maintenance and Industry 4.0, the MRO industry can achieve a higher level of sustainability and competitiveness and provide better customer satisfaction and loyalty.

5.3 Global Civil Aviation Growth perspective

The demand for air transportation is exceeding the pace of economic growth. According to the Airbus Global Market Forecast 2023, the outlook for air transport indicates an annual passenger traffic growth of 3.6% and a 3.2% increase in freight traffic [4]. This projection closely aligns with the Boeing Commercial Market Outlook [5], which also anticipates a 3.5% annual growth over the next two decades. As the demand for air travel steadily increases, aviation decarbonization will be crucial to achieving the 2050 carbon-neutral goal. In 2018, air transport direct emission was estimated at 3.5 % of global GHG emission, and if aviation were unmitigated, air transport emission could account for 22% of global GHG emission by 2050 [71]. Both major aircraft manufacturers' growth forecasts project the delivery of 42,000 new aircraft by 2042, details shown in Figures 4-1 and 5-2. These new deliveries with latest generations of technologies are aimed at enhancing fuel efficiency and reducing the environmental footprint. Consequently, this creates a substantial demand for the aviation maintenance sector to swiftly adapt to these new technologies and

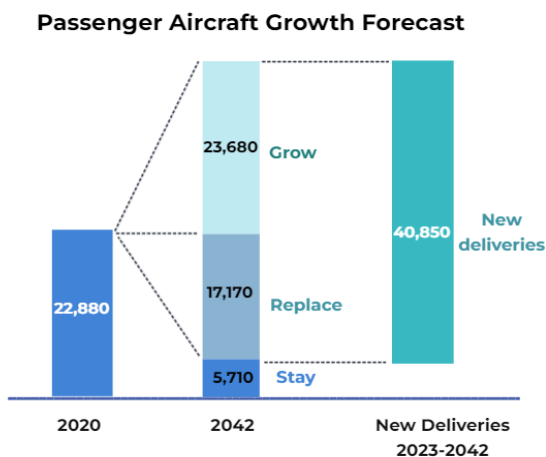


Figure 5-1: Passenger aircraft Outlook

Airbus GMF 2023

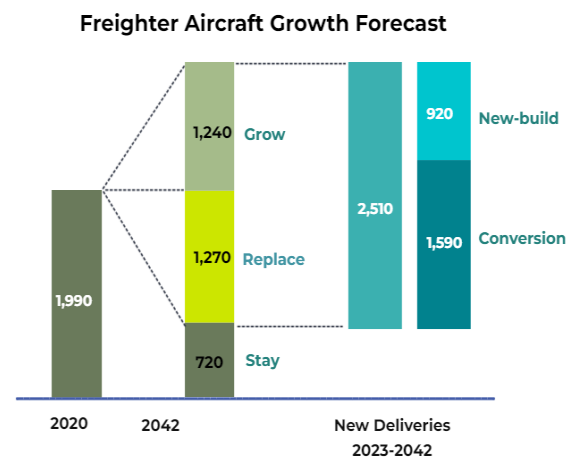


Figure 5-2: Freighter aircraft Outlook

Airbus GMF 2023

efficiently scale up to ensure the safety, reliability, and seamless operation during upcoming transitions and technological advancements.

5.3.1 The Evolution of Sustainability Concept within the aviation industry

To understand the concept of sustainability, it is often necessary to refer to the extended definition of a sustainable development which it was published in the Brundtland Report in 1987, known as "Our Common Future," by the World Commission on Environment and Development (WCED) as a development that “meets the needs of the present generation without compromising the ability of future generations to meet their own needs.” The term “Sustainable development” was originally defined in the 1980 World Conservation Strategy by the International Union for Conservation of Nature (IUCN) as described that “for development to be sustainable it must take account of social and ecological factors, as well as economic ones.” [95] . In brief sustainable development aims to achieve a harmony among economic, environmental, and social aspects of a business, often referred to sustainability pillars as depicted in Figure 5-3. In aviation sector, safety stands as an additional fundamental pillar, mandating obligatory standards alongside traditional sustainability dimensions. This involves specific safety standards to guarantee that aircraft operations are conducted in full compliance with safety measures to prevent accidents, injuries, or damages.



Figure 5-3:Sustainability pillars in aviation

5.3.2 Sustainability in aviation maintenance sector

Aircraft maintenance is defined as the set of necessary actions required for restoring or maintaining an aircraft system's, subsystem's, or component's function in a serviceable condition, including inspection, repair, modification, and overhaul, in a way to ensure no harm to the environment and people while being economically efficient [12]. Aircraft maintenance holds a pivotal role in airline

operations as it is vital for passenger safety and on-time performance (OTP) of airline. It is imperative to prevent unexpected failures that could potentially result in safety incidents at all costs. Aircraft maintenance encompasses various activities aimed at retaining and restoring an item to a functional state, including servicing, repairing, modifying, overhauling, inspecting, and assessing its condition. The primary objective of maintenance is to deliver an aircraft that is fully operational when needed by the airline, while also minimizing costs [96]. For most aircraft 50-70% of the total Life Cycle Cost (LCC) is spent during the 25 years of operation and maintenance phase. In this competitive Civil air transport market, maintaining low Direct Operating Costs (DOC) plays a crucial role in enhancing airline profitability and competitiveness. Based on the figures provided by airline companies, maintenance expenses constitute between 10% - 20% of the total aircraft-related DOC [29]. This percentage can vary depending on factors such as fleet size, aircraft age, and utilization. All these proves aircraft maintenance as a vital function in airline operational performance not only economically but also environmentally and socially.

5.3.3 Aircraft maintenance sustainability objectives

In the air transport industry, the objectives of maintenance are to provide safe, reliable, and airworthy aircraft with high availability for daily scheduled operations. However, the expense associated with aircraft maintenance significantly impacts the overall costs incurred by aircraft operators [97]. Considering the industry is facing severe competition, there are limited choices available to reduce an airline's direct operating costs (DOC) because key expenses like fuel, taxes, and mandatory fees for landing or air traffic control cannot be negotiated. However, the airline can potentially negotiate its direct maintenance costs (DMCs), which could significantly contribute to lowering its DOC as a key to airline profitability and competitiveness [1]. It is noticeable that, the air transport sector is in charge of 3.6% of the global GHG emission [78]. However, aircraft and more specifically engine maintenance have great impact on fuel consumption and GHG emissions. It was estimated that an optimization on engine performance recovery by compressor washing could reduce 2735 t of the fuel consumption which could prevent 8626 t GHG emission per 100 units of CFM-56 engine type per year [98]. In conclusion, given the continuous expansion of air travel and Civil Aviation long-term aspirational goal (LTAG) toward net-zero carbon emissions by 2050, it is crucial to prioritize the development of sustainable aircraft maintenance program. This

will ensure that air transportation remains safe, reliable, affordable, and environmentally friendly. Figure 5-4, illustrates the aircraft maintenance sustainability objectives.



Figure 5-4: Sustainable Aircraft Maintenance Objectives (Source: Author)

5.4 Aircraft Maintenance Program (AMP) Development Practices

5.4.1 Maintenance Approaches

Aircraft maintenance practices are typically based on two fundamental approaches:

1- Process-Oriented approach: It involves three main maintenance processes to conduct scheduled maintenance tasks. These processes are referred to as hard-time (HT), on-condition (OC), and condition monitoring (CM).

- **Hard -Time:** It is a preventive process where a component is taken out of service or undergoes overhaul at pre-determined intervals specified in flight hours, flight cycles, calendar time or operating hours.
- **On-Condition:** A preventive maintenance process under which a part undergoes periodical inspections, measurements or tests against pre-defined standards or acceptance criteria to determine its continued serviceability.

- **Condition-Monitoring:** Unlike HT and OC, it is not a preventive process, instead, it involves continuously analyzing data collected from relevant measurements to detect any issues and apply corrective actions as needed. It applies to a part whose failure does not directly impact safety or exhibit a decline in reliability due to aging [96],[12]. All three maintenance processes along with examples of applications are provided in Table 5-1.

Table 5-1: Process Oriented Maintenance

Maintenance Process	Method	Requirement	Interval	Action	Application
Hard-Time (HT)	Preventive	Condition check not possible & Safety critical parts	Flight Hour Flight Cycle Calendar Limits	Replace Restore Overhaul	Engine Life-limited parts replacement / Landing gear Overhaul
On-Condition (OC)	Preventive	Condition measurement is feasible	Frequent Inspection/ Check against physical Limits	Inspect to verify the parts failure resistance until next OC /or to replace	Brake /Tire wear measurement by indicator pins
Condition-Monitoring (CM)	Corrective	Parts with no adverse effect on Safety /The CM item must not have any hidden function	Data analysis / Trend monitoring	To track the failure rate/removals/trend shifts/ Performance parameters changes	components or systems that do not have a definite lifetime or a noticeable wear-out period

2-Task-Oriented approach: This technique is a Top-Down failure's consequence analysis approach, which is analyzing the failure of highest functioning level of the systems rather than focusing on components level. Some generic maintenance tasks could be listed as Inspection (IN), Lubrication (LU), Servicing (SV), Visual Check (VC), Operational Check (OPC), Functional Check (FNC), Restoration (RST), and Discard (DIS). These generic maintenance tasks description along with some examples are shown in Table 5-2.

Table 5-2: MSG-3 Airframe Systems maintenance tasks [82],[83]

Task	Description	Frequency	Reference
Inspection-IN	Detailed examination of aircraft or components to ensure they meet safety and operational standards	Pre-flight, post-flight, and during scheduled maintenance	MPD, AMM, CMM
Lubrication-LU	Application of lubricants to moving parts like gears, bearings, and pulleys	As manufacturers instruction or inspection findings	AMM, CMM, Lubrication chart
Servicing-SV	Routine tasks to maintain aircraft readiness, such as replenishing fluids	Pre-flight, after certain FH or FC	AMM, CMM,
Visual Check -VC	An observation to capture the apparent failures/defects aimed to determine the overall integrity	Pre and post flight	Check list, AMM
Operational Check- OPC	Verifying the proper function of aircraft systems under operational conditions	Pre-flight, after maintenance or repairs	AMM, Flight Manual
Functional Check-FNC	A detailed and quantitative examination of specific components or systems to verify their functional integrity by use of test equipment	After maintenance actions, at designated intervals	AMM, CMM
Restoration-RST	Repairing or refurbishing parts to restore them to a specific standard	As needed, based on inspection or failure	AMM, CMM, SRM
Discard-DIS	Removal and replacement of components that are no longer serviceable	As determined by inspection, life limit, or failure	AMM, CMM

5.4.2 AMP Development Methodology

In practice a significant percentage of an aircraft's Life Cycle Cost (LCC) during its operation phase also its availability performance is the result of decisions were made during initial AM program development [1]. This proves the significance of an aircraft initial maintenance program development not only from safety and airworthiness but also its economical impact. Civil Aviation industry is widely adopting the Air Transportation Association's (ATAs) Maintenance Steering Group 3rd Task Force (MSG-3) logic as the only approved process by Federal Aviation

Administration (FAA) for aircraft maintenance program development. MSG-3 is a task-oriented methodology developed to derive scheduled maintenance requirements. It focuses on the consequences of failure of aircraft systems, aiming to identify critical components that require specific maintenance needs [96]. It provides a standardized format for analysis and determination of scheduled maintenance tasks to prevent functional failures and uphold the inherent level of system reliability.

In the context of MSG-3 logic, functional failures' consequences are identified and categorized as "SAFETY" and "ECONOMIC" whereas functional failures with SAFETY related consequence are analyzed and addressed with a conservative and thorough level of maintenance tasks, while NON-SAFETY (ECONOMICAL) failures consequence might be addressed with different maintenance options that are potentially less cost intensive.

The key point in MSG-3 as being a task-oriented methodology, is to avoid blind and intensive preventive maintenance and instead to focus on how to retain aircraft systems functionality, and objectively define and assign appropriate maintenance tasks as barriers against the potential functional failures [96].

MSG-3 objectives to develop a maintenance program are as following [1, 26]:

- To maintain the inherent safety and reliability levels of the aircraft.
- To restore safety and reliability to their inherent levels when deterioration has occurred.
- To obtain the information necessary for design improvement of those items whose inherent reliability proves to be inadequate.
- To achieve these goals at a minimum cost, including maintenance costs and residual failures.

As aircraft operators accumulate more operational experience, they may choose to make additional adjustments to uphold an efficient maintenance schedule. (ATA MSG-3, 2007). This ongoing effort to optimize maintenance tasks and schedules is aimed at enhancing safety, reliability, availability, and reducing unnecessary maintenance costs. The MSG-3 framework prescribes categorical tasks for the aircraft's Systems, Structures and Zonal.

MSG-3 Logic Tasks assigned for Airframe Systems

According to the MSG-3 method, there are eight maintenance tasks established for airframe systems. These tasks are allocated based on the outcomes of decision analysis and the particular needs of the system and its components and are as the following: Lubrication, Servicing, Inspection, Functional checks, Operational check, Visual check, Restoration, Discard.

MSG-3 Tasks assigned for Aircraft Structures

The MSG-3 process prescribes structural inspection techniques into three distinct types [12]:

- **General visual inspection (GVI):** A visual check to realise evident defects and discrepancies, might need door, panel removal for access.
- **Detailed inspection (DET):** A through visual inspection of a specific part, component, or installation, aiming to detect any sign of unconformity; it might need proper surface cleaning, lighting, mirror, and magnifiers.
- **Special detailed inspection (SDI):** A thorough inspection of a particular area, resemble to a detailed examination but with using specialized tools and techniques. For e.g. it might require a non-destructive testing (NDT) such as Ultrasonic test (UT), High frequency eddy current (HFEC), etc.

MSG-3 Tasks assigned for Zonal

The zonal maintenance program ensures the surveillance and condition of systems and components within specified zones on an aircraft. Zonal maintenance and inspection techniques are conducted in two distinct categories, as outlined in the following:

- General visual inspection.
- Detailed visual inspection.

Maintenance Review Board Report (MRBR)

The Maintenance Review Board (MRB) process involves collaboration between manufacturers, regulatory bodies, vendors, operators, and industry experts to develop the initial maintenance and inspection schedules for a new aircraft or/and on-wing powerplants [34]. The maintenance tasks

selected through the MSG-3 process by MRB are documented and made available by the aircraft manufacturer in an FAA-approved report known as the Maintenance Review Board Report (MRBR). Operators utilize the MRBR to create maintenance programs approved by the FAA, aligning with their specific operations specifications. (Kinnison and Siddiqui)

Airworthiness

Based on ICAO Annex 8 “The status of an aircraft, engine, propeller or part when it conforms to its approved design and is in a condition for safe operation”[99].

Airworthiness Limitation Section (ALS)

It is an airworthiness repository, used for the development of the initial maintenance requirement of an aircraft. It includes a set of individually approved airworthiness documents derived from design data as follows [1] :

- Safe Life Airworthiness Limitation Items (the Life Limited Parts document)-For structure
- Damage Tolerant Airworthiness Limitation Items (the ALI document) -For Structure
- The Certification Maintenance Requirements (CMR) document -For systems
- The Ageing Systems Maintenance (ASM) document -For systems
- The Fuel Airworthiness Limitations (FAL) document – For systems

5.4.3 Maintenance Planning Document (MPD)

As the result of MSG-3 framework, MRBR is developed which it includes the initial maintenance program for a new model aircraft. Aircraft manufacturers are using MRBR and ALS documents together to develop and publish their own maintenance planning document (MPD) per each aircraft type [1, 12]. The MPD document is intended to be the basis of aircraft maintenance planning. It groups and schedule the tasks often by flight hours (FH), Flight cycles (FC), Calendar time, and by Letter checks.

5.4.4 Air carrier approved maintenance program document (AMPD)

As mentioned earlier, the selected choices for initial scheduled maintenance development, could significantly affect the aircraft availability performance and its life cycle cost, therefore its imperative to continuously review and explore the avenues for maintenance program optimization aiming to improve the program effectiveness and tasks efficiencies [1]. This is the basis for the air carriers to customize their own maintenance program based on their operating conditions, utilization, local and regional authorities and designated operational targets. Figure 5-5 presents the AMPD development process mapping.

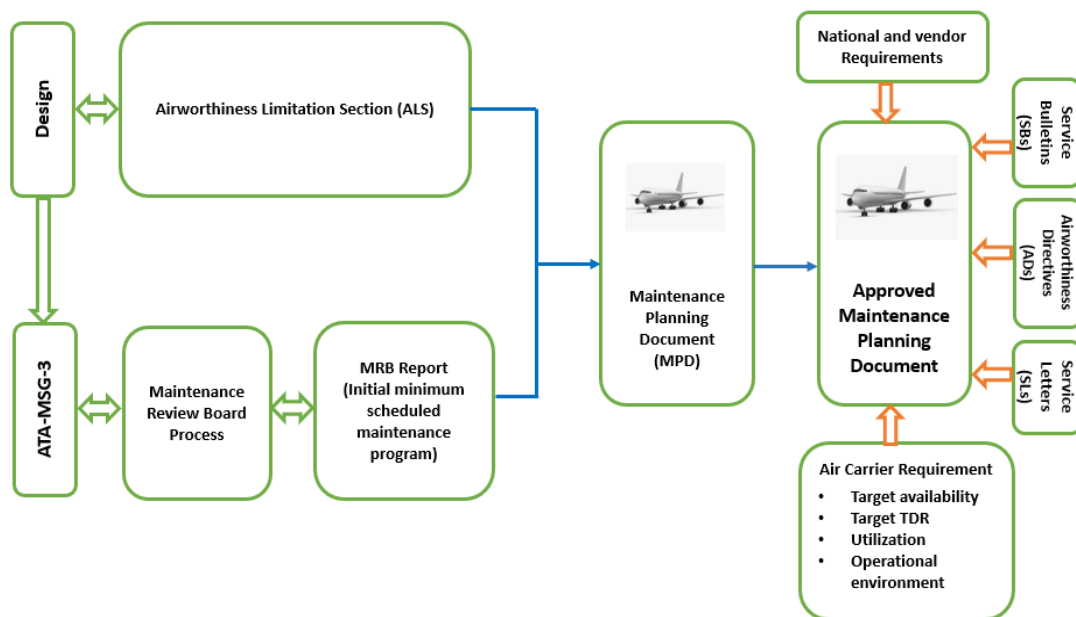


Figure 5-5: Aircraft maintenance program development (Adapted from [1])

5.4.5 Maintenance Interval

The maintenance schedule for aircraft is determined through collaboration between the aircraft manufacturer and the airline operator. Standard maintenance checks are defined in the MSG-3 process, but airlines can establish their own intervals as long as they could maintain the integrity of original maintenance program or obtain FAA deviation approval. The airline operators under FAA regulatory, have to establish a Continuous Airworthiness Maintenance Program (CAMP) adapted to their operational profile [12]. The CAMP program defines the routine and detailed

inspections events that are known by operators and airworthiness bodies as “checks”. Aircraft maintenance checks are typically scheduled based on Flight hours (FH), which it stands for flying hours of an aircraft, or Flight cycles (FC), which it means the number of a landing cycle of an aircraft or based on calendar time. There are different basis checks, but most common ones are as following:

- **Daily checks:** It includes some simple yet critical tasks such as engine oil levels, other fluid levels, brakes, and tires inspection. Extended range twin engine operations (ETOPS) type aircraft also have a pre-departure service check that its in included in their daily checks.
- **Flight hours limit checks:** according to MSG-3 analysis, certain tasks are driven by the flight hours that a component or a system been operated. for e.g. 300, 550 hours.
- **Flight cycle limit checks:** some other tasks are scheduled based on numbers of aircraft landing cycles. this applies to those units been operated or /and been under stress mostly during takes offs and landings; for e.g. landing gears, and engines hot section components.
- **Letter checks;** Under initial version of MSG-3 framework, most of aircrafts maintenance programs had various checks nominated by letters A, B, C, D. However, nowadays letter checks like B and D are eliminated and instead their task either incorporated into service checks or re-assigned based on flight hours or cycles into A and C checks. This change was derived toward optimization on maintenance program by assigning the tasks on their most appropriate time and reducing overall down time. Moreover, it makes the program more flexible for the operators to adapt their maintenance checks based on their operating profile.

Note: An example of aircraft maintenance checks was presented in literature review at Table 2-2.

5.4.6 Aircraft Maintenance Strategies

In aviation, reliability centered maintenance (RCM) is the principal framework employed to determine the essential scheduled preventive maintenance tasks through the MSG-3 logic, required to achieve the inherent reliability and safety of equipment while minimizing the expenses [1]. As a typical aircraft maintenance check shown in Table 2-2, there are multiple block checks with different time interval and work package that are governed by the aircraft maintenance program (AMP), in which Airlines, depending on their fleet size, network, and business strategies, undertake

their maintenance checks through various approaches. The choice of in-house or outsource aircrafts maintenance strategies is a multi dimensional decision that is depending on Aircraft operator fleet size, capacity, core business, and growth vision [97]. According to industry practices heavy checks' options are as following:

- **In-house or Subsidiary;** Large airlines often handle their maintenance internally or through a subsidiary. They might also extend their services to other carriers.
- **Independent Providers;** Independent maintenance companies, unrelated to airlines or aircraft manufacturers, specialize in providing maintenance services.
- **Joint Ventures;** Some maintenance providers are established in collaboration with aircraft or engine manufacturers, often in different countries, to leverage local cost advantages and technical expertise.
- **Manufacturers (OEM);** Aircraft and engine manufacturers offer maintenance services to airlines for their own products.

There are numbers of qualitative and quantitative research studies exploring and assessing various cost models and how they affect airline operations in both short and long terms. However, there is no unique strategy to drive best cost-effective result for every aircraft operator in the same way, but following are some noticeable research findings:

- Advancements in technology are making aircraft maintenance quicker and more efficient. This may result to a transition of some tasks from prolonged ground checks (C and D) to line maintenance (A and B), improving fleet utilization [29].
- A mix of in-house and outsourced maintenance checks is advised.
- High-cost heavy checks (D) should be outsourced, while less costly ones can be handled in-house.
- The aircrafts require more expensive checks as they age. The cost of in-house heavy maintenance checks grows faster than outsourced for older aircraft [97].

5.4.7 Aircraft maintenance sustainability foundation

As previously highlighted, a significant portion of an aircraft's LCC and its availability and reliability performance stems from its maintenance program. This underscores the pivotal role of

an aircraft's maintenance program not only in ensuring safety, airworthiness, and regulatory compliance but also in its economic, social, and environmental implications. In fact, the key objective in a sustainable AMP is to maintain safe, reliable aircraft for air transport operations while avoiding blind and intensive unnecessary maintenance tasks and instead focusing on how to retain aircraft systems functionality, and objectively planning and implementing necessary tasks at their most appropriate time. By emphasizing on effective task scheduling, and continuous performance tracking and program optimization, a well-developed maintenance program serves as the cornerstone and foundation of a sustainable aircraft maintenance management. It drives operational efficiency, reducing environmental impact, and contributes to air carriers' punctuality and reputations and overall competitiveness.

5.4.8 Maintenance Sustainability attained by Collaboration

Addressing challenges in Aircraft Maintenance (AM) are often complex, requiring a multidisciplinary approach and substantial research efforts. However, AM organizations have resource constraints in both personnel and expertise. To this end, forming strategic partnerships between academia and AM organizations to address the industry challenges by providing innovative solutions can create significant value for both parties. A clear definition of problem context, translated to a precise research agenda that results to an innovative solution could significantly contribute to sustainability and competitiveness of the business. Here are only a few examples of pressing challenges in the airline maintenance context that require effective, research-driven solutions:

1. Optimization of Line-Maintenance (LM) planning and resource allocation.
2. Spare part management - Acquisition and Allotment optimization.
3. Engine and major components Remaining Useful Life (RUL) prediction.
4. Implementation of green supply chain and reverse logistics to optimize sourcing, minimize unnecessary shipment cost and emissions, and maximize value of unserviceable parts.

5.5 Climate change and Sustainability in Aircraft Maintenance sector

Climate change is closely linked to sustainability in aviation sector and intersects with the air transport industry in two significant ways. In one hand, there is a growing regulatory requirement

for the aviation sector to decrease its Greenhouse Gas (GHG) emissions in order to mitigate its environmental impact. In the other hand, climate change leads to more frequent and extreme weather conditions, which have substantial effects on air transport operations, Necessitating the implementation of specific adaptation measures. While climate change is indeed a global phenomenon, it manifests with varying regional severity and implications [100]. Therefore, it necessitates a 'Glocal vision' that aligns 'global objectives' with 'local strategies and policies.' As a result, maintenance policies, inspections and service checks must align with regional climatic challenges to effectively adapt to these climatic risks, guarantee safe air transport operation, and uphold control measures.

Therefore, Climate change implications on Aviation maintenance could be categorized in two groups: Transitional impacts, and Physical impacts.

Transitional impacts) The impacts associated with climate change “mitigation efforts” toward environmental emission reduction, governed by global or and regional regulators. Figure 7 shows the global aviation decarbonization path set forth by ICAO. As shown black graph represents the CO₂ emission which is proportional with industry growth forecast which if it remains unmitigated it will account for 22 % of global GHG by 2050, and the green graph is the aspirational path toward 2050 net zero carbon set forth by aviation industry key players, through four major GHG emission mitigation options. It is noticeable that, three of those mitigations such as: technological improvement, operational improvements, and Sustainable Aviation Fuel (SAF) have significant impact on aviation maintenance sector. For e.g. utilization of SAF in legacy engines requires maintenance procedures to be adapted to accommodate the use of SAF. This includes changes in inspections, maintenance intervals, tools, technics, and troubleshooting protocols to address any potential challenges associated with SAF use or new aircraft technologies will require maintenance industry to swiftly adapt toward new technological shifts to be capable and compliant with new requirements.

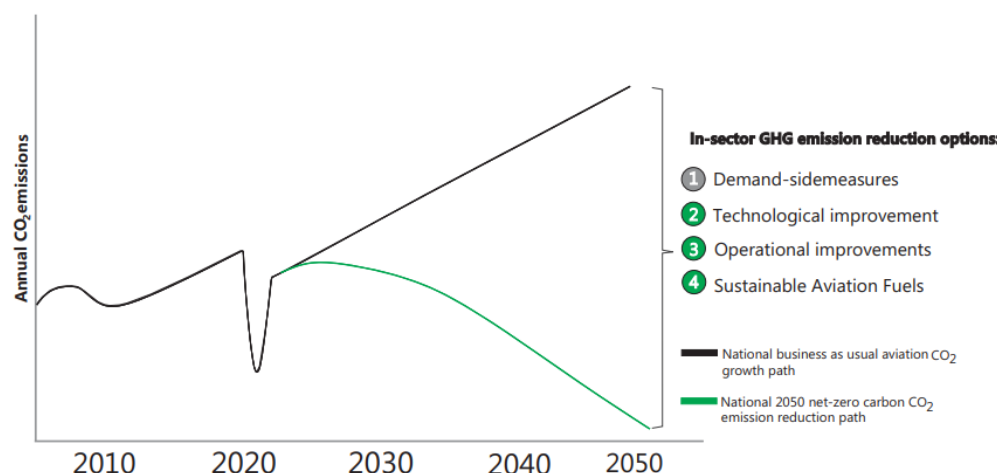


Figure 5-6: Aviation Decarbonization path - World Bank SAF Report [2]

Physical impacts) The climatic risks that requires maintenance “adaptation measures” to ensure safe and reliable air transport operations. Figure 5-3 is a brief summary of the most prevalent climatic risks versus existing maintenance practices and some recommended maintenance adaptation measures.

Table 5-3: Sustainable Maintenance Practices Vs Climate Change

Cause	Effect	Maintenance Measures	
Environmental Deterioration	Impact on Aircraft	Existing Measures	Sustainable Adaptation Measures
Lightening strike	AC Fuselage Arcing, structural damage	Structural General Visual Inspection, and repair	Full fuselage high resolution Drone scanning and anomaly detection (Powered by AI) / Lightening Strike protection system upgrade
Hurricane & Turbulence	Strong wind shear, structural or and surface control damage	Structural General Visual Inspection	Flight surface detailed Inspection / Full Fuselage high resolution scanning and anomaly detection (Powered by AI)
Hail damage	Aircraft surface & Flight deck windshields damages / Engine damage (if ingested)	Structural /Engine General Visual Inspection and repairs	Full Fuselage high resolution scanning and anomaly detection (Powered by AI)

Table 5-4: Sustainable Maintenance Practices Vs Climate Change (Continued and End)

Cause	Effect	Maintenance Measures	
Environmental Deterioration	Impact on Aircraft	Existing Measures	Sustainable Adaptation Measures
Flood	Engines & Landing gear damage (if water ingested during take off and landing)	Engine Borescope Inspection & Landing Gear Cleaning, and Lubrication	Additional checks for parked Aircraft & Intensive lubrication and restoration tasks/ Landing Gears' reduced overhaul interval
Icing	Flight control surface /Instruments /landing gear Ice blockage and malfunction/ damage	De-icing	More frequent de-icing, Flight control surface checks
Extreme High Temperature	Limiting engines performance /High EGT	Engine Inspection (Borescope)	Engine performance tracking & Compressor washing / Engine reduced Overhaul interval
Extreme Low Temperature	Fuel and hydraulic line freezing and thickening/ Batteries poor performance which could impact on avionics, /Sensor's ice blockage /Engine performance drop	Winterization procedure /flight surface and sensors de-icing and functional checks	More Frequent and detailed checks to verify affected system functional integrity
Dust	Limiting engines performance /High EGT/Engine fouling /Foreign Object damage (FOD)	Engine internal inspection (Borescope inspection)	Engine performance tracking & compressor washing Optimization / Engine reduced overhaul interval

5.6 Investigating Sustainable AM in Society 5.0 paradigm

Figure 5-7 presents a concept for implementing sustainable maintenance within the context of Society 5.0. To explore this framework, it is essential to identify its building blocks. At its core, the framework is built on four key pillars of aircraft maintenance: inspection, repair, overhaul, and preventive maintenance policies. These pillars are situated within a triangular relationship involving knowledge, standards/guidelines, and governance, as depicted in Figures 5–7, 5-8, 5-9. The interplay between compliance with standards, knowledge and expertise, and policymaking is critical for ensuring the sustainability of aviation maintenance.

At the top of the framework, three essential components are integrated: human-centered operations, value creation through sustainability, and social implications and acceptability. These elements represent the core paradigms for the future of air mobility.

Within the evolving Industry 5.0 paradigm, the inclusion of social implications, stakeholder engagement, and human involvement is critical. In aviation maintenance, this approach enhances safety, efficiency, quality, and compliance by ensuring that maintenance tasks, tools, and procedures are user-friendly, effective, and reliable. Value creation through sustainability seeks to minimize environmental impact and maximize the social benefits of maintenance activities by optimizing resource use, reducing waste and emissions, and extending the lifespan of aircraft and components. Social acceptability, as a factor influencing public and regulatory perceptions, plays a vital role in building trust, improving the industry's image, and ensuring adherence to ethical and legal standards.

By integrating these three aspects—human-centered operations, sustainability-driven value creation, and social acceptability—aviation maintenance can create a dynamic, value-added ecosystem aligned with the environmental, social, and economic objectives of both the industry and society.

Achieving this requires leveraging relevant and applicable knowledge, standards, guidelines, and governance in critical maintenance activities, such as inspection, repair, overhaul, and maintenance policies.

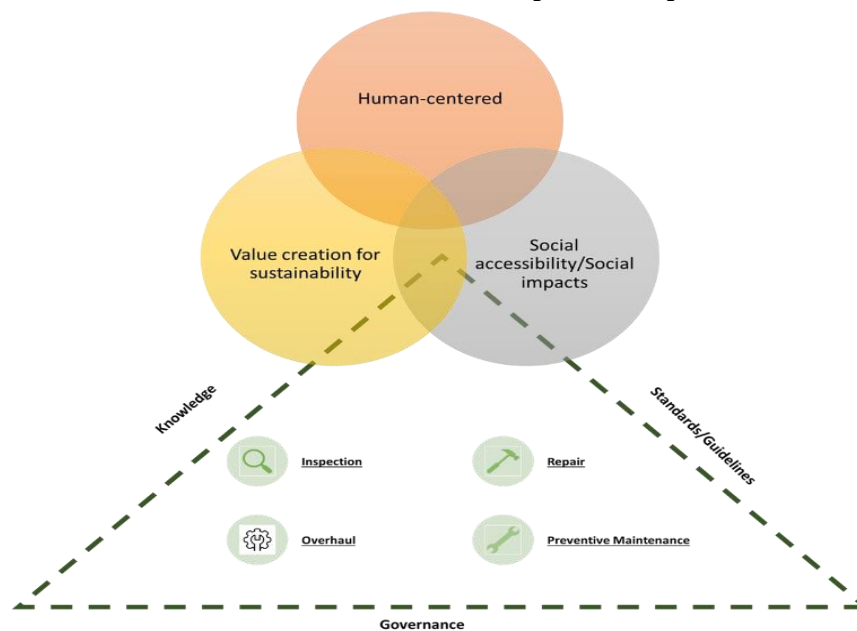


Figure 5-7: Four essential building blocks of aviation maintenance (Source: Author)

<u>Knowledge</u> This refers to the understanding of the technical, regulatory, and operational facets of aircraft maintenance. It involves the ability to perform maintenance tasks, use appropriate tools and technics, follow manufacturer's instructions and industry best practices, and being compliant with applicable laws and regulations.		
Example 1 Aircraft Maintenance Manual It's a document that provides detailed information on how to maintain, repair, and troubleshoot an aircraft .	Example 2 Component Maintenance Manual Provides detailed procedure for conponnets inspection, repair , overhaul , ensuring safety , compliance and relaibility	Example 3 Aircraft Maintenance Engineer License This is a certificate that authorizes a person to perform maintenance on aircraft or aircraft components

Figure 5-8: Knowledge in AM with examples

<u>Standards/Guidelines</u> These are the criteria or specifications that define the acceptable level of quality, performance, or safety for aircraft maintenance. They are usually based on the recommendations of the aircraft manufacturer, the civil aviation authority, or the industry best practices. They help to ensure consistency, reliability, and compliance in the maintenance processes.		
Example 1 Maintenance Control Manual Checklist; This is a document that helps an Approved Maintenance Organization to systematically review and verify its adherence to established procedures, standards, and regulations throughout the aircraft maintenance process.	Example 2 FAA (Federal Aviation Administration) Advisory Circulars (ACs); The FAA issues advisory circulars that provide guidance and best practices on various aspects of aircraft maintenance, such as inspection procedures, repair techniques, and maintenance program development. For e.g., AC 43.13-1B provides guidelines for aircraft inspection and repair.	Example 3 EASA (European Aviation Safety Agency) Part-M; Part-M sets out requirements for the continuing airworthiness management of aircraft and related components in the European Union. It includes standards for maintenance programs, maintenance planning, and maintenance organization approvals.

Figure 5-9: Standards/ Guidelines in AM with examples

<u>Governance</u> This refers to the system or structure outlining roles, responsibilities, and relationships of the stakeholders involved in the aviation maintenance industry. It includes the policies, processes, and mechanisms that ensure accountability, transparency, and effectiveness in the management and oversight of the maintenance activities. It also involves the alignment of the objectives and interests of the stakeholders with the public interest and the environmental sustainability.		
Example 1 Corporate Governance; This is a set of principles and strategies that guide the direction and performance of an aviation maintenance enterprise.	Example 2 National Governance; This is the set of rules and guidelines that regulate the aviation maintenance industry at the national level among different stakeholders such as manufactures, Airlines,Airports, MROs, etc.	Example 3 International Governance; This refer to global aviation rules ,standards and recommeded practices set forth by International organizations like (ICAO) to ensure harmonized governance among member states and across the industry.

Figure 5-10:Governance in AM with examples

To implement the proposed approach, various tools from Sustainability, Lean management, Total Quality Management (TQM), and Industry 4.0 are essential. These tools facilitate the adoption of sustainability practices, expedite their execution, and enhance and maintain more sustainable outcomes. It is crucial to acknowledge that sustainable aviation maintenance relies on a combination of tools, integrated methodologies, and diverse expertise.

As illustrated in Figure 5-11, Green tools provide strategies for monitoring and reducing material usage, energy consumption, and emissions. Lean management focuses on eliminating waste and prioritizing high-value activities.

TQM, grounded in continuous improvement and the Plan-Do-Check-Act (PDCA) cycle, supports the implementation of standards and best practices. Industry 4.0, with its integration of digital and physical systems, leverages technologies such as the Internet of Things (IoT), big data, advanced analytics, augmented reality, additive manufacturing, and predictive maintenance to enhance maintenance capabilities, performance, and innovation.



Figure 5-11: Multidisciplinary Toolbox (Source: Author)

Table 5-4 shows a brief definition of each tool, the applications in aviation maintenance and the opportunities and challenges of its applications.

Table 5-5: Green Tools

Tool	Application	Opportunities and Challenges
Life Cycle Analysis	A method to quantify the environmental impacts of aircraft and their components throughout their entire life cycle. It can help to identify hotspots, trade-offs, Potential improvement for reducing emissions, pollution and resource consumption	Data availability and quality, uncertainty and variability, system boundaries and scope, integration with other tools and methods. Access to inventory data during operation and disposal is challenging
Life Cycle Costing	A method to estimate the total cost of ownership of an aircraft or a system, considering all phases from acquisition to disposal. It can help to optimize the design, planning, and management of maintenance activities and resources.	Cost estimation models and relationships, risks and uncertainties, economic factors, data collection and validation.
Eco-Design	A method to integrate environmental aspects into the design and development of aircraft and its components. It can help to reduce the environmental footprint, enhance the performance, and extend the lifespan of the aircraft	Stakeholder involvement and collaboration, trade-offs and synergies, regulatory frameworks and incentives, data acquisition limitations during life cycle, multidisciplinary design team, Design team familiarity with eco-design practices
Material Flow Analysis	A method to quantify the flows and stocks of materials or substances in a system. It can help to improve the efficiency, quality, and safety of the material handling and processing in the aerospace maintenance.	Material tracking and tracing, material flow optimization, waste reduction and recovery, material flow simulation and visualization for circularity analysis.
Circularity Index	A method to quantify the circularity of an aircraft, its components, and materials based on material flows, value retention, and environmental impacts	Circularity indicators consistency and comparability in communication and reporting. Enhanced visibility

Table 5-6: Lean Tools

Method	Application	Opportunities and Challenges
Value Stream Mapping	To visualize and analyze the flow of materials and information, identifying waste, optimizing efficiency, and improving overall process performance.	To optimize maintenance scheduling, reduce downtime, increase capacity, and improve quality. However, it requires data collection and validation, stakeholder involvement and collaboration, and continuous monitoring and evaluation
5S	A tool to organize the by sorting, simplifying, systematizing, standardizing, and sustaining.	Improves safety, efficiency, quality, and morale in the maintenance environment. However, it requires training and education, management support and commitment, and regular audits and feedback.
7 Wastes	A tool to identify and eliminate the seven types of waste in a process: transport, inventory, motion, waiting, overproduction, overprocessing, and defects.	Reduces costs, improve productivity, enhance customer satisfaction, and increase profitability in the maintenance operation. However, it requires a clear definition of value, a culture of continuous improvement, and a systematic approach to problem-solving.

Table 5-7: Industry 4.0 Tools

Method	Application	Opportunities and Challenges
VR/AR	The tools to create immersive and interactive environments for training, inspection, and repair of aircraft.	Enhancing the skills and capabilities of technicians, Improving maintenance processes consistency and efficiency. Its evolving requiring further adoption and development by OEMs and airframers, and industry acceptance.
Unmanned Aerial Vehicle (Drone)	Autonomous High resolution fuselage inspection for structural anomaly detection.	To improve fuselage General Visual Inspection (GVI) reducing labor and time, no need extensive access. It is evolving, its in validation and certification by airworthiness authorities to become an accepted practice.
Data Analytics	A tool to analyze large and complex data sets to gain insights and predictions for maintenance activities.	To optimize maintenance schedules, reduce costs and downtime, improve safety and performance, and extend asset lifespan. It requires data acquisition and validation, analytical tools integration with existing maintenance processes
Block Chain	Secure and Trustable maintenance data exchange platform	Enhanced data visibility for aircraft and component's life cycle data, utilization and repair history tracking, technological constraints regarding to transaction throughput limited and high transaction fees.
Additive Manufacturing	A tool to produce customized and complex parts on-demand using digital designs and layer-by-layer deposition of materials.	Reduces lead time and inventory costs, enable part consolidation, potential weight reduction, it's evolving technology which requires regulatory acceptance and certification.

Table 5-8: TQM Tools

Practice	Application	Opportunities and Challenges
Checklists	A tool to ensure that all the required tasks and steps are performed in full compliance with approved processes, improving safety, efficiency, quality, and compliance.	Enhanced visibility over systems functional integrity. Digitized check list needs to be integrated with existing maintenance platforms.
Fishbone Diagram	It aids to visualize and analyze the root causes of a problem or event, along with their relationship to the effect. A fishbone diagram for a major component failure illustrates categories such as human, machine, environment, and method, with corresponding causes and sub-causes under each.	Requires a clear definition of the problem or event, a systematic approach for data collection, validation and analysis, and effective problem-solving technic
Pareto Diagram	A tool to display the frequency or magnitude of different causes or factors in a descending order. They can help to prioritize the most significant or critical issues that need to be addressed. A Pareto diagram for the maintenance costs of different aircraft subsystems, which shows the percentage of total cost and the cumulative percentage for each subsystem, and the 80/20 rule for identifying the major cost drivers.	It requires a reliable and representative data set, a suitable categorization and measurement of the causes or factors, and a balanced trade-off between cost and benefit

5.7 Application discussion – MRO Industry

To integrate sustainability and Industry 4.0 technologies into aviation MRO, several solutions can be implemented. One approach is leveraging digital platforms to streamline maintenance work processes, tasks sequences, validation, and reporting. This minimizes non-value-added tasks and delays, also enables the use of data analytics and decision support tools to improve the efficiency of maintenance operations. Other application is to leverage AI-powered reliability tools for parts' failure and remaining useful life (RUL) prediction, aiming to replace or reduce “non-safety critical” scheduled maintenance tasks with predictive maintenance. This approach can significantly reduce the cost and environmental burdens, creating competitive edges by performing more effective maintenance practices.

Other solution toward achieving circularity, lies in the sustainable management of removed unserviceable and end-of-life parts. This requires the implementation of a reliable data exchange technologies, such as blockchain, to manage parts data, provide visibility, and facilitate transactions among stakeholders. Such platform ensures transparency regarding the quality and quantity of removed parts, aiming to retain their highest possible value in alignment with circularity objectives.

Table 5-9: Examples of Airline/MRO Sustainable Maintenance Practices

Airline/ MRO	Operation Activity	Sustainability Practices	Impact
Example 1	Engine testing	Using sustainable aviation fuel (SAF) in test cells	Reduced carbon emissions and fossil fuel dependency
Example 2	Engine Operation	Use of IoT and AI for engine Health Monitoring and performance tracking for timely performance restoration	Reduced fuel consumption and emission/ Increased service life
Example 3	Engine Overhaul	Application of IoT in engine parameters monitoring for Life Limited Parts (LLP) Actual Life Tracking System (LTS)	Higher Time-on-Wing (TOW), Reducing cost, material use, waste
Example 4	Lubrication	Use of biodegradable or synthetic lubricants with lower toxicity	Prevents or minimizes Water or and soil pollution.
Example 5	De-icing Operation	Use of biodegradable de-icing agents or effluent containment, treatment, and recovery system	Prevents or minimizes Water or and soil pollution
Example 6	Maintenance Planning	Use of AI-powered Analytical tools for components RUL prediction and predictive maintenance planning.	Reduces downtime and maintenance costs
Example 7	Component Repair	Partnership with OEM to access the latest repair tools and technics to enable safe and economically viable repairs.	Lower Cost, Reduced waste, Higher Component utilization
Example 8	Ground Operations	Using electric vehicles and renewable energy sources	Reduced ground emissions and energy consumption
Example 9	Supply Chain	Adopting Green and closed loop supply chain practices for material sourcing and removed unserviceable parts handling	Reduced shipment cost and emissions
Example 10	Spare part inventory and availability	Use of AI analytics to effectively forecast parts demand and allotment	Reduced spare part capital, reduced down time, reduced scope 2 & 3 emissions.

5.8 Conclusion

Given the rapid growth forecast for the aviation industry, sustainable development has become a critical priority, with the sector aiming to achieve green flights by adopting and investing in eco-friendly practices. These sustainability efforts span the entire aircraft life cycle, with a notable focus on maintenance operations. The aircraft maintenance phase involves a range of processes and activities aimed at ensuring aircraft remain airworthy and available for safe, reliable operation while minimizing economic and environmental burdens, as well as social impacts.

Aligned with aviation's 2050 net-zero decarbonization goal, this study underscores the pivotal role of the aviation maintenance sector as a key enabler in achieving decarbonization objectives. It presents a comprehensive framework, along with various tools and techniques, that hold the potential to transform Maintenance, Repair, and Overhaul (MRO) practices toward greater sustainability. This chapter presented the case studies and practical examples from the industry, illustrating how new technologies facilitate green and eco-friendly maintenance processes. Additionally, it explores both the opportunities and challenges associated with implementing these sustainable innovations.

CHAPTER 6 CONCLUSION AND RECOMMENDATIONS

6.1 Findings

The literature on “sustainable aviation maintenance” can be primarily categorized into three main contexts:

- (1) MRO firms’ sustainable maintenance performance review and evaluation at organizational level.
- (2) MRO lean and green maintenance tools and technics from sustainable MRO’s “processes and practices perspective”.
- (3) Aircraft maintenance environmental or and economical sustainable performance.

Given these contexts, a substantial body of research found addressing the MRO sustainability performance at organizational level by assessing the Corporate Social Responsibility Report (CSR), or and Environmental, Social and Governance (ESG) reports. Moreover, a growing number of study found presenting IndustryX.0 various technologies, lean, and green tools aiming to promote operational excellence and environmental preservation in MRO processes and practices.

Additionally, in light of aviation sustainability challenge toward 2050 decarbonization goal, there are significant efforts aimed at enhancing the efficiency of existing fleet and adopting new, more fuel-efficient and supposedly more sustainable aircraft development. However, there are some significant observations showing the potential risk of inadvertent shift of the economic and environmental burdens to the maintenance phase instead of eliminating them in new developments.

The fact that sustainability efforts can not be managed if sustainability performance couldn’t be measured shows the importance of assessing and benchmarking maintenance sustainability performance (MSP) in aircraft maintenance and eco-design sectors.

Despite the significance of MSP in air transport maintenance, limited research has been conducted to address this issue. This study introduces a novel method for assessing aircraft MSP in a comparable and relatively straightforward manner. Such an MSP assessment offers an enhanced visibility into the sustainability performance of various technologies and design configurations, serving as a benchmark for improved eco-design practices in future developments. Furthermore, it could accelerate efforts to prioritize and develop solutions aimed at eliminating or minimizing the avoidable sustainability burdens in the maintenance phase of the existing aircraft fleet.

This research also highlights the strong association between operational excellence, enhanced productivity, and the adoption of Industry X.0 technologies in promoting sustainability within aircraft MRO processes and practices. The study explored the potential integration of a multidisciplinary suite of Industry X.0, lean, and green tools to advance more efficient and sustainable MRO practices.

6.2 Research Implications

This research study has significant implications for both industry and academia. From an industrial standpoint, it can provide enhanced visibility into the maintenance sustainability performance across different aircraft fleets' service lives. This information can support decision-making processes for airlines and aircraft lessors in their future investments and acquisitions. Furthermore, the proposed MSP assessment provide supporting data as maintenance feedback into improved eco-design practices. Additionally, it sheds light on both the opportunities and challenges associated with integrating various lean and green tools and Industry X.0 technologies into more sustainable MRO practices.

Moreover, this research contributes to the literature from multiple perspectives, including the role of sustainability performance assessment in aircraft maintenance, the connection between aircraft maintenance program and the sustainability outcomes, the critical role of the maintenance sector in addressing climatic challenges, and the investigation of more sustainable MRO practices. Ultimately, these contributions are aligned with the broader objectives of sustainable aviation, supporting efforts to reduce emissions and pollution, promote the responsible use of resources while maintaining operational excellence and ensuring the highest safety standards.

6.3 Limitations

The following can be outlined as the limitations of this study:

- Compared to an aircraft overall maintenance program events, the available data assessed for the presented C-check are very limited.
- Due to limited access to detailed data for each task, material consumed per task was not incorporated in task's environmental assessment.
- Qualitatively scaling maintenance tasks based on expert's opinion has the potential for subjectivity.

- The sustainability indicators were selected for their relevance and significance to the assessment context; however, some details of certain sustainability dimensions may be overlooked.
- The presented linear weighted some aggregation might not be the ideal aggregation technique for sustainability indexing.

6.4 Future Research

There are increasing efforts to adopt new technologies for more sustainable air transport, necessitating further research into aircraft life cycle sustainability assessment and improved eco-design practices. The proposed MSP assessment approach holds significant potential for refinement, validation, and adaptation for improved accuracy, consistency and comparability across various fleets.

It can also be extended to a more detailed MSP analysis per aircraft systems and subsystems, with the potential of integration into maintenance program development processes and Maintenance Planning Documents; which offers a significant contribution towards a new and “Sustainability-Embedded” aircraft maintenance program development paradigm. Furthermore, the multidisciplinary tools investigated in the book chapter has the potential for further expansion and research to explore and develop more detailed and tailored solutions to support more sustainable MRO practices.

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