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Safety and Initial Airworthiness Requirements for New Generation Aircraft Electric Propulsion Architectures

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APPROVAL

The jury members certify that the study conforms to acceptable standards of scholarly presentation and is fully adequate in scope and quality as a dissertation for the degree of Master of science in Aviation Management.

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DECLARATION

I hereby declare that this is my original work and has never been presented for a degree or any award in any university or any academic institution of higher learning. It is all the result of my own effort and under the supervision of **Prof. Dr. Süleyman Tolun.**

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PREFACE

After working as a safety and quality assurance engineer for 13 years in an airline and facing closely with hundreds of safety events, tens of incidents, and one accident during my experience, the concept of safety and airworthiness found a tangible place in my mind. When in 2020, I joined Kyrenia university to follow my aviation pathway in academia, my horizon widened more to the other aspects of aviation such as sustainability and green aviation. The motivation of this study was initiated by Dr. Melih Yildz, who encourages and supports to connect of my engineering background, aviation experience, and master's studies, making the end of this story possible. I would like to express my deepest appreciation to my dear supervisor, Prof. Dr. Süleyman Tolun whose support and help throughout the study period were essential to finalizing this thesis. I should also send a deep sense of appreciation to my family for their endless support.

I hope the results of this study can be used by researchers and industry professionals as a guideline to enhance new generation electric aircraft safety.

ABSTRACT

Improvement in battery technology and motor development, increasing oil and fuel prices and growing the need to limit air traffic emissions are factors aimed to be addressed by the introduction of the electric propulsion system (EPS) as the key technology for future aviation. It is a topic of interest by industry and academia in a wider range of application and design considerations. However, the reliability and certification issues of the new generation propulsion system could not find a place yet. This study points out that the industry standards, as well as regulations, fail to cover the application to a full extent regarding the main subsystems of EPS, specifically for the commercial large aeroplane. Moreover, the focus of this thesis is on the three main essential units of the EPS (Battery-Battery Management System-Power Electronics) certification process and safety assessment. Lithium-Ion Battery (LIB) due to its preferable performance characteristics over other battery types is the most potential candidate for application in hybrid and all-electric propulsion system. However, using it in electric aircraft specifically in a range of thousands of Wh, may not be free of hazards. In this study, the fishbone diagram visualizes the causes of important categories of hazards, to facilitate the design of effective proactive and reactive measures. In addition, risk assessment of LIB in electric aircraft for the loss of capacity as a framework is performed utilizing the Bow-tie model to assess the inherent and residual risk of operations. Then it is determined how technology, regulations, standards, operational procedures and personnel training are capable of effective LIB risk reduction to an acceptable level throughout the life cycle. Finally, it is concluded that cumulative practices and availability of data in the whole process of design and development are vital for novel electrical propulsion systems. The results of the study will draw the attention of authorities, designers and manufacturers to the certification issues of the new generation propulsion systems which is an important element in making clean aviation possible.

Keywords: Electric Propulsion System, Safety, Airworthiness, Certification, Lithium-Ion Battery, Advanced Battery Management, Risk Assessment

ÖZ

Batarya ve motor teknolojilerindeki gelişmeler, yükselen yakıt fiyatları ve hava trafiği emisyonlarını sınırlama ihtiyacı, elektrikli tahrik sisteminin havacılığın geleceği için kilit teknoloji haline getirmiştir. Elektrikli tahrik sistemi üzerine akademi de ve sanayide giderek artan oranda çalışmalar yapılmaktadır. Ancak bu yeni nesil tahrik sisteminin güvenilirliği ve sertifikasyon sorunları henüz literatürde kendine yer bulamamıştır. Bu çalışma, endüstri standartlarının ve yönetmeliklerin, özellikle ticari büyük uçaklar için elektrikli tahrik sistemine ve ana alt sistemlerine ilişkin uygulamayı tam olarak kapsamadığına işaret etmektedir. Ayrıca, bu tezin odak noktası, elektrikli tahrik sisteminin (batarya, batarya yönetim sistemi, güç elektroniği) sertifikasyon süreci ve güvenlik değerlendirmesidir. Lityum iyon batarya (LIB), diğer batarya türlerine göre performans özellikleri nedeniyle tercih edilmektedir ve hibrit ve tamamen elektrikli tahrik sistemlerinde uygulama için en potansiyel adaydır. Ancak, elektrikli uçaklarda özellikle binlerce Wh aralığında kullanılması bazı tehlikeler içerebilir. Bu çalışmada, balık kılçığı diyagramı ile proaktif ve reaktif önlemlerin tasarımını kolaylaştırmak amacıyla önemli tehlike kategorilerini görselleştirmek için kullanılmıştır. Ek olarak, elektrikli uçaklarda LIB'nin kapasite kaybı için risk değerlendirmesi yapılmış, operasyon sırasında karşılaşılması durumuna karşı Bow-tie modeli kullanılarak bir çerçeve geliştirilmiştir. Daha sonra teknolojinin, yönetmeliklerin, standartların, operasyonel prosedürlerin ve personel eğitiminin, yaşam döngüsü boyunca LIB riskini kabul edilebilir bir düzeye nasıl etkili bir şekilde indirilebileceğine yönelik çalışma yapılmıştır. Son olarak, tüm tasarım ve geliştirme sürecindeki kümülatif uygulamaların ve verilerin mevcudiyetinin yeni elektrikli tahrik sistemleri için hayati önem taşıdığı sonucuna varılmıştır. Çalışmanın sonuçlarının, sürdürülebilir havacılığı mümkün kılmada önemli bir unsur olarak görülen, yeni nesil tahrik sistemlerinin sertifikalandırma konularına yetkililerin, tasarımcıların ve üreticilerin dikkatini çekeceği değerlendirilmiştir.

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ABBREVIATIONS

A/C	Aircraft
AEA	All-Electric Aircraft
AI	Artificial Intelligence
BMS	Battery Management System
CB	Certification Basis
DAL	Development Assurance Level
DOD	Depth of Discharge
EA	Electric Aircraft
EASA	European Aviation Safety Agency
ECM	Equivalent Circuit Model
EPS	Electric Propulsion System
ESD	Energy Storage Device
ETA	Event Tree Analysis
FAA	Federal Aviation Administration
FHA	Functional Hazard Analysis
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis

HALT	Highly Accelerated Life Testing
HEA	Hybrid Electric Aircraft
HL	Hierarchical Level
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
LIB	Lithium-Ion Battery
MEA	More Electric Aircraft
ML	Machine Learning
MOC	Means of Compliance
MTBF	Mean Time Between Failure
NN	Neural Network
PE	Power Electronics
PSSA	Preliminary System Safety Assessment
QA	Quality Assurance
RUL	Remaining Useful Life
SC	Special Condition
SLR	Systematic Literature Review
SOC	State of Charge
SOF	State of Function
SOH	State of Health
SOP	State of Power
SOT	State of Temperature
TC	Type Certificate
UN	United Nations

1. INTRODUCTION

To prevent intolerable catastrophic losses, the safety and reliability of the aircraft system during the whole life cycle from design to operation must be assured. To achieve an acceptable level of safety, restricted airworthiness requirements are imposed by aviation authorities (Zio et al., 2019). On the other hand, in coping with global environmental disasters, the United Nations (UN) has developed a sustainable goal target to address climate change to be achieved by 2030 (United Nations, 2015). Notably, the aviation industry accounts for the generation of almost 2.1% of human-induced CO2 emissions and it can rise to 22% by 2050 (Cames et al., 2015). Figure 1 is IATA CO_2 emissions reduction roadmap. Based on it, advanced aircraft configurations such as Hybrid Electric Aircraft (HEA) can reach up to 40% fuel efficiency, and 100% for all-electric aircraft (AEA) using renewable sources in the total energy life cycle compared to the predecessor engines (IATA, 2019). Therefore, to resolve the greenhouse gas emission challenge and enhance efficiency and reliability, the introduction of modern aircraft architecture is unavoidable (Barzkar & Ghassemi, 2020). In the future, electric aircraft can be an important element in a sustainable air transport system.

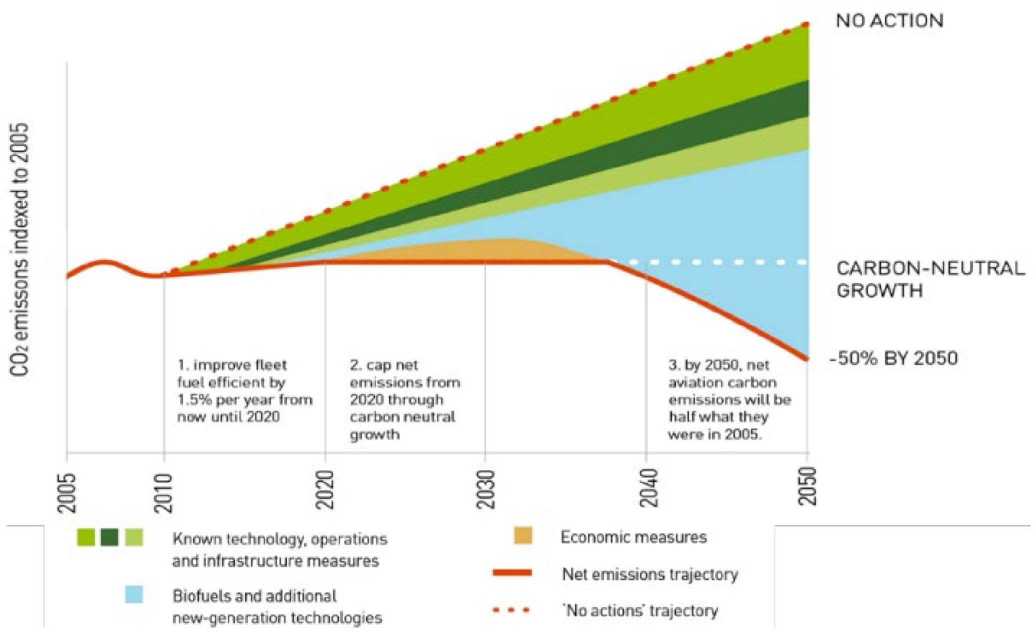


Figure 1. CO_2 emissions reduction roadmap (IATA, 2019)

1.1. Background of study

Despite the high necessity and interest in the literature and industry, the reliability and certification issues of the new generation propulsion system could not find a place (Berger, 2017; Emmanouil, 2020). The fundamental differences exist between conventional aircraft and electrical propulsion aircraft system safety design requirements, the process of certification, methods of demonstration of compliance, and verification. Identifying the dissimilarities will clarify the limitations and requirements toward the implication of electrical propulsion systems. It is also true for reliability assessment which has interlinked nature with safety (Emmanouil, 2020). The application of reliability modelling and system safety principles helps initial airworthiness certification requirements to be defined and captured effectively. In addition to regulations regarding the certification process of electric aircraft, technological restraints also exist, specifically regarding batteries which are one of the important components to make the concepts of HEA and AEA possible (Damiano et al., 2018).

Until now, different types of batteries have been used to provide the energy of the propulsion systems, and they are emerging to have more efficiency. State-of-the-art battery electro chemistries, such as lithium-sulfur, aluminium-air, and lithium-air, which are in progress, offer further improvement in the long term. In theory, based on the active materials, lithium-sulfur (2680Wh/kg), aluminium air (8140Wh/kg), and lithium-air batteries (11,000Wh/kg in the charged state; 3500Wh/kg in the discharged state) are quite magnificent for hybrid propulsion application. However practical battery-specific energies are dramatically lower mostly because of the extra weight of current collectors, separators, battery electrolytes, and battery cases (T. Yang et al., 2018). Among different battery types with a variety of electrochemistry and design, Lithium-Ion Battery (LIB) due to its higher energy density, nominal voltage, and power density, as well as efficiency and affordability made it possible to be used in wide areas from light to heavy-duty vehicles (Ali et al., 2019; Lisbona & Snee, 2011; Saevarsdottir et al., 2014) and also aircraft power systems (Hendricks et al., 2015; D. Ouyang et al., 2019; Voskuijl et al., 2018). The application of LIBs in electric propulsion system needs battery modules to be consistent with the large number of battery packs formed by battery cells to provide adequate propulsive energy. The energy required may be in the order of tens of kWh in unmanned aerial vehicles and urban aviation and hundreds or thousands of kWh in commercial aircraft to support the defined mission of flight (Sripad et al., 2021; Yildiz, 2021). Besides that due to the criticality of energy storage devices in providing fraction or all of the electric energy of aircraft powertrain, usage of LIB presents safety drawbacks considering variable ambient pressure and temperature (Q. Wang et al., 2019), which is one of the main challenges of LIBs usage. Environment conditions, as well as excessive operational situations, could easily direct the LIB beyond its safe characteristic window; mainly leading to thermal runaway failure mode. In aircraft application addressing ingrained hazards such as fire requires the usage of the well-established methods, and diagnosing and prognostic of failure by applying reliable preventive and protective systems which are complex (Damiano et al., 2018; Emmanouil, 2020). On the other hand, while a lithium-ion cell as an energy storage unit is just composed of two electrodes, a separator, and an electrolyte, the discharging characteristics show completely non-linear behaviour in terms of output voltage (Hornung & Sizmann, 2013). This non-linear characteristic arises from various parameters such as rate of charge and discharge, number of cycles as well as environmental conditions (Diao et al., 2019). All those factors make it more difficult to predict the critical failure modes such as power reduction and capacity fade which is crucial in electric propulsion applications. Therefore, a Battery Management System (BMS), capable of measuring voltage, current, and temperature, monitoring, supervising, and estimating the battery intended functions (Lelie et al., 2018; Rahimi-Eichi et al., 2013), is indispensable for developing battery-powered electric devices (Y. Wang et al., 2020). BMS is essential to ensure the safety and reliability of the system in any application. BMS, especially in AEA and HEA, is the most important safety mechanism to predict and prevent hazards from being activated and reduce the overall risk of the flight. Among different strategies for battery management including model-based and data-driven approaches, the data-driven is suggested as a solution for conquering the experimental difficulties and inaccuracies involved with physics-based techniques (Heinrich et al., 2021). In the data-driven-based methods battery is considered a black box while enormous volumes of data are applied to learn the internal dynamics of the battery (Y. Wang et al., 2020), using artificial intelligence (AI) and Machine Learning (ML) approaches. Data-driven supervised learning methods can map the input to output data without using any physical model (W. Li et al., 2021). The ability of mapping nonlinear battery characteristics is an important feature of intelligent methods such as neural networks

(Y. Wang et al., 2020). Moreover, intelligent algorithms have better performance in terms of accuracy and efficiency (Hossain Lipu et al., 2021).

1.2. Problem Status

Application of Electric Propulsion System (EPS) in aircraft as a response to the climate change concerns, requires addressing inadequacies in the design certification process and safety vulnerabilities of its essential units of it. This study is performed to present a potential solution to the following stated problems:

- The inappropriateness of design approaches as typically used in preliminary aircraft leveraging conventional engines for electric aircraft
- Lack of safety, reliability, and initial airworthiness requirements including regulations, for essential units of EPS during its life cycle
- Inadequate knowledge and experience regarding advanced innovative technologies of battery management in EPS
- Hazards and failure modes of batteries in EPS that threaten the safe operation of AEA and HEA

1.3. Purpose

The employment of electric propulsion in future commercial transport aircraft is a solution that has to be addressed and examined in more detail (Stückl, 2016). Thus, a deeper understanding of electrical aircraft safety and reliability requirements and defining the differences and needed changes in the present certification practices is essential. To address the stated problems, the objectives of this research are as outlined as the following:

- To review safety and reliability models that could be applied to electric aircraft
- To identify safety and initial airworthiness requirements of essential units of electric propulsion system
- To evaluate the body of knowledge about battery management strategies and implementation techniques supported by intelligent algorithms

- Study of the current status of aviation regulation including the application of AI/ML approaches in the electric propulsion system
- To perform a comprehensive analysis for identification of various sources of hazard associated with LIB in electric aircraft and its consequence on propulsive system performance
- To design appropriate control measures and possible mitigation actions to manage the risks of LIB
- Identify challenges and gaps for implementation of AI subset in future EA BMS
- To find out the measures that could be taken to design the safer electrical propulsion system

1.4. Importance of Study

Due to the novelty of the topic and day-to-day progress of the AEA and HEA technology of electrical propulsion system and sub-systems, it is necessary to perform an in-depth study on the safety aspect of design and initial airworthiness requirements of associated systems and sub-systems.

Moreover, admitted by Brelje and Martins (2018), LIB is known as a source of hazard in aircraft operations with less service experience (lack of data) at the same time complexity of failure modes, so identification of battery hazards and failure modes, is an enabler for design of adequate safety mechanism to enhance safety and reliability of electric propulsion system.

To the best of our knowledge fewer studies performed specifically about AEA and HEA propulsion systems in which artificial intelligence techniques assist the safety management of energy storage system. However specific requirements of intelligent techniques considering the real-work condition in electric aircraft and safety assessment requirements are not studied nor discussed adequately. Nevertheless, the experience of different mobile and stationary devices in which AI techniques are employed can be used to benefit electric and hybrid-electric aircraft safety and reliability. Providing that, a higher level of operational risk of EA and HEA, due to the more severe consequence of any unsafe conditions, is perceived.

The findings of this paper can be used to guild design engineers to proceed through safer aircraft system design and production of EPS.

1.5. Limitation

Due to the high pace of technological progress, some novel scientific improvements might not be considered in this study. In addition, access is restricted to details of some industry standards which in case of numbers are over hundreds. Furthermore, authority and industry project information may not be released because of Intellectual Property Rights (IPR). Moreover, the scope of this research is limited to hybrid and fully electric propulsion aircraft and turbo-electric propulsion is out of scope. Regarding certification aspects, although some areas of continuing airworthiness requirements for electrical propulsion system such as preventive maintenance is mentioned, all other aspects of it as shown in (Figure 2, right side) is not considered in this study, and the focus of the research is on initial airworthiness requirements (Figure 2, left side) (EASA, 2021b, 2021a). Finally, while various kinds of batteries may intend to be used in future electric aircraft, a risk assessment of LIB is performed in this study due to its characteristics and popularity of the application.

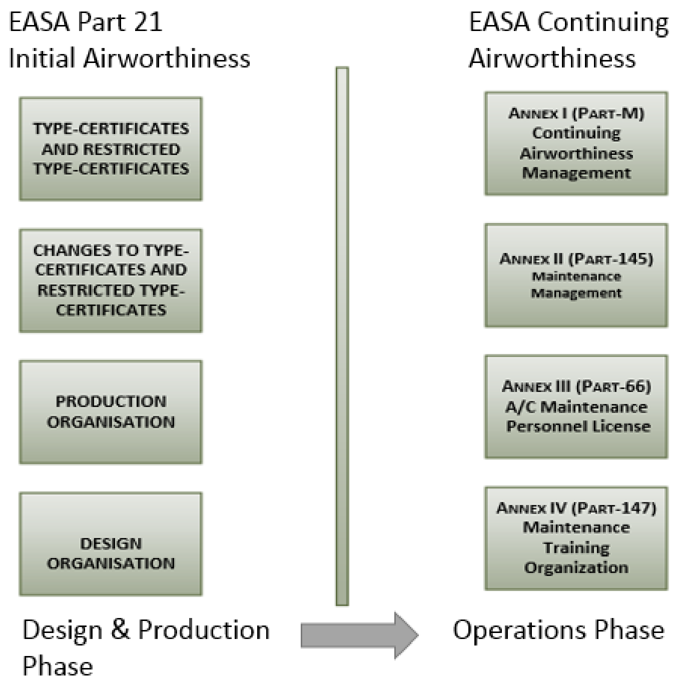


Figure 2. Initial Airworthiness & Continuing Airworthiness Regulations

1.6. Definition

- Airworthiness: For an aircraft, or aircraft part, is the possession of the requirements for flying in safe conditions, within allowable limits (Florio, 2016).
- All Electric Aircraft (AEA): Electrochemical energy source (i.e. batteries) is used to drive electric motors, mechanically linked to the fans (Zhang et al., 2018)
- Battery Management System (BMS): are real-time systems controlling many functions vital to the correct and safe operation of the electrical energy storage system in Electrical vehicles. This includes monitoring of temperatures, voltages, and currents, maintenance scheduling, battery performance optimization, failure prediction and/or prevention as well as battery data collection/analysis (Vezzini, 2014).
- Hazard: The potential for harm; A hazard is not an accident. Per FAA Order 8040.4 a " Condition, event, or circumstance that could lead to or contribute to an unplanned or undesired event." (Federal Aviation Authority, 2000)
- Risk: Risk is an expression of possible loss over a specific period or the number of operational cycles. It may be indicated by the probability of accident times the damage in dollars, lives, and/or operating units. Hazard Probability and Severity are measurable and, when combined, give us risk (Federal Aviation Authority, 2000).
- Hybrid Electric Propulsion: At least two power sources are utilized to drive a fan; in addition to the gas turbine, batteries are used to supply a fraction of the power source in one or more phases of flight based on aircraft design (Gesell et al., 2019)
- Power electronics (PE): Power electronics can be defined as the use of electronic devices to control and convert electric power.
- Reliability: the probability of successful operation or performance of systems and their related equipment, with minimum risk of loss or disaster or system failure (Stapelberg, 2009).
- Safety: The state in which risks associated with aviation activities, related to, or in direct support of the operation of aircraft, are reduced and controlled to an acceptable level (ICAO, 2013).

- Type Certificate: A document issued by a Contracting State to define the design of an aircraft type and to certify that this design meets the appropriate airworthiness requirements of that State (ICAO, 2007).

1.7. Thesis outline

To achieve the research objectives, this study is performed in different stages. First, safety and initial airworthiness requirements of EPS including Systematic Literature Review (SLR) of AI subset application in advanced BMS, as well as LIB hazards identification, classification, and safety risk management.

The first section focuses on the safety and airworthiness requirements of battery, BMS, and PE as essential units of electric propulsion system. Noticeably, the safety and initial airworthiness requirements of the electric propulsion system depend on essential units' safety. Therefore, safety management of the battery system is done in the second phase to define the design characteristics of the safety mechanism. Results of the safety assessment of LIB operations in section 2, could be applied to airworthiness certification of the design, production, and operations of EPS. The other important unit which directly affects the safety, reliability, and availability of electric propulsion system is BMS. Conventional methods of battery management seem inadequate to fulfil the safety requirements of electric aircraft. Thus, new methodologies in safety functions of BMS needed to be reviewed and applied in electric aircraft cases. Reviewing AI and ML in BMS applications provides a comprehensive framework for state-of-the-art methods of battery management. Results could be applied to the airworthiness requirements of the electric propulsion system. A summary of the taken steps in the thesis is shown in Figure 3.

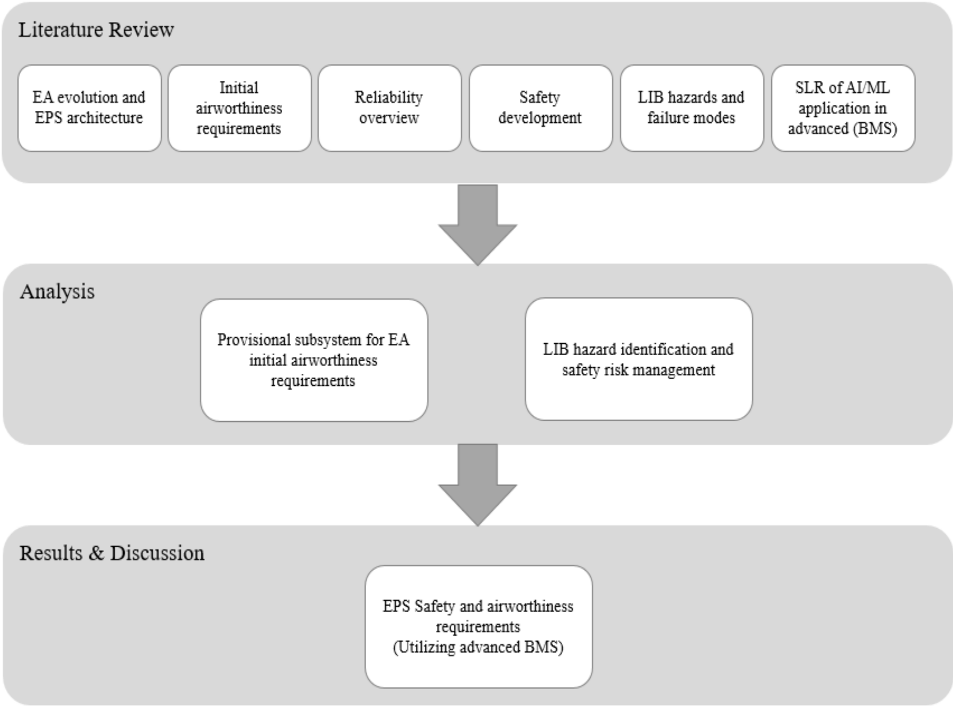


Figure 3. Thesis steps outline

The thesis is organized as follows: section 2 is a conceptual/theoretical framework and relevant literature review of electrical propulsion architectures, safety and airworthiness requirements, LIB hazards models, review of advanced battery management strategies. Section 3 is the methodology of the research; section 4 is the analysis and section 5 is the results, and finally, section 6 is the conclusion, recommendations, and future study opportunities.

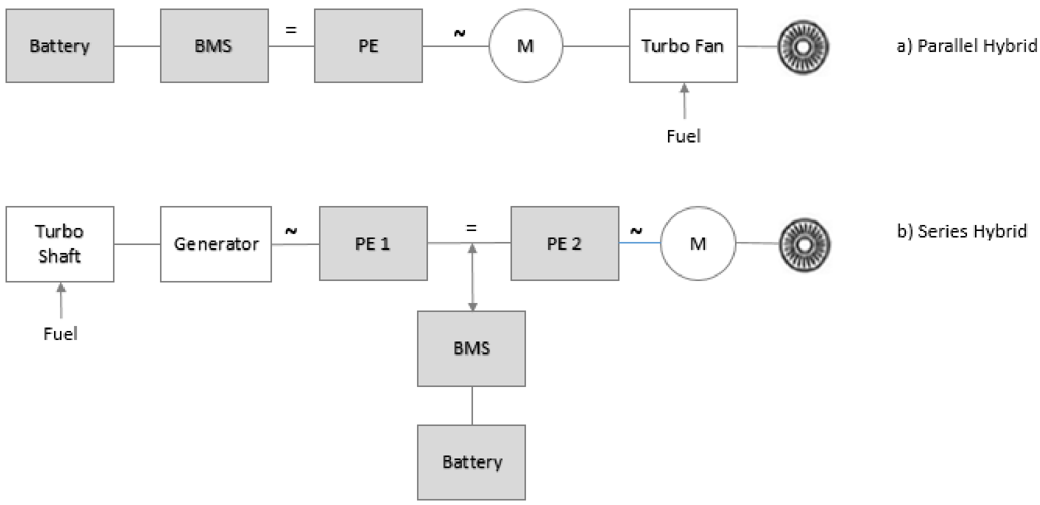
2. THEORETICAL FRAMEWORK AND LITERATURE REVIEW

This chapter first discusses the theoretical framework regarding the evolution of the concept of EPS architecture, reliability, and initial airworthiness principles and requirements. Then safety assessment of A/C and A/C systems and the process of safety risk assessment are explained. Afterwards, since batteries are the most essential component of the powertrain, hazards and failure modes of LIB were reviewed as per literature. Finally, an SLR regarding AI/ML utilization in an intelligent battery management system is performed.

2.1. Path to the electrification

In line with technological progress, the concept of electric propulsion is attractive considerably for both researchers and industry pioneers in a wider range of designs and applications (IATA, 2019). During the past decades, successful actions have been undertaken mainly by utilizing two main concepts of electrification. The first technology is More Electric Aircraft (MEA), focusing on replacing systems that are mostly run by hydraulic, pneumatic, and electromechanical sub-systems, with onboard loads using electrical sources. Hybridization of propulsion system is a recent aspect of MEA concept technology (Nøland et al., 2020). There are incredible advantages combined with MEA in comparison with conventional aircraft, improving reliability and efficiency and lessening fuel consumption, emission, as well as operational cost, are some of them (Xu et al., 2019). The second technology is AEA in which electric systems are used instead of conventional forms. Power of propulsion produces by other sources of energy such as electrochemical batteries and or fuel cells, bringing more opportunities in comparison to MEA, such as zero fuel consumption, no emission, and even lower operational costs (Barzkar & Ghassemi, 2020). So aviation industry approach is to utilize HEA and AEA concepts in commercial aircraft in the future (da Silva et al., 2021).

EPS put into service in new-generation aircraft is generally classified into three main categories based on the applied architecture; which are Turbo-electric, Hybrid-electric, and fully electric. In the Turbo-electric propulsion system, electric power is produced in the air. The power from the gas turbine engine is converted to electricity and only jet fuel is used as an energy source. While in a hybrid electric system at least two power sources are working to operate a fan; in addition to the gas turbine, batteries are employed to source the fraction of the power source is one or more phases of flight according to the aircraft design (Zhang et al., 2018). Therefore, in the same flight mission, hybrid-electric propulsion consumes less fuel than turbo equivalent (Gesell et al., 2019) and in an AEA only an electrochemical energy source (i.e. batteries) is used to drive electric motors, mechanically linked to the fan or propeller. Three kinds of hybrid-electric propulsion systems are classified as Parallel hybrid, Series hybrid, and Series/Parallel partial hybrid shown in Figure 4- a, b and c, respectively. In a parallel hybrid system, no generator is used, a battery-powered motor and gas turbine engine is connected to the fan shaft, and both sources together or distinctly can produce the required thrust. In a series hybrid, thrust is generated by multiple electrical motors connected to multiple fans. Motors are driven by a generator powered by a gas turbine. (Felder, 2018). But in a Series/Parallel partial hybrid system, one or many fans can be moved by gas turbine power or battery system, while the system can use turbofan propulsion too. Finally, in an All-electric system, electrochemical energy sources (i.e., batteries) drive electric motors, mechanically connected to the fans as depicted in Figure 4-d.



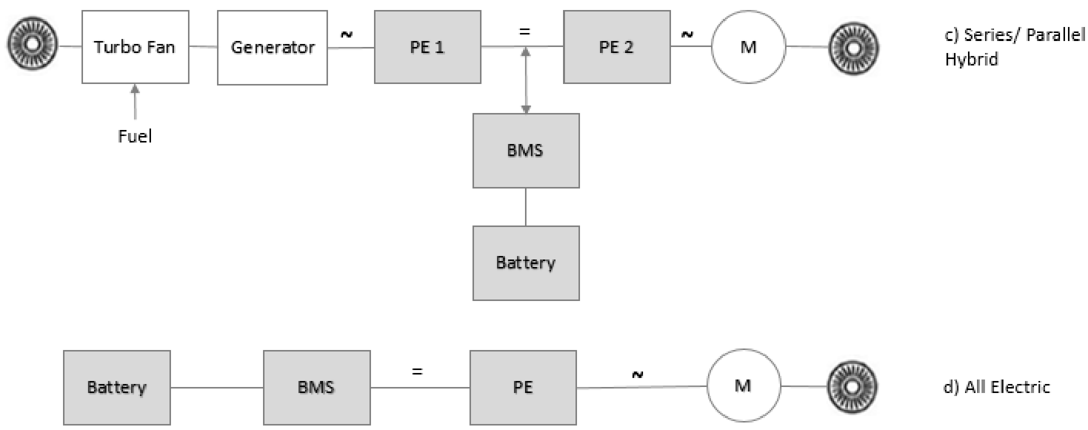


Figure 4. HEA and AEA Architecture

The level of hybridization commences with turbo-electric architecture and ends with the all-electric aircraft (da Silva et al., 2021). In the flow of this progress, electrical energy sources contribution in the propulsive generation is between 0 in conventional aircraft to 100%, in AEA, simultaneously for other electrical loads from 10% into 100%. Therefore, due to this increase in the level of dependency on energy storage devices, more safety, reliability, and availability requirements in design are needed to be applicable in the certification process. Table 1 summarizes the evolution of electric power of aircraft from conventional to AEA.

Table 1. Aircraft electrical capacity evolution

Evolution of Aircraft	Conventional Aircraft	More Electric Aircraft (MEA) Hybridization →			All-Electric Aircraft
		Conventional propulsion	Turbo Electric Aircraft	Hybrid Electric Aircraft	
Propulsion System	Jet engine	Jet engine	Jet engine and Electric motors	Jet engine and Electric motors	Electric motors
Source of propulsive energy	Jet Fuel	Jet Fuel	Jet Fuel	Jet Fuel and Electrochemical (Battery)	Hydrogen fuel cell/ Aluminum-air batteries
Sample case	Airbus 330	Boeing 787	STARC-ABL	E-Fan X	Wright Spirit
Electric power capacity	0.25 MW	1 MW	2.6 MW	2 MW	10-12 MW

The provisional architecture of electric propulsion for hybrid and fully electric consists of energy storage devices (composed of battery and battery management system) and Power Electronics (PE). Regarding the necessity of growing progress in battery systems and introduction of new emerging technologies for batteries, however, combined with ingrained hazards such as fire, requires altering of previous well-known and well-established methods, and initiating more forecasting in the rate of failure as well as protection and prevention methods (Emmanouil, 2020). The Battery Management system (BMS) role is failure prediction and preventing it through measuring, controlling, and reporting. Factors being considered for BMS design are battery cell characteristics, system context, and functional needs (Lelie et al., 2018). PE units play a dominant role in aircraft electrical propulsion systems. Although many previous studies about PEs focus on the electric power system, few detailed studies were performed on the architecture of electric propulsion aircraft (Dorn-Gomba et al., 2020), this idea is applicable for the analysis of the reliability of electric propulsion system.

2.1.1. Barriers to the application of new electrical propulsion system

The most significant barriers to the electrification of propulsive systems are summarized in two main groups: technology and regulations (Berger, 2017). Technology issues are directly linked to electrification. The first is battery operated, which is around the battery capacity and weight. Implementing new generation propulsion systems in medium-range and long-range commercial aircraft highly depends on the level of battery characteristics development. In HEA and AEA propulsion architecture, the battery is an important unit. For propulsive purposes, energy storage should provide at least 500-1500 Wh/kg energy density, while today's highest battery range is around 150-250 Wh/kg, technology has a long way to provide battery power with more than 1800 Wh/kg required for a regional AEA (T. Yang et al., 2018). On the other hand, the safety and reliability matter of battery systems is challenging. The second technological restraint is motors and generators characteristics, which significantly impact the electrification path. More efficiency with the higher power density and lower weight motors and generators is essential for turbo, hybrid, and all-electric propulsion systems. The third obstacle is PE, which is important for converting, inverting, switching, and storing the power with minimum loss and high safety and reliability (Barzkar & Ghassemi, 2020). The fourth problem is the distribution of high voltage electricity, particularly in distributed electric propulsion systems that can escalate the cable weight. Moreover, to reduce the electrical losses of high power levels in an aircraft, it is essential to raise voltage, which has a limitation through insulation break down and arcing (Berger, 2017). There are also some other technical challenges listed below:

- Environmental situations (mainly: changes in temperature, humidity, and altitude, abnormal input of power electricity, radio frequency interference, etc.)
- Electrical components integration in HEA
- Electrical load balancing
- Integration of electrical equipment and gas turbine engine
- Temperature increases during the operation

In the electric aircraft case, there is not any commercial aircraft operational experience data to be used in the design and modelling of aircraft components. Furthermore, due to fundamental differences in operational characteristics of conventional aircraft and electric aircraft, weight accounting, for instance, design features of conventional aircraft is not appropriate for electric propulsion anymore (Stückl, 2016).

To deal with these challenges of achieving safety and efficiency, reliability data in four categories are needed, including initial and matured design data, manufacturing data, test data, and operational data (Emmanouil, 2020). After evaluation of these data, reliability or use modes of new technology can be addressed. As far as yet there is not enough experience in the use of electric propulsion technology, results are not adequately mature to be used in the aviation in a broader means, another barrier which is immaturity in the design, manufacturing, and operations of electric propulsive systems emerge.

The lack of satisfactory regulations is considered another difficulty in the implementation of EPS. Regulations act in two ways. The first step provides a starting point for new design projects. The second is a basis for certification of the final system. Based on EASA (European Aviation Safety Agency) regulations, although Certification Specifications such as CS-E Engines, CS-22, and CS-25 subpart H are designed for different engine types, EPS is considered by none of them. This is the same for the initial airworthiness process for advanced BMS technologies benefitting from AI and ML algorithms or big data cloud.

2.2. Reliability overview and techniques

2.2.1. Reliability principals

Reliability is essential to achieve an acceptable level of safety, therefore restricted reliability requirements are imposed by aviation authorities on an aircraft. Even though there are many challenges involved with reliability issues, the overall industry outcome is acceptable (Zio et al., 2019), however much more effort needs to be performed to eliminate aviation accidents, especially in the design stage of electric aircraft.

Considering the concept of integrity in design engineering, subjects including reliability, maintainability, availability, and safety of the systems and processes needed to be identified so that each of these criteria either theoretically or practically can be applied (Stapelberg, 2009). In theory, subjects are defined quantitatively for probability and statistics (Defense, 1998). Knowing the relation between components and system, component reliability is defined as the chance of successful intended operations for a stated time under certain circumstances, while system reliability is dependent on the reliability of components that compose the system and architecture of that system (Stapelberg, 2009). Aiming to assess the reliability of a system, the network approach is considered to show the connection of the components in series, parallel, and combinations of them (Xu et al., 2019). While reliability focuses on designing for the performance of a function without failure, maintainability concerns designing an item that in case of failure is repairable as fast as possible. A combination of high reliability and high maintainability will result in high availability. Finally, durability refers to measuring an item's useful life which is somehow a kind of reliability (Defense, 1998).

2.2.2. Reliability Requirements in the aircraft life cycle

With the knowledge of the importance of reliability during the whole aircraft life, in Figure 5, activities performed during the life cycle of an aircraft are depicted in three main phases. It is worth mentioning that as a cyclic procedure, authority regulation mandates the type certificate owner to keep track of the equipment/system/part during its operation, type holder is required to collect data to be able to offer rectification/correction/development on the system. Also, EASA Part-M and Part-145 requirements for continuing airworthiness and maintenance organization regulations respectively urge the operator and maintenance organization to feedback critical data and safety issues to the type certificate holders.

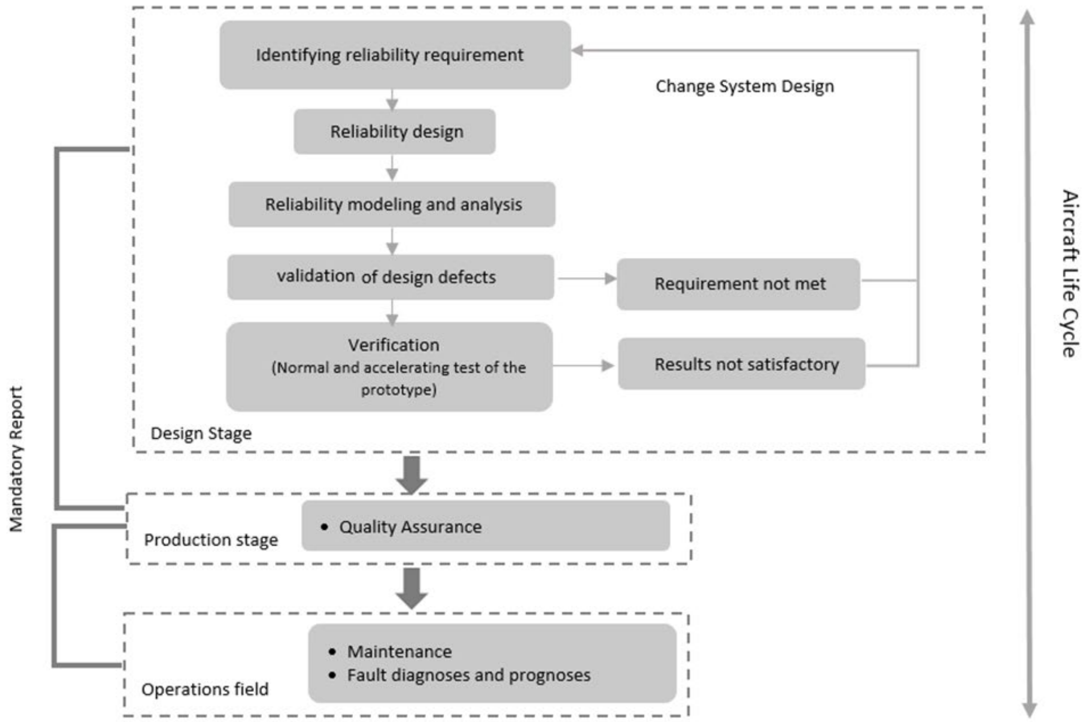


Figure 5. Reliability activities during the aircraft life cycle

- Design and development stage

In the first step of the design stage in Figure 5 (Identifying reliability requirements), various quantitative reliability indexes are used to determine different effects on system aspects including availability, durability, maintainability, reliability, and safety.

For defining reliability requirements, specific values should be set for each index. Reliability indexes used in commercial aircraft at a system level are shown in Figure 6 (Zio et al., 2019). Indexes specified (bolded) in Figure 6, states the inherent reliability of an aircraft must be determined in the design and production stage while the others are affected by operational and environmental issues and maintenance situation. The indexes are system-level reliability requirements that should be assigned to the subsystem as well as the component level (Zio et al., 2019). To obtain component reliability requirements from system reliability requirements, there are many reliability allocation techniques such as equal appointment, ARINC appointment, the feasibility of objective, and minimization of effort algorithm (Defense, 1998).

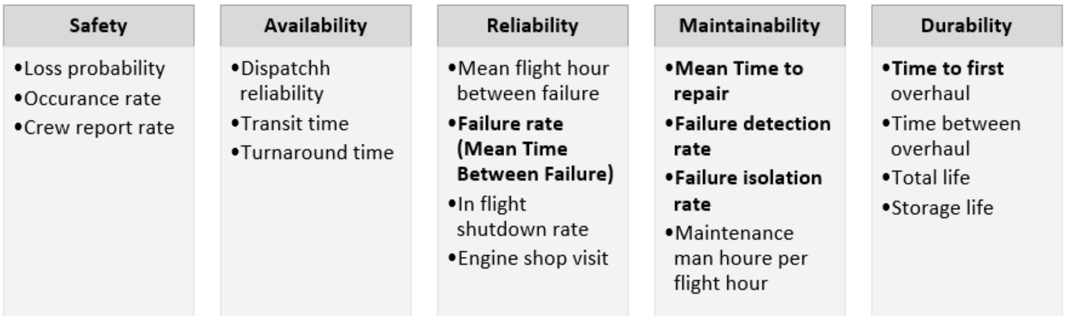


Figure 6. Reliability indexes

Following quantifying reliability requirements, the next step is reliability design. Reliability design mostly focuses on not only providing system function goals but also on preserving function without any failure during the system life cycle process (Zio et al., 2019). In Figure 7 two reliability design techniques for hardware and software design are depicted. Since software plays an important role in modern complex aircraft, software reliability analysis in the design stage must be considered. The first reliability technique either for hardware or software is fault avoidance, which aims to reduce the rate of failure. The other is fault-tolerant which tries to keep normal functionality of the system in case of any failure or implementation of redundancy principal.

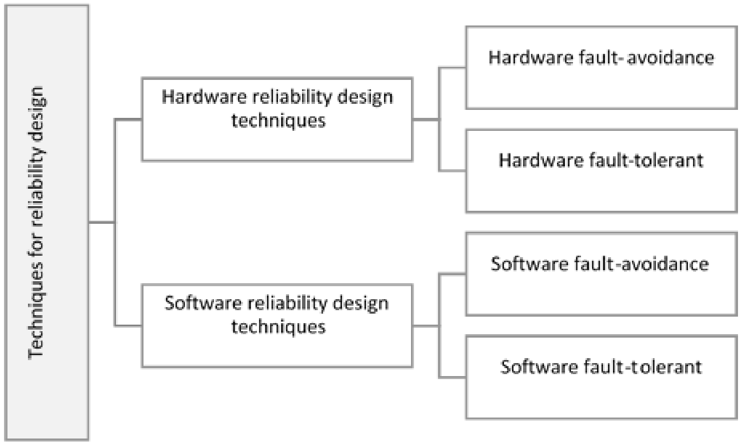


Figure 7. Reliability design techniques

For the next step which is reliability modelling and analysis, the process is followed by using a reliability technique such as reliability prediction technique, reliability block diagram, Fault Tree Analysis (FTA), and Sneak circuit analysis (Defense, 1998). For example, sneak circuit analysis deal with identifying sneak-in circuits as undesired status in a system, in the beginning, stages of design, using analysis tools even manually or utilizing software programming technique (Defense, 1998).

Afterwards to verify design defects, a variety of methods such as Design Failure Modes and Effect Analysis (FMAEA), Process Failure Modes and Effect Analysis, Failure Reporting, Analysis, and Corrective Action Systems, Reliability growth test, and Highly Accelerated Life Testing (HALT) applied, if the results satisfy the proposed requirements, the process proceeds to the next level, otherwise some changes might perform in system design (Zio et al., 2019).

Following the performance of reliability modelling and analysis, during the verification and validation step, the prototype airborne system will be tested to make sure it is reliable enough and meets the requirements criteria. Samples of applicable guidance for the test program including test plan, test method, and environmental profile, are shown in Table 2.

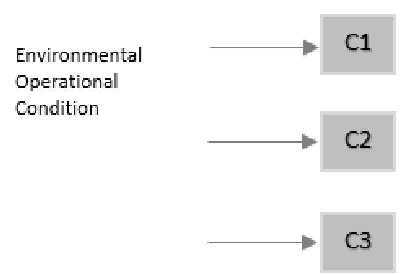
Table 2. Tests for verification

Handbooks for reliability testing	Test Guidance	Origin
MIL-HDBK-781A (DOD, 1996)	typical test plans, test methods, and environment profile	USA
GJB 899A—2009 (Zio et al., 2019)	environmental test conditions, statistical tests plans, parameter estimation methods and procedures	China
IEC 61123 (IEC, 1991) IEC 61124 (IEC, 2012)	standards on reliability testing	International

After completing the required testing, results will be analyzed and compared with pre-defined accepted levels to satisfy the verification and validation phase, then proceed toward manufacturing.

Xu et al. (2019), introduce a Hierarchical Level (HL) approach as a method that is used for reliability modelling in the design stage to evaluate onboard aircraft electrical systems. Based on this method, reliability is calculated on 3 levels. The first one referred to as HL 1, deals with failure rate at the component level considering operational characteristics such as load (power/ current) and temperature. The second one is HL 2, in which the reliability of subsystem-composed of components- is modelled and finally, the third one is HL3, to quantify system reliability, based on a system representative graph and subsystem reliability model. This method quantifies system reliability features using a bottom-up approach. A summary of the hierarchical approach is illustrated in Figure 8.

HL1



Component Level:

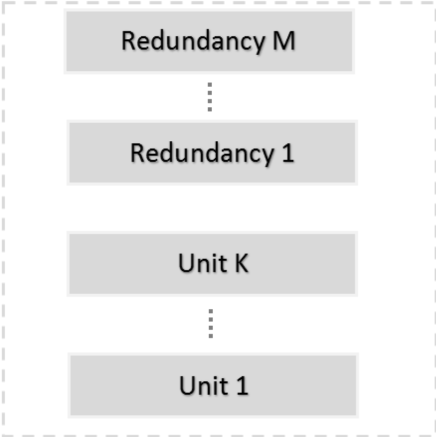
Operational Failure Rate C_i: $\lambda_{C1} = f^{*} (\lambda_{b\,Ci}, \lambda_{ENV\,\&\,OP})$

$\lambda_{b\,Ci}$: Basic Failure Rate C_i

$\lambda_{ENV\,\&\,OP}$ = Environmental, Operational Failure Factor

*Function is dependent on the architecture

HL2



Subsystem Level:

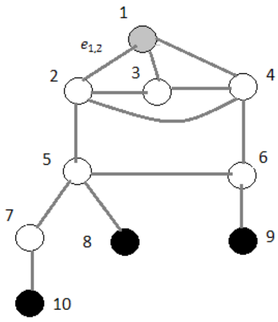
Unit Failure Rate: $\lambda_{Unit} = f^{*} (\lambda_{C1}, \lambda_{C2}, \lambda_{C3}, \ldots)$

Subsystem Reliability: R_{Sub}

$R_{Sub} = f(R_{Unit}, Red_{K\&M})$

$Red_{K\&M}$: Redundancy Factor if K of M works properly

*Function is dependent on the architecture



HL3

System Level:

Unreliability of system: $Q_{Sys} = f^{*} (Q\ e_i, j, Q\ e_{k,n}, \ldots)$

$R_{Sys} = 1 - Q_{Sys}$

$Q\ e_{i,j}$: Unreliability of minimum cut set in topology (Xu et al., 2019)

*Function is dependent on the topology

Figure 8. Hierarchical approach for reliability modelling

There are some advantages combined to using this method, such as identifying susceptible parts helps analyze the effect of components and sub-systems on the total system, also enhancement of reliability by utilizing thermal control techniques, adding redundancies, and implementing maintenance on components or subsystems led to the fulfilment of system reliability requirements.

- Production stage

A high level of reliability can be achieved by the implementation of quality assurance (QA) in the production lifecycle of an aircraft, aiming to meet the defined reliability requirements. There are many QA techniques in place including Quality Function Deployment, Statistical Process Control and Design of Experiments (IEC, 2013).

- Operational field

After an aircraft begins its operational life cycle, maintenance must be implemented to assure a high level of reliability and maintainability (Zio et al., 2019). Accompanying the evolution of technology, several methodologies for maintenance introduced; based on (Khazraei & Deuse, 2011), maintenance policies are categorized into 5 types: Corrective Maintenance which is performed after any failure, Preventive Maintenance, or Time-Based Maintenance in which maintenance is conducted in predefined intervals, Condition-Based Maintenance or Predictive Maintenance by monitoring data in real operations, Autonomous Maintenance (AM) establishing by the cooperation of manufacturer and maintenance and finally Design Out Maintenance mainly focuses on system design for implementation of more comfortable maintenance techniques. As assessed by Xu et al. (2019), the performance of preventive maintenance effectively promotes a reliably level of the system. The other reliability activities in the operational phase are fault diagnoses and prognoses techniques aiming at collecting data and knowledge of the system fault and failures to support the maintenance affairs (Zio et al., 2019).

2.3. Airworthiness overview

2.3.1. Airworthiness principals

Florio (2016) defined the term airworthiness as "For an aircraft, or aircraft part, is the possession of the requirements for flying in safe conditions, within allowable limits". Requirements and limits are two imperative keywords which mostly specified by industry standards and imposed by top-level authorities. Generally, the certification process for the design and production of an aircraft is performed through national aviation authorities in the world, based on International Civil aviation Organization (ICAO) Standards and Recommended Practices (SARPs). In line with the type and application of the airborne equipment, various sets of regulations are defined by each authority; by establishing these regulations, authorities ensure all the applicable design and production requirements, as well as safety requirements, are satisfied. To attain this, for instance, EASA issued “Airworthiness and Environmental Certification (Regulation (EU) No 748/2012)” known as “Part 21” document to define the applicable rules for environmental certification of an aircraft and its product, parts, and appliances, also for the design and production organizations (EASA, 2021a). Supplementary documents for the regulations are Acceptable Means of Compliance (AMC) and Guidance Material (GM) and specific Certification Specification (CS). Likewise, in EASA, the same process is for initial certification by Federal Aviation Authority (FAA) (FAA, 2021).

2.3.2. The initial airworthiness certification process

Based on Part 21 regulation, EASA Type Certification (TC) process, and associated certification specification, there are 4 main phases for obtaining TC:
First, the applicant's eligibility is checked based on offered evidence and then a team of experts from EASA will be established to define application requirements and which will be EASA type certification basis (CB). The second phase consists of definition and then agreement on the proposed means of compliance (MOC) for each requirement and also Certification Program (CP). Phase 3 demonstrates compliance with the applicable certification basis and environmental protection requirements to provide the Agency with specific means by which such compliance has been demonstrated (declaration on compliance). The final stage is completing the investigation for validation and issuance of the proposed TC. The summary of aircraft TC processes based on EASA and FAA is shown in Figure 9 (EASA, 2021a; FAA, 2021).

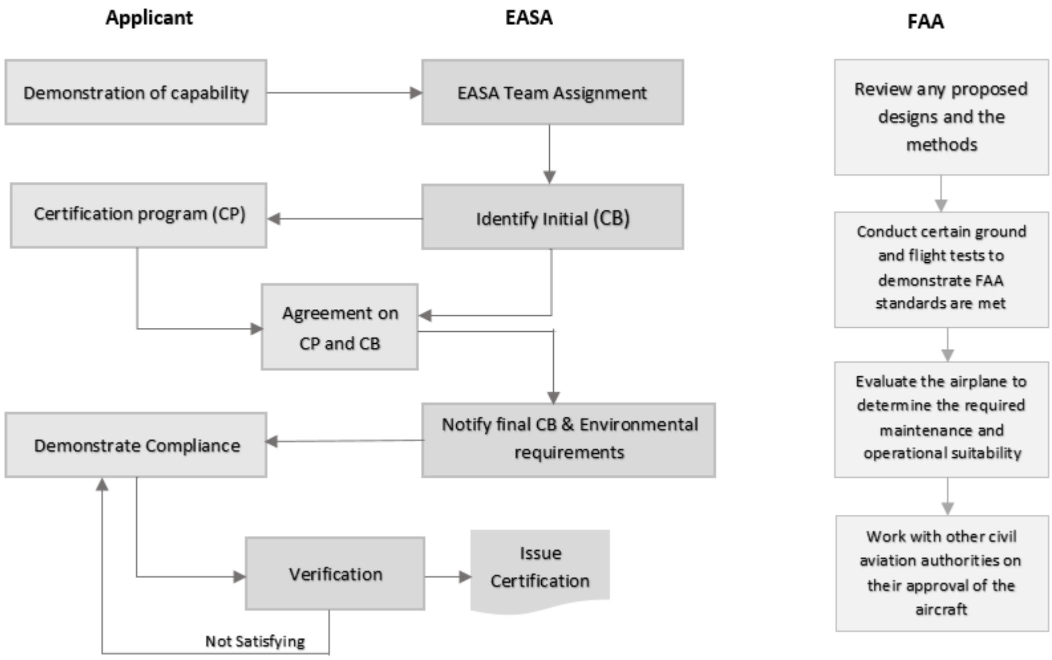


Figure 9. Certification Process

Certification specification, Means of Compliances (MOC) including EASA documents as well as industry standards and also Special Conditions (SC) for electric propulsion system based on aeroplane category in addition to CS-E which covers propulsion system requirements are listed in Appendix 1: EASA MOC. However, in CS-E, electric propulsion requirements are not included.

2.4. Safety Development process for A/C and A/C systems

2.4.1. System safety requirements

There is a direct link between system development, certification, and reliability process. The reliability process and safety assessment are similar in their approaches. According to the CS-25 AMC-25.1309 system design and analysis for large aircraft, industry documents and standards as a means for demonstration of compliance are accepted by EASA during the certification process (EASA, 2020). This is also applicable to the FAA according to FAA Advisory Circular AC-20-174 (FAA, 2011). The AMC are including SAE ARP 4754 "Certification Considerations For Highly-Integrated Complex Aircraft Systems" which is issued by the Society of Automotive

Engineers (SAE) to describe the system-level information to prove the compliance to regulations of complex systems. ARP 4761"Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment"(SAE, 1996), RTCA-DO 160 "Environmental Conditions and Test Procedures for Airborne Equipment", RTCA-DO 254 and RTCA-DO 178 dealing with hardware and software development respectively are other essential documents in the process of certification. Adherence to all requirements is crucial to achieving the certification.

ARP 4761 safety tasks and processes are mainly performed using reliability prediction methods, such as FMEA, FTA (Saglimbene, 2009), Common Cause Analysis, Failure Modes and Effects Summary (Vieira et al., 2016), due to a concurrence between safety assessment and reliability requirements.

The complete system design and development process according to the aviation industry requirements include requirements and functional inputs, outputs and interfaces between sub-processes which is shown in Figure 10.

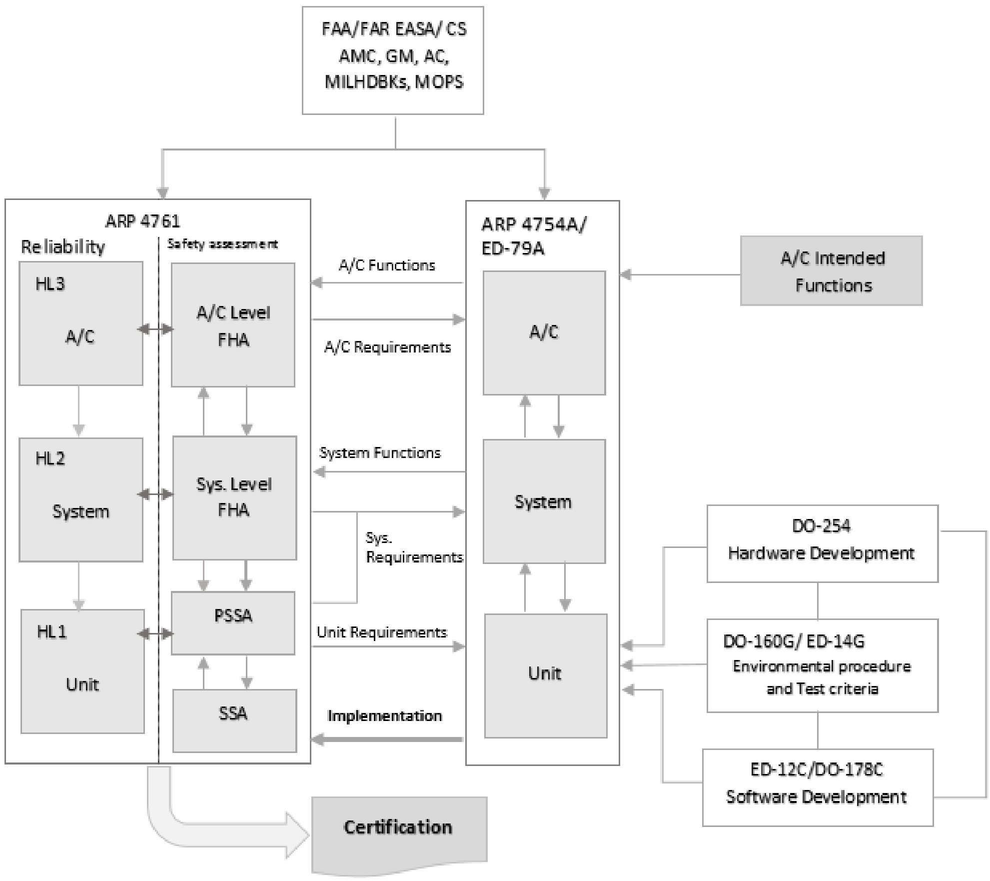


Figure 10. System design process

The safety analysis process based on ARP 4761 is a practical method for airworthiness requirements demonstration of compliance. The total process includes assessment of different stages in system development considering interaction with other supporting systems such as safety and reliability requirements (SAE, 1996). The safety assessment includes: Functional Hazard Analysis (FHA) in both A/C and System levels, in which based on required functions, potential failures are identified and hazards of failures classified. Then in Preliminary System Safety Assessment (PSSA), based on results of FHA, system and item level safety requirements is defined. The next step is System Safety Assessment, data from FHA and PSSA is gathered and analyzed to verify if all requirements are met. In all these steps, reviewing processes and feedback loops are required to be implemented (SAE, 1996).

As mentioned before, reliability requirements in three hierarchical levels provide different levels of requirements to assure system safety and reliability. The development assurance levels (DAL) are also considered for the severity of a failure at the component level, and unit level that propagates to a system-level failure. criteria of the DAL aircraft systems and components, qualitative and quantitative severity is defined in CS-25 AMC 1309 (EASA, 2020). To achieve a safe design, a combination of techniques should be applied, aiming to ensure both severity and probability factors are at an acceptable level, for instance, in a state of failure with catastrophic severity result, the probability must be Extremely Improbable, and in case of failure with hazardous severity consequence probability of failure must be Extremely Remote as shown in Figure 11.

Derived from FHA Failure Condition Classification	Derived from FHA Development Assurance Level	Safety Objectives Fail-Safe	Safety Objectives Quantitative Requirement
Catastrophic	A	Required	$P < 10^{-9}$
Hazardous/ Severe-Major	B	May be needed	$P < 10^{-7}$
Major	C	May be needed	$P < 10^{-5}$
Minor	D	No	None
No Safety Effect	E	No	None

Figure 11. Development Assurance Level (rate of probability shown per flight hour) (SAE, 1996)

The Revised documents ARP 4754A is the guide to the development of civil aircraft and systems and aims at covering the full cycle of design and production of aircraft and complex aircraft systems and offers to apply the V-model of the design process and also requires verification as shown in Figure 12 (SAE, 2010).

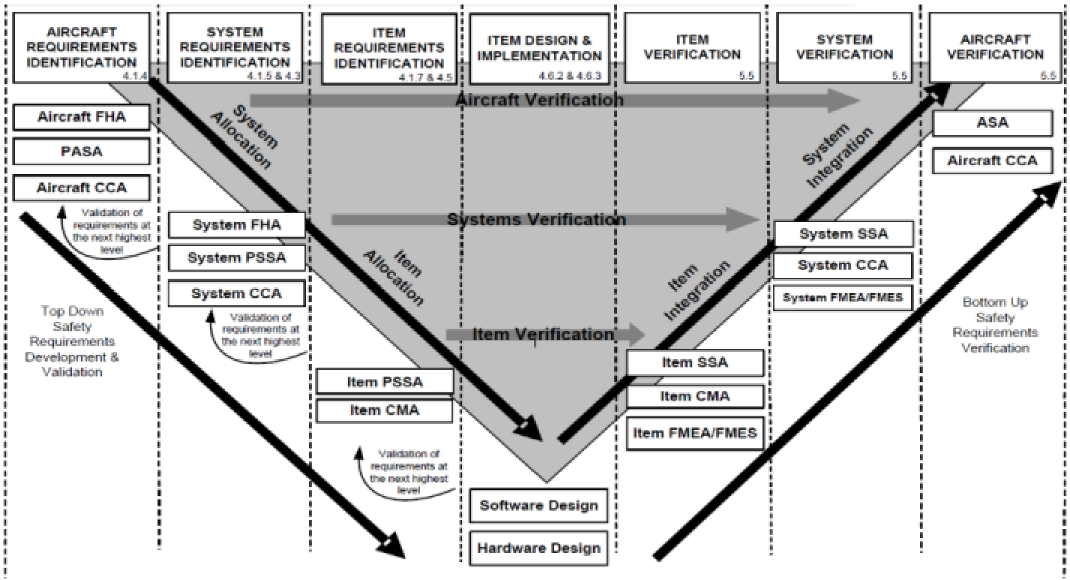


Figure 12. V-model of the aviation engineering design process (SAE, 2010)

Primary Aircraft Safety Activities per ARP4754 are listed in Table 3.

Table 3. Primary Aircraft Safety Activities per ARP4754 & ARP4761

Activity	Description
FHA	Identify potential failures, and their effects, and classify the severity of each.
PSSA	Analyzing the proposed architecture, to determine how failures identified in FHA could occur, offers safety requirements.
SSA	Evaluate aircraft systems to determine whether safety requirements are fulfilled.
CCA	Verify independence of functions and systems is sufficient for defined safety.

2.4.2. Risk Assessment in aircraft design

Hazard analysis and risk assessment are crucial not only in the design exploration phase but also during operations of a system, or in other words "throughout the system life cycle". There are many techniques stated in aviation industry standards such as ARP4761, for risk assessment, however, regardless of the techniques or the phase or level in which the assessment is performed, risk reduction strategies are applied by formulating mitigation policies (Graydon et al., 2020). The first step of risk assessment is the classification of the probability of occurrences and severity of consequence, afterwards safety risk index which is a combination of probability and severity will be assigned and finally, by applying tolerability criteria, tolerability will be determined. The likelihood of occurrence of a hazard could be classified both qualitatively or quantitatively, based on the availability of reliable data (Courtin & Hansman, 2019; ICAO, 2018). Severity classification is based on the effect on aircraft, occupant, and flight crew, and quantitative categorization of likelihood is considered based on the number of occurrences in-flight hours, both are shown in Figure 13 (1) and (2) respectively.

Severity of the Effects						
	Effect on Aeroplane	No effect on operational capabilities or safety	Slight reduction in functional capabilities or safety margins	Significant reduction in functional capabilities or safety margins	Large reduction in functional capabilities or safety margins	Normally with hull loss
	Effect on Occupants excluding Flight Crew	Inconvenience	Physical discomfort	Physical distress, possibly including injuries	Serious or fatal injury to a small number of passengers or cabin crew	Multiple fatalities
	Effect on Flight Crew	No effect on flight crew	Slight increase in workload	Physical discomfort or a significant increase in workload	Physical distress or excessive workload impairs ability to perform tasks	Fatalities or incapacitation
Classification of Failure Conditions		No Safety Effect	Minor	Major	Hazardous	Catastrophic

(1) Severity Classification

Classification of Failure Conditions	No Safety Effect	Minor	Major	Hazardous	Catastrophic
Allowable Qualitative Probability	No Probability Requirement	<-Probable->	<--Remote-->	Extremely <--------------> Remote	Extremely Improbable
Allowable Quantitative Probability: Average Probability per Flight Hour on the Order of:	No Probability Requirement	<--------------> $<10^{-3}$ Note 1	<--------------> $<10^{-5}$	<--------------> $<10^{-7}$	$<10^{-9}$
Note 1: A numerical probability range is provided here as a reference. The applicant is not required to perform a quantitative analysis, nor substantiate by such an analysis, that this numerical criteria has been met for minor failure conditions. Current transport category aeroplane products are regarded as meeting this standard simply by using current commonly-accepted industry practice.					

(2) Quantitative and Quantitative probability Classification

Severity of Failure	Tolerability Criteria For Residual Risk/ Mitigated Risk			
Catastrophic (4)	$<10^{-9}$			
Hazardous (3)		$<10^{-7}$		
Major (2)			$<10^{-5}$	
Minor (1)				$<10^{-3}$
No effect (0)				
Probability	Extremely Improbable (A)	Extremely Remote (B)	Remote (C)	Probable (D)

(3) Risk tolerability table

Figure 13. (1) Severity classification, (2) Probability classification, (3) Risk tolerability (EASA, 2020)

Tolerability of risk is categorized into 3 levels, (1) Intolerable, under any situation risk is not acceptable, design engineer (or safety practitioner) must remove this risk or reduce the severity, (2) Tolerable, this risk considers acceptable as a trade-off of production (flight) and risk, it means that these kinds of risks are inevitable, however, must be reduced as low as practicable, (3) Negligible, the effect of these risks are insignificant and no further action is required, however especially if they previously ranked as higher risk level, they should be monitored (Stapelberg, 2009), depicted in red, yellow and green in Figure 13 (3). In LIB in the electric propulsion system, the severity of occurrences in both discussed hazards (thermal and aging), considering the worst-case scenario, is categorized as "Catastrophic". It means that inherent risk without any mitigation, is intolerable, therefore to relocate the risk to a tolerable area, the probability of occurrence and/or severity of outcome must be reduced by applying effective countermeasures.

2.5. LIB in EPS

Lithium-ion battery consists of lithium ions, an anode, cathode, and separator. Anode usually is made of a lithium compound like graphite, while the cathode is coated in a thin layer of aluminium. And the separator prevents the direct connection between cathode and anode. In the LIB charging process, the ions move from cathode to anode. On and in the discharge process ions go from anode to cathode. In these ion transfers between anode and cathode, the electrolyte is a medium for ion transferring which contains an organic solvent and dissolved lithium salt (Hashemi, 2021).

LIB has been widely used as the main unit of the energy storage system in different applications. It is mainly owing to LIB's prolonged life span, higher specific energy, high power density, low self-discharge, and high reliability. LIBs evolved successfully from the specific energy of 98 Wh/kg in 1990 to 195 Wh/kg in 2008 (W. Liu et al., 2022) and more than 400 Wh/kg today. On the other side, the application of LIBs is involved with capacity depletion which resulted from various precursors including storage condition and handling, material parameters which link to cell chemistry and design factors, ambient condition, and abuse condition (Hendricks et al., 2015; Vetter et al., 2005). The other bottleneck of LIBs is the possibility of fire or explosion in case of miss management. Both circumstances can lead to fatality in electric aircraft. Therefore, a comprehensive study is needed to consider LIB failure modes and hazards to assess the overall risk and propose appropriate countermeasures.

2.5.1. Modelling studies for LIB hazard identification

Along with technological progress and using electric vehicles with higher battery characteristics, incidents have increased, and there are even more safety concerns regarding the application of batteries with a more specific energy in AEA and HEA (Sripad et al., 2021). Although considerable effort has been invested in thermal hazards and fire issues in LIB to provide effective preventive and reactive strategies (Lisbona & Snee, 2011), (Balakrishnan et al., 2006), (Q. Wang et al., 2019), (D. Ouyang et al., 2019), safety concerns of LIB use cases such as capacity reduction is less covered. Reviewed studies provide a wide perspective of hazards type, propose mitigation strategies, discuss related standards and safety tests, and risk management methods, as well as consideration of ambient and operational conditions. For instance, in high capacity applications literature generally addressed hazards and failure at the pack level (Larsson & Mellander, 2017; D. Ouyang et al., 2019; L. Yang et al., 2019) while a little effort is focused on a wider perspective starting from the atomic level up to pack level (Abada et al., 2016). Lisbona and Snee (2011), offer safety mechanisms categorized as hardware and software either at the cell level or system level. The environmental and operational conditions must be regarded, such as to determine the effect of low-pressure conditions on thermal runaway behaviour (D. Ouyang et al., 2019) or to analyze the impact of the state of charge and pressure on hazard fire (M. Chen et al., 2017). Assessment of risk for battery hazards to propose safety mechanisms, mostly performed in a qualitative manner (Larsson & Mellander, 2017; Q. Wang et al., 2019). However, Hendricks et al. (2015), offered the rating method for risk prioritization using Failure Mode and Effect Analysis, others due to the lack of adequate data, suffice the risk assessment to propose possible countermeasures. Bow-tie risk assessment methods proposed in (Bisschop et al., 2020) for fire hazards in electric vehicles.

Besides the cell chemistry, various mechanical, and electrical mechanisms, as well as Battery Management systems (BMS), are offered as reactive and preventive means for the safety of LIBs. Recent studies such as (Dai et al., 2021) focus on multilayer design for advanced battery management to establish data platforms and intelligence technologies to achieve higher safety performance.

2.5.2. Sources of hazards in LIB

According to (ICAO, 2018), a hazard is defined as "A condition or an object with the potential to cause or contribute to an aircraft incident or accident", if hazards are not controlled or managed they may lead to undesirable events. There is different categorization for hazards/ causes of LIB in the literature. In (D. Ouyang et al., 2019), thermal hazards of LIBs are addressed and categorization of them is based on the causes (physical, electrical, thermal, and manufacturing as well as ageing) performed. While according to (Sripad et al., 2021), LIB failure could be divided into thermal and functional, however, the thermal failures might lead to functional deficiencies and vice versa. Classification and finding the causes of LIB hazards is crucial, for designers to have a better approach to defining effective barriers and robust mitigation actions. Poor thermal stability of LIB is addressed as a significant issue in literature (Larsson & Mellander, 2017; Lisbona & Snee, 2011; Q. Wang et al., 2019) for a high number of applications other than aircraft and also as one of two major hazards in NASA X-57 aircraft project (Clarke et al., 2017). The other important group of hazards in this critical application is chronic or ageing hazards which mostly link to the history of the life cycle and operational condition of the LIB. The importance of chronic hazard is due to new technology of LIB, lack of experience from the field use, and insufficient data collected which make it difficult to determine or predict a complete life cycle behaviour.

2.6. Battery Management System (BMS) required functions

Battery Management System (BMS) is a system responsible for observing battery operational safety and efficiency issues (Damiano et al., 2018). In other words, BMS aims to predict failure and prevent it by employing measuring, controlling, and reporting. Factors being considered for BMS design are battery cell characteristics, system context, and functional needs (Lelie et al., 2018). The main functions of BMS are as listed below:

- Monitoring of battery via measurement of voltage, current, and temperature
- Evaluation & Estimation of State of Charge (SoC), State of Health (SoH), etc
- Management and Safety (Prevention of overheating, over current, and over-voltage)
- Data Communication (Between battery pack and other systems)
- Electromagnetic Interference (EMI) protection
- Battery charging/ discharging management (Damiano et al., 2018; Lelie et al., 2018)

According to safety, reliability, certification, and hierarchical approach of system development, aircraft top-level functions are defined for the intended aircraft as shown in Figure 14, left side based on Verrastro & Dimino (2018). For the aircraft level function (Generate and manage internal power/ Plan, generate A/C movement), the involved system is EPS in electric aircraft case. Since EPS consists of ESD (Energy Storage Device), electric motor(s), and Power Electronics (PE), system-level requirements determine performance requirements for these subsystems derived from the aircraft level. Therefore based on system-level requirements ESD units' requirements are composed of battery and battery management system presented in

Figure 14, right side according to Dai et al. (2021) which mostly focus on battery thermal, charging, balancing, safety, aging, and fault management.

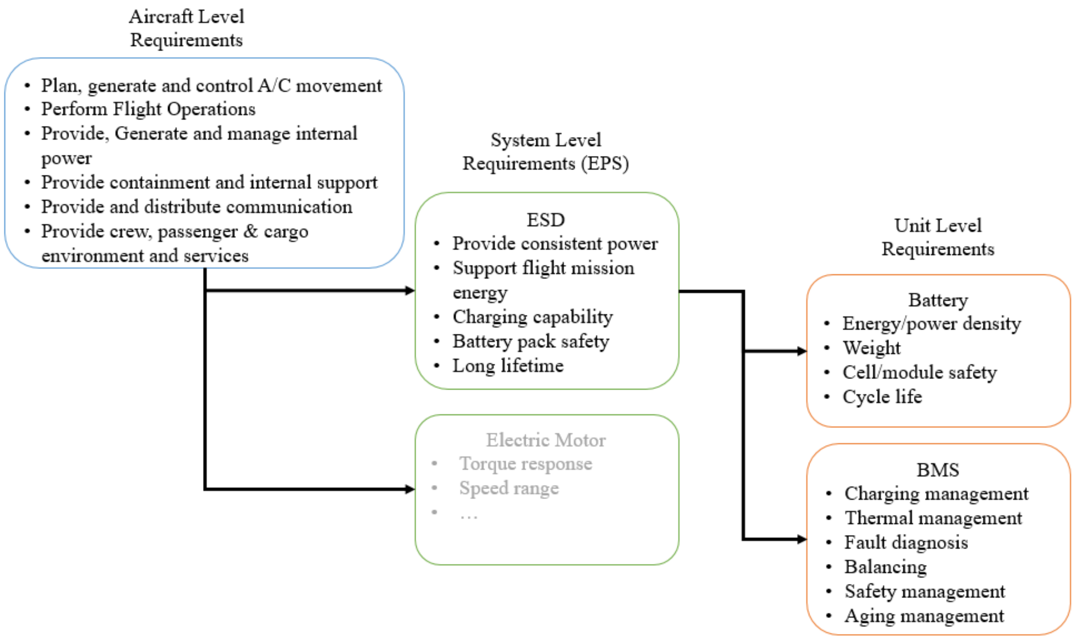


Figure 14. BMS functional requirements are based on aircraft level and EPS level requirements

To fulfil the required functions of BMS and provide adequate information for performing the determined functions, battery modelling, state estimation, and prediction is necessary for utilizing data acquisition and processing (Dai et al., 2021). Figure 15, shows the prerequisite of battery management functions initiated by data acquisition and processing and performance of battery modeling and state estimation.

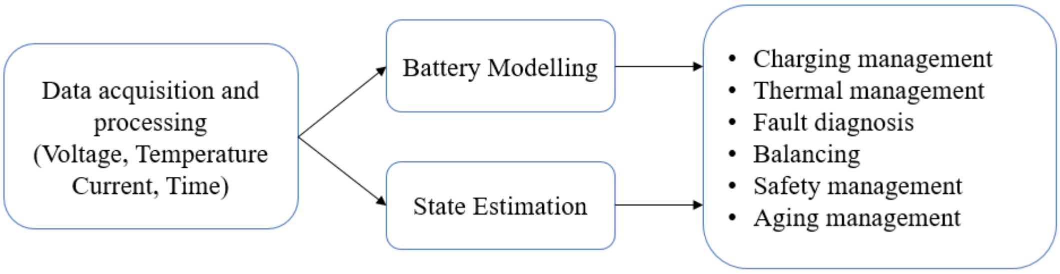


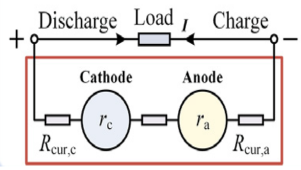
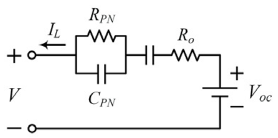
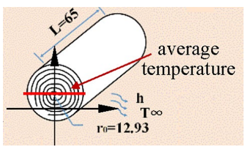
Figure 15. Hierarchical architecture of the advanced battery management technology adopted from (Dai et al., 2021)

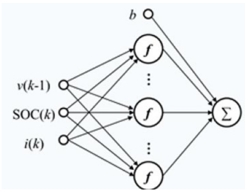
2.6.1. Battery modeling and state estimation methods

State estimation and battery modelling techniques are thoroughly analyzed in review papers (Dai et al., 2021; Hossain Lipu et al., 2021; W. Liu et al., 2022; Park et al., 2020) in the electric vehicle, power grids, and renewable energy resources application.

Battery Modelling: Accurate battery modeling is essential for precise state estimation and performance of required functions. Battery modelling is significant as stated by W. Liu et al. (2022) to improve charging/discharging strategies, maintain required capacity, develop advanced BMS, and prevent safety occurrences. A summary of methodologies for battery modelling is listed in Table 4.

Table 4. Battery modelling methodologies

Battery Modelling	Description	Features	Reference
Electrochemical Model 	Utilizing partial differential equations to describe the dynamics of electrodes and electrolytes to simulate the battery behaviours (P2D)	• Physics-based approach • Due to complexity is not appropriate for online application • Medium accuracy	(Doyle et al., 1993; W. Liu et al., 2022)
Equivalent Circuit Model (ECM) 	Using the basic electrical components to describe battery behaviours	• Medium accuracy • Suitable for online applications • Appropriate for SOC and SOP	(W. Liu et al., 2022)
Thermal Model 	The heat generation in the battery is modelled using battery temperature and electrical parameters	• Temperature impacts battery life and safety, the accurate thermal model is important	(Dai et al., 2021; Gümüşsu et al., 2017)
Aging Model	Aging models simulate the dynamics of battery aging mechanisms such as lithium	• the physics-based aging model has high accuracy and complexity	(Dai et al., 2021)

	plating, film growth, and loss of active material	• semi-empirical models are medium complexity and accuracy • Appropriate for prediction of RUL	
Data-Driven Model/ Black box Electrical Model  	Map nonlinear functions by building a mathematical model or discover the weight parameters using trained data	• No internal mechanisms nor physical or chemical processes considered • High accuracy • Medium complexity • Appropriate for (SOT, SOH, and RUL)	(Dai et al., 2021; Junping et al., 2006; W. Liu et al., 2022)

State estimation and prediction: Methodologies for battery state estimations are mostly categorized into three groups: (1) direct estimation method, (2) model-based method, and (3) data-driven method (W. Liu et al., 2022). Conventional/direct estimation methods like the Ah counting method, Open Circuit Voltage (OCV) method, and the impedance track method are used for SOC estimation; while these methods are less complicated and have lower computational costs, are less accurate, because temperature and aging are not taking into account (Park et al., 2020). Model-based methods such as ECM combined with optimization algorithms like unscented Kalman filters (UKFs), particle filters (PFs), and sigma-point Kalman filters (SPKFs) to minimize the error and achieve the real-time battery states estimation (Dai et al., 2021). The accuracy of these methods is directly depending on the accuracy of the model implemented and has fairly low computational complexity. Data-driven or model-less methods utilize artificial neural networks (ANNs), support vector machines (SVMs), and fuzzy logic (FL) in which hidden correlations are extracted from numerous trained data for state estimation. The internal characteristics of battery mechanisms are not considered for these methods, and the accuracy of these methods depends on the amount and validity of data and also the condition in which training is performed (Park et al., 2020). The data-driven leveraging intelligent algorithms are appropriate specifically for lithium-ion batteries to overcome the complexity of dynamic behaviour and nonlinear characteristics (Zhao et al., 2020). Due to the criticality of electric aircraft ESD, AI/ML algorithms are suitable candidates for satisfying battery management design requirements. Therefore, in this study deeper analysis of AI techniques in battery state estimation and fault diagnosis is performed in the following sections.

2.6.2. Review of AI Subset Application in Advanced BMS

Precise battery modeling and state estimation can guarantee the safety and reliability of its operation (Y. Wang et al., 2020). With the advancement of data-driven algorithms like ML methods, important progressive steps taken to the accuracy of SOC measurements by improving learning capabilities (K. Liu et al., 2021). Chandran et al. (2021) proposed a method for SOC estimation employing six machine learning algorithms including ANN, support vector machine (SVM), linear regression (LR), Gaussian process regression (GPR), ensemble bagging (EBa), and ensemble boosting (EBo). Results of error analysis show that ANN and GPR are the best methods based on Mean Square Error (MSE) and Root Mean Square Error (RMSE). In another study on the benefit of high-fidelity aging, data set generation, Tang, Liu, Li, et al. (2021) proposed a machine learning method with 1% error and a reduction of experimental time up to 90%. In this study combination of industrial data with fast-tracked aging tests applying migration-based machine learning, leads to the recovery of high-quality battery aging datasets.

Keyword co-occurrence analysis visualizes the relations and links between keywords that authors select for their work to demonstrate the overall structure of the field of study (Mariani et al., 2021). By applying the query in "VOSviewe" software, among 1839 keywords 49 meet the criteria of at least 8 times occurrences. The keywords found in the same keyword co-occurrence networks or clusters shown in the same colour are conceptually close, while their proximity to other keyword clusters and keywords could be interpreted as how close those concepts are to each other. The results of the keyword co-occurrence analysis are shown in Figure 16. It should be noted that the size of each node in the map demonstrates the number of repetitions in keywords, the bigger node the more occurrences, and the thickness of the link between the elements explain their co-occurrences of them in the same research (van Eck & Waltman, 2021). As depicted in Figure 16., BMS is located in the centre of the map near LIB and EV and SOC shows the interrelation of the concepts and can demonstrate the volume of the studies has been performed around the subjects. Also, the closeness of Neural networks (NN), Artificial Neural networks (ANN), and ML to the centre of the map can prove the application of those techniques in battery management especially estimation of SOC and SOH.

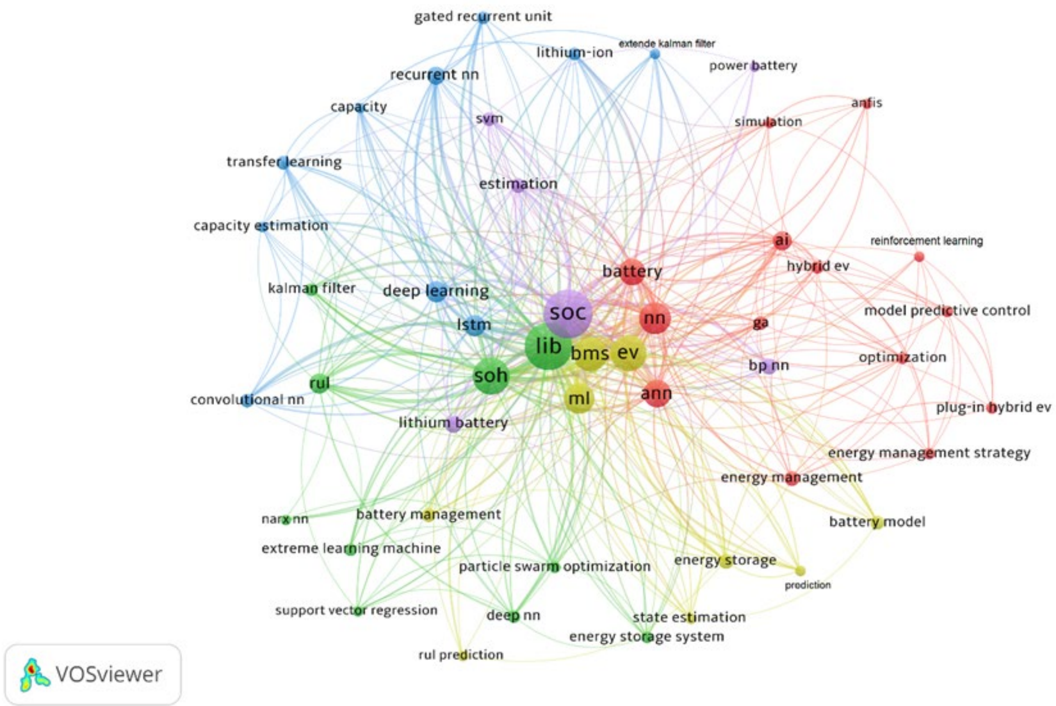


Figure 16. Author Keyword co-occurrences in the field of aircraft maintenance digitalization

The most repeated AI subset in the field of battery management are listed below:

- **Neural Network (NN) and Artificial Neural Network (ANN)**

"The NN method has an excellent ability to form a non-linear map to demonstrate a complex nonlinear model" (Y. Wang et al., 2020). An artificial neural network (ANN) is capable of self-learning, associative memory, and high-speed exploration for optimum solutions (Guo et al., 2017). Recently, for the sake of advancement in computing power, neural network-based methods have been employed more in battery management strategies. Chemali, Kollmeyer, Preindl, Ahmed, & Emadi (2018) proposed a method to estimate SOC for Li-ion batteries accurately using a Recurrent Neural Network (RNN) with Long Short-Term Memory (LSTM). The method can encode dependencies in time and estimate SOC without using any kinds of battery models, filters, or inference systems.. C. Sun, Sun, & He (2017) developed a neural network-based velocity predictor to forecast the driving behaviours using historical data. The proposed method can achieve enhanced fuel economy and a steady battery SOC trajectory while reducing fuel consumption by up to 3%. Similar strategies could be applied by BMS to contribute to the energy management of hybrid-electric aircraft. Chaoui & Ibe-Ekeocha (2017) established a technique using Dynamically Driven Recurrent Networks (DDRNs), in which no need for any model nor to identify internal battery parameters, instead uses the battery's voltage, charge/discharge currents, and ambient temperature to perform SOC and SOH co-estimation. The advantages of this online analysis are simplicity and robustness which make it appropriate to be used in BMS. Incremental capacity analysis (ICA) and radial basis function neural network (RBFNN) model was introduced by. She, Wang, Sun, Liu, & Zhang (2020) for battery aging assessment, which is crucial for the reliability and safety of battery systems operation. The RBFNN model can show the battery aging level and its influencing factors relationship based on operational datasets. Chang, Wang, Jiang, & Wu (2021) offer an online method according to the fusion of incremental capacity (IC) and wavelet neural networks (WNN) with a genetic algorithm (GA) to estimate SOH under current discharge.

- **Deep Learning**

The improvements in Deep Learning lead to the proliferation of new data-driven approaches to solve high complex non-linear problems (Ren et al., 2018). Ren et al. (2018), present a framework for RUL prediction of LIB using deep learning, which consists of three stages. The first stage is Feature Extraction in which characteristics during charge and discharge are extracted from the original data. The second step is the feature fusion that is performed by the auto encoder model. In the third, fused features are input to the DNN model to predict the RUL of the LIB. Finally, the output is predicting results. The experimental results show the more accurate results of the proposed approach in comparison with the linear regression, Bayesian regression, and support vector machines.

- **LSTM (Long- Short Term Memory)**

W. Li et al. (2021) developed a model for capacity estimation of LIB cells under real working situations with RNN having LSTM capability. LSTMs can work with changing sizes, meeting the requirements, and decreasing the processing work. The advantage of this method is the capability of working in case of fewer input data, presence of noise, or sensor error. Che et al. (2021) developed a method to predict RUL following online model correction using a combination of transfer learning and an RNN network. The reason for using transfer learning is to advance the estimation accuracy by transferring the maximum useful information of source data. Indeed, transfer learning techniques can contribute to more accuracy and decreases the computational load, by transferring the most relevant data. Transfer learning became the most repeated keyword among all intelligence techniques in recent years.

- **BP Neural Network (BP NN)**

To prevent sudden loss of power as an undesirable event resulting from aging hazards, there are different approaches to the management of batteries and estimating the State of Charge (SOC) (He et al., 2014). Guo et al. (2017) proposed a method for accurate estimation of SOC based on a BP neural network. BP NN is robust in nonlinear mapping able to accurate simulation of the nonlinear problems. In the study performed by Mao, Song, & Ding (2022) particle swarm optimization (PSO) algorithm is proposed for the optimization of the BP NN weights and thresholds. Results show that the prediction accuracy of SOC will be improved.

2.6.3. BMS function analysis utilizing AI/ML

Leveraging artificial intelligence techniques, BMS integrates necessary functions based on aircraft level and system level required performance including battery state estimation and battery modelling to fault diagnostics and prognostics, and control strategies as shown in Figure 17. BMS by performing these functions can detect and prevent substantial hazardous conditions resulting from aging or performance degradation and thermal issues.

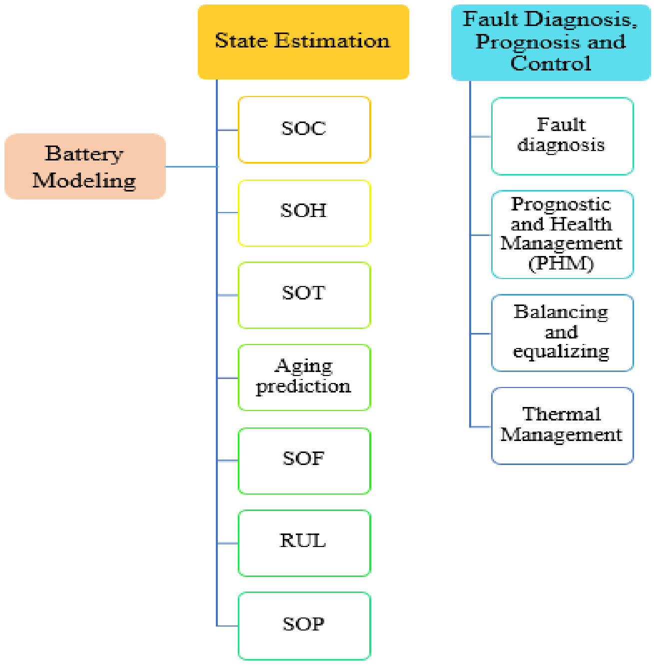


Figure 17. Fundamental functions of BMS in the literature supported by intelligent methods

- **State estimation**

BMS is designed to fulfill safe operational requirements by delivering state indicators. BMS state estimation indicators can be derived by model-based and data-driven methods. Model-based methods whether ECM or electrochemical models can benefit from intelligent algorithms to accurately predict battery parameters and state estimation. Chen et al. (2018) proposed a method for SOC estimation of LIBs based on an inclusive ECM, utilizing the neural network to assess the uncertainties in the battery model online. Chun, Kim, Yu, & Han (2020) presents a neural network structure to detect the parameters of an electrochemical LIB model in a real-time manner to perceive the electrochemical conditions of batteries. Can describe the microstructure changes in the charging and discharging processes of LIB. The electrochemical model is used also in the prediction of power or state of power (W. Li et al., 2022). In the following part, current progress in various state estimation and applied techniques are thoroughly examined.

- SOC: Battery SOC is a significant indicator of the battery; accurate estimation of the lithium battery SOC is a base for battery management. SOC can contribute to effective and efficient battery usage, avoid overcharge/discharge to increase safety, forecast electric vehicle mileage, and finally prolong the battery service life. A summary of recent literature and techniques used in SOC estimation with the highest rank of Citation per Year (CpY=No. of citation/ (current year-publication year)) is shown in Table 5.

Table 5. Results of the intelligent algorithms for SOC estimation in BMS

Algorithms	Input/ Output	Accuracy	Specific features	CpY	Ref.
LSTM-RNN	Inputs: Voltage, current and temperature Output: SOC	Mean Absolute Error (MAE) of 0.573% at a fixed ambient temperature, MAE of 1.606% on a dataset with ambient temperature	Algorithms can self-learn their parameters, even when exposed to scarce datasets Estimate SOC over different ambient temperature conditions In time estimation No model or filter is used	47.0	(Chemali, Kollmeyer, Preindl, Ahmed, et al., 2018)
Deep Feed Forward Neural Networks (DFFNN)	Inputs: Voltage, current and temperature Output: SOC	MAE of 1.10% over a 25 °C dataset MAE of 2.17% over a −20 °C dataset	Self-learns network weights Efficient computation Increased SOC estimation accuracy by adding noise to train data Estimate SOC over many ambient temperatures In time estimation No model or filter is used	42.0	(Chemali, Kollmeyer, Preindl, & Emadi, 2018)
Dynamically Driven Recurrent Networks (DDRNs)	Input: Voltage, charge/discharge currents, and temperature Output: SOC and SOH	RMSE IN SOC 0.5305 for 25°C RMSE IN SOH 0.1126 in 1800 cycle	Co-estimation of SOC and SOH Nonlinear dynamic nature, hysteresis, aging, dynamic current profile, and parametric uncertainties are considered Method simplicity and robustness	35.5	(Chaoui & Ibe-Ekeocha, 2017)

Gated RNN	Inputs: Voltage, current and temperature Output: SOC	MAE of 2.5%	Suitable for real-time onboard applications Data well trained under different ambient temperature	33.8	(F. Yang et al., 2019)
Radial basis function (RBF NN)	Inputs: Battery pack current and voltage Output: SOC	MAE of less than 2%	Estimation framework for multi-cell series-connected battery pack An equivalent circuit model and parameter identification are used Off-line data training On-line SOC estimation	31.7	(F. Sun et al., 2016)

- SOH: The SOH defines the degree of battery aging and can be described by the capacity loss or the resistance increase (Shen et al., 2017). Battery performance degrades during its operation and needs to be replaced when the maximum existing charge/discharge capacity reaches 80% of the initial capacity. In this situation, the battery is not able to respond to the demanded peak load (Park et al., 2020). SOH is often assumed to maintain the battery performance within the design borders and storage lifetime (P. Li et al., 2020). SOH estimation accuracy is indispensable for safety because SOC estimation also is influenced by SOH changes. Therefore, battery system safety and operational efficiency of the energy storage system are linked with SOH estimation accuracy (Park et al., 2020). A list of algorithms application in SOH estimation stated in the top-cited literature is shown in Table 6.

Table 6. Results of the intelligent algorithms for SOH estimation in BMS

Algorithms	Input/ Output	Accuracy	Specific features	CpY	Ref.
Support Vector Machine (SVM)	Inputs: SOC0, Temperature, Ah, Time and Cycle number Output:	-	Co-estimation of SOH and RUL Using method for training data processing by load collectives	34.8	(Nuhic et al., 2013)

	SOH and RUL		Applicable for on-board battery management		
Random Forest Regression	Inputs: Charging voltage-capacity curve and capacity Output: SOH	The maximum root-mean-square error of 1.3%	Online battery capacity estimation Accurately estimate the capacity of batteries aged under different cycling conditions	28.4	(Y. Li et al., 2018)
A variant long-short-term memory (LSTM) neural network (NN)	Inputs: Voltage, Current, Capacity, Time, Temperature Output: SOH and RUL	Root mean square, 0.0216	Co-estimation of SOH and RUL Offline training and online estimation are performed The AST-LSTM cell determines old information and new data simultaneously Hybrid Algorithms are applied	28.3	(P. Li et al., 2020)

- RUL: RUL represents the remaining number of load cycles or times of a battery cell to satisfy its performance requirement. SOH is the base of the calculation and determination of RUL (Park et al., 2020). Real-time prediction RUL is a vital feature in the battery management system (Patil et al., 2015). Patil et al. proposed a method using Support Vector Regression (SVR) to predict the accurate RUL to demonstrate if the battery is close to the end of life (EOL). To this end, cycling data of LIBs under different operating circumstances are analyzed, and then critical features are extracted from the voltage and temperature profiles, by doing so and the multistage approach, accurate RUL prediction of multiple batteries is performed concurrently (Patil et al., 2015).

- State of Temperature (SOT): Battery characteristics varied by temperature. Therefore estimating temperature, especially in high-density packs is crucial (Park et al., 2020). The electrochemical thermal model is capable to present the heat produced by the chemical reactions of LIB, such as over-potentiation at the reaction surface, ohmic loss in the electrodes, ion transport in the solid electrolyte interphase (SEI), and entropy during charging/discharging (Park et al., 2020). Feng et al. (Feng et al., 2020) developed an electrochemical-thermal-neural-network (ETNN) model to estimate core temperature and terminal voltage under the ambient temperatures of -10–40 °C and the discharge rate of 10-C. In this study, the Unscented Kalman filter (UKF) is integrated with ETNN to achieve reliable co-estimation of SOC-SOT. Experimental results show that executed ETNN-UKF can eliminate initial errors and provide acceptable co-estimation performance.

- Aging and degradation prediction: Battery performance and characteristics are highly affected by aging status. Therefore to ensure efficient, reliable, and safe operation of the energy storage system, accurate battery aging estimation is necessary (She et al., 2020). Liu et al. (2020) developed a machine learning method for calendar aging prediction employing Gaussian Process Regression (GPR) technique to capture the primary mapping between capacity, storage temperature, and SOC. Results are satisfactory to predict calendar aging with RMSE less than 0.0105. One feature of this study is utilizing calendar aging data from nine storage cases to model training, validation, and comparison, rather than using the data from a single condition. Moreover, since storage condition is one of the aging process cases calendar aging besides cycle aging is prominent.

- State of Function (SOF): The SOF reflects how the battery performance can meet the real load demands (Shen et al., 2017). It is an indicator to predict the maximum instant output capability and operation within the defined thresholds (safe operation area), such as voltage limits, current limits, and SOC limits (Park et al., 2020; Shen et al., 2017). J. Ouyang, Xiang, & Li (2020) proposed the Fuzzy Logic Control Algorithm (FLCA) to evaluate the SOF of the battery pack. SOC, Temperature, and C-rate are considered input variables. However, this method is capable to add other inputs such as SOH, battery internal resistance, and cycle life to improve the accuracy.

- State of Power (SOP): SOP as a battery indicator or soft sensor explains critical information about energy storage systems to ensure battery-optimized performance and longer life span (Tang, Liu, Liu, et al., 2021; Wei et al., 2019). The SOP is the percentage of peak power or maximum continuous power over a short period compared to rated power (Y. Wang et al., 2020). Wei et al. (2019) developed an extremum-seeking algorithm to identify parameters based on the ECM model to predict SOP while voltage and current limitations of the battery are considered. Considering both voltage and current as input variants can ensure the exploit of the battery in a safe operational range. The simplicity and numerical stability of the method make it suitable for real-time battery management applications.

As shown in Figure 18, SOC and SOH estimation as a basic indicator of battery status, using intelligence algorithms, is well studied in the recent decade. While application of intelligent technology in SOF which is one of the most imperative functions of the BMS (J. Ouyang et al., 2020), has not been adequately addressed. In electric aircraft cases, SOF and also SOP provide valuable information to the pilot for decision-making before or during the flight.

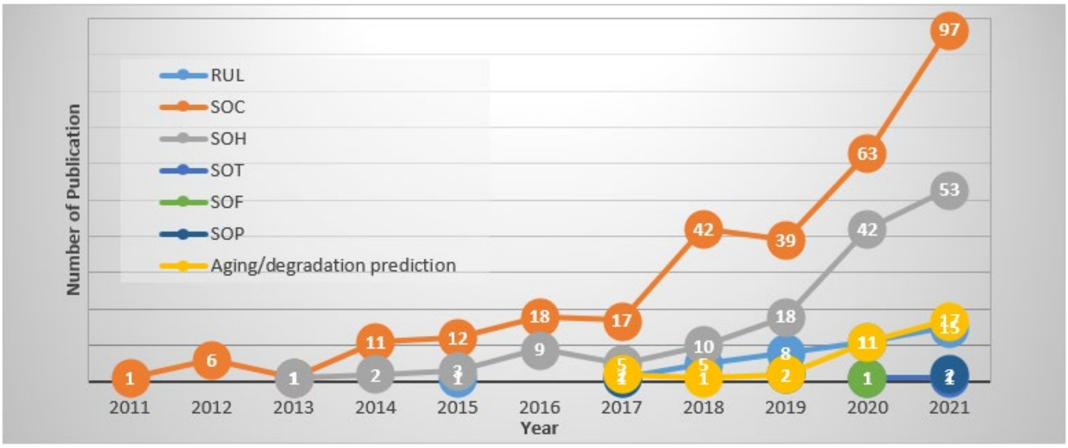


Figure 18. The trend of top keywords regarding AI application in state estimation in recent 10 years

- **Fault Prognostics, Diagnosis, and control**

The safe operation of battery-powered applications is greatly affected by the safety and reliability of the energy storage system. Therefore, one important feature of battery management is Fault Prognosis, Diagnosis, and control. In this section, recent studies about Fault Prognosis, Diagnosis, and control mechanism of BMS that are supported by intelligent algorithms will be discussed.

- Fault diagnosis: The first step of fault management is fault diagnosis and detection. It is also considered the first stage in condition-based maintenance (Khumprom & Yodo, 2019). Condition-based maintenance is a preventive maintenance strategy, in which component or system performance constantly is under evaluation until a maintenance task is required (Camci & Chinnam, 2010). If BMS is armed with a precise and intelligent fault diagnosis scheme safety of power systems could be assured (Hashemi et al., 2021). It becomes more significant when a minor fault could finally lead to severe problems (Hossain Lipu et al., 2021). Mechanical and operational abuse conditions might lead to an internal short circuit which is the main cause of the thermal runaway in LIBs. Naha et al. (Naha et al., 2020) proposed a random-forest-classifier method based on the ML approach for real-time detection of the internal short circuit. The accuracy of the result is more than 97%. One positive feature of this study is that the normal operation of the device is not affected by the algorithm, and also the trained model can be applied to any device for online fault diagnosis. Sensor fault is another possible condition that can deteriorate BMS functions. Lee et al. (2020) proposed a deep learning algorithm to predict unreliable data from sensors. The proposed model can be executed on a local server or a cloud computing platform. Censor cell voltage, current, and SOC are inputs of the model.

- Prognostics and Health Management (PHM): PHM can manage the risk of failure before its occurrence, this is an essential technique for ensuring the safety and reliability of the battery. PHM can ensure the battery meets its application power and energy demand. Prognostics is considered the second step of the condition-based maintenance as shown in Figure 19. The prognostics process involved two steps. The first is the assessment of the current status of battery health or SOH, and the second stage is the calculation of the time of failure by prediction of degradation trend or RUL (Khumprom & Yodo, 2019). Khumprom & Yodo (2019) proposed a data-driven prognostic technique, applying a Deep Neural Networks (DNN) approach to predict the SOH and the RUL of the LIB. The accuracy of the results proves the possibility of the replacement of traditional physics-based models with data-driven models in different fields and applications.

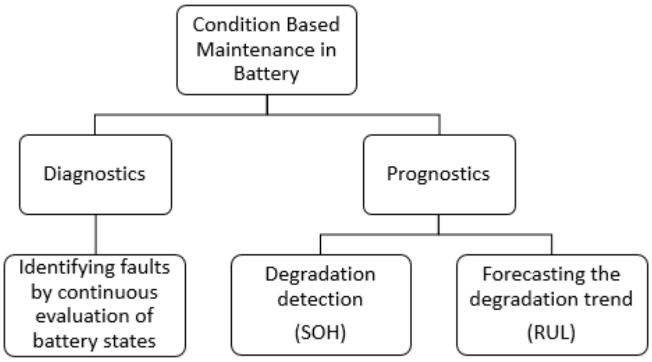


Figure 19. Condition Based Maintenance in Battery (Adopted from (Khumprom & Yodo, 2019))

- Balancing and equalizing: The battery pack consists of several single batteries in series and parallel to respond to the required voltage, power, and energy. However, due to differences in internal resistance, capacity, aging, and alteration of the ambient temperature typically there are inconsistencies among battery cells, which threaten the safety of the battery pack (B. Wang et al., 2020). Xia & Abu Qahouq (2021) develop a method for SOC balancing according to the SOH of each cell using ANN algorithms. In which correlation between impedance and capacity reveals information about the SOH and aging of each cell. Then this information is fed to the SOC balancing controller to adjust cell SOC. This method accurately prevents over-discharge of cells with low SOH.

- Battery Thermal Management: Battery performance and characteristics are greatly affected by temperature. Thus the different mechanisms for cooling and preheating are proposed to ensure the safe operation of the battery in the safe operation area (W. Liu et al., 2022). Intelligence algorithms can support the process of thermal management by heat generation rate detection (Panchal et al., 2016) prediction of the cooling capacity of Battery Thermal Management System (BTMS) (Panchal et al., 2018), battery thermal modelling (Q.-K. Wang et al., 2017), and improving temperature uniformity (Y. Liu & Zhang, 2020; Panchal et al., 2018). Panchal et al. (2016) developed a model using the NN approach to predict the heat generation of LIB at different discharge rates and various temperature ranges within the temperature border. Y. Liu & Zhang (2020) propose a self-adaptive NN-based model to implement a predictive control strategy for an air-based BTMS. The pre-control temperature uniformity leads to improve control flexibility. Although this method can control maximum temperature requirements, thermal effects from other elements such as the air conditioner energy intake are not considered.

Figure 20 shows the trend of fault diagnosis and PHM techniques as well as BTMS and balancing strategies in BMS assisted by intelligence algorithms in ten recent years based on article author keyword, title, and abstract. As illustrated, applying AI approaches to support the implementation of thermal management and balancing and equalization schemes is more studied in comparison with fault diagnosis and PHM. While many studies focus on battery fault diagnosis and prognosis, PHM which has become a noticeable area for exploration of dynamic system degradation, intending to enhance decision-making for contingency progress (Kohtz & Wang, 2020), required further attention specifically in critical applications like EA and HEA.

Figure 20.The trend of top Fault diagnosis, prognosis, and control strategies in BMS supported by AI in recent 10 years

3. METHODS

3.1. Reliability and initial airworthiness requirements analysis methodology

The primary methodology of this part of the study is a review of academic literature, industry practices, aviation authority regulations, and applicable standards aiming to answer the research questions. Besides that, the case study of electrical aircraft will be reviewed concerning the architecture and airworthiness requirements. Academic research is filtered based on relevance, date of publication, the validity of the journal and number of citations. Aviation legislation is selected according to applicability and the latest revision from official regulatory websites.

All data was gathered by reviewing articles, rules, regulations and standards mainly from academic journals, International Civil Aviation Organization (ICAO) publications, International Air Transportation Association (IATA) documents and manuals, European Aviation Safety Agency (EASA) Regulations, Federal Aviation Administration (FAA) regulations and policies, International Electrotechnical Commission (IEC), American Society for Testing and Materials (ASTM) standards, The Engineering Society For Advancing Mobility Land Sea Air and Space (SAE) procedures and US military handbooks.

Considering the topology of Battery-BMS-PE depicted in Figure 21 which is composed of three main subsystems as a common essential architecture employed in hybrid and all-electric propulsion configurations, an attempt will be made to find the initial airworthiness and reliability requirements for each subsystem.

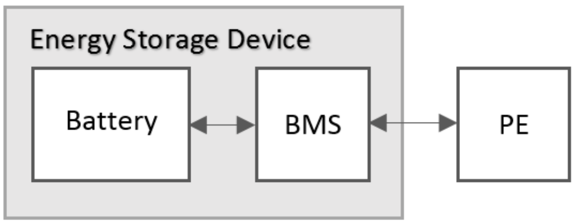


Figure 21. Provisional subsystems of EPS

Although in the conventional large A/C equivalent essential subsystems of the electrical propulsion system (ESD and PE) are utilized widely in various systems, the level of energy/ power and application in EPS is different. Therefore, a comprehensive study is needed to find out initial airworthiness practices and reliability requirements.

3.2. LIB hazards identification, classification and safety risk management methodology

To enhance safety in the application of electrical propulsion depth analysis of Energy Storage Devices (Lithium-Ion Battery (LIB)-Battery Management system) considering proposed mitigation to manage the associated risks will be performed as a part of system safety assessment for FHA of the proposed unit. In this regard LIB as a unit of the electric propulsion system, hazards will be classified, contributing factors, outcomes, and consequences will be listed then for each hazard, the risk assessment will be performed considering the probability of occurrences and severity of consequences. Then appropriate control measures on software and hardware and possible mitigation strategies will be identified. The root cause analysis and risk assessment method used in this study is a fish-bone diagram and bow-tie model respectively will be discussed in the next part.

3.2.1. Fish-bone diagram

Fishbone (Ishikawa) diagram is a method for suggestive demonstration of the relationships between an event (effect) and its various causes. It is a method for the identification of the root causes of the problem (Ilie & Ciocoiu, 2010). In particular, a fishbone diagram (the figure is comparable to a fish skeleton) is a method used for a cause-and-effect analysis and visualization to classify a complex interaction of causes for solving a specific problem as Figure 22. In this study, we applied a method for analysis of LIB hazard contributing factors.

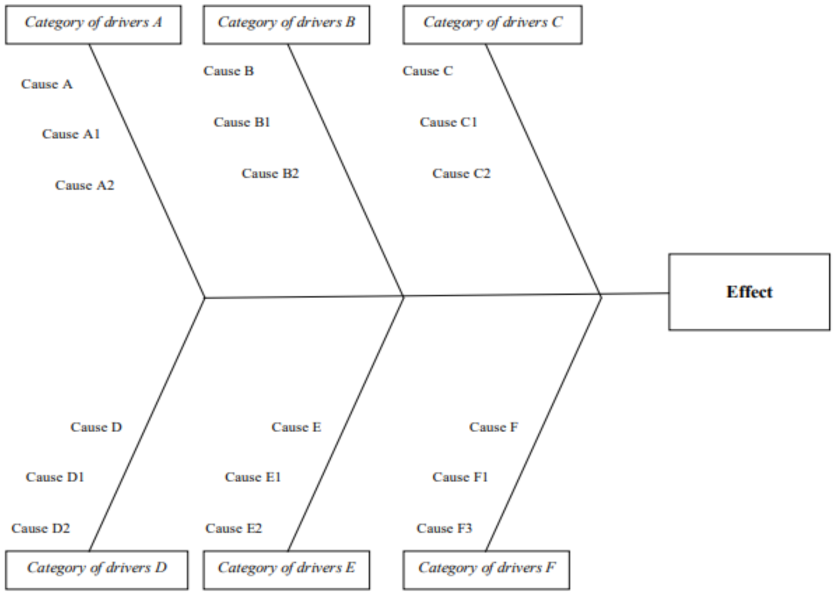


Figure 22. Fishbone diagram (Coccia, 2020)

3.2.2. Bow-tie hazard analysis model

The Bow-tie model is a combination of Fault Tree Analysis (FTA) on the left-hand side and Event Tree Analysis (ETA) on the right side (Alizadeh & Moshashaei, 2015). FTA is applied to illustrate the failure of a system in a diagram format, aiming to show the steps of one or several paths to a critical event at the end and ETA on the other hand initiates with an event followed by multiple tree branches/ paths of system failure outcomes or consequences (de Ruijter & Guldenmund, 2016). The schematic overview of the bow-tie diagram is depicted in Figure 23. This qualitative model consists of causes, barriers or controls, that converge with the undesirable event (loss of control/ hazard release/top event), mitigation actions/ recovery and outcome/ consequences (de Ruijter & Guldenmund, 2016).

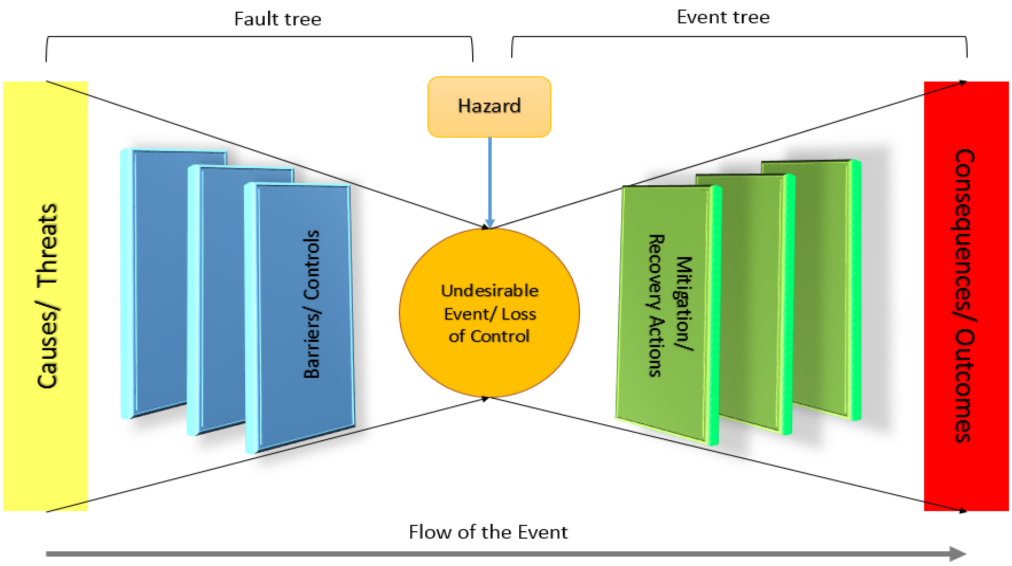


Figure 23. Bow tie Model

The bow-tie process consists of seven main steps (Alizadeh & Moshashaei, 2015). This process initiates with a hazard which is identified through different sources, then:

- Define the undesirable event/ loss of control
- Assess the threat/ hazard
- Assess the consequences
- Define controls or barriers.
- Define mitigation actions/ recovery
- Identifying failure conditions of control
- Identify the controls for the threats to the controls

3.2.3. BowTieXP Software

For visualizing hazard analysis and risk assessment of LIB, BowTieXP 10.4 software, is used. BowTieXP is designed by "CGE Risk Management Solutions" as powerful and easy-to-use software for bow-tie analysis (CGE, 2021).

3.2.4. Assumptions and limitations

Key assumptions and limitations of hazard analysis are listed below:

- The battery is being used in electric propulsion to drive a fixed-wing regional aircraft.
- Based on aircraft fixed-wing design, the vehicle is supported by wing lift during all phases of flight.
- Wings size are capable to provide a survivable landing speed without power in case of power loss.
- However, the structural design characteristics are not shown in mitigation strategies in the bow-tie model, they are considered in the process of risk tolerability assignment.
- The process of charging on the ground facilities is disregarded in hazard analysis.
- Environmental conditions are not considered in the process of risk assessment.
- All risk control and mitigation strategies are based on the current assumption, not beyond the current aircraft safety capabilities.

4. ANALYSIS

4.1. Provisional subsystem for HEA and AEA airworthiness requirements

4.1.1. The current state of initial airworthiness certification requirements for the electric propulsion system

To respond to industry applicants regarding the design and installation of Electric/ Hybrid propulsion systems Special Condition SC E-19 "Electric / Hybrid Propulsion System" was issued, but still, some areas exist that are not addressed. For instance, in large aeroplanes, emissions requirements need to be developed as a complementary specification for CS-25 (EASA, 2021a).

American Society for Testing Materials (ASTM) F3338-18 is introduced as an acceptable means of compliance along with other introduced SCs in the SC E-19 document. Indeed, ASTM F3338 refers to the design of EPS for General Aviation and does not support requirements for other aircraft categories, for instance, large commercial aeroplanes. Although EASA relies on ASTM standards in the electrical propulsion system, there are some gaps in these standards which need progress to meet technological advances. Taking a look at ASTM standard organization, F (37, 39, and 44) committees are responsible for working on light sport aircraft, A/C systems and General aviation aircraft respectively (ASTM, 2020b). Each committee consists of a different subcommittee that works on specific standards according to Appendix 2: ASTM standards for aircraft electric systems. There are inadequacies involved with ASTM references such as standards are limited to small general aviation while do not address all-electric propulsion systems. In addition, it seems that not all ASTM standards regarding electric propulsion systems are followed by EASA regulations.

It is important to note that ASTM standards might be more broadly applicable however the applicant is responsible to prove the suitability of those standards as a specific means of compliance. This would enable applicants and regulatory authorities to extend the standards to wider scope as a short-term solution for providing agreement on the subject. Considering the requirement capture as the first step, the type design approval process continues with the certification plan and final demonstration of compliance. The process steps are summarized in Figure 24 (Serrao et al., 2018). After acceptance of the certification plan by the authority and building a prototype, conformity inspections, detail level and component level compliance activities as well as flight tests will be performed and the satisfactory result might lead to TC issuance. However, lack of adequate industry experience in validation and verification, the issuance of a type certificate for an electric engine or aircraft is challenging for both design organizations and regulatory parties.

Besides that, some of the requirements of FAA & EASA regulations, which are defined to fulfil airworthiness requirements in the operational phase as post-certification activities, however, do not cover electric propulsion. EASA, for instance, applies commission Regulation (EU) No 1321/2014, Annex I (Part-M) subpart F and Annex II (Part-145) for specifying maintenance organization requirements, to *piston* and *turbine* propulsion, cover neither electric motor, including power electronics nor batteries. It is also true for certifying staff licensed category under EASA Part 66 which above mentioned subsystems are not considered in their training syllabus and knowledge rating.

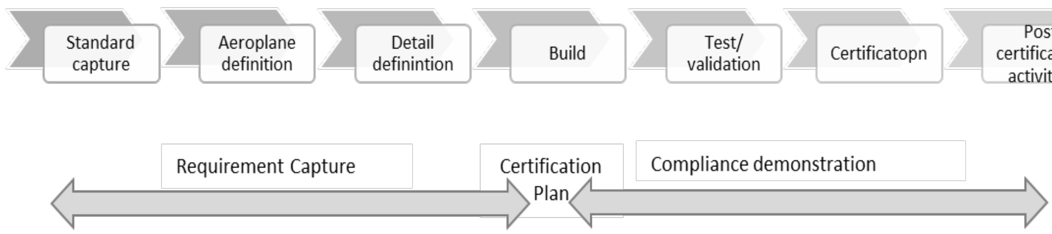


Figure 24. Type Design Approval Process

4.1.2. Power Electronics Reliability and Certification Requirements

Taking into consideration the concepts of HEA and AEA discussed before, PE units play a dominant role in aircraft electrical propulsion systems. Although many previous studies about PEs focus on the electric power system, few detailed studies performed on the architecture of electric propulsion aircraft (Dorn-Gomba et al., 2020). Based on the different architectures of the electric propulsion system reviewed before, at least 3 types of PEs are needed; AC/DC (rectifier), DC/AC (inverter) and DC/DC (DC converter). According to mentioned topology, a specific focus is given to DC/DC converters and DC/AC inverters which are mainly used in hybrid and all-electric propulsion systems to convert the DC output of the energy storage unit to AC as input for driving an electrical motor(s) as shown in Figure 25. PE connected to the battery pack is a bi-directional converter interface with the bus (Barzkar & Ghassemi, 2020) with a possible functionality to recharge the battery.

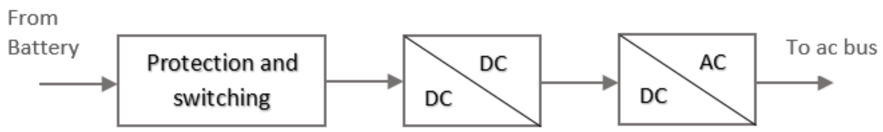


Figure 25. Power Electronic in electrical propulsion system architecture

DC/DC conversion could be provided using isolated bi-directional DC/DC converters. Converters used in aircraft must have high power density, high efficiency and reliability. Dual Active Bridge is one of the most popular DC/DC converters (Rahrovi & Ehsani, 2019). DC/AC inversion is mostly performed by Voltage Source Inverter in HEA and AEA to drive propulsive motors. Like other PEs power density is a critical requirement in the design process of DC/AC inverters (Dorn-Gomba et al., 2020).
Since many faults such as short circuits, arcing and overload might occur in the electrical system, protection devices must be developed to prevent unsafe conditions in flight. Circuit Breakers (CB) are common in electrical power systems, they connect PE converters and energy storage units with a low resistance to improve efficiency and also, prevent failure to be spread. Besides CBS, semiconductor-based devices such as SSPC (Solid-state Power Controller) are utilized in PEs to protect and diagnose faults (Dorn-Gomba et al., 2020).
Power electronics converters serve the propulsion system, depending on the redundancy in the powertrain allocated high safety severity levels from DAL A to DAL C (high failure severity) due to their effect on failure condition.
Acceptable MOCs to demonstrate in the process of certification from the view of EASA and FAA regulations for system and unit level development life cycle of PEs framework depicted as Figure 26.

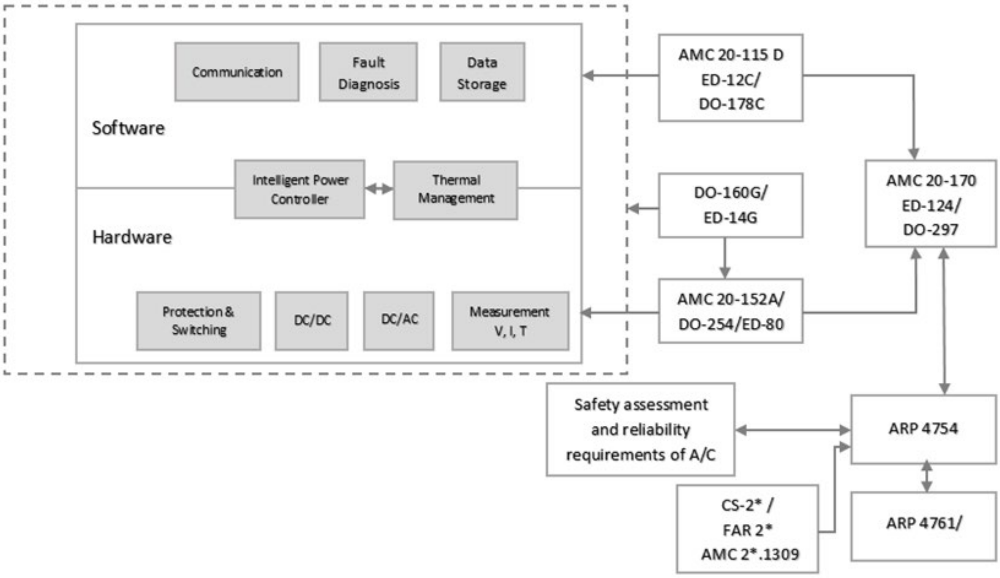


Figure 26. PE architecture and applicable requirements

The hierarchical levels approach is employed to assess reliability systematically, considering loading and environmental conditions. In addition, using this method enable to analyse results of failure characteristics of different HL1 (components) and HL 2 (subsystems) on HL 3 (system) reliability.

Using MEA power electronic practical experience regarding reliability issues such as component and subsystem failure rate, along with experience gained in accelerated testing of PEs in the electrical power system in current aircraft, is an efficient way to evaluate different architectures of power electronic system for electrical propulsion in the process of reliability design and certification.

4.1.3. Battery Reliability and certification requirements

As discussed before regarding the necessity of growing progress in battery systems, the introduction of new emerging technologies for batteries, however, combined with ingrained hazards such as fire, requires altering previous well-known and well-established methods, and initiating more forecasting of the rate of failure as well as protection and prevention methods (Emmanouil, 2020).

Batteries might fail to provide defined performance due to different degradation mechanisms. The FMMEA (Failure modes, mechanisms, and effects analysis) is an effective solution for identifying failure mechanisms and the models to forecast the degradation or failure. Battery reliability and safety used to rely on testing standards based on the pass/ fail concept which today the results are not enough for system design or risk assessment; while the FMMEA process is capable to quantify the effect of tests on the safety of a battery or battery system. Safety test results are the inputs for battery models and make it possible to predict the system's response to environmental conditions (Hendricks et al., 2015).

From the certification aspect, due to lack of relevant experience, although in case the special conditions such as SC-LSA-F2480-01 issued by EASA (EASA, 2017) for LSA category aircraft as a generic specification, this document discriminates neither type of electrochemistry nor capacity or safety features of batteries. Moreover, further adaptation is needed in the future distinctively for Propulsive Energy Storage other than conventional Service Batteries used to feed avionic loads or engine start (Yildiz & Koruyucu, 2021), especially for categories other than LSA. Due to the criticality of battery function, the decision about using separate energy storage devices for propulsive purposes and service batteries is another crucial issue (Yildiz & Koruyucu, 2021). This concept is reflected in SC E-19, in which the Propulsion Battery is defined as "Means a battery or a set of batteries intended to provide electrical power to the electric engines of the EHPS (Electric/ Hybrid Propulsion System)". Also, it is mentioned that Propulsion Batteries can provide electrical power to other EHPS sub-systems or to systems (EASA, 2021a), to clarify the different requirements of propulsion batteries.

Even though due to current inadequate practical experience about the usage of rechargeable lithium batteries, for instance, in MEA commercial aviation, it should be mentioned also that it is neither enough for fully electric nor for hybrid propulsion systems to address requirements along with the technological progress.

In the certification process, the suitability and reliability of batteries are demonstrated by experience or by performing tests according to applicable standards such as RTCA DO 311, DO 347, UN T 38.3, and UL 1642 can be accepted upon agreement with the Agency. However, the requirements of CS-25.1309 "Equipment, systems and installations" should also be satisfied. A sample of catastrophic and hazardous condition safety requirements is "self-sustained, uncontrolled increases in temperature or pressure, as a result of any failure within the battery" must be extremely improbable less than one in $<10^{-9}$ flight hours and "Self-sustained, uncontrolled increases in cell temperature or pressure, as a result of any foreseeable charging or discharging condition” must be extremely remote less than one in $<10^{-7}$ flight hours and other failure conditions and assigning DAL must meet the requirement of FAA § 25.1309 or EASA CS-25.1309 (for large aircraft) and any other applicable airworthiness regulations. However, criteria for severity and probability of failure mode for propulsive battery may be expected to be different compared to conventional ones and requires new establishment in MOCs or industry standards, which principally depends on the cumulative experience of technological progress of batteries in the aviation industry.

It is worth mentioning, that batteries used for propulsive purposes may be designed as distributed or redundant architecture to increase reliability. While redundancy may not be possible because of weight limitation, distributed batteries may bring the possibility for redundancy due to providing balanced weight and centre of gravity and finally increased safety and operability (Yildiz & Koruyucu, 2021).

Table 7 is the list of airworthiness requirements, acceptable MOCs and standards regarding the certification process for lithium-ion batteries (LIB) for large aircraft as an example, although are not particularly defined for propulsive purposes could be adopted along with other standards such as ASTM F3235-17a Standard Specification for Aircraft Storage Batteries. Although ASTM F3235 deals with propulsion energy storage requirements, large aircraft criteria are not addressed.

Table 7. LIB requirements for large aircraft

Acceptable Means of Compliance (MOC)	**Test Requirements**	**System Safety Assessment**	**Complex Electronic Hardware.**	**Flammability**
Part 21 CS-25.1301 Equipment Function and Installation CS-25.1309 Equipment, Systems, and Installations CS-25.1351 Electrical Systems and Equipment, General	DO-160G/ ED-14G Environmental Conditions and Test Procedures for Airborne Equipment RTCA DO-311 Minimum Operational	ARP 4761 AMC CS-25.1309	AMC 20-152A/ DO-254/ED-80	CS 25.869 Fire protection: systems CS 25.863 Flammable fluid fire Protection CS 25.853 Compartment interiors

CS-25.1353 Electrical Equipment and Installations SC E-19 EHPS.380 Propulsion Battery	Performance Standards for Rechargeable Lithium Battery Systems

RTCA-DO-311 which deals with functional and thermal safety, fail to cover batteries over 200 Wh. Moreover, it lacks the measure of safety requirements regarding overcharge/discharge, especially in in-flight emergency conditions in which there is the possibility of over-discharge. Besides, functional safety about partial or complete loss of power has not been considered in DO-311A (Sripad et al., 2021).

4.1.4. BMS Reliability and certification requirements

To increase reliability, redundancy in BMS is crucial in the design stage. For instance, detecting voltage from two separate sources of battery cells, using two different chips (Lelie et al., 2018). To cover all intended functions, BMS consists of software and hardware. Considering BMS as a unit, to fulfil safety requirements, DO-254 for hardware development and DO-178C/ED-12C for developing software are required to be satisfied.

In the view of certification requirements according to Annex 1 SC-ELA.2015-01 "Installation of Li-type storage batteries in sailplanes/powered sailplanes, LSA and VLA", minimum requirements for BMS providing overcharge and critical discharge protection of battery are defined. Along with that, a Guidance Material (GM) to specify electromagnetic interference, and environmental and software aspects of BMSs is provided (EASA, 2018). However, airworthiness requirements of BMS regarding other categories of aircraft are not addressed by this document and need more progress for a regulatory aspect to fulfil technology advances, distinctively for the electric propulsion system. In this regards some steps have been taken for example, according to EASA (EASA, 2021a), SC E-19, EHPS.380 (b): “the energy losses with regards to the State of Charge (SoC) and State of Health (SoH) of batteries which could help to determine the maximum available power used for aircraft performances calculation, must be demonstrated". Which requires designers to determine energy losses of SoC and SoH in propulsive batteries taking into account the importance of calculating maximum available power. A typical BMS architecture and applied requirements framework are illustrated in Figure 27.

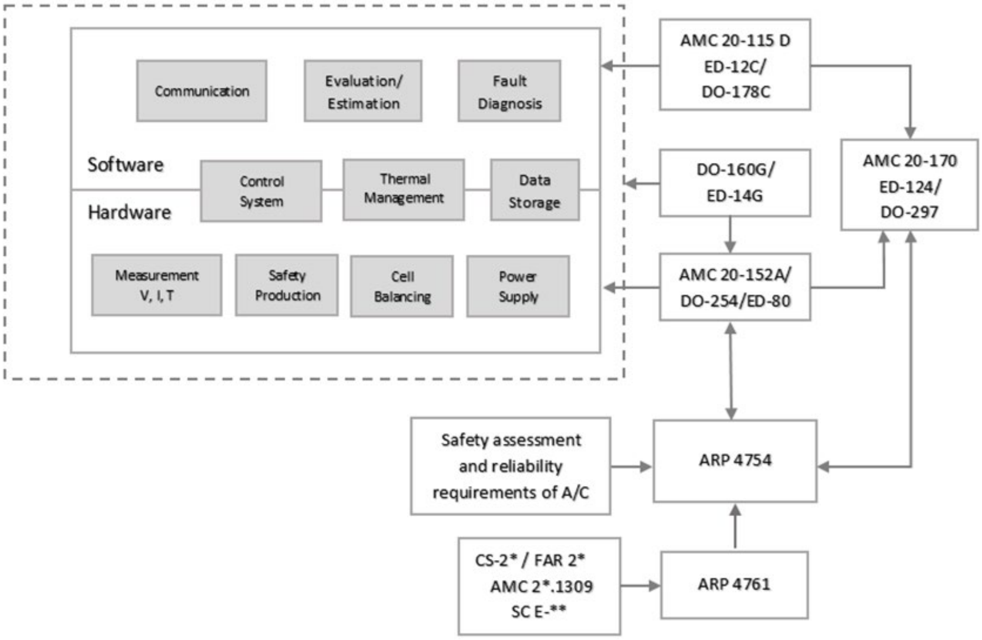


Figure 27. BMS Architecture and applicable requirements

Since high accuracy is essential for battery management of EPS, data-driven approaches are more likely to be applied. Therefore, initial airworthiness requirements of advanced BMS utilizing AI algorithms should be developed. In the following section, the current status of EASA regulation regarding AI application in aircraft design will be discussed.

- **Current status of EASA Regulations regarding AI application in BMS**

As stated before, design requirements for any aircraft unit are derived from aircraft intention function requirements, safety assessment and applicable requirements defined by the authority. EASA's basic regulation defines the requirements of aircraft design and production under the title of Part 21, completed by several certificate specifications for each criterion (EASA, 2021b). In addition, EASA accepts industry standards as a means of compliance during the process of certification. The Acceptable Means of Compliances are including SAE ARP 4754 "Certification Considerations For Highly-Integrated Complex Aircraft Systems" which is issued based on an FAA request from the Society of Automotive Engineers (SAE) to describe the system-level information to show compliance to regulations of complex systems and also ARP 4761

"Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment"(SAE, 1996), RTCA-DO 160 "Environmental Conditions and Test Procedures for Airborne Equipment", RTCA-DO 254 and RTCA-DO 178 dealing with hardware and software development respectively. Nevertheless, so far none of them covers the application of artificial intelligence in aircraft systems and yet no formal regulatory development comes into force. Recently to predict upcoming EASA guidance and requirements for safety-related machine learning (ML) applications, EASA developed "EASA Concept Paper: First usable guidance for Level 1 machine learning applications" to guide applicants including design organizations, manufacturers, and operators to be prepared for AI/ML technologies applied in systems in safety or environmental applications in all scopes of EASA Basic Regulation (Roadmap, 2021). The EASA concept paper, at this stage, covers only supervised learning, AI level 1 applications, and the offline training process in which the model is frozen at the time of approval. AI Level 1 means "Automation support to information acquisition, Analysis and decision-making" (Roadmap, 2021). The objective of safety assessment in the concept guidance is to help applicants to demonstrate systems with AI/ML components are at least as safe as traditional systems using existing development assurance processes and safety assessment practices. Moreover, the proposed guidance is aimed at integrating AI application safety assessment with existing aviation safety assessment processes (Roadmap, 2021).

- **EASA Safety Assessment of ML Application and Learning Assurance**

Safety assessment in the design phase is necessary to demonstrate an acceptable level of safety. There should be a reverse relation between the probability of occurrences and the severity of the outcome of a system failure (EASA, 2020a). ML applications, because of the statistical nature and complexity of the model, cannot be easily predicted. However, AI technology should not introduce higher risks imposed on persons and properties. Systems embedding AI/ML required extra steps to fulfil safety assessments. As proposed by the EASA concept paper, Defining AI/ML component performance/reliability metrics, Analyse and mitigate the effect of AI/ML component exposure to input data outside of the operational design domain, and Perform AI/ML component FMEA (Roadmap, 2021). Besides safety assessment integration, the concept of 'learning assurance' is proposed by EASA to provide new means of compliance. The objective is to make sure the ML application supports the planned functionality, thus opening the 'AI black box' as much as possible. To explain the expected "learning assurance” process stages, a W-shaped process is outlined by EASA. As shown in Figure 28 composed of two V shapes, the First for training and the second for implementation. The W-shaped process is parallel with the V-cycle required for traditional development assurance of non-AI/ML components (Roadmap, 2021). Design organizations are required to follow the W-shape learning assurance process in line with previous design assurance criteria to meet initial airworthiness requirements.

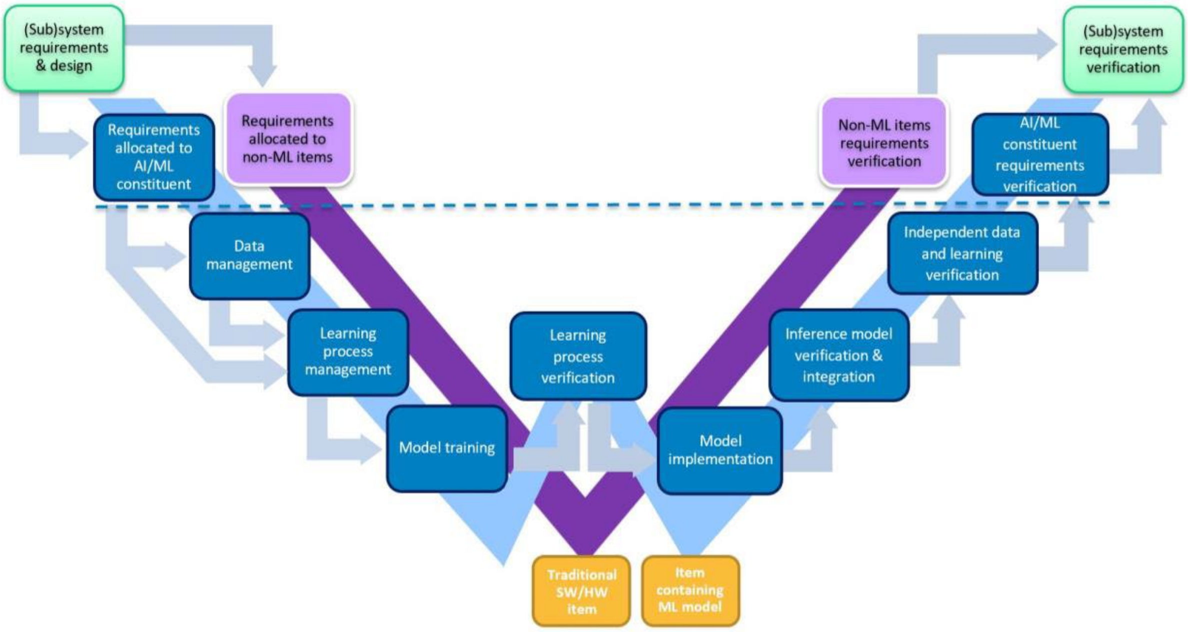


Figure 28. Learning assurance W-shaped process, non-AI/ML component V-cycle process and safety assessment process (Roadmap, 2021)

4.2. First EASA type certification approval for an electric aircraft: a case study

Type Certificate Data Sheet (TCDS) NO. EASA.A.573 (EASA, 2021d), for the type Virus SW 121, TC issued on June 2020 and TCDS No. EASA.E.234 (EASA, 2020b), for E-811Engine including electric motor and PE unit, issued on May 2020, by EASA is the first time the world for an AEA. The summary of the EASA TC basis and technical characteristics of the aircraft type and the engine is in Table 8.

Table 8. Virus SW 128 EASA type certification basis and technical characteristics

Aircraft Type (Electric engine, two-seat, high wing cantilever composite, T-tail empennage, fixed tricycle landing gear & three-bladed fixed pitch propeller)			
Airworthiness Requirements	Certification Specifications and Acceptable Means of Compliance for Light Sport Airplanes CS-LSA	Certification Specifications and Acceptable Means of Compliance for Airborne Communications, Navigation and Surveillance CS ACNS	
Special Conditions (SC)	SC-LSA-F2480-01 - LSA Propulsion Lithium Batteries;	SC-LSA-15-01 - Electric Power plant Installation for CS LSA aeroplanes	SC-ELA.2015-01 - Lithium battery installations
Engine (W268 MV LC VHML motor (57.6 k) & a H300C power electronics (311A, 400Vdc))			
Airworthiness Standards	CS-22, Subpart H, Amendment 2		
Special Conditions (SC)	SC E-1 - Electrical Engine for powered sailplanes, LSA or VLA		

The Energy Storage Device (ESS) is composed of two parallel 11kWh capacity lithium batteries, with a nominal voltage of 345 VDC inclining BMS. One of the batteries is located in the bow of the aircraft while the other is behindhand of the cockpit to provide redundancy of the power source; if any failure happens, the faulty battery is disconnected from the system automatically. Battery-BMS-PE as common units of EA architecture for Virus SW 128 propulsion is shown in Figure 29.

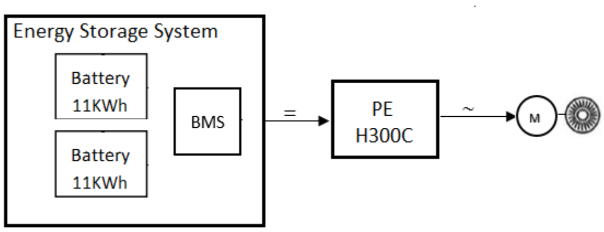


Figure 29. Virus SW 128 Propulsion Architecture

The certification process for SW 121 took less than three years which is a symbol of a collaboration between EASA and designers for a strong initiation of this era. The certification of the electric aircraft is historically important and gathered experience can be used in future aircraft type certification processes for other electric aircraft types.

Continuing airworthiness requirements for the Virus SW 128 ensures aircraft airworthiness is continued in the operations lifecycle. Therefore the Civil Aviation Authority of The Netherlands issued a "General Approval" under the title of ILT-2020/51992 under Article 71(2) of Regulation (EU) No. 2018/1139, which grants an exemption for the continuing airworthiness requirements of the extent of approval, personnel requirements including certifying staff and airworthiness review staff, specifically for Virus SW 128 on 1 Oct 2020 (Human environment and transport, 2020).

4.3. Development assurance level assignment for an AEA

According to ARP 4761A, a safety assessment is performed at the A/C level and system level, as shown in Figure 30. In AFHA failure of aircraft functions will be identified and the severity of the consequences and DAL will be assigned. Then in PASA the proposed architecture is analyzed, to determine how failures identified in FHA could occur, offers safety requirements.

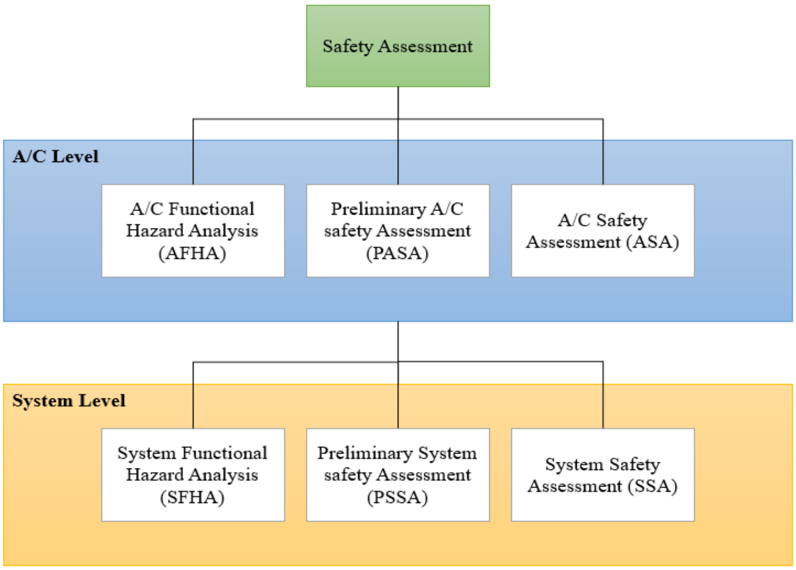


Figure 30. The safety assessment process per ARP 4761A

ARP4754 defines two methods for DAL assignment, first without considering the system architecture and second, considering system architecture (SAE, 2010). To perform AFHA it is necessary to define failure conditions, the effect of a failure condition, the classification of failure conditions and the A/C functional criticality level (FDAL). In the electric A/C case based on assumptions mentioned in the methodology section, EPS is responsible to provide sufficient thrust in all phases of flight which is a subfunction of "Perform Flight Operations" as A/C top functions. AFHA, consider the failure of functions at the A/C level with the most severe consequences.

Table 9. AFHA for providing lift (A/C function level)

A/C FHA					
Function	Failure condition	Phase of flight	Effect of a failure condition	Classification	DAL
Providing forward thrust	Loss of thrust (total or partial)	Climb	Loss of control (LOC)	Catastrophic	FDAL A
	Loss of total thrust	Take off after V1	Unable to take off (runway overrun or runway excursion)	Catastrophic	FDAL A

Then in the next stage, PASA will be performed considering aircraft architecture. In an AEA, EPS is accounted to provide adequate thrust during the flight. Therefore, a single system (EPS) is responsible to provide thrust (EPS). According to ARP 4754A when there is only one member (system) functional failure will be set with that system. Which is FDAL A in this case.

Thus, battery, PE and Motor shall be designed to FDAL A, based on the catastrophic classification of loss of thrust either during climb or take off. In the following section, a complete analysis of the battery will be performed to show how battery DAL A derived from A/C level requirements and SFHA can be obtained.

4.4. LIB hazard identification and safety risk management

4.4.1. Sources of hazard in LIB using fish-bone diagram

- **Thermal hazards**

Since the component of the battery including electrolyte, plastic packing and separator are mostly flammable, unsafe conditions during operation may result in chain reactions in the battery and lead to fast heating (exothermic) of the battery (Larsson & Mellander, 2017; Ouyang et al., 2019). Thermal runaway is the cause of most reported events in the LIB applications, due to the possibility of spreading out from a cell to the adjacent one and the battery pack and finally to the whole of the battery system (Larsson & Mellander, 2017; Sripad et al., 2021). To manage thermal hazards, the causes and contributing factors must be thoroughly identified, thus making it possible to take appropriate measures. According to (Hendricks et al., 2015), at the moment of temperature rise in a cell, as it would be difficult to prevent thermal runaway, heating in a cell must be predicted before such event. There are some external and internal failures which contribute to thermal runaway in LIB, they vary from electrical to mechanical causes (Larsson & Mellander, 2017; Sripad et al., 2021) and also battery components (anode, cathode, electrolyte), their design and construction (Lisbona & Snee, 2011) can also be counted. To illustrate the contributing factors which lead to thermal runaway, the fishbone diagram is applied. This method is used to analyze an event with a collection of causes divided into cause and sub-cause (Ilie & Ciocoiu, 2010). As illustrated in Figure 31, contributing factors are categorized into physical, electrical, thermal, design and manufacturing factors (D. Ouyang, Chen, Huang, Weng, Wang, et al., 2019) and ambient/ operational conditions.

Physical hazards not only caused by penetration or deformation in a crash but also electrode expansion or deformation of battery components due to abuse/stress can be counted as physical defects (D. Ouyang, Chen, Huang, Weng, Wang, et al., 2019). A result of degradation of a battery cell component during its lifecycle may also lead to thermal hazards; for example composition of dendrite around the anode which leads to a short circuit (Sripad et al., 2021), thickness of the Solid electrolyte Interphase (SEI) layer increase as a result of aging leads to increasing in internal resistance and leads to higher heat generation (D. Ouyang, Chen, Huang, Weng, & Wang, 2019). Electrical damages mostly resulted from internal and external short circuits and overcharge/ discharge (Larsson & Mellander, 2017; D. Ouyang, Chen, Huang, Weng, & Wang, 2019). In an external short circuit, if the battery is in discharge condition the current might exceed the normal state, therefore leading to immediate temperature rise and initiating thermal runaway. On the other hand during overcharge, due to internal reactions, internal resistance may increase (D. Ouyang, Chen, Huang, Weng, & Wang,

2019) and as a side effect of heating, thermally driven cathode decomposition may lead to additional temperature increase (Hendricks et al., 2015). Similarly, in over-discharge, anode construction may deform and chemical corrosion leads to dissolved copper which damages the separator and causes internal short circuits (Hendricks et al., 2015; D. Ouyang, Chen, Huang, Weng, & Wang, 2019). In both charge and discharge situations, the possible cause is the failure of protection systems such as BMS faults.

Regardless of the reason, heating may lead to the decomposition of electrodes, electrolytes and melting of the separator which end up in a short circuit; at this moment electrochemical energy of the battery will be released instantly and generates additional heating. Thermal hazards may happen due to poor manufacturing including but not limited to low-quality/ thin separators, material particle contamination and improperly arranged constituents (Wu et al., 2018).

Another important factor in airborne application is ambient pressure. According to (Xie et al., 2019), environment pressure and temperature affect the thermal runaway behaviour; cycling an aged battery in low-pressure ambient conditions (which is the case for aircraft application) is more possible to initiate thermal runaway which may occur in an instant and there will be less time to react. It is worth mentioning that operational conditions, loads and voltage level charge/ discharge profile also affect the thermal runaway behaviour (Lisbona & Snee, 2011). Therefore, for aircraft operations, different flight phases shall be considered; for instance, in cruise operations in which the battery is in a low pressure/temperature environment or take-off in which a higher load is applied, essential to be considered the analysis of LIB thermal runaway behaviour.

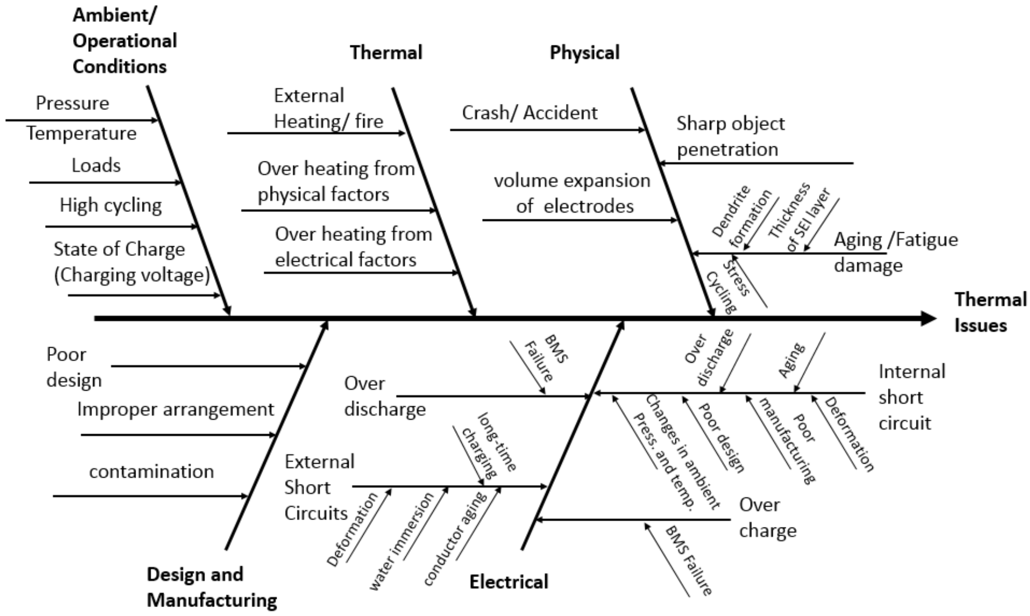


Figure 31. Fishbone model for LIB thermal hazards

- **Chronic or Aging Hazards**

Chronic hazards threaten the functionality of the battery in the form of capacity and power reduction, which develops gradually over the lifetime of the battery (Sripad et al., 2021). The hazards originating from the aging process are considered operational or functional chronic hazards which lead to power reduction, capacity fading and impedance increase (Vetter et al., 2005). To effectively address the aging hazard, it is essential to first identify the causes. However due to the complexity of the LIB aging mechanism, the study of root causes of capacity reduction and power fading is not much straightforward; noticeably these failures have not resulted from a unique source but originated from different causes (Vetter et al., 2005). The process of aging in each LIB component (anode, cathode and electrolyte) is different (Hendricks et al., 2015; Vetter et al., 2005). In an anode under the effect of cycling, electrolyte decomposition leads to loss of lithium causing capacity and power to fade, simultaneously with the increase in impedance. On the other hand, lithium corrosion in the active carbon happens, which resulted in self-discharge and capacity fade because of lithium loss, also contact loss of active material particles as a result of volume changes during cycling leads to loss of active material causes capacity reduction and impedance increase. On the cathode side, phase transitions and changes in the structure of bulk material strongly impact aging and is more important than the processes in the anode (Vetter et al., 2005). A summary of causes which contribute to chronic hazards/aging in LIB which lead to capacity fade, power reduction and resistance increase, is depicted in the form of a fishbone diagram (Ilie & Ciocoiu, 2010) in Figure 32. They are categorized as storage condition & handling, material parameters which link to cell chemistry and design factors, ambient condition and abuse condition (Hendricks et al., 2015; Vetter et al., 2005).

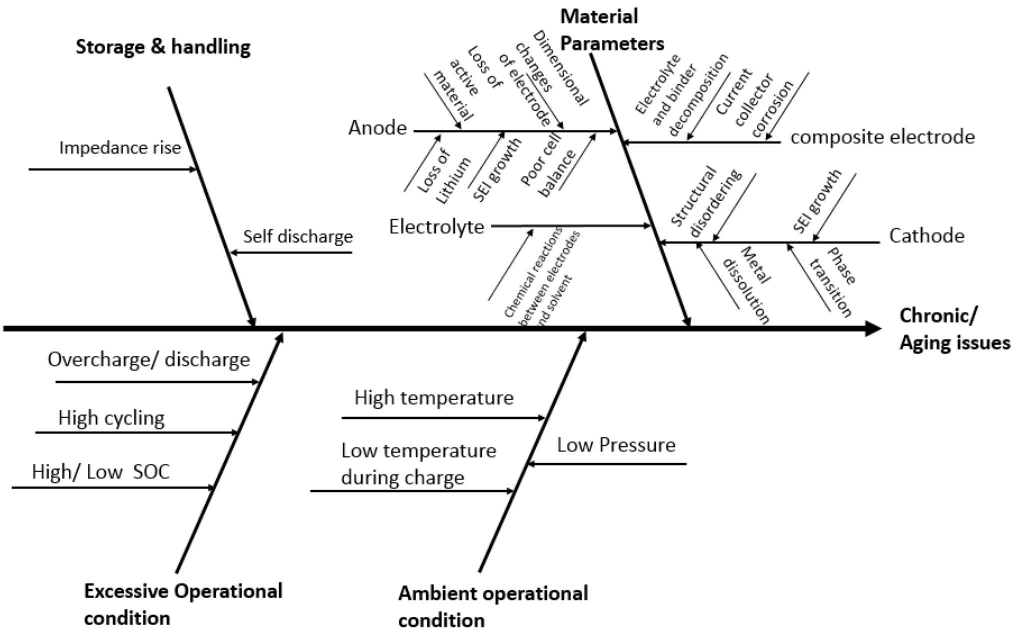


Figure 32. Fishbone model for battery aging hazards

According to the results of the aging study performed by (Juarez-Robles et al., 2020), by reducing 200 mV at either end of the voltage cut-off, the life of the battery would be increased by 100%, in return capacity utilization reduces only as 20%. Also, it is shown that reduction of lithium due to the SEI formation, electrochemical deactivation of the cathode because of delamination and particle cracking are the major degradation mechanisms which result in the cell capacity fading under frequent cycling.

State of Charge (SOC) is a parameter that shows how much energy is accessible and Depth of Discharge (DOD) indicates the amount of energy that has been withdrawn. The output voltage of a battery cell depends on the rate of discharge which shows how much current is being delivered by the battery according to its nominal capacity and also the SOC (Hornung & Sizmann, 2013). In addition to discharge rate, charging rate, ambient temperature, SOC range of operations and combination of them contribute to the degradation of LIB capabilities (Diao et al., 2019). Based on (Juarez-Robles et al., 2020), analyses of separate voltage and temperature show SOC depends on the internal resistance and rate of heat generation. Under the effect of cycles of charge and discharge, the maximum energy capacity of the battery (Ah) decreases. State of Health (SOH) is defined as the actual capacity of the battery normalized to the initial capacity. While literature mostly focused on SOH modelling, considering the functional safety of electric aircraft, predicting the power capability and the risk of knee point or sudden functional loss is important (Sripad et al., 2021). Addressing these sorts of hazards is crucial for preventing undesirable mission failure in electric aircraft (Bills et al., 2020).

4.4.2. Risk assessment of LIB process using bow-tie model

Bow-tie analysis based on the defined assumptions will be developed in this section. Considering the phases designed for bow-tie analysis, the following steps are taken.

- **Unsafe events/ undesirable events (centre of the bow-tie model)**

Classification of the two major types of hazards of LIB in electrical aircraft requires the evaluation of any cause of hazard activation. The aim of this section is the identification of areas in which LIB functions are bound to be out of control and countermeasures required to keep it in a safe operating envelope.

  - **Heating or thermal events in LIB**

The flow of temperature rise is considered to be started from a cell and propagated to the battery pack, however, the onset of high temperature could be initiated in each level (cell, battery module or battery pack) even out of the battery system (Larsson & Mellander, 2017). Therefore, identification of the sequence of events is crucial to define preventive or control measures. According to the causes visualized by the fishbone diagram, thermal runaway in a cell from a variety of internal or external causes leads to flammable gases such as ethane, and methane being released then flammable electrolytes will ignite and finally, fire will happen with a high possibility of explosion.

  - **Loss of power or capacity**

Considering different flight phases of electric aircraft, required energy and power during take-off, climb, cruise and landing shall be provided by the LIB, Any loss of power or capacity in a critical phase of flight may end in catastrophe (Ma et al., 2017). Notably, any decrease in power provided by the battery compared to the designed level during normal operation shall be known, this issue becomes more critical in the case of an emergency. The pilot must be informed about battery power before and during the flight to verify the possibility of any flight mission success; however, the battery is not equipped with equivalent tank dipping to make sure there is sufficient fuel onboard (Courtin & Hansman, 2019). The knee point phenomenon or fast increase in the rate of performance is a sudden undesirable event and can quickly lead the battery to fail. Modelling battery performance regarding aging or component degradation is essential to predict those failures which directly threaten aircraft operation (Sripad et al., 2021).

- **Ultimate consequences of LIB unsafe events (Right side of the bow-tie model)**

If the impact of a hazard is not controlled, an undesirable event will occur as mentioned. The subsequently undesirable event as the starting point of loss of control may lead to severe consequences if any recovery/ reaction measure is not taken or fail. This flow is depicted in Figure 33. In the case of LIB utilization in the aircraft propulsion system, possible major hazards and undesirable events are defined in the previous parts.

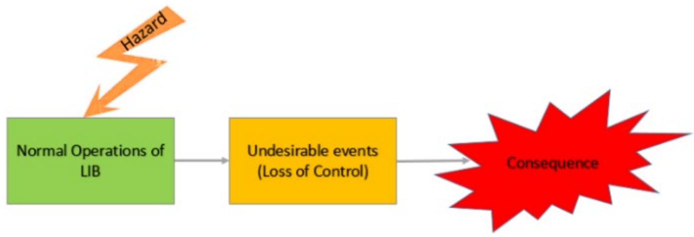


Figure 33. The flow of unassessed hazards to consequence

In case of thermal hazard, undesirable events in a form of heating might be initiated at the cell level and propagated to the battery pack level (Larsson & Mellander, 2017). Consequences of hazard are directly linked to the application of LIB. If thermal hazards are activated in electric aircraft, possible one or a combination of some consequences might take place as illustrated in Figure 34.

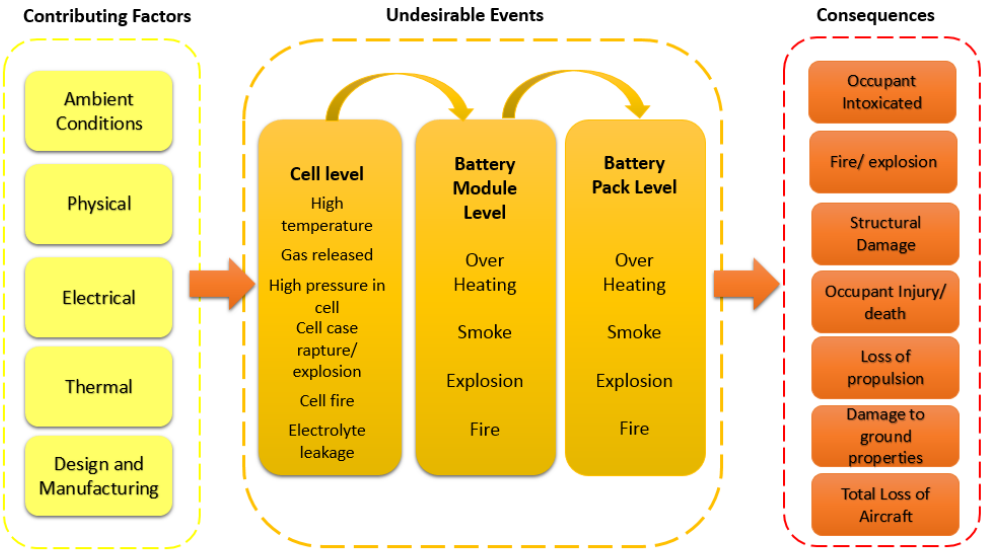


Figure 34. LIB thermal hazard flow to consequences in electric a/c

Similarly for other unsafe events, loss of power or capacity which might occur in LIB application for electric propulsion, if any appropriate control actions are not taken, the flow of subsequent factors could lead to some critical consequences as shown in Figure 35.

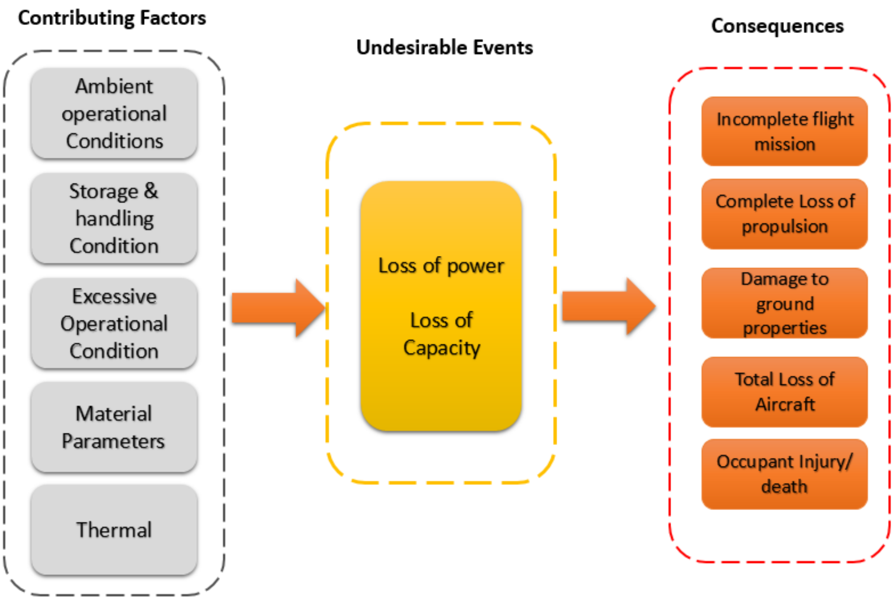


Figure 35. LIB aging hazard flow to consequences in electric A/C

- **LIB Safety Mechanism**

Different measures could be taken to prevent LIB events from happening by reducing the probability of occurrences and properly mitigating in case of occurrence, aiming to lower the severity of consequences. The first group are called barriers on the left side of the bow-tie diagram, which are expected to prevent the causes proceed to the top event. To design the barriers, there should all causes/ contributing factors which were identified before (in the Fish-bone diagram) are considered. Defences are defined as "Specific mitigating actions, preventive controls or recovery measures put in place to prevent the realization of a hazard or its escalation into an undesirable consequence" (ICAO, 2018). In general mitigation strategies for hazards could be categorized as (i) Technology of Design, Manufacturing and maintenance, (ii) Regulations, standards and procedures, and (iii) personnel training (ICAO, 2018).

- **Technology**

Layer by layer "Onion safety mechanism" including cell chemistry, cell design and packing, short circuit protection (fuse), battery connector (contactor), BMS, System design and cell housing, thermal management system and mechanical crash protection offered in literature (Larsson & Mellander, 2017). In practice, technological mitigations fall into 3 levels from the angle of the life cycle, which are design, manufacturing and operations. The technological safety mechanism is summarized in Figure 36 in the order of priority of action. Along with the bow-tie model, airworthy defence layers of LIB design could be categorized as cell chemistry, digital mechanism, analogue measures, firefighting and redundancy.

- **Cell chemistry**

Cell chemistry refers to the material used in LIB cells (e.g., separator, electrode, and electrolyte). Proper selection and design of separators in terms of material, thickness, and chemical/mechanical/thermal stability (D. Ouyang, Chen, Huang, Weng, & Wang, 2019) are required to prevent short circuits and onset overheating in the early stages of thermal runaway (Sripad et al., 2021). Electrode composition is important in heat generation and transfer or heating capacity of the cell (Sripad et al., 2021). Furthermore using fire-retardant electrolyte (Balakrishnan et al., 2006; D. Ouyang, Chen, Huang, Weng, & Wang, 2019) and electrolyte additive materials like Fluoride, ionic liquids and composite additive, provides reduction of the flammability of the organic carbonates in the electrolyte (D. Ouyang, Chen, Huang, Weng, & Wang, 2019). The mentioned mechanism is mainly effective for thermal hazards while measures for reducing aging effects such as stable SEI, carbon pre-treatment and proper binder choice are proposed (Vetter et al., 2005).

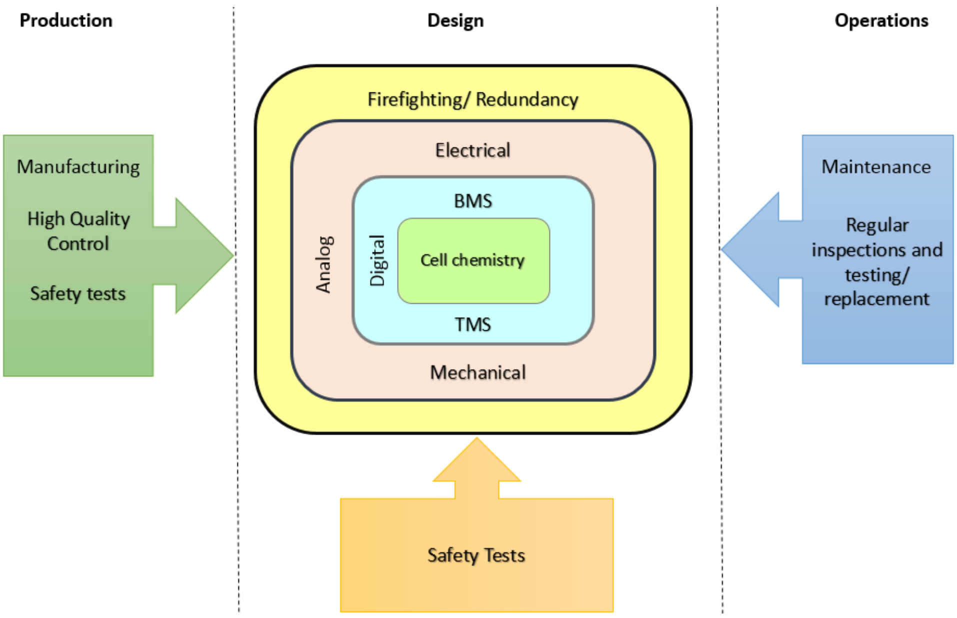


Figure 36. Technological LIB hazard barriers and mitigations during the aircraft life *cycle*

Battery Management System

Application of LIB in electric aircraft under different ambient temperatures, pressure and abuse operational conditions needs a more complex and efficient system to control different variables which could affect the safety of the flight. BMS will ensure features such as charge control, capacity monitoring, remaining run-time information and charge cycle counting (Buccolini et al., 2016; Yildiz, 2021). Requirements for BMS depend on its application, obviously for electric aircraft definition of requirement as a starting point of the design is critical (Lelie et al., 2018). Detection of any deviation or failure is the role of BMS using sensors for temperature, voltage and current at the cell level (Larsson & Mellander, 2017). Another task of BMS is an estimation of capability or state of function (SOF) to determine the maximum charge and discharge currents that the battery is capable to support at any time. In addition to estimation of SOC and SOH tracking and recording real-time data is another function of BMS. Noticeably, BMS protection should not impact critical functions of electric propulsion. When the battery is shut off by BMS for its protection, this may degrade system-level safety, therefore battery damage as a result of deep discharging could be less harmful than missing an important functionality of the propulsion system (Lelie et al., 2018), which is important to be taken into account in BMS logic design. Advanced BMS by applying the next generation of battery management technology could be applied in electrical aircraft, which includes:

- Data acquisition methods by using smart sensors
- Application of big data platform for sharing data of the battery in the LIB life cycle to improve the process of design, manufacturing, maintenance and associated regulations and standards.
- Utilizing Artificial intelligence (AI) technology in battery degradation, modelling tools and diagnostics, bring the opportunity for smart control and management of batteries and increase the battery lifetime.

Thermal Management System

A thermal Management System (TMS) is critical for the mitigation of overheating in a cell (Sripad et al., 2021). As far as the performance of the battery is strongly linked to the temperature, it is important to maintain the temperature of every cell under control by activating heaters or coolers to keep the temperature under defined limits (Buccolini et al., 2016). This action is performed by one or a combination of air cooling, liquid and Phase Change Material (PCM) (D. Ouyang, Chen, Huang, Weng, & Wang, 2019). The weight penalty of TMS shall be regarded in the overall battery design and its specific energy. Using more electronic equipment in aircraft will increase the heat dissipation, which leads to increased weight and power consumption of TMS, therefore more integrated approach in design is needed like thermal accumulators by using phase change materials to accumulate heat during high transients or cold at high altitude, and use them for cooling or heating during other phases of flight; or performing a more integrated and optimized design for propulsion, electric systems, batteries and thermal management systems (Affonso et al., 2021). Advanced TMS in LIBs has the capability of temperature changes prediction accurately for a battery pack under the external ambient and operating conditions to ensure the optimum temperature window of the battery (Dai et al., 2021), this ability increases the accuracy and functionality of TMS in critical application of electric propulsion system.

- **Mechanical Means**

In case BMS and TMS fail to prevent overheating, to reduce the effect of excessive heating and dissipation to other cells or modules, some mechanical measures are needed. Minimizing side wall ruptures using heat sink materials, increasing spaces between cells, protecting adjacent cells by applying cell vent opening and utilizing flame arresting vent ports are some methods applicable to higher density batteries in electric aircraft (Darcy, 2016). In addition, gas and temperature sensors can also be applied to alert the system (D. Ouyang, Chen, Huang, Weng, Wang, et al., 2019). Battery-protected box, reinforced deformation structure, detox (anti-dote) gas filters (Larsson & Mellander, 2017), thermal fuse, module links and heat-absorbing plates between cells (Sripad et al., 2021) are other mechanical methods proposed as LIB safety mechanisms. However, for electric aircraft application, all the mechanisms require critical design decisions, for example, heat-absorbing plates may significantly affect the specific energy of the battery pack which must be taken into account (Sripad et al., 2021).

- **Electrical Means**

Electrical safety mechanisms like mechanical means can protect the LIB system in case of BMS failure during the flight. Current Interrupt Device Individually (CID) can interrupt the battery current in case of overcharge/ discharge and short circuit (Ouyang et al., 2019). Using circuit breakers/ fuses/ contactors, electrical insulation (Larsson & Mellander, 2017), high voltage connectors and low voltage wire harnesses (Dai et al., 2021) are other electrical mechanisms applied for improving LIB safe performance.

- **Firefighting system**

Firefighting is considered a reactive mitigation action on the right side of the bow-tie diagram in case of thermal hazard. Firefighting of Li-ion batteries due to lack of access to the battery packs which are compactly designed (e.g. IP67) is difficult while LIB fire needs to be cooled at the cell level; Water has the excellent cooling capability, however, it might cause some negative effects, e.g. short circuits (Larsson & Mellander, 2017). Besides that, LIB electrolyte is salt, therefore its reaction with water will release hydrogen and might lead to an explosion, so there is no chance for use of it.

Redundancy

To design high reliable systems, the designer must duplicate components or assemblies, and even whole sub-systems, to fulfil the overall system reliability goals, therefore systems are said to be redundant, or in parallel (Stapelberg, 2009). In the case of electric aircraft a single-use emergency battery, for example, could be installed as a backup system, which could be replaced after usage (Courtin & Hansman, 2019).

- **Regulation, Standards and Procedures**

Regulations are established by aviation authorities and industry standards to provide designers, manufacturers and operators with the applicable requirements under two main categories of initial airworthiness (EASA, 2021b) and continuing airworthiness (EASA, 2021c). One of the important approaches for critical system design is, a fail-safe design concept based on CS-25 to adopt some design principles and techniques such as:

- Design integrity and quality including life limit
- Redundancy or backup systems
- Isolation and/or segregation of systems especially when failure of one element, component or system affect the others
- Proven reliability in a way that multiple, independent failures are improbable to occur together
- Failure warning
- Flight crew procedures specifying corrective action
- Checkability/ condition monitoring
- Designed Failure Effect Limits and,
- Error tolerance considers the adverse effects of errors during design, test, production, operation, and maintenance

(EASA, 2020a). DO-311A - Minimum Operational Performance Standards for Rechargeable Lithium Batteries and Battery Systems is a standard, issued by the Radio Technical Commission for Aeronautics (RTCA), which is approved by regulators as an acceptable means of compliance, meeting this standard, assures the batteries and battery systems will perform their intended function(s) safely under conditions which happened in aeronautical operations (RTCA, 2017). According to continuing airworthiness requirements regarding the operation of aircraft, all parts and appliances must be maintained based on an approved maintenance program (Part M, M.A.302) in defined intervals including tests and inspections, to assure the continuation of safety in the operation phase. Pilot operational procedures are also applied for better performance of LIB employment by applying different flight planning based on LIB SOF estimation. Furthermore, emergency procedures should be defined and followed by the crew in case of any crisis.

➢ **Training**

Based on the SHELL (Software Hardware Environment Liveware Liveware) model which is well known for identifying human (Livewire) interactions with other elements of a complex system of systems (ICAO, 2018; Wise et al., 2016), operations of any system directly affected by human performance, therefore in the area of LIB application, also, involved organizations should promote the personnel in terms of knowledge and skills. Different training for improving maintenance staff regarding storage and handling (Balakrishnan et al., 2006), maintenance and testing as well as for pilots regarding operational issues to prevent unsafe events and respond to them if take place, is designed based on regulatory requirements such as EASA continuing airworthiness regulations, Part 147 and Part 66 which deals with requirements of maintenance training organizations and certifying staff training syllabuses and licensing requirements respectively (EASA, 2021c).

- **Identifying failure conditions of safety mechanisms and controlling them**

Safety considerations in the design of electric aircraft must be at the same level as conventional aircraft, therefore considerations of failure modes for systems and sub-systems, redundancy, and MTBF (Mean Time Between Failures) must be performed; in addition, it is required to take into account the reliability and maintainability of the TMS, BMS, other components and operational limitations (Affonso et al., 2021). In line with bow-tie analysis, all failure modes of control/ barriers and mitigation measures must be well identified to increase the reliability and overall safety of the energy storage system. The functionality of the LIB system mostly depends on BMS as the most effective protection system, therefore it's more crucial to address the failure mode of BMS. One of the challenges of BMS design is, securing the BMS power supply. Table 10, demonstrates some failure modes of BMS as the most important barrier in LIB operational risk assessment.

Table 10. BMS failure mode and control strategies

BMS Failure mode	**Control strategies**	
	Design consideration	Operational consideration
Failure in Power supply	BMS Separate power source with backup	Regular BMS Maintenance Tests Inspections
Software failure	Redundancy of Microprocessor	
Input signal failure	Data acquisition from different sources (Sensor's redundancy)	
Total failure of BMS	Electrical and Mechanical safety mechanism	

4.4.3. Risk Assessment of LIB aging hazard

Aging hazard is less addressed in literature in comparison with thermal hazards. In contrast with automotive applications in which assessment of aging hazards is aimed at reducing maintenance costs (Dai et al., 2021), electric aircraft application is directly linked with human loss and property damage if not controlled. Application of the bow-tie model for risk assessment of LIB in electric aircraft is depicted in Figure 37, using Bow-tie XP software. To perform the bow-tie analysis below steps are taken:

- Hazard group selected: Chronic or Aging
- Contributing factors placed on the most left side of the bow-tie diagram based on Figure 32 fishbone diagram
- Top event/ undesirable event defined in the centre of the model: Loss of LIB capacity
- Consequences listed according to the section Figure 35
- A barrier designed considering the causes depicted in Figure 32, from the safety mechanism offered (Technology, Regulation and Training)
    - ➢ *Material Parameters*: mainly caused by the cell element characteristic changes under the effect of aging, like changes of the particle surface, electrode cracks,

loss of active material, SEI growth and other alteration in electrodes, electrolytes and composite electrodes. To design the robust barrier, cell chemistry design is important to reduce the effect of aging on the material parameters such as electrolyte additives, carbon pretreatment, proper binder selection, and separator material. Furthermore, design regulations and standards can effectively define initial criteria for design and manufacturing to limit the effect of aging during the LIB lifecycle. One another crucial element of control is BMS. As discussed before the capability of BMS in fault diagnoses, state estimation and aging prediction are essential in the management of aging hazards. Maintenance of LIB sub-systems and components also is important to fulfil the requirements of continuing airworthiness, in line with the approved maintenance program including condition monitoring and reliability analysis.

- *Storage and Handling*: Incorrect storage conditions and handling could affect the battery performance and lifetime which can cause an increase in internal resistance and self-discharge. Therefore, manufacturers should provide instructions regarding storage temperature and handling of the battery to prevent thermal conditions out of the defined window and mechanical damage which could lead to thermal hazards and gradual degradation of battery performance. Operators are also required to issue procedures for storage and handling and installation while providing suitable storage facilities, and training the staff attentively to implement the procedures.
- *Ambient Operational Conditions*: LIB performance is sensitive to ambient operational conditions such as pressure and temperature, therefore positioning of LIB in aircraft should be considered in design in a pressurized and temperature-controlled zone. Besides that, utilizing an effective TMS will reduce the impact of temperature change. In addition, during charging of the battery on the ground, it should be applied to prevent the effect of ambient conditions on battery aging.
- *Excessive operational conditions*: High cycling, overcharge/ discharge and rate of charge are the contributing factors to aging hazard. To prevent them to lead to loss of capacity, some mechanism should be designed. BMS is the most effective safety barrier and is capable to prevent excessive conditions during the flight to extend the battery lifetime. However, it should be noticed that

robust programming of BMS is crucial to logically prioritize the battery protection and adequate power generation to assure the safety of the flight. Appropriate fault warning, power limitation and emergency cut-off must be performed by BMS providing that flight missions are guaranteed. Operational procedures are also effective to consider LIB state estimation to prepare and execute the efficient flight plan by the crew in a way that less abused conditions threaten the LIB. Moreover, in case of BMS failure to prevent the excessive condition, other electrical safety mechanisms can prevent the abuse condition using fuses and circuit breakers.

- Mitigation actions or recovery are also selected from the safety mechanism offered (Technology, Regulation and Training) for each ultimate consequence. In this case, the same set of mitigations are proposed for determining consequences: If defined barriers fail to prevent the leading of threats/ causes to the top event, mitigation strategies should be activated to reduce the severity of consequences. Redundancy or backup system as a major element of failsafe design should be considered to assure the continuity of LIB function. Besides that, operational emergency procedures and pilot training, especially in the form of flight simulation, can effectively reduce the severity of the risk in case of loss of capacity.
- Identifying failure modes of defined barriers and mitigation mechanisms based on the methods.
- Defining strategies for controlling failure mode of barriers, considering fail-safe design principles ranging from redundancy, failure warning and proven reliability of control and validity test during initial airworthiness process, quality control in manufacturing besides maintenance and inspection in the operational phase. For instance, leveraging built-in test features to minimize maintenance with the ability to highlight the charge status or whether the cells need to be balanced.
- Define the level of risk based on the severity of consequences and probability of occurrences before and after proposing safety mechanisms for each ultimate consequence are illustrated in Figure 38 and Figure 39 respectively. The predetermined list of consequences is categorized based on the severity, therefor both inherent risk and residual risk severity are identical and due to our assumptions fixed-wing aircraft is capable to glide and survivable landing speed without power, so the severity of the consequences could be "Minor" in case of depletion of

batteries before reaching its mission or intended destination. Before applying the safety mechanism, the probability is considered "Remote", the justification behind that is, that during the takeoff, which is the most consequential phase, loss of capacity is not probable. After applying controls and mitigations, the probability of the occurrence must be reduced to "Extremely Remote", to assess as tolerable. In the process of initial airworthiness certification, the designer must prove that the probability of catastrophic occurrences is less than 1 in 10^9 flight hours during the verification process. Based on the Fail-safe concept applying 2 or more design techniques is essential (EASA, 2020a). In this analysis, a combination of Redundancy in the form of the backup battery system, failure warring or detection utilizing BMS state estimation and prediction, flight crew procedure for reaction to the failure, checkability or Maintainability of the LIB sub systems and limiting the designed failure effect by using multi-layer of safety mechanism, are implemented. The overall risk of an aging hazard in this analysis considering the worst-case scenario reduced from [C4] in the intolerable region to [A4] in the tolerable area. It should be noticed that any operation in which the risk is assigned as tolerable needs to be precisely monitored to ensure the effectiveness of each safety mechanism.

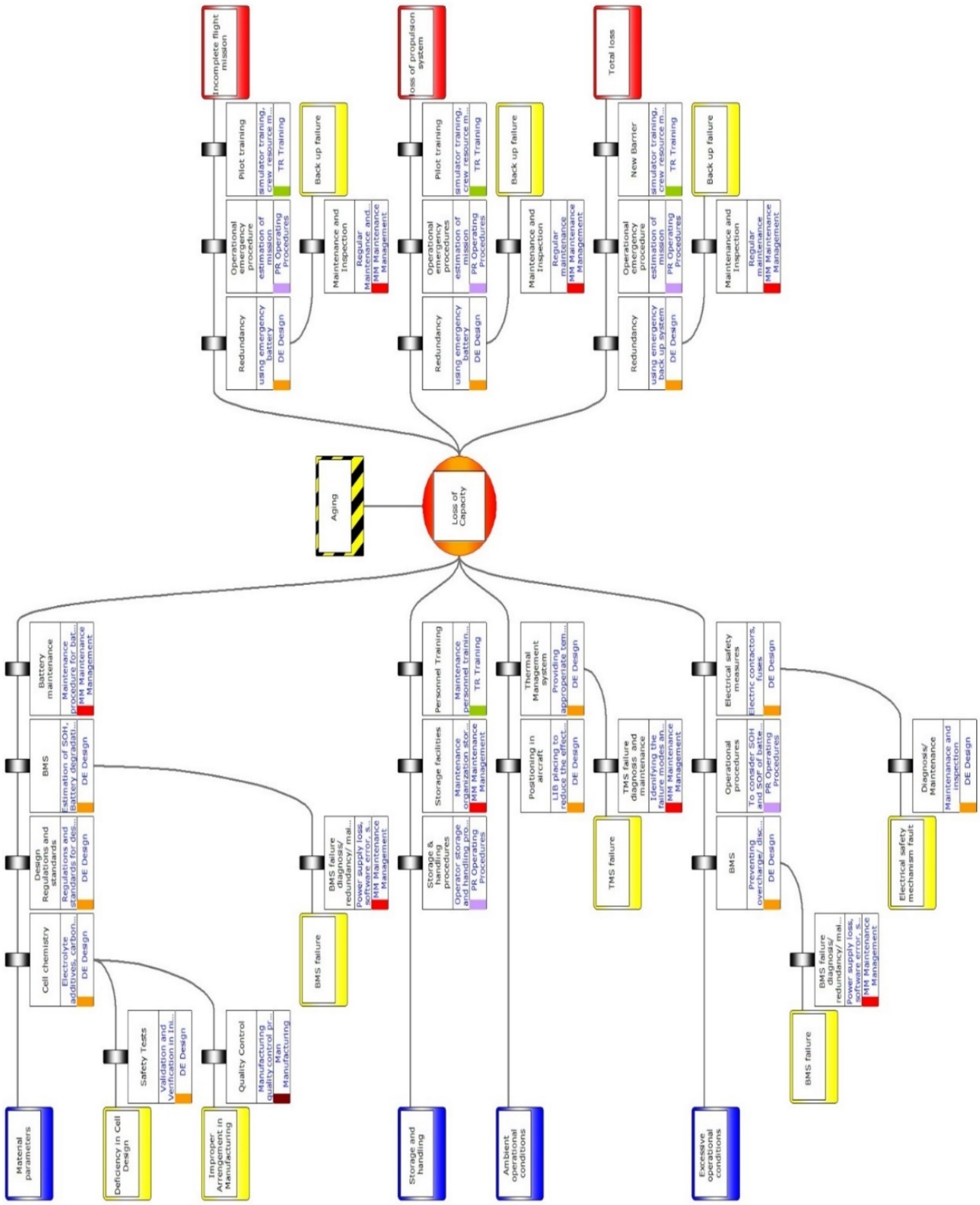


Figure 37. Bow-tie risk assessment for aging hazard

Severity of Failure	Tolerability Criteria for Inherent Risk/ Unmitigated Risk			
Catastrophic (4)	$<10^{-9}$		**Total loss**	
Hazardous (3)		$<10^{-7}$	**Loss of propulsion System**	
Major (2)			$<10^{-5}$	
Minor (1)			**Incomplete flight mission**	$<10^{-3}$
No effect (0)				
Probability	Extremely Improbable (A)	Extremely Remote (B)	Remote (C)	Probable (D)

Figure 38. Inherent Risk

Severity of Failure	Tolerability Criteria for Residual Risk/ Mitigated Risk			
Catastrophic (4)	$<10^{-9}$ **Total loss**			
Hazardous (3)	**Loss of propulsion System**	$<10^{-7}$		
Major (2)			$<10^{-5}$	
Minor (1)	**Incomplete flight mission**			$<10^{-3}$
No effect (0)				
Probability	Extremely Improbable (A)	Extremely Remote (B)	Remote (C)	Probable (D)

Figure 39. Residual risk

5. RESULTS and DISCUSSION

5.1. AEA and HEA propulsion system airworthiness requirement

Discussed topology (Battery-BMS-PE) is an essential communal unit in a fully electric and hybrid propulsion system and represents valuable data regarding finding discrepancies in the pathway of implementation of new propulsive systems.

Authority airworthiness documents which are mainly supported by industry standards are not adequate to address specific requirements for electric propulsion systems, for instance, current ASTM standards cover mainly small aircraft types. Contemporary industry standards for possible hybrid-electric configurations where an EPS and an internal combustion engine are used in relation need to be covered through requirements, such as energy management, interface and coordinated use. Moreover, further adaptation is needed in the future specifically for propulsive energy storage and PEs other than conventional similar units in MEA aircraft. Although certification process lessons learnt from conventional MEA units can be used, considering operational conditions of electric propulsion systems, especially in the test programs and definition of acceptable results in the validation phase is essential.

However, using MEA's current practical experience regarding reliability issues such as component and subsystem failure rate along with experience gained in high accelerating tests of PE, BMS and Battery in the electrical power system in current aircraft, is an efficient way to evaluate different architectures of PE, BMS and Battery for electrical propulsion in the process of reliability design and certification.

Battery technology also needs to be developed further to cope with long-range aircraft designs.

5.1.1. Reliability System engineering in electric propulsion system and lessons learned

All the mentioned stages for reliability in the life cycle, for new generation propulsion systems, require more consideration due to the novelty of the technology. The cumulative experience in the whole process of certification including system design and development is essential, specifically for new EPS that will be used in future. (Emmanouil, 2020).

Additionally, more reliable components enhance system reliability and are improved by implementing product quality control and monitoring by manufacturers.

Moreover, increasing reliability by applying fault tolerance techniques including redundancy, isolation/ segregation and warning shall also be taken into account.

Finally, high-quality tests such as accelerated tests to simulate situations more severe than normal operations for validation and verification and validation of the certification process are essential (Zio et al., 2019) to achieve the desired level of reliability.

Reliability, and definition of authority safety requirements for EA essential units, are crucial. It is noticeable that the approval process and safety management requirements may grow as regulators obtain supplementary experience by maturing the electric propulsion technology and extension of operations.

Since the application of AI/ML in battery management of EPS will improve the safety and reliability of AEA and HEA, the certification process of systems is required to be taken into account.

5.2. LIB hazard identification and risk assessment

LIB system safety performance is greatly related to the material used, design and manufacturing factors as well as operational and ambient conditions. Therefore, safety management of LIB in any application is challenging much less in the propulsive system of electric aircraft as a sole onboard source of energy. Although the history of the application of LIBs in aircraft systems is not long, the experience, and data from other industries in terms of safety, could be applied, providing that the specific conditions, limitations, and airworthiness requirements are satisfied. This approach is also applicable for studies performed regarding hazard analysis of LIB in applications other than aircraft. For instance, aging hazard in automotive application mostly deals with the reduction of maintenance cost and improving the performance of batteries while this hazard in aircraft, could significantly reduce the safety margins and leads to injury or fatality of human, if not being controlled. Furthermore, considering the weight limitation of aircraft, any overdesign of safety mechanism will cause poor functionality, so safety design is a trade-off between safety and feasibility. In this study, the risk assessment of LIB based on aging hazards which might threaten the safe operations of the electric aircraft developed as a framework. The results of this study can be used as a guideline in the design safety of electric propulsion, specifically in LIB design. A Fishbone diagram is applied to visualize the hazard causes as well as the bow-tie model to visualize the risk assessment of LIB. The advantages of this method over previous studies could be considered as the first to combine two models of visualization (fish bone and bow-tie), where the flow of a sequence of events from root causes to ultimate consequences can be clearly illustrated. The results of this study can also be used as an effective tool for real-time risk management, based on the causes of the hazard. Besides that, another novelty of this study in the process of risk assessment is that it considers the total life cycle of LIB, for identification of contributing factors, the definition of barriers and mitigation of all possible options in battery lifetime from design to operations. The other important aspect of this analysis is the consideration of the fail-safe design principles and techniques in the design of the barriers and control strategies of those, to ensure that major failure conditions are remote, hazardous failure conditions are extremely remote, and catastrophic failure conditions are extremely improbable. The application of multi-layer defence for reducing the risk is one of the fail-safe design representations. Results of the bow-tie analysis show that among safety measures, which are effective in aging hazards, technological barriers and mitigations such as applying BMS and TMS in design and maintainability of them along with cell chemistry design and production are the most effective control measures which are incompatible with other studies (Larsson & Mellander, 2017; D. Ouyang, Chen, Huang, Weng, & Wang, 2019; Sripad et al., 2021). Placement of the battery in aircraft is also important to reduce the effect of ambient temperature and pressure as much as possible. Besides training, regulations and standards are robust supportive reinforcement for technological barriers. Redundancy is also seen as an effective mitigation strategy to ensure functionality is continued in case of failure of the main system and subsystems hardware and software. Modelling battery performance regarding aging or component degradation is essential to proactively predict those failures which directly threaten aircraft operation and it is a function of BMS. Estimation of reserve energy for the mission also is an important factor for the flight crew to be informed and make the best decision based on defined operational procedures. Finally, risk allocation is performed based on the assumptions of the analysis. For the worst-case scenario (total loss) inherent risk level [C4] in the intolerable region is assigned. By applying a combination of five techniques of fail-safe design, as barriers and mitigation strategies, it is shown in this research that a reduction in the level of residual risk to [A4] in a tolerable area is expected, which means, if it could be demonstrated that proposed safety mechanism is capable to perform their functions, LIB system is safe enough against an aging hazard. However, designed safety items are required to be verified by applying precise tests to complete the V-shape safety engineering process to complete certification requirements.

5.3. Lessons for AI application in BMS of future AEA and HEA

Although data-driven approaches employing intelligent algorithms in BMS bring opportunities such as more accuracy, independence to battery model, better performance for non-linear systems and robustness to system noise, it is involved with drawbacks including depending on sample training, complex calculation and slow response (Y. Wang et al., 2020), which is necessary to be considered in battery management of EA and HEA propulsion system. According to the analysis of available literature on intelligent approaches in BMS, the specific features and challenges for future EA and EHA are proposed which are specified in the following section.

5.3.1. Real-world operation consideration

Since the battery is affected by environmental and operational conditions such as current and DOD, besides battery degradation dynamics/aging which must be followed, operating characteristics of intended function or real-world operation must be well-thought-out. She et al. (2020) utilize datasets gathered from real-world electric buses for Radial Basis Function Neural Network (RBFNN) model training, validation, and test, rather than using datasets collected under a restricted amount of well-controlled situations in laboratories. In future, further research is required to develop an embedded prototype system for the real-world operation of BMS for EA. As stated by Hashemi et al. (2021), real flight cycle and operating temperature should be applied to test and validation of the proposed scheme. Therefore in the process of certification, training validation and model verification of EA, real flight conditions must be taken into account.

5.3.2. More accuracy, Less error

Based on analysed literature, applying hybrid algorithms instead of a single algorithm, combining the intelligent method with any kind of filter and co-estimation can improve the accuracy of BMS functions. Li et al. (2019) propose the improved bird swarm algorithm optimization least squares support vector machine (IBSA-LSSVM) model to estimate the RUL of LIBs. Test results show that the root means a square error of the IBSA-LSSVM model for a selected battery type is 0.01, proving the prediction accuracy of the applied model compared to other models. To reduce the estimation fluctuant, especially when the network is used unscented Kalman filter (UKF) can be added behind the network to filter out the fluctuations in the estimation (P. Li et al., 2020) and (Bonfitto, 2020). In a study performed by C. Chen, Xiong, Yang, Shen, & Sun (2019) a battery model using an FFNN is built. Based on the FFNN model and the extended Kalman filter algorithm, the SoC estimation method is designed, and its robustness is verified by experimental data at diverse temperatures. Because battery states are closely interrelated, applying co-estimation methods can increase accuracy and simultaneously reduces computation burden (P. Li et al., 2020). Bonfitto, (2020) suggests a combined estimation method of SOC and SOH of batteries in hybrid and fully electric vehicles. The accuracy of the joint estimation of SOC and SOH is around 97%. The maximum accepted error rate is a criterion which should be defined by regulation and standards, so that being used in the process of safety assessment and initial certification of the aircraft.

5.3.3. Lowering computational time in Real-time operation

The more complex algorithms applied in AI approaches of BMS, the more accuracy will achieve, but simultaneously, computation burden and time will increase which is challenging for real-time BMS functions. In literature, there are some methods proposed to decrease computation time. Khaleghi et al. (2022) utilize a straightforward method with the ability to use data that are available during real-time operation to the benefit of applying the proposed model in real-time applications. Patil et al. (2015) applied the multistage approach, a combination of classification and regression stages to make the computations faster, and therefore a trained model can be used for real-time onboard RUL estimation for battery packs.

X. Li et al. (2017) propose SVM to build the battery degradation model and forecast the battery cycle numbers with higher accuracy and less computation time. Transfer learning recently has attracted research because of the ability of computational burden reduction and accuracy of estimation. Y. Li, Li, Liu, Wang, & Zhang (2021) propose a framework integrating the concepts of transfer learning and network pruning to build compressed Convolutional Neural Network models on a quite small dataset with improved estimation accuracy while reducing the size and computational complexity and time. Thus, Transfer Learning can be considered as a solution for a large amount of data accessibility to reduce the computational time.

5.3.4. Data sources

While NASA's battery data is vastly employed in the training validation of applied intelligent algorithms (Mao et al., 2022), using different sources of data instead of one source is vital for the process of training validation (Khaleghi et al., 2022; K. Liu et al., 2020). With the progress of big data technology, implementing intelligent methods is supported by the large memory device, computation and analysis. The voltage, current, temperature, and other data can be constantly transmitted to the big data platform, hence, intelligent approaches can be trained under real-time tests and distribute more precise results (Hossain Lipu et al., 2021). The online estimation will be possible using the cloud for training and serving localized devices leveraging real data from other vehicles will improve state estimation and fault diagnostics. Especially aging data which needs a long experimental time could benefit ML techniques to address the aging data shortage. Tang, Liu, Li, et al. (2021) develop a migration-based machine learning for joining industrial data with accelerated aging tests to recapture high-fidelity battery aging datasets. Employing this model reduces experimental time by up to 90% and at the same time, aging data can be recovered with lower error within 1%. The other important factor about data besides high quality and a massive amount of data for training model, extracting the key features from massive data to train the model is also a significant technical challenge (X. Li et al., 2017), required to be addressed.

5.3.5. Reliable Sensing

Advanced sensing technologies lead to development in battery management. Developing real-time, accurate and robust sensors, joint with multi-sensor data fusion technology, to obtain the knowledge of the internal mechanism of the battery is essential (Y. Wang et al., 2020). Furthermore, most intelligent algorithms are validated under laboratory situations involved with noise caused by Electro Magnetic Interference and sensor faults. Hence, the advanced sensing technology-based Battery Test System is required to decrease the effect of the measurement noise and consequently raise the estimation accuracy (Hossain Lipu et al., 2021). Besides the learning process, it is necessary to apply a model that can provide viable outputs under limited inputs or sensor error/offsets, interrupted or erroneous inputs, and degrading sensor fidelity. W. Li et al. (2021) proposed a data-driven capacity estimation model applying RNN with LSTM capability. The voltage-time sensor from the constant current phase charging curve is input. This model can produce a sustainable estimation even with incomplete inputs in case of sensor errors.

5.3.6. Main challenges from EASA perspectives

Based on the EASA concept paper, some challenges are identified which are listed below:

- Learning processes need to be covered by assurance frameworks and errors in AI/ML components should be addressed
- Data management to prevent the bias and completeness of data sets in ML training and verification process
- Preventing model bias in the various steps of ML processes
- Considering unpredictable behaviour of ML/DL applications, because of their statistical nature and to model complexity
- Attention to strength and on blocking 'unintended function' in ML/DL applications
- Reduction of residual risk in 'AI black box' which is considered unverifiable.
- Helping trust of end-users to the system (Roadmap, 2021).

6. CONCLUSION AND RECOMMENDATIONS

6.1. Conclusion

Along with the global demand for the reduction of fossil fuels and replacing it with clean renewable sources of energy, the application of AEA and HEA utilizing electric propulsion attracts great attention.

In this study, possible architectures of EPS were discussed. Then challenges toward electrification of propulsive system ranging from technological inadequacies such as battery performance limitation, reliability issued of the new components and also certification process gaps were analysed. Afterwards, reliability principles along with type certification as well as system design and development requirements were reviewed. Reviewing samples of state-of-the-art projects conducted by industry leaders revealed that the future of the aviation industry will be intertwined with electric propulsion system providing that obstacles toward electric propulsion are removed. Then reliability requirements in aircraft life cycle discussion emphasized the importance of identifying reliability requirements and implementing them using a variety of reliability techniques. For instance, reliability design using 3 hierarchical approaches for electrical systems and its advantages were discussed. It was shown that 3 HL modelling may enable the designer to analyse the effect of components and sub-systems on the total system by identifying susceptible parts. Besides that, enhancement of reliability by utilizing thermal control techniques, adding redundancies and implementing maintenance on components or subsystems will be provided by utilizing the 3 HL approach. Steps toward type certification were reviewed from the sight of EASA and FAA regulations. A gap analysis was performed for identifying propulsive system regulation as well as industry standards deficiencies. Knowing that battery, BMS and PE, are both common and essential components of hybrid and fully electric propulsive architecture, we discussed the requirements and current state of regulations, including gaps.

The latest part deals with a review of the progress of intelligent technology applications in BMS. Most applied intelligent techniques were assessed. Then, the BMS function was thoroughly analysed in terms of battery state estimation and battery modelling, fault diagnostics and prognostics, and control strategies based on literature.

finally, the current status of EASA authority regulation including safety assessment requirements studied to find the recently developed authority regulations

Following a comprehensive literature review about hazards and unsafe events of LIB, two important hazard categories which are thermal and aging/chronic hazards are identified and analysed considering causes and contributing factors, unsafe events as an initial result and ultimate consequences are defined using the fish-bone method. Identification of hazard causes facilitates the process of risk management to propose appropriate barriers and control measures. The Bow-tie model which brings the advantages of FTA and ETA at the same time was selected to perform a risk assessment of LIB hazard. Comprehensive preventive and reactive safety mechanisms are proposed in three categories of technology, regulations/ procedures as well as training. In thermal hazards, since the initiation of temperature rise might happen at any level, identification of the sequence of events is crucial to define preventive or control measures. For aging hazard safety analysis which is less addressed in the literature, loss of capacity as a top event was selected and assessed using BowTieXP software. On the left side of the bow-tie model, multiple barriers considering the identified contributing factors are proposed to reduce the probability of a capacity loss occurring as an undesirable event. On the right-side reactive mitigation is placed to reduce the consequence of loss of control. Besides that, the failure mode of each safety mechanism was identified to suggest new controls to prevent barriers and mitigation from failure. The most important one is the definition of components and system failure modes and performance of regular maintenance, inspection and condition monitoring. Considering the weight limitation in aircraft design, any over-design could result in a decrease in the specific energy of the battery. It is also true for TMS, which weight penalty of it shall be regarded in overall battery design and its specific energy. Therefore, enhancing the performance of BMS and TMS as a major battery element is crucial in an electric aircraft application. Considering reliability index in the design stage specifically for BMS and TMS including failure rate (Mean time between failure), failure detection rate and mean time to repair in the design process could effectively impact their reliability and maintainability of them. Moreover, the application of advanced smart BMS and TMS utilizing accuracy of multi-dimensional data measuring, modelling, state estimation and prediction which are significant innovations of battery management technology, will effectively enhance LIB safety.

6.2. Recommendations

For applying design processes and reliability analysis for electric propulsion systems, design and certification criteria should be revised to consider electrical propulsion system components together with the current aircraft systems. EASA Part 21 certification specifications including CS-22,23,25, CS-E and FAA equivalents regulations, must be updated to cover EPS requirements to nourish design criteria to effectively address validation and verification processes. The following items are recommended to address deficiencies in requirements:

1- The close collaboration of authorities and standard developers including ASTM, RTCA, and SAE can open opportunities for providing required guidelines for EPS designers and manufacturers.

2- BMS and PE software and hardware requirements including Item DAL need to be covered in DO-178C/ED-12C and DO-254/ED-80.

3- ASTM standards should be developed to consider EPS requirements specifically for large aircraft.

4- DO-311A should cover requirements for large propulsive LIB that might be used in EPS which are above 5KWh, while it is limited to addressing total battery energy of thousands of kWh. Moreover, functional safety of partial or complete loss of power should be considered.

5- A new regulation must be established to define the requirements of AI/ML application in advanced BMS of EPS, while the following items must be taken into account:

   Utilizing new technologies such as AI and Machine Learning may lead to the better safety performance of LIB in electric aircraft, specifically to develop an integrated framework for fault diagnosis, prognosis, and health management. AI/ML applications in aircraft systems are not covered by current EASA regulations such as Part 21 and related certification specifications. However, the concept paper issued by EASA is an initial step for preparing clients for future regulation. In this stage, the guidance does not support unsupervised learning or reinforcement learning nor adaptive or online training. Also, Overseen automatic, Overridable automatic and Non-Overrideable decision making and action implementation are not covered by the EASA regulation (Roadmap, 2021). Therefore, there are some restrictions at the current stage for certification of AI applications in BMS. For instance, online training using cloud data, deep learning and self-training are not supported by even issued guidance of EASA. Therefore, airworthiness requirements and standards are a gap which is recommended to be addressed by authorities. On the other hand, due to the complexity of the ML models, design verification can be difficult and interpretation of their behaviour during operation also is challenging.

It is crucial to consider all trustworthiness challenges stated in EASA guidance to be thoroughly assessed and answered by academia and designers, to unlock the opportunities for applying AI and ML in aviation and specifically in the next generation of EA and HEA BMS design.

6- To solve the real-world battery data scarcity challenge, it is suggested to transfer running data of current operative EA batteries to the data server for future offline network training and validation of intelligent models.

Cumulative experience in the process of system design and development in any level of EPS including light aircraft or Urban air Mobility vehicles is essential specifically for future electrical propulsion systems of large aircraft.

In the current situation, cooperation between authorities and design organizations to broaden the scopes and prove the suitability of available standards as much as possible to enable regulatory authorities to extend to use of project experience and results in future airworthiness requirement establishment.

6.3. Future study

Future study is recommended in the area of continuing airworthiness and operation of aircraft with the electrical propulsion system. For this purpose, selection of reliability analysis method and application of it to the specific aircraft type shall be conducted. Moreover, to assure a high level of reliability and maintainability, different methodologies for maintenance should be applied as well.

There is much room for additional exploration for developing intelligent algorithms and models for BMS safety responsibilities, considering real-world operation (flight conditions) in training validation, test, and model verification.
The application of intelligent techniques in state of function estimation, specifically, is less studied in the literature. SOF estimation can provide essential information to the pilot to make appropriate decisions, therefore, further study is needed for accurate estimation of SOF using intelligent algorithms in future EA BMS design.
PHM as a preventive maintenance technique provides accurate, early, and online health state analysis, besides prediction of the remaining useful life precisely, independent of the operating situations. Therefore, applying intelligent algorithms for the implementation of the PHM technique aiming at collecting data and knowledge of the system fault and failures to support the maintenance affairs (Zio et al., 2019), is essential in advanced BMS and needs more investigation to be used in future EA and HEA. Robust estimation of SOH is vital for the operation, maintenance, and optimization of the cell (W. Li et al., 2021). This is the same for RUL prediction, which is necessary to provide information for predictive maintenance (K. Liu et al., 2021b). Noticeably, SOH and RUL state estimation is imperative not only in initial certification but also in the continuing airworthiness process of the aircraft.
Finally, since aviation is considered a system of systems, comprehensive analysis of other aspects of it including economic features, social acceptance, ground facility requirements, operational procedures and personnel training of AEA and HEA are possible subject candidates for future research. Generally, the concept of EPS for commercial aircraft will come true, providing that overcoming and addressing all mentioned criteria in the future.

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APPENDICES

Appendix 1: EASA MOC

Aeroplane/ Product	EASA Certification Specification/ FAA Parts	EASA CS/SC/AMC	Industry Documents Mentioned by EASA as Acceptable Means of Compliance
Light Sport Aeroplanes	CS-LSA	CS-LSA.35, CS-LSA.37 SC-LSA-F2480-01" LSA Propulsion Lithium Batteries" SC-ELA.2015-01 "Installation of Li-type storage batteries in sailplanes/powered sailplanes, LSA and VLA" SC-LSA-15-01 - Electric Powerplant Installation for CS LSA aeroplanes	ASTM F2840-11 "Standard Practice for Design and Manufacture of Electric Propulsion Units for Light Sport Aircraft (LSA)" ASTM F2339-06" Standard Specification for Aircraft Electric Propulsion Systems" ASTM F2538-07a ASTM F2245-12d, Standard Specification for Design and Performance of a Light Sport Airplane
Vertical Take-off and Landing aircraft (VTOL)	-	aircraft SC-VTOL-01Special Condition for small-category VTOL MOC SC-VTOL Proposed Means of Compliance with the Special Condition VTOL	ASTM F3232/F3232M-17
Sailplanes and Powered Sailplanes	CS-22	SUBPART H — ENGINES Special Condition EA-42 "Airworthiness Standard for CS-22H Electrical Retractable Engine to be operated in Powered Sailplanes" SC E-01 "Airworthiness standard for CS 22H electrical engines to be operated in powered sailplanes"	ASTM F2480 - Standard Practice for Design and Manufacture of Electric Propulsion Units for Light Sport Aircraft
Normal-Category Aeroplanes	CS-23 Level 1 (Aeroplanes with a maximum seating configuration of 0 to 1 passengers) / FAA Part 23 Airworthiness Standards: Normal Category Airplanes	SC E-18 "Electric Propulsion Units for CS-23 Normal-Category Aeroplanes up to Level 1"	ASTM F3338-18 "Standard Specification for Design of Electric Propulsion Units for General Aviation Aircraft" F3235-17a "Standard Specification for Electrical Storage Batteries in Small Aircraft"
	CS-23 Level 2, 3, 4	SC E-19 "Electric / Hybrid Propulsion System"	ASTM F3338-18 "Standard Specification for Design of Electric

	(Aeroplanes with a maximum seating configuration of 2 to 19 passengers) / FAA Part 23 Airworthiness Standards: Normal Category Airplanes		Propulsion Units for General Aviation Aircraft" F3235-17a Standard Specification for Electrical Storage Batteries in Small Aircraft
Large Aeroplanes	CS-25 Turbine powered Large Aeroplanes/ FAA Part 25 Airworthiness Standards: Transport Category Airplanes	SC E-19 "Electric / Hybrid Propulsion System" AMC 1309	ASTM F3338-18 "Standard Specification for Design of Electric Propulsion Units for General Aviation Aircraft"
AMC 20 General Acceptable Means of Compliance for Airworthiness of Products, Parts and Appliances	Software	AMC 20-115 D / AC 20-115D	ED-12C/ DO-178C ED-215/ DO-330 ED-216/ DO-333 ED-217/DO-332 ED-218/DO-331
	Hardware	AMC 20-152A Development Assurance for Airborne Electronic Hardware (AEH)	ED-80/ DO-254
		AMC 20-170 Integrated modular avionics (IMA)	ED-124/DO-297

Appendix 2: ASTM standards for aircraft electric systems

Committee	Subcommittee	Electric Propulsion standard	Reference (Related to Electric Propulsion)	proposed revisions of	Limitations
F37 Light Sport Aircraft	F37.20 Airplane	F2840-14 Standard Practice for Design and Manufacture of Electric Propulsion Units	EASA CRI F-58 Lithium Battery Installations SAE J2344 Guidelines for Electric Vehicle Safety	-	Only LSA VFR Aircraft

		for Light Sport Aircraft (ASTM, 2014)			
F39 Aircraft Systems	F39.05 Design, Alteration, and Certification of Electric Propulsion Systems	F3338-20 Standard Specification for Design of Electric Propulsion Units for General Aviation Aircraft (ASTM, 2020a)	IEC 60034-1 Rotating electrical machines Part 1 Rating and performance IEC 60349-4 Electric traction Rotating electric machines for rail and road vehicles CS-E CS-P 14 CFR 33: Aircraft Engines 14 CFR 35: Propellers	WK70381 WK67455 WK66523	hybrid configurations is not addressed Electric Propulsion Units (EPUs) that include gearboxes, thrusters, or any energy storage systems is not addressed
F44 on General Aviation Aircraft	F44.40 Power plant	F3239-19 Standard Specification for Aircraft Electric Propulsion Systems (ASTM, 2019b)	F3316/F3316M F3338 S FAA AC23-16 Power plant Guide for Certification of Part 23 Airplanes	WK73027 WK66028 WK65629	focus on hybrid electric propulsion systems with conventional system layout
	F44.50 Systems and Equipment	F3235-17a Standard Specification for Aircraft Storage Batteries (ASTM, 2017)	RTCA/DO-311 Minimum Operational Performance Standards for Rechargeable Lithium Battery Systems	WK73037	Only applicable for “small” aircrafts
		F3316/F3316M-19 Standard Specification for Electrical Systems for Aircraft with Electric or Hybrid-Electric	F3231/F3231M F3239 F3338 DOT/FAA/AR-00/12 Aircraft Materials Fire Test Handbook	WK73040	Not address all of the requirements necessary for possible hybrid-electric configurations where an EPU

	Propulsion (ASTM, 2019a)			and a combustion engine Only Normal Category Airplanes
	ASTM F3231 / F3231M - 21 Standard Specification for Electrical Systems for Aircraft with Combustion Engine Electrical Power Generation (ASTM, 20212)	DOT/FAA/AR-00/12 Aircraft Materials Fire Test Handbook F3235 F3316/F3316M	WK73033 WK72193	Only Normal Category airplanes