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Review

Initial and Continued Airworthiness: Commonalities and Differences Between Civil and Military Aviation

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Abstract: Besides the fact that civil and military aerospace are governed by the same physics and design fundamentals, differences exist between the initial and continued airworthiness criteria for these two aviation fields. Whereas civil aerospace is highly regulated by national and international organizations, the military is mainly governed by national regulations or, in multinational projects, by agreed-upon regulations. A trend exists towards the homogenization of rules in both fields; however, due to national security interests, these are generally agreed upon on a case-by-case basis. This review aims to provide an overview of the processes employed for initial and continued airworthiness of civil and military aviation, focusing on the similitudes and differences.

Keywords: initial airworthiness; continued airworthiness; repair; military aviation; civil aviation; maintenance; repair and overhaul

1. Introduction

The International Civil Aviation Organization (ICAO) distinguishes between two different regulated air traffic regimes, the civil and the state or governmental aircraft. The governmental one includes state-owned aircraft such as military, customs or police aircraft. Whereas civil aviation is highly regulated, having an internationally agreed upon understanding of the design and operation rules, state aviation is governed by each state for sovereignty reasons. Also, the objective of both regimes is different: civil aviation's main objective is to ferry passengers and/or cargo from one destination to another, known as commercial air transport. In addition, other activities are performed, such as aerial work, e.g., for agriculture, photography or surveying. Besides commercial aviation, with the purpose of generating revenue, private aviation exists, where pilots fly for recreational purposes. In general terms, aircraft and their operations are financed (mainly) by private companies, and revenues have to be generated during operation.

In contrast, the sole purpose of non-civil aircraft is to protect the national interest of each country. In the following, the focus will be on military aviation. The acquisition, certification and operation of aircraft are financed by taxpayer's money. In addition to the roles covered by civil aviation, such as logistic missions to transport personnel and freight, a variety of roles are covered by the military air force, such as ensuring the defense of a territory by intercepting unknown aircraft (e.g., combat air patrolling); attacking enemy territory (e.g., bombing of installations); gathering information in intelligence, surveillance, target acquisition and reconnaissance missions (ISTARs); and providing support (e.g., air-to-air refueling). Also, in contrast to civil aircraft, the type of missions and the allowed risks may change during a mission, as well as during peacetime and battle operations [1].

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Only a few reviews were found in the open literature comparing civil and military aviation. Former reviews focused either on the present challenges of continuing airworthiness [2,3], harmonization and standardization efforts [1], the aircraft design [4], aircraft system safety [5,6], the airworthiness management framework [7], predictive maintenance [8] or a specific region [9]. In contrast, this review focuses more on providing a holistic overview of military and civil airworthiness requirements and focusing on the field of maintenance in order to ensure continuing airworthiness of the aircraft.

The rest of this publication follows the following structure: First, the factors influencing aircraft design for civil and military aviation are revisited. Then, Sections 3–6 present the differences and commonalities for civil and military aviation for initial, continued and continuing airworthiness, as well as flight safety management. Within the Continuing Airworthiness subsection, the focus is mainly on structural damage. Before drawing conclusions in Section 8, the findings are discussed in Section 7.

2. Aircraft Development

In both fields, civil and military, a new aircraft program within a design and production company is initiated upon external requests. In the military field, the request for an air platform with specific capabilities is initiated by the Ministry of Defense (MoD). One current example is the capability of collaboration between manned and unmanned aerial vehicles [10,11]. In contrast, within the commercial sector, design and production companies look for a market void in order to satisfy the needs of potential customers. The current trend within civil aerospace is moving towards more environmentally friendly aircraft with alternative energy sources, e.g., the Airbus ZeroE program [12].

2.1. Military

One major difference between military and civil aviation is the involvement of the "customer" within the aircraft development. In the case of civil aviation, the customers are airlines, whereas for military aviation, the customer is the MoD.

In the case of military aircraft, the MoD sets tentative operational requirements for the future platform, a combination of numerous and various desired capabilities, which is presented to several design companies to further develop the aircraft considering the requirements of the different communities within the MoD. In the case of military jets, companies designing these future platforms are required to implement novel technologies such as stealth or new materials in order to cover future threats and gain advantages over existing platforms and countermeasures. For example, over time, the implemented materials and design solutions have been refined to reduce the radar signature of aircraft to cope with better reconnaissance methods [13]. Therefore, during the design process, not only requirements in terms of airworthiness, meaning flight envelope, operability or maneuverability, but also requirements in terms of, e.g., radar signature, weapon systems or countermeasures have to be agreed upon between the customer and the design/production company. As state-of-the-art materials and manufacturing processes and beyond are employed, within the development process, one or several prototypes are manufactured to demonstrate and validate fulfillment of the requirements by the new solutions. As federal budgets are reviewed yearly, governments might influence the design process by adding further requirements or even cancelling the project on an ongoing basis. This risk also leads to further delays within the design and manufacturing process as companies will postpone capital investments for serial manufacture of the platform until final commitment of the MoD is obtained.

2.2. Civil

In contrast, within the civil industry, the design and requirements such as capacity (max. passengers/cargo), range, reliability and fuel consumption are defined and set by the design company. The potential customers act as an advisory group, only having input in these high-level requirements, with little influence on the details of the aircraft design. Also, during the development phase of new aircraft, the employed technologies are fairly well understood and industrially available in order to reduce risks in the project. This is shown, e.g., by the incremental increase in the percentage of composite materials within Boeing and Airbus aircraft, where over time, the parts manufactured with composite materials has increased and changed from application in secondary structures to primary structures [14]. In contrast, within the military field, composite materials have found a much earlier and wider application.

As military aircraft are designed to push the possibilities beyond normal operations, such as high-g maneuvers for fighters or landing/starting on short and unpaved grounds, the design service goal in terms of flight hours or cycles is lower for military aircraft than for civilian ones [15].

Whereas within military aircraft development, R&D tasks and validation of novel technologies are also part of new aircraft development projects, within civil aircraft manufacturing technology, development processes are performed in parallel to aircraft development. A constant technology watch is performed by the original equipment manufacturers (OEMs). Both internal as well as publicly funded research projects are carried out in order to push technology to high technology readiness levels (TRLs) [16]. Once the technologies are found to be implementation-ready, they are considered for introduction in new aircraft programs. An example, therefore, is the Multifunctional Fuselage Demonstrator, where the ability to produce a thermoplastic fuselage was demonstrated within a large consortium within a European-funded FP7 research project [17].

3. Initial Airworthiness

Before a new aircraft design is allowed to fly, it must first be certified as meeting the authority requirements based on recommendations from the International Civil Aviation Organization (ICAO). In the civil sector, the process is described by the civil aviation authority, e.g., the FAA in the USA or the EASA in Europe. A wide range of bilateral acceptance agreements exist that ensure that if an aircraft design is certified by one civil aviation authority, it is accepted by the others, even though differences between the procedures exist [18]. In contrast, within the military, each country has its own certification procedure.

3.1. Civil

In the case of a certification performed by the EASA, a four-step process is followed once the preliminary design of the new aircraft or a change in a current aircraft design has been defined by the design authority [19] (see also Figure 3). For other certification authorities, like the FAA, similar approaches are followed. First, a technical familiarization is performed and the certification basis—meaning the applicable design rules—is decided. The certification authority and the production company agree on the requirements that will be applied during the certification of the specific aircraft and thereby establish the validation basis. The extent of this is specified in the certification basis. Afterwards, the certification program is established, where the means to demonstrate compliance of the new aircraft type with each requirement of the certification basis are established. Then, the verification phase starts, where compliance with the requirements is demonstrated by the aircraft manufacturer. This can be performed either by tests or by an analysis supported by tests. For the structural validation, the validation ranges from the definition of design allowable by coupon level to full scale static and fatigue tests as well as flight tests in a variety of conditions in order to validate the design and all the systems (Figure 1).

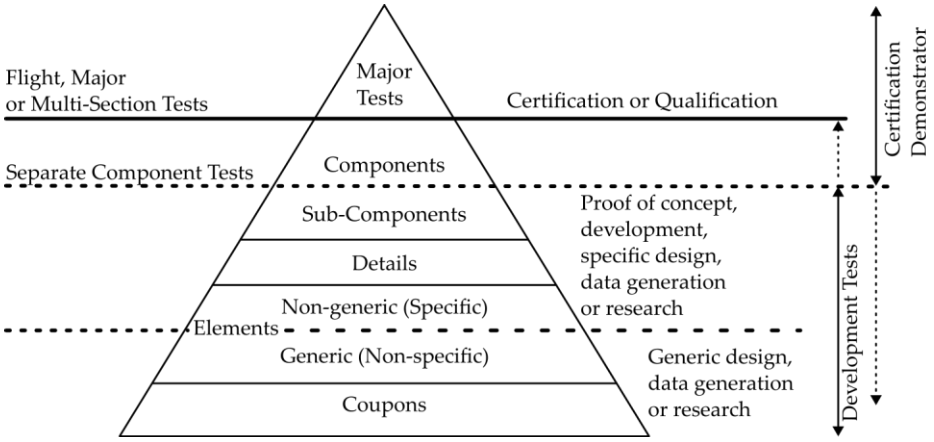

Figure 1. Testing pyramid adapted from [14].

In a last step, the project is closed and the type certificate of the new aircraft type is granted. Besides this defined process, the design organization and the production organization have to be approved by the authorities to be able to perform the different tasks. The authority responsible for granting the type certificate is the one where the aircraft was designed.

3.2. Military

For national security reasons, each country has its own (standardized) process for achieving airworthiness certification [20–22]. Also, in terms of qualification, meaning meeting the defined operational requirements and achieving airworthiness certification simultaneously, the exact process is defined on a case-by-case study. This generally leads to delays as an exact process has to be agreed upon by the different involved parties by selecting applicable airworthiness codes from the civil and military framework and also defining new standards to be compliant with [23]. In addition, the performance requirements have to be established and validated. The parallel working of the airworthiness certification and performance qualification is shown in Figure 2.

This becomes more challenging in multinational development programs such as the Eurofighter Typhoon [24] or future systems such as the FCAS or Tempest [11]. Therefore, a trend towards standardization exists, in order to improve the qualification process and to ensure the compatibility of systems within defense alliances such as NATO [15,25]. For example, regarding the observed benefits of civil aircraft airworthiness certification, the UK Defence Standard 00-970 follows many of the EASA Certification Specifications [22]. In order to further streamline the certification process, cooperation between the civil and military airworthiness certification authorities exists in order to permit military aircraft to fly in civilian airspace. Therefore, in an homogenization effort, the European Defence Agency (EDA) put forward the European Military Airworthiness Requirements (EMARs) [26]. These act as guidelines and are not regulations [1]. Their implementation is a decision made by each member state that is adapted to the national needs, e.g., DEMAR for Germany [27]. However, the aim of the EMARs is to standardize the certification and to enhance collaboration between the military aviation authorities from different nations as well as the transfer of products and services between civil and military airspace [1,27]. A structure similar to the EASA regulatory structure is adopted by the EMARs.

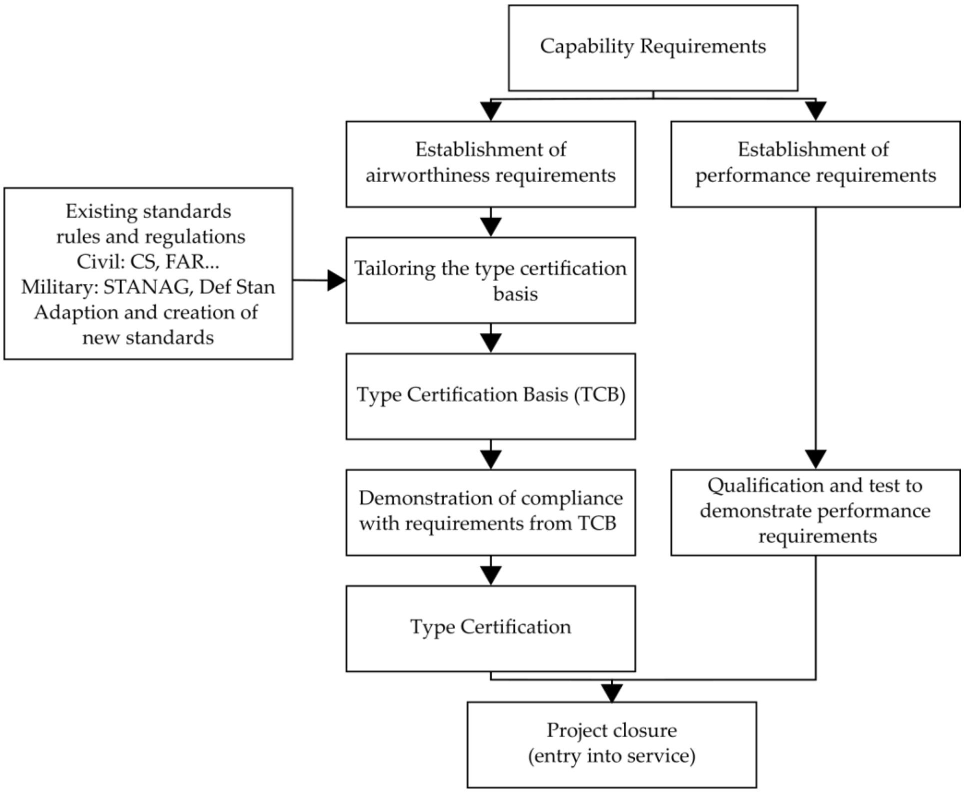

Figure 2. Generic process showing the relationship between the initial airworthiness certification and qualification process for military aviation adapted from [23].

In terms of airworthiness certification, the following process is followed within the EMAR framework, which is in line with the EASA process [23,28], in order to obtain agreement between the National Military Airworthiness Authority (NMAA) and the manufacturer on the type certificate basis (refer to Figure 3). In a first step, within a technical description, the general design and the potential types of roles and missions of the air system are described. This includes both the type of aircraft, e.g., combat aircraft, military transport or ISTAR, as well as a statement of the operating intent. With this knowledge, the airworthiness standards as well as specific military system design specifications, e.g., air-to-air refueling or weapon system integration, are selected. These standards define the reliability and safety objectives for the platform.

These safety and reliability requirements are adapted depending on the deployment scenario of the aircraft. The allowed flight envelope might be reduced during peacetime operations such as air patrolling or transfer flights in order to increase the reliability of the system and to increase the lifetime of the components of the aircraft for safety and economic reasons. However, in combat situations, the allowed flight envelope might be increased to allow for increased performance, allowing for a more risk-prone operation and degradation of the components of the aircraft. This is further detailed in the section about flight safety management.

In a next step, the applicable criteria that will be the rules to be followed within the certification process are selected. First, from the European Military Airworthiness Certification Criteria (EMACC), the applicable criteria are selected and documented. In cases in which further requirements are needed, additional primary certification codes or standards are added to the requirement ground base. These codes and standards are also partly adapted to the needs for the certification of the aircraft system. However, prior to approval and issuance of the type certification basis (TCB), it is important to verify that the to-be-applied rules and regulations are self-consistent and no contradictions exist between them. Then, through analysis and tests, compliance of the type design with the agreed-upon requirements (TCB) is demonstrated, and finally, the NMAA issues the military type certificate.

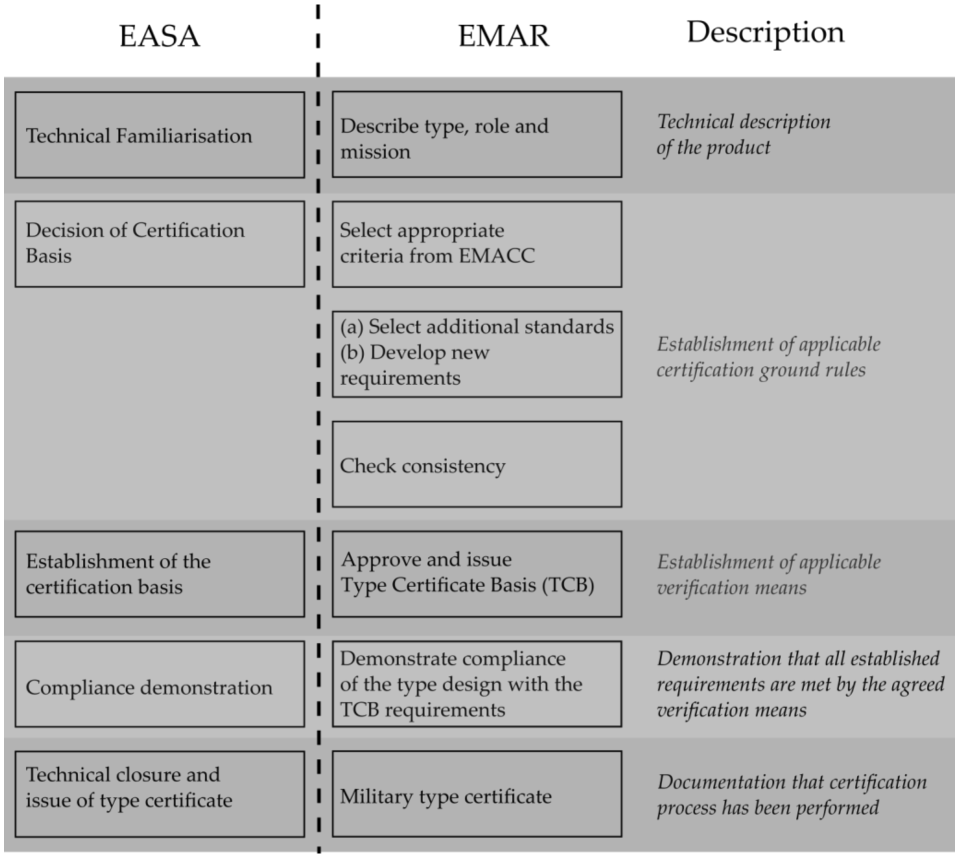

Figure 3. Process to achieve type certificate according to EASA and EMAR processes adapted from [27,28].

4. Continued Airworthiness

Within aviation, continued airworthiness refers to the support obtained by the design organization of the aircraft during the lifecycle of the aircraft. Note that from a certification perspective in civil aviation, the design and production of the aircraft are performed by two different entities that might or might not be different companies. In contrast, continuing airworthiness includes the actions performed during operation of the aircraft to maintain the aircraft airworthiness (refer to Section 5) [29]. Both military and civil aviation consider that the initial design is finished once an aircraft has received a type certification. However, it is generally in agreement that the design organization will continue to support the aircraft during its entire lifecycle. Over time, design changes are introduced, for example, to eliminate later detected design flaws, remediate actions initiated by airworthiness directives, adapt inspection intervals or repair accidental damage. These changes both affect the production of new aircraft as well the maintenance, repair and overhaul (MRO) process (continuing airworthiness) of already produced aircraft [27].

5. Continuing Airworthiness

Each aircraft needs an airworthiness certificate demonstrating the ability to fly in safe conditions within allowable limits. In order to do so, the certificate covers the type certificate of the aircraft model, the documentation that the aircraft has been produced according to the type certificate model and documentation showing that maintenance is performed according to the requirements of the aircraft. Therefore, it can be stated that the objective of maintenance is to maintain the airworthiness of an aircraft.

Civil aircraft maintenance is currently based on the MSG-3 philosophy, where tasks and task intervals are assigned to all aircraft systems and components based on failure effect analyses [30]. Maintenance is performed (1) after it has a hard time, after which the part has to be maintained (servicing, full or partial overhaul, and/or replaced); (2) conditionally, i.e., the part is inspected at specified intervals to an appropriate standard to determine whether it can continue to remain in service, and if the part is not up to standard it has to be serviced/repaired or exchanged; or (3) routinely, with condition monitoring information on items collected in a continuous manner either directly or indirectly in order to assess the state of the part.

In addition, maintenance can be either preventive and generally scheduled, or reactive and generally unscheduled. This includes servicing operations, e.g., when replenishing consumables or washing/cleaning, for hard-time tasks, for conditional tasks or during condition monitoring. This approach is followed both in civil as well as military aviation and is generally known as reliability centered maintenance (RCM). Therefore, the maintenance tasks and intervals are defined and scheduled according to failure probabilities, considering the effects of the failure on safe operation [31].

5.1. Scheduled Maintenance (Routine Maintenance)

Part of the certification is the creation of initial scheduled maintenance plans in order to ensure safety of the aircraft. During operation, a certain degradation of the employed systems is accepted due to wear and tear, and after a specified timeframe, specific servicing tasks are needed such as lubricating, inspection, or discard and replacement.

5.1.1. Line Maintenance

All maintenance activities that are carried out without hangar space and require a short timeframe are referred to as line maintenance. These tasks are daily or weekly events and are both performed within civil and military aircraft. These routine and immediate maintenance tasks are performed on an aircraft typically at the gate or on the tarmac between flights, e.g., pre-flight and post-flight inspections or maintenance tasks. In the following, examples of potential tasks are stated:

- Flight-ready checks, such as general visual inspections performed by the pilots or by maintenance personnel as well as system checks and other assessments.
- Minor repairs, such as minor leaks, adjusting controls or replacing small parts (filters).
- Fluid checks, such as checking and replenishing fluids, e.g., hydraulic fluids, engine oils or kerosene.
- Tire changes, checking, inflating and replacing tires as well as assessing and maintaining brake systems.
- Software updates and calibrations.
- Replacement of Line Replaceable Units (LRUs).

Also, line maintenance has to take into account the feedback from the flight crew and, on a day-to-day routine, is the first point of contact for any damage to the aircraft, which might lead to unscheduled maintenance activity. Then, decisions have to be made regarding whether the aircraft is safe to be flown or needs to be grounded.

Whereas for civilian aircraft, in which one challenge is to fit the line maintenance within the aircraft schedule and the network [32], military aircraft generally perform flights to a low number of bases, making this planning easier. Also, depending on the scenario (peacetime versus deployment), the amount of line maintenance tasks can be adapted. Additionally, in the case of military aircraft, the inspection intervals may depend on the area where they are deployed, e.g., in dusty or salty regions, the interval might be reduced for motors [19].

5.1.2. Base Maintenance

Base maintenance is defined as everything that is not line maintenance. Therefore, aircraft are put out of service and ferried to specialized bases, where the maintenance is performed. Some of the maintenance tasks are directly performed on the aircraft (on-wing maintenance), whereas other parts are partly removed from the aircraft and either serviced in the hangar (near-wing maintenance) or returned to specialized shops or OEMs for extended services or repair/overhaul (refer to component maintenance). In order to improve aircraft availability, new or serviced parts are installed on the aircraft and the to-be-serviced parts are installed on another aircraft.

These base maintenance checks are generally known as letter checks, namely A-, C-, and D-check, on which a variety of maintenance tasks are grouped. Examples of the tasks and duration of these letter checks are summarized in Table 1. In the past, additionally, so-called B-checks were performed; however, currently, the tasks to be performed during B-check are normally incorporated into A-checks. Also, for improved availability, it is possible to break the tasks from longer checks (C and D) into subtasks and perform them (partly) during A and C checks [33].

Table 1. Description of letter checks [33,34]. Exact interval and duration depend on aircraft type.

	Typical Tasks	Typical Interval	Typical Duration
A-check	Checking and servicing oil, filter replacement, lubrication, operational checks and inspections	14 days	1 day
B-check	Similar to A-check, but in a more detailed examination	6–8 months	1–3 days
C-check	Functional and operational checks, cleaning and servicing, attendance to minor structural inspections and service bulleting requirements	12–20 months	1–3 weeks
D-check	Paint stripping, outer panel removal, uncovering the airframe, supporting structure and wings for inspection of most structurally significant items	6–12 years	3–8 weeks

The planning of maintenance operations of civil aircraft is based on the operational necessities to maintain the network, as well as internal or external resources available for performing the maintenance actions. In case the planning and execution of these tasks with internal ressources are not possible, either external ressources are contracted, e.g., maintenance facilities or leasing of aircraft, or flights are cancelled [34].

Within military operations, maintenance is slightly differently scheduled. Base or depot maintenance is planned around the fleet to assure that a certain number of aircraft is available for a certain amount of time. It is envisaged to have a maintenance-free operation period (MFOP) during deployment in order to be able to operate with a reduced range of specialist personel, spares, facilities and maintenance/support resources.

The maintenance is performed as such in order to ensure the availability and the reliability of the aircraft. This period of operation of time is then followed by a Maintenance Recovery Period (MRP), where all the maintenance operations that were not performed during the MFOP are performed in order to prepare the aircraft for the next MFOP. Generally, a health and usage monitoring system (HUMS) is employed to have an onboard diagnostic able to defer some of the maintenance activities from minor faults. Also, further redundancies are incorporated within the aircraft, and modular designs of the engines for quick exchange are incorporated [31].

5.1.3. Component Maintenance

Components, such as avionic bays or hydraulic pumps within the aircraft are also subjected to maintenance intervals. Depending on the complexity of the system, they are either maintained directly on the aircraft or removed from the aircraft and sent to the OEM for overhaul [27].

5.2. Unplanned Maintenance (Non-Routine Maintenance)

Besides planned activities, unplanned maintenance tasks exist. Thereby, the part is used until the end of its lifetime. This can be either due to accepted degradation due to wear and tear or due to accidental loadings. When this occurs, in a first step, diagnosis has to be performed in order to isolate the faulty part. Once the failure location is identified, the relevant authorities are informed in order to plan the repair or replacement in order to put the aircraft back into service as soon as possible [27]. Due to time restraints, generally, failed equipment that can be replaced is replaced by working ones (either new or refurbished). However, in the case of structural damage, replacement is not always feasible due to the costs or spare part availability. The general process of how a failed part is treated is shown in Table 2.

Table 2. Process steps in order to handle unplanned maintenance adapted from [35].

Step	Description
Damage event	For structural damage: Possible damage events: excessive loads, bird strikes, fire, etc.; In case of military weapon damage (kinetic energy, explosion). For other damage types: Wear and tear of the equipment, e.g., failure of a resistance or light bulb.
Damage detection	By the flight crew due to observations such as change of flight behavior (e.g., vibrations), noise. By an on-board health-monitoring system (e.g., structure, engine, electronics). Through routine maintenance tasks (visual inspection, non-destructive testing).
Characterization of damage	For structural damage: assessment of damage (type, size, location) and documentation of damage. For other damage: assessment of backup systems exist that permit (degraded) operation of the aircraft, e.g., failure of anti-iceing equipment in non-iceing flight conditions.
Assessment of mitigation strategy	Definition of further actions depending on damage criticality. Does the damage have to be repaired permanently, can a temporary repair be performed or can the repair be postponed? In the case of non-structural damage, can the equipment, e.g., avionic bay, be replaced? Within civil aircraft, economic considerations are the main driver, whereas for military, in addition, mission criteria apply.
Planning and Preparation	For structural damage: In case of damage present within the repair manuals, repair materials and resources have to be deployed. This damage is generally referred to as minor damage. In the case of major damage, the design office of the aircraft has to be contacted and a repair solution has to be designed and implemented. In this case, the airworthiness authorities have to be involved. For non-structural damage, replacement parts have to be sourced.
Execution	For structural damage, the actual process of repair varies based on the mitigation strategy, ranging from removal and replacement to cleaning of the affected area, removal of the paint system, lightning strike protection, removal of the damage, patching the damage with new material, and putting back the lightning strike and paint system. Afterwards, the structural integrity is assessed. For non-structural damage, generally, parts are replaced by working ones.
Documentation	The entire process of the repair has to be documented in order to assure traceability.

In the following Sections 5.2.1–5.2.5, the focus will be placed on structural damage and the mitigation strategies. These are considered during the design and certification process of aircraft, e.g., full-scale static and fatigue tests are performed in order to assure the structural integrity of the aircraft.

5.2.1. Structural Damage Within Civil Aviation

The source of damage can be due to accidental loading, e.g., bird strikes, impact to the cargo door area due to airport vehicles, lighting strikes or excessive loads. Also, degradation phenomena such as corrosion and fatigue degrade the aircraft structure over time.

For composite materials, damage initiation generally occurs at locations where high through-thickness stresses are present, such as at ply drops or thickness changes, which leads to delaminations within the structure.

For metallic structures, the focus is on fatigue and corrosion damage, initiating from stress concentration like bore holes.

Within civil aviation, structural damage is treated differently depending on the type of material. For composite materials, a damage no growth criterium (see Figure 5) is applied, limiting the allowable strain on the structure to inhibit the damage growth [36]. AC 20-107B [37] from the FAA defines five different types of damage (see Figure 4) in composite materials:

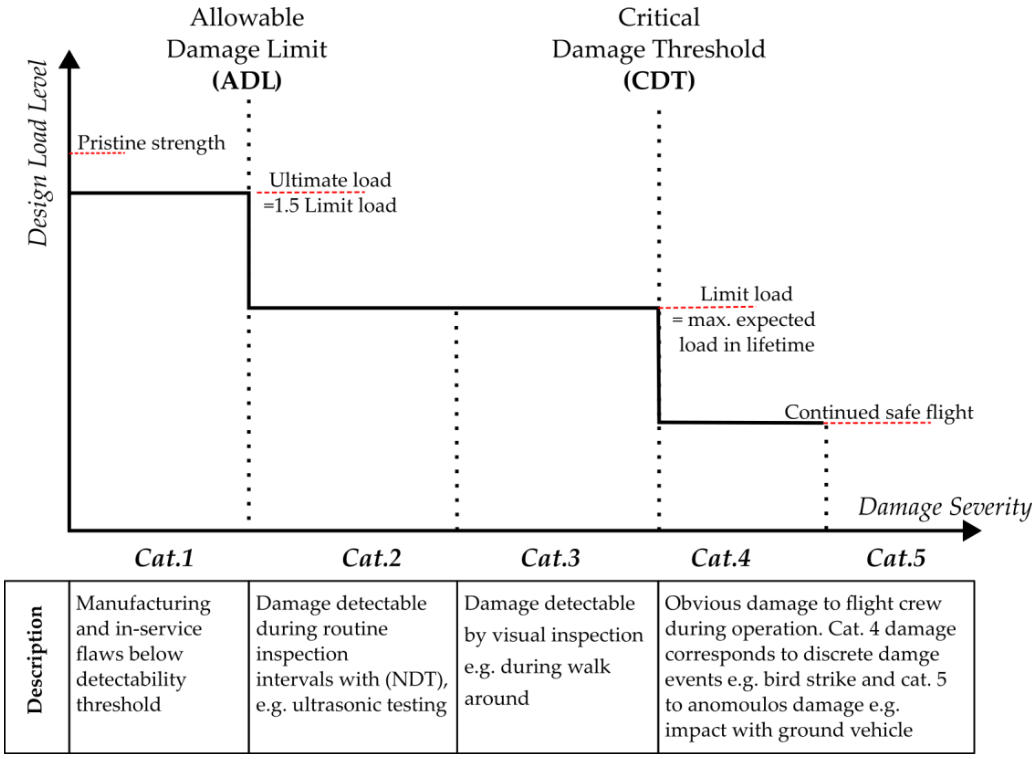

Figure 4. Schematic diagram of design load levels versus damage categories for composite materials adapted from [37,38].

Category 1: Allowable damage corresponding to damage which is not readily detectable by scheduled or unscheduled inspection or acceptable manufacturing defects. This damage is taken into account in the design process, and it is shown that the structure maintains ultimate strength in the presence of this damage. The ultimate strength corresponds to 1.5 times the limit load, which is the maximal estimated load that the aircraft will suffer during the lifetime.

Category 2: Damage that is reliably detected within the scheduled or directed field inspections, e.g., ultrasonic inspection or another non-destructive testing (NDT). Before detection of the damage, the structure has to be able to sustain sufficient load above limit load capability.

Category 3: Damage that is readily detected within a few flights after occurrence by operations or ramp maintenance personnel. The damage is generally detectable by visual inspection.

Category 4: Discrete source damage from a known incident, such as bird strikes, tire bursts, rotor bursts or severe in-flight hail, which leads to a reduction in the flight envelope. However, a save flight is assured.

Category 5: Severe damage created by anomalous ground or flight events, which are not covered by design criteria or structural substantiation procedures. Category 5 damage includes severe service vehicle collisions with aircraft; anomalous flight overload conditions; abnormally hard landings; maintenance jacking errors; and loss of aircraft parts in flight, including possible subsequent high-energy, wide area (blunt) impact with adjacent structures.

For metallic materials, the approach followed for treating damage has changed over time. Currently, two approaches exist: safe life, where a hard limit exists, after which the part is exchanged, and a damage tolerant approach, where either the inspection interval is chosen so that potential propagating cracks are detected or multiple load path with crack arresting features are present [39]. Figure 5 summarizes the approach for metallic and composite materials.

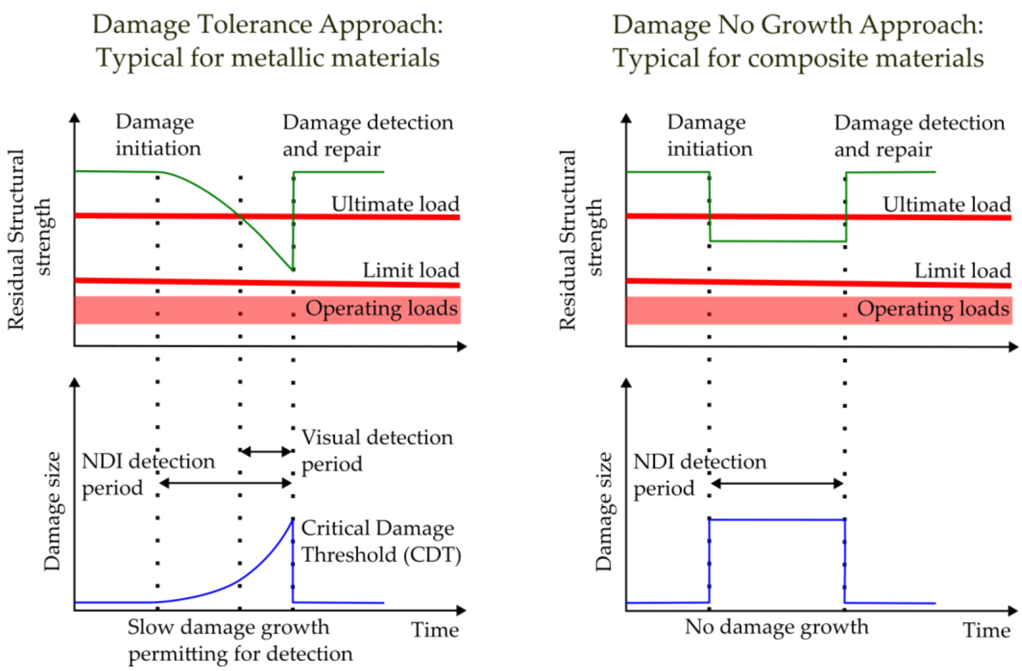

Figure 5. Schematization of design approaches for dealing with damage within metallic structures (**left**) and composite structures (**right**) [14,37].

5.2.2. Structural Damage Within Military Aviation

In addition to the damage present in civil aviation, military aircraft are also prone to other damages, e.g., due to weapons/explosions. Also, aircraft are partly operated at airports with lower-quality runways. This is considered during the design process; for example, military cargo planes have a high wing design to reduce impact damage from runway debris. However, not many details are publicly available.

5.2.3. Inspection in Civil and Military Aviation

For both civil and military aircraft, in order to obtain an airworthiness certificate, an aircraft maintenance manual (AMM) has to be established by the design authority. The AMM includes the inspection procedure and interval for the different structural items. The employed technologies range from "naked eye" visual inspections performed on pre- and post-flight go-around operations to more detailed inspections using advanced equipment like borescopes, ultrasonic inspection or eddy current testing [40]. More advanced techniques for monitoring the structural state, called structural health monitoring (SHM), are also currently employed both in the civil and military sectors. In the latter, the usage of integrated monitoring techniques is more extensive to allow for quick turnaround times and load monitoring in order to estimate the remaining operating life (ROL) [24,31,41,42]. For civil and military aircraft, similar techniques are employed, whereas for military, more thorough inspections are performed in order to permit a maintenance-free operation period. Also, the usage of SHM techniques is more established in military than in civil aviation [41,42].

5.2.4. Repair in Civil Aviation

The aim of structural repair is to return the aircraft to a state of structural integrity and functionality corresponding to the same level as the undamaged part, thereby regaining the type certificate status [43]. For damage corresponding to categories 2 to 5 (refer to Figure 4), standardized damage types are established during the design process. For these damages, standardized repair solutions are summarized within the Structural Repair Manual (SRM) [27,43,44]. For these documented repairs, the maintenance organizations are allowed to perform the repair without further information from the design organization of the aircraft. In terms of damage within the SRM it is distinguished between

1. Allowable or negligible damage: In this case, the damage is documented and the repair is postponed in order to reduce the impact on operation. However, corrosion and moisture ingression protection might be necessary.
2. Damage where temporary repair is acceptable: In this case, a relatively quick non-permanent repair is performed, e.g., bolting a doubler plate. Then, within a specific time, a permanent repair is performed. In the meantime, restrictions on the aircraft operation might be established, but the aircraft can be put back into operation permitting a scheduled repair. Partly, these types of repairs are also performed in order to fly the aircraft to a more suitable maintenance facility.
3. Repairable damage within the SRM, in which the maximum size and quantity of damages are specified. In case the present damage is beyond this specification, the design authority has to be contacted and a repair solution has to be engineered or the decision to replace the part is made.
4. Damage that is not repairable or beyond economic repair. In this case, it is more economical to replace the part of the aircraft.

5.2.5. Repair in Military Aviation

A similar approach as in civil aviation is followed in military aviation. During the design process, a structural repair manual is established. However, in contrast to civil aviation, where the type certificate is held by the design authority (generally the OEM), in military aviation, the type certificate is transferred for sovereignty and safety reasons to the MoD [27]. However, as the MoD does not have the capability to take over the responsibilities of the design authority, contracts with industrial companies are established. Also, depending on the location of the aircraft and type of operation, the capabilities and priorities change. However, besides recovering structural integrity, other functions like stealth and electromagnetic properties are also important within military repair.

In the case of wartime, returning aircraft on site as quickly as possible back to operation can make a strategic difference between accomplishing a certain mission or not accomplishing it. For example, the Israelian air force was able to recover 50% of the damaged aircraft within 24 h, resulting in maintaining sufficient airpower during the 1973 Jom Kippur war. Similar experiences where gathered during the Vietnam war by the US air force [45]. During these wars, dog fights and visual attacks of land-based targets were the ways in which fighter and bomber aircraft operated. However, now, with the advancement of stealth technologies and missile systems, aircraft generally engage beyond a visual line. Missiles are fired at a certain distance and have a (semi-)autonomous system for seeking the target. Once an aircraft is tracked by such a missile, evasive countermeasures are performed, but in case of the missile reaching the aircraft, the aircraft is destroyed. Therefore, the scenario of battle repair has changed over time. However, aircraft might be damaged during the landing and take-off phases, on the ground or even during cruise flights, leading to repairable damage. Also, in the case of helicopters that deliver operators within contested regions, damage may be caused by kinetic weapons. In addition, since the end of the cold war, the number of available military aircraft has been dramatically reduced due to cost reduction reasons making availability and repairability of resources a high priority. In the case of aircraft battle-damaged repair (ABDR) or aircraft expedient repair, the main goal is to bring the asset to a temporary serviceable condition with the available resources within the lowest timeframe in order to meet the necessities of the combat condition. The idea is that due to the wartime, the maintenance conditions are reduced in order to continue the airworthiness for a reduced timeframe [1]. Therefore, the ABDR team has a variety of toolboxes in order to put the aircraft back into service, prioritizing availability of the aircraft over reliability. Also, a commissioned aircraft structure engineer who can plan out and authorize depot-level repairs in the field is dispatched with the ABDR team [46]. In terms of repair strategy, a triage-type approach (see Figure 6) is followed in order to determine which aircraft is repaired first, with the aim of recovering the full static strength and not the full fatigue life, as in the case of peacetime. In the case of the US Airforce, the first quick repair is based on a strength versus stress analysis using a reverse engineered approach [47]. In order to be able to perform such rapid repairs under austere conditions with limited resources, the aircraft has to be designed for rapid salvage and repair, and acceptable repair schemes/procedures for both minor and major repairs should be pre-authorized [31]. Also, some parts like the engine are designed in a modular way in order to permit quick repair by replacing some parts from stock or to cannibalize them from other aircraft.

In addition to the structural assessment, a systems assessment, e.g., impact on wires, pipes or computers, is necessary [31]. Once the damage is identified and localized, a similar logic as for the structural ABDR is followed. After analyzing the impact of damage on the aircraft functions, depending on the mission, the minimum repair or replacement of the systems is decided. This might even lead to the cannibalization of parts from other aircraft.

Analogous to the SRM, an ABDR guideline is prepared for each aircraft model in order to support triage-type assessment of the aircraft. Therefore, the structure is divided within different structural categories and repair zones [47]:

Category I: Primary Structure: a structure which carries significant flight or weight loads and without which the aircraft could not maintain structural integrity.

Category II: Secondary Structure: a structure which carries significant flight or weight loads but without which the aircraft could maintain structural integrity. However, these structural items transfer the loads between the primary structural elements.

Category III: Tertiary structure: superfluous structures that neither carry load nor serve aerodynamic purposes, e.g., tail cones, landing gear pods and pylons.

Category IV: Aerodynamic Components: their sole purpose is maintaining aerodynamic qualities. They are important for aircraft performance and controllability.

Category V: Not reparable using ABDR.

In the case of the US Airforce, assessments are performed for each zone, starting from the most critical one [31,47].

Class A: Degraded Capability: damage that can be left unrepaired and still allows for partial capability, also termed "restricted" sortie.

Class B: Maximum damage that can be repaired using ABDR techniques while allowing for an unrestricted sortie.

Class C: Acceptable Damage: damage that can be left unrepaired while allowing for an unrestricted sortie.

Class E: Engineering Disposition Required: the damage requires an engineer's assessment of reparability. Generally, this class corresponds to the primary structure.

Therefore, the damage is assessed within the following categories [31,47]:

1. Fully reparable on site with the resources available on site;
2. Fully reparable on site with an ABDR or depot field team;
3. Partially reparable on site with an ABDR or depot field team;
4. Beyond local repair, but salvageable by ABDR or depot field teams;
5. Beyond economical repair.

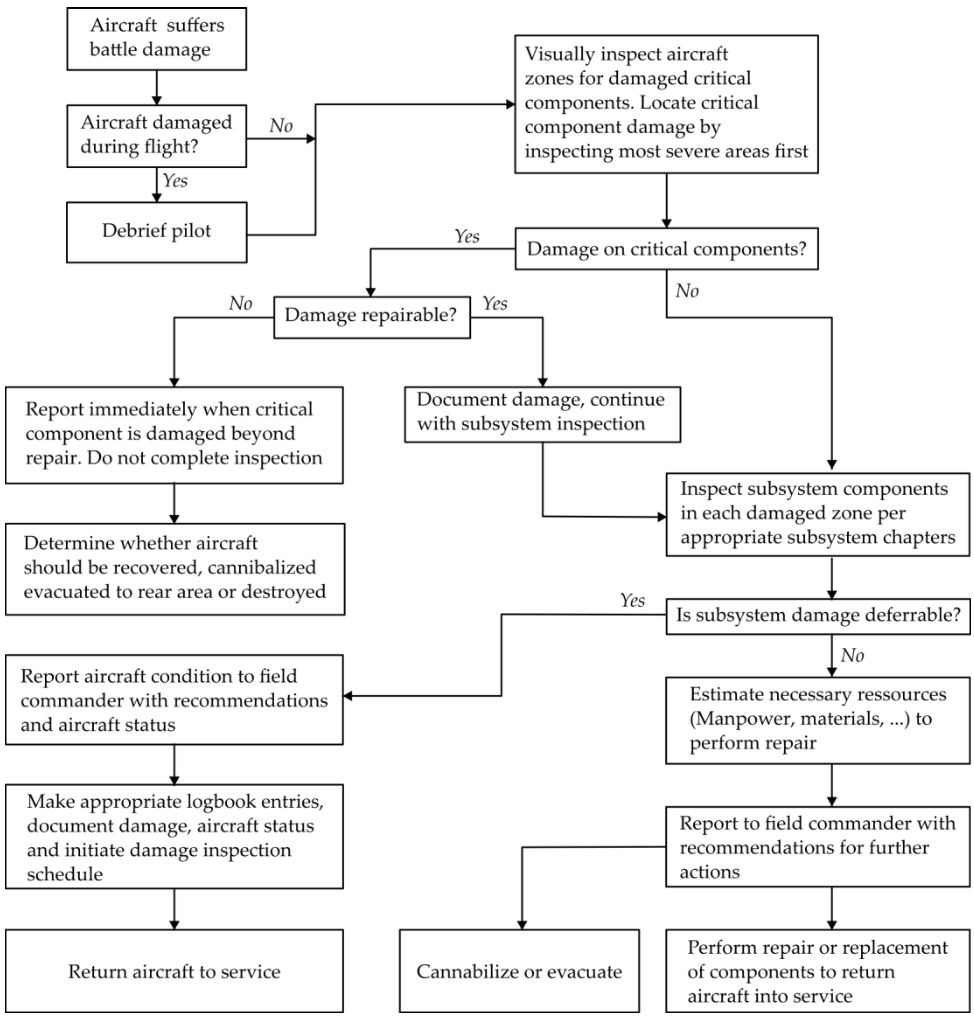

Figure 6. Schematic of "triage" after battle damage adapted from [47].

6. Flight Safety Management

Until now, the focus has been on functional safety, focusing on the design, development and maintenance of the aircraft. However, operational safety is also considered while civil and military aircraft are operated. For example, the introduction of checklists due to the increasing complexity of the aircraft was introduced in 1935 within military aviation and has been not only adopted within civil aviation but also in other safety-critical industries like health care, engineering and construction [48]. Safety is generally accepted as the freedom from unacceptable risk of harm [6]. In order to confirm the acceptance of the risk, in both fields, a failure mode and effects analysis is performed and probabilities of failure are defined. This then leads to the acceptance or not acceptance of the risks.

For civil aircraft, system safety requirements are defined in the SAE ARP 4761 [49]. The failure severity is classified into five different regimes, as shown in Table 3.

Table 3. Safety effect of failure within civil aviation [29,49].

Safety Effect of Failure	Description	Probability per Flight Hour
None	No effect on aircraft functional capability or occupants	-
Minor	Slight reduction in aircraft functional capability or occupant physical discomfort	$\approx 10^{-5}$
Major	Significant reduction in aircraft functional capability or non-fatal injuries	$\approx 10^{-6}$
Hazardous	Large reduction in aircraft functional capability or small number of occupant fatalities or severe injuries	$\approx 10^{-7}$
Catastrophic	Loss of aircraft or multiple occupant fatalities	$\approx 10^{-9}$

An inverse relationship exists between the severity of failure conditions and the allowed probability of occurrence, so minor failures are probable and could occur several times in the aircraft's life, major failures are remote and might arise once in an aircraft's life, and hazardous conditions are extremely remote and might arise once in the whole fleet's life. Catastrophic conditions are extremely improbable [29].

A similar approach is followed by the US Airforce, where four mishap severity categories (negligible to catastrophic) and five probabilities (impossible to frequent) are defined [50] (refer to Figure 7). In addition to the effects on equipment and human health, economic and environmental criteria are also stated explicitly and risk acceptance levels are calculated.

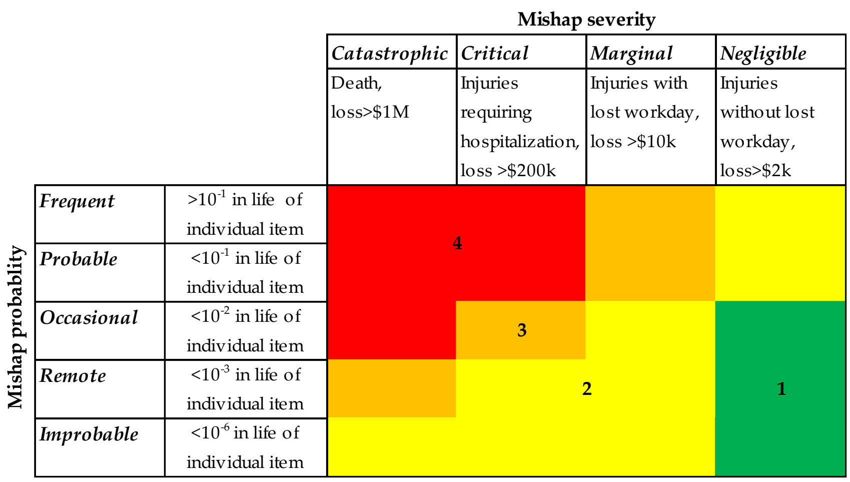

Figure 7. Representation of the mishap probabilities and mishap severities as defined in [50]. The numbers correspond to the mishap acceptance level defining who can accept them (1, as directed; 2, program manager; 3, program executive officer; 4, component acquisition execution).

6.1. Civil

Safety Management System is a standard throughout the worldwide aviation industry. Therefore, proactively thinking about safety is encouraged within organizations, specifically considering technical, human and organizational factors by incorporating the necessary organizational structures, accountabilities, policies and procedures for managing safety [51].

During operation, the performance of the aircraft, as well as incidents and accidents, are monitored. During the Monitor Safety—Analyze Data (MSAD) process, flight aviation data are acquired and filtered to identify event data that might lead to safety issues and shared with the airworthiness authorities. A risk assessment is then performed to identify the probable causes. These are then mitigated by containment and corrective actions. Therefore, a systematic risk assessment, called the transport airplane risk assessment methodology (TARAM) process, is followed in order to determine the quantitative risk of reoccurrence in the fleet in order to determine the type and speed of corrective actions. The corrective actions are then applied to the entire fleet to reduce the risk via the issuance of airworthiness directives [52,53]. This safety and feedback culture is also employed within the investigation of (fatal) aviation accidents, the primary goal of which is to prevent reoccurrence of such events, besides defining liabilities.

6.2. Military

Military aviation involves not only transport but also war vehicles, increasing therefore the complexity and the work load on the operating personnel. Generally, military missions are not operated as single aircraft operations but as several entities acting in combination. Therefore, briefing sessions are established, where prior to operation, not only are a synopsis of the intended actions, the mission profile, lines of communication, etc. discussed but also safety considerations are highlighted. After the mission, a debriefing session is immediately held, summarizing what went well and wrong and any safety concern observed during the mission. This briefing/debriefing culture has the benefit of improving teamwork and safety and creating a common operational mindset [54].

Pre-flight briefings are also performed in civil aviation, where responsibilities, flight path, safety considerations and weather conditions are discussed and agreed upon between the pilots.

Similar to civil aviation, military aviation follows a risk identification and mitigation strategy. In contrast to civil aviation, where failure probability goals are established, within the military, an approach is followed to accept risks that are “as low as reasonably acceptable (ALARP)”. This means that the risks, specifically the probability of occurrence of the risk and the severity of the consequence, are balanced with the time, costs and difficulty to mitigate them as well as with the potential mission gains [6]. Also, military aviation is meant to meet the safety requirements when flying in civilian airspace. In terms of accident investigation, many nations have the authority to identify incident or accident causes with the primary goal of preventing them from happening again. In contrast to civilian aviation, these authorities are also responsible for investigations into accidents with airborne weapon systems [55,56].

7. Discussion

Civilian aircraft have followed the same “tube with wings” philosophy since the beginning of aviation. The design of the structure of the first commercial airliner, the de Havilland DH.106 Comet, and the latest designs from Airbus (A350), Boeing (B787) or COMAC (C919) are all similar. All follow the same “tube with wings” philosophy, and besides prototype studies, up to now, no other aircraft designs have been used commercially.

The main evolution within these aircraft has been on their engines, employed materials and avionics in order to improve performance.

In contrast, within military aviation, evolution in aircraft design has been driven by the goal to gain a competitive advantage over adversaries, e.g., improvements in radar technologies for detection have led to improvements in low-observability technologies. Comparing the fighter aircraft of the Second World War such as the deHavilland Mosquito, Spitfire or Messerschmitt with current fifth-generation fighter aircraft such as the Eurofighter Typhoon, F-35 or Sukhoi Su-35, little commonalities exist from the design point of view. This is mainly due to changes in the mission profiles of the aircraft. Whereas early fighters engaged in close combat, firing machine guns, current fighters engage with missiles beyond visual range that can automatically seek their target. The extension of the weapon range is an answer to the improved countermeasures of detection.

In terms of certification for initial and continued airworthiness in civil aviation, the International Civil Aviation Organization (ICAO) sets minimum standards that are followed worldwide. These rules are then adopted by national authorities like the FAA (USA) and EASA (responsible for the European Union member states since 2008). An international consensus exists on the certification process. One potential explanation for the specification and adherence to certification rules is the necessity of civilian aircraft to be insured [57]. In contrast, military aircraft are generally not insured and the potential economic risk coming from an accident is covered by the state operating these aircraft. This is due to the fact that insurance companies have to know in detail the product they have to insure in order to assess the potential risks and costs in case of liability. In the case of products subjected to confidentiality such as military aircraft placed in a high-risk scenario such as a battlefield, no insurance company would want to cover these risks. Nevertheless, a trend within the military aviation exists to follow the certification process employed in civil aviation for cost and timeline reduction. For the same reasons, more commercial off-the-shelf (COTS) products are employed.

This has been observed within the Ukraine war, where first-person-view (FPV) unmanned aerial vehicles (UAV) have been used and adapted for usage in ISTAR applications and for attack purposes [58]. These changes will change the design and usage scenarios of future military aircraft.

So, whereas military aviation has to adapt to new battlefield scenarios, civil aviation has to adapt to customer requests, combining safety, fuel economy for sustainability and cost efficiency, as well as passenger satisfaction.

In terms of continuing airworthiness, civil and military aviation follow similar procedures while performing planned preventive maintenance and unplanned reactive maintenance. Partly, military aircraft are currently maintained by civil companies. Some differences exist between the planning of planned maintenance, as military aircraft tend to always return to the same base; the type of damage encountered; and the fact that military aircraft might be maintained in a way to be operated for a certain time without access to thorough repair bases.

In terms of safety considerations, both industries have rigorous standards in place. Whereas in civil aviation, a transparent international framework exists, where clear safety goals are stated, military aviation follows a risk-based approach, where certain risks are allowed in case the benefits of the mission are higher than the costs for preventing said risks.

8. Conclusions

This paper provides a comparison of civil and military aviation in terms of aircraft development, initial and continuing airworthiness, as well as flight safety management.

Both civil and military aviation share many commonalities, such as a strong safety culture, where various entities challenge each other so that the aircraft are fit for their respective operational environments. This regulatory framework is stricter for civil than for military aviation, where flexibility for performance adaptability is based on strategic needs.

This strict regulatory framework means that new technologies are implemented slower in civil aviation than in military aviation. Also, new aircraft designs that might lead to better performance such as blended wing body aircraft or novel propulsion systems have to go through the entire regulatory framework, thus prolonging the time to entry into the market. However, civil aircraft manufacturers have the advantage of a transparent certification process as well as a larger economic scale due to higher production rates, leading to cost reductions. Combining the advantages and gained knowledge of both industries will lead to benefits for both. Military aviation can benefit from the large-scale production of aircraft and the straightforward certification process in civil aviation, which in Europe has been adapted by the EMAR legislation, while civil aviation should make use of military aviation as a kind of test bed where new technologies and more courageous designs are tested. Contrarily, civil designs have already partly been modified to suit military applications, like the Airbus A330MRTT (multi-role tanker transport).

For both fields, the level of rigor for aircraft maintenance is similar, with the main difference being that due to the harsh environment and high-performance capabilities needed for military aviation, their maintenance philosophy ensures fault- and maintenance-free operation. In contrast, civil aviation is focused on the availability of aircraft while ensuring economic profit. Both sectors benefit from each other as the available technologies are pushed further by military aviation, whereas due to profitability and a larger economic scale, more efficient processes are established by civil aviation. Within the field of continuing airworthiness, often, civil companies are employed to perform the maintenance due to a lack of resources within the military. Nevertheless, the military has to maintain a certain number of qualified and capable workers, as the deployment of civil personnel in hostile environments is challenging.

In terms of safety management, civil and military aviation have similar rigorous safety cultures. Whereas civil aviation's main focus is on transporting passengers and goods safely from one location to another, military aviation often also has additional mission requirements due to operating in an hostile environment. Therefore, slightly different approaches from those in civil aviation are followed in terms of safety, where risks are accepted to a reasonable level for mission success.

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