

Article

A Systematic Approach towards the Integration of Initial Airworthiness Regulatory Requirements in Remotely Piloted Aircraft System Conceptual Design Methodologies

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Abstract: The regulatory framework of Remotely Piloted Aircraft Systems (RPASs) has recently experienced an extraordinary evolution. This article seeks to improve the integration of certification considerations in RPAS conceptual design approaches so as to enhance the safety, certifiability and competitiveness of their resulting designs. The first part of the research conducts a two-stage analysis of contemporary regulations related to an RPAS's initial airworthiness. In the first stage, the broad international regulation paradigm is evaluated attending to a set of criteria that are tightly related to both airworthiness and design considerations. The second stage keeps the most promising documents from a design–integration standpoint, which are assessed according to their applicability considering both design and operational aspects. The results of this analysis provide insights regarding the main issues in airworthiness design criteria extraction and integration in design methodologies. To aid the designer in surmounting these challenges, a flexible procedure named DECEX is developed. Considering the documents and findings from the survey, and attending to the scope of the design methodology being developed, it aids in establishing a complete regulatory document corpus and in comparing and extracting the applicable airworthiness design criteria. Two case studies for different RPAS types are conducted to demonstrate its application.

Keywords: remotely piloted aircraft systems (RPASs); initial airworthiness regulations; RPAS regulations; RPAS airworthiness; regulation analysis; RPAS conceptual design; design–airworthiness integration; design criteria extraction



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1. Introduction

Remotely piloted aircraft systems (RPASs), often also called unmanned aircraft systems (UAS) or drones, are currently experiencing a noteworthy expansion within the field of aeronautics. The potential spectrum of applications and missions that these aircraft can accomplish [1] has led to an outstanding growth of this industrial sector in recent years [2]. A crucial driver towards fully harnessing their potential is to achieve their safe integration in non-segregated airspace, which is expected to open up a much wider and promising array of missions, allowing further leveraging of the potential of RPASs [3]. However, in order to achieve this integration in a manner that can maintain the overall level of safety of the aviation system, several aspects related to the safety and risk of these operations have to be investigated in detail [3–5].

As a result of previous works that have conducted safety analyses on the integration of RPASs within the airspace, four key dimensions have been identified that have been deemed critical towards the safe integration of RPASs within the current aviation paradigm [6]: airworthiness certification [3,6–10]; Air Traffic Management (ATM) integration [3,5,11,12];

interaction with other aircraft, including Detect and Avoid (DAA) considerations [5,11–13]; and flight crew certification [8,10,14,15]. All of these dimensions are experiencing a heightened interest within the fields of academic research, industrial technical developments and rulemaking activities. The references above in relation to each of them represent a sample of current research in these areas. A more detailed evaluation of the main characteristics and scope of these works is presented in Table A1 within Appendix A. The investigation presented in this paper, as it will be supported further in the text, is primarily focused on the first of these dimensions—that of airworthiness certification—since fundamental gaps have been detected within the current state-of-the-art with respect to the analysis of up-to-date initial airworthiness regulations for RPASs as well as their interaction with Remotely Piloted Aircraft (RPA) design activities.

When studying the topic of RPAS legislation, previous authors have suggested that the particularities of RPAS when compared to traditional manned aircraft demand a novel regulatory framework tailored to their context and operations, which is expected to result in a markedly distinct paradigm from that of traditional aviation [8], requiring particular methods of study and analysis [4]. One of the main differences of the RPAS framework when compared to the traditional manned aviation one is that there is a much tighter coupling between different regulatory areas in RPASs. For instance, aspects of initial airworthiness and design appear in many regulatory documents alongside operational categories and constraints, as the category to which the design should be certified is not only linked to the inherent characteristics of the aircraft, but also to the operational scenario where it will be flown, as anticipated by previous research [4]. Some other particularities of the RPAS regulatory field are commented in Section 2.2.

In the past decades, there has been outstanding regulatory work from different aviation authorities accompanying the industrial growth of RPASs. Figure 1 represents an overview of historical regulatory milestones related with the main work of international authorities within the area of initial airworthiness, also including those regulations that have laid out operational categories and restrictions. Undeniably, the RPAS regulatory paradigm as a whole has experienced a noteworthy evolution, and not only within the international framework of initial airworthiness and operations. Previous research works have covered other relevant dimensions of the international RPAS legal framework evolution, such as personnel licensing [8,14], RPAS registration [14], operator certification and registration [10,14], integration into non-segregated airspace [3,5] or privacy [8,16], amongst other aspects. The evolution of national RPAS regulations has also attracted significant research effort, such as in the works of [10,17,18].

A discipline that is tightly related with the area of initial airworthiness is that of aircraft design. This subject can be considered as the sequence of activities within the aircraft project that, starting from a set of initial requirements, seeks to arrive to a final definition of an aircraft that satisfies the aforementioned requirements as efficiently as possible [19,20]. Therefore, instead of an “analysis approach”, where the aircraft’s geometry and main characteristics are known beforehand and the objective is to estimate its aerodynamics, structural behaviour, performance, etc., the philosophy of aircraft design instead follows a “synthesis approach”, where the geometric characteristics of the aircraft are not known and they must be determined so that it fulfils the initial requirements. Aircraft design is a multidisciplinary endeavour, and airworthiness requirements constitute one of the paramount inputs to its workflow, affecting many disciplinary areas (aerodynamics, flight mechanics, structures, etc.) that the designer must consider [19]. It has been regarded that these airworthiness aspects should ideally be taken into consideration as early as possible in the design continuum to ensure that a safe, certifiable and competitive aircraft is achieved at the end of the process [20]. Some further aspects of the connection between aircraft design and airworthiness requirements are expounded in Section 2.1.

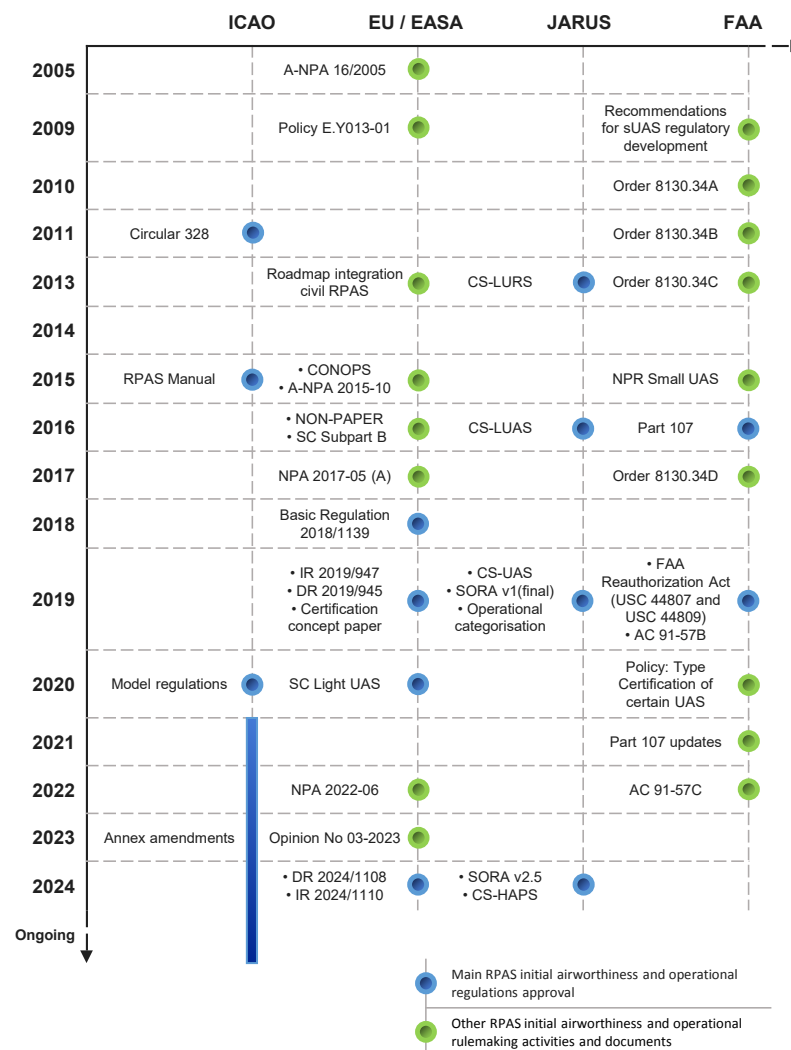


Figure 1. Summary of main regulatory highlights in the area of initial airworthiness from civil organisations with marked international influence.

It has already been emphasised that the particularities of RPASs demand a novel regulatory paradigm adapted to them. In the same way, previous research has highlighted that the field of RPA design presents several challenges, mainly owing to the differences that these aircraft present with respect to conventionally piloted ones: abundance of unconventional configurations, different internal layouts, diversity of payloads and missions, distinct powerplant architectures, integration of emerging technologies such as advanced materials, etc. [21–23]. Thereby, it has been argued that these aircraft require specifically tailored design procedures to account for their particularities [21,24]; thus, research considering novel methodologies for the design of RPASs is a notably dynamic field, as it will be seen in more detail in the Literature Review section.

Taking all of the above into account, and considering the aforementioned dynamism of the field of RPASs, it can be seen that the development of novel design methodologies particularly tailored for RPA constitutes a remarkable asset for further development in this field. However, whereas the much more mature area of manned aircraft design methodologies usually integrates certification constraints in the design process, and in spite of the recognised relevance of accounting for certification aspects in the aircraft design process [19,20,25,26], there are currently few works within the field of RPASs that have dealt with the combination of the disciplines of initial airworthiness and aircraft design simultaneously. Moreover, the few works that have been found that considered certification aspects in RPA design have either (a) employed regulations of manned aircraft such as

Part/CS-25 [27], therefore not accounting for particular rules of RPASs, or (b) employed RPAS regulations that—considering the rapid evolution of the legal field of RPASs—are now obsolete [28] and would not be applicable to develop an aircraft that can be certified or approved for operation in the new paradigm. In view of the above, both an update to previous design methodologies attending to the new regulations, and also the development of novel design approaches considering RPA certification aspects, would constitute outstanding advancements towards the design of safe and certifiable RPASs.

In order to tackle these issues, this study conducts, in the first place, an up-to-date analysis of current initial airworthiness regulations of RPASs, and in particular, of detailed airworthiness codes. This evaluation is not only valuable from a design standpoint but also from a purely airworthiness perspective, as few previous works have focused on the dimension of initial airworthiness in RPASs; also, some years have passed since they were conducted and the paradigm has evolved significantly, so those surveys would not be current. In order to conduct this regulatory analysis, a set of characteristics should be defined, which will be evaluated in the selected regulations. Since the objective within this work is mainly focused on studying the integration of airworthiness aspects in design methodologies for RPA, these characteristics should not only include aspects purely related to airworthiness but also others related to the usability and feasibility of integration of the regulations in design methodologies. In order to do this, it is first required to establish and define the aforementioned characteristics. Both the definition of these criteria, which take into account design and airworthiness aspects at the same time, as well as the evaluation of the regulations attending to them, constitute two of the novel contributions of this work, as design-related aspects have not been at the forefront of previous RPAS legislation reviews.

As will be seen from the results of this regulatory analysis, and in spite of the recent harmonisation efforts within the field of RPAS regulations, which are commented on in more detail in Section 2.2, there are still remarkable differences in the philosophy and content of initial airworthiness regulations, and particularly of certification codes. Depending on the legal context of the envisioned operation and the regulations applicable therein, there can be a significant variety in the requirements that the designer must integrate. This constitutes a significant challenge, as it has been highlighted in other areas of aviation that harmonisation amongst regulatory paradigms is a significant aid in achieving uniform and widespread safety levels [29,30]. It also affects the designer, as the airworthiness requirements that must be integrated in the design continuum could be heterogeneous and even conflicting. Another issue, which particularly affects the designer, is that design methodologies can be very diverse in their scope and objectives, owing both to differences in the design stage that is being considered and also to the disciplines that are being integrated in the process (flight mechanics, structures, aeroelasticity, etc.). Thereby, no single set of regulatory requirements can be proposed in a straightforward manner to be integrated in RPA design methodologies, as they do not only depend on the regulatory paradigm of application but also on the design methodology scope. To acknowledge this issue, instead of proposing a single set of airworthiness requirements or a specific certification-driven design methodology—which would limit its scope, applicability and reusability—in this work, a novel procedure for Design Criteria Extraction, called DECEX, is developed. This constitutes a flexible approach, which has been tailored to aid the designer in navigating the RPAS airworthiness landscape to extract relevant criteria for the development of certification-driven design methodologies, or for application to particular design cases, within the scope of these design application cases. This procedure accounts for the challenges related to the domain that are discussed in the regulatory evaluation, such as the heterogeneity of documents, the low level of specificity of certain requirements and the difficulty of reaching a complete certification basis, amongst others. The authors expect that this procedure can serve to integrate initial airworthiness aspects in future RPAS design methodologies, in such a way that the requirements that are integrated are specifically tailored to the scope and needs of each design case, thereby constituting a reusable approach that can also account for updates in the regulations. This last aspect

constitutes a noteworthy advantage because, in view of the dynamism of the regulatory paradigm, design methods that cannot adapt to changes in regulations could be rendered obsolete in a few years. A preliminary version of this work was presented elsewhere [31]. With respect to that preliminary version, major improvements have been conducted for this article. These include the update of the regulatory analysis with recent developments and more documents, such as the EASA SC Light UAS and SC-RPAS.SubpartB-01. Most importantly, the previous version of this work did not contain the DECEX procedure, which is a novel research addition developed for this paper that allows for the effective link between the results of the regulatory analysis and the population of certification aspects in design methods attending to their scope, making the DECEX procedure the foremost contribution of the research presented in this paper.

1.1. Research Scope

As mentioned beforehand, the main topical scope of the research is related with the disciplines of RPA airworthiness and design. However, these two subjects are very broad, and the way of studying different areas within them can present significant dissimilarities. Therefore, some aspects are highlighted here with respect to the boundaries of the research in order to clarify its applicability.

Regarding the topic of aircraft design, particular emphasis shall be placed on approaches related to the early conceptual design stage. Within the area of airworthiness, the main focus is set on initial airworthiness regulations, which are of particular interest for aircraft design. Going back to design aspects, as the main focus is on early conceptual design, which mainly deals with the overall airframe synthesis and sizing, the main emphasis when analysing initial airworthiness documents shall be on those sections and requirements related to the air vehicle. Furthermore, as it will be expounded in Section 3, the most relevant gap for RPA design has been seen in airworthiness integration in the early phases of design. Also, the main focus shall be set on fixed-wing RPA.

With respect to the regulatory evaluation, the main focus shall be set on the main authorities with marked international influence involved in civil RPAS rulemaking. This is in contrast with previous research, which has mostly focused on national regulations [10,17,18], thus constituting one of the main highlights of this research. These types of organisations are also usually more relevant to the aircraft designer due to the potential broader applicability of airworthiness aspects integrated in the design continuum. The main entities considered here are as follows: the International Civil Aviation Organization (ICAO), the European Union Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA). Documents from the Joint Authorities for Rulemaking on Unmanned Systems (JARUS) shall also be considered, due to their tight relation and mutual influence with EASA. Furthermore, documents from the North Atlantic Treaty Organization (NATO) have been included due to their relevance in the certification of various existing RPASs and their synergy with civil documents and standards.

1.2. Research Structure

With respect to the organisation of this article, firstly, some background for the research is introduced in Section 2, providing a brief overview of the theoretical aspects involved in the research including some considerations with respect to the influence of airworthiness aspects in the design space. Section 3 contains an overview of related works within the state-of-the-art and the gap analysis with respect to those works. Section 4 expounds the materials and methods, dealing with the process of searching for the outstanding regulations, and also containing the set of criteria that will be employed in the regulatory evaluation, which will serve to analyse and compare the documents of study. Section 5 contains the analysis of initial airworthiness regulations in the international RPAS paradigm, with a special emphasis on the aspects that are of particular interest for the aircraft designer, which is one of the main objectives and contributions of this work. This analysis is conducted in two stages, firstly dealing with a broader array of documents and then focusing on those more

relevant to the air vehicle conceptual design. Taking into account the results of the previous analyses and using those regulations as a possible source for extracting airworthiness requirements, in Section 6, the DECEX procedure, which is the main contribution of this work, is described, and two brief cases of its application are conducted. Finally, Section 7 presents the overall conclusions of the research. Figure 2 illustrates the main workflow of this investigation and the connections between the main topics.

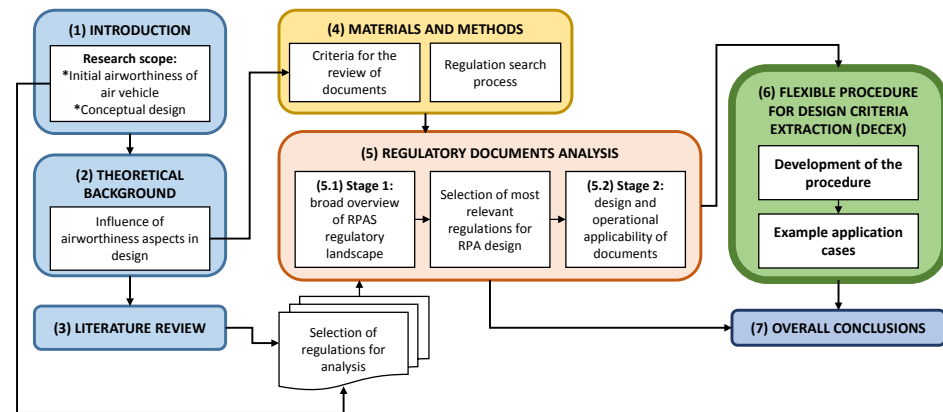


Figure 2. Main workflow of the research and corresponding sections of the article.

2. Theoretical Background

This section provides a brief theoretical background on key aspects related to the scope of the research presented in the article. The first subsection tackles the main stages and concepts of aircraft design as well as the influence of airworthiness aspects in this discipline. The second subsection expounds some main distinctive aspects of the RPAS initial airworthiness regulatory landscape, which will be key when defining the criteria for the review as well as for conducting the regulatory analysis; here, some aspects related to harmonisation challenges are also addressed.

2.1. Aircraft Design and Relation to Airworthiness

As mentioned in the introduction, the aircraft design process can be considered as the set of activities that encompasses the aircraft project, starting from the initial definition of requirements with which the final design must comply, in order to arrive to a final definition of the manufacturing blueprints of the aeroplane. At this point, the aircraft project can advance to its next stage—that of production—and on to further ones of operation and maintenance [19].

As this process of aircraft design is very expansive, it is usually tackled in an incremental approach following a series of stages. This allows a progressive refinement of the aircraft in such a way that at the first stages, a large design space is explored, and the most promising candidate configurations are evaluated to select those that advance to the next stage [32]; whereas, in the final stages, fewer variations are evaluated, albeit these are studied with increased effort and fidelity. The design stages that shall be considered in this paper, alongside their definitions, are presented here. They are based on the classical division of the design process, as provided by [19,25]. This schema is widely recognised in the aircraft design field and has also been used in recent works, such as those of [32–35]:

- Conceptual design: Starting from the initial requirements, a basic geometric definition of the Outer-Mold Line (OML) of the air vehicle is sought. Methods usually involve statistical approaches and rapid physical-based approaches, and only a few disciplines are considered;
- Preliminary design: Once the main layout and architecture of the aircraft is defined, the design is further refined by employing methods with a higher level of fidelity and usually employing a multidisciplinary approach involving optimisation procedures;

- Detailed design: Very specific aspects of the design are refined by employing methodologies with a high degree of fidelity and computational cost, such as Computational Fluid Dynamics (CFD) and Finite Element Method (FEM) analyses.

A terminological distinction, which is relevant for this paper, is commented in the following lines. This research shall distinguish between the concepts of “design methodology” and “design process”. A design methodology is considered as a systematic set of guidelines and steps that can be followed to conduct the design of an aircraft, or just a particular step within the design continuum (for instance, stabiliser surface initial sizing). In contrast, a design process is considered here as a set of steps that may either follow a design methodology, or rather employ an ad-hoc approach, which is applied for a particular “design case” with a specific set of initial requirements and objectives. Comparing both approaches, the main advantage of design methodologies would be their broader applicability and reusability, whereas design processes are adapted to each design case but they are not developed with the main intent of broad application. The DECEX procedure developed in Section 6 will be compatible with both cases.

A common consensus that can be found within the aircraft design literature is that safety and certifiability of an aircraft are two paramount aspects that the aircraft designer should consider early on in order to ensure reaching a product that satisfies those characteristics [19,20,36], and these ideas can also be found in the field of RPAS design [17,27,33]; albeit, in this latter case, as it will be seen in Section 3.2, they have seldom been put to practice through integration in design approaches.

The way in which airworthiness aspects can be integrated in a design methodology or process is highly dependent on the scope of the design approach, as the certification constraints or aspects that are considered should be those that affect the main design variables of interest within the limits of the design method. Furthermore, it should be noted that the process of airworthiness criteria extraction towards their integration in the design continuum is usually not straightforward, and previous work such as that of [37] have commented on the challenges that arise: from the difficulties resulting from having to consider several documents at the same time and finding the relevant requirement in each of them, moving on to several regulatory documents giving at times different requirements for the same design variable, to the regulations often not specifying quantitative criteria, being more qualitative in nature and thereby not establishing specific numerical constraints. However, even in this latter case, they can be considered within the aircraft design process as guidelines that the designer must consider so as to make general decisions with respect to the design that can aid in complying with those qualitative requirements; also, numerical constraints can be generated from them to aid in substantiating the compliance with the requirement. This links with the qualitative and quantitative approaches to aircraft design, which are commented below. It should be noted that the issue of having distinct requirements in different regulatory documents has also been highlighted, albeit outside design processes, in the work of [38], which commented on the issues of verifying the criteria of all documents simultaneously. This highlights the relevance of the regulatory paradigm being homogeneous and harmonised, connecting with some aspects regarding the harmonisation efforts within the regulatory field of RPASs that are commented in Section 2.2. With respect to the challenge related to the regulations often not establishing specific criteria, rather being more qualitative in nature, this was also tackled in the work of [39], where qualitative stability and control requirements in the Part/CS-23 were integrated into the flight test phase to evaluate whether the dynamic response of the aeroplane was adequate, and the work of [40] for manned aircraft disruptive technologies, proposing a process of seeking additional documents and standards to fill the gaps in a manner that could be expected to yield positive results when negotiating the certification basis with the Authority. It is clear that the process of integrating airworthiness criteria in the first stages of design requires specific procedures to tackle its main challenges.

In the same way that airworthiness requirements can be qualitative or quantitative, as mentioned beforehand, aircraft design methods employ both quantitative and qualitative

tools. An example of the former are the second segment climb flight mechanics equations, which can serve to select the thrust/weight ratio in a matching diagram [25]; a case of the latter can be general arrangement selection criteria for choosing the most appropriate combination of tail layout, engine position, etc. The way in which airworthiness criteria might enter the design process depends heavily on the nature of the requirement, amongst other aspects. Here, the concept of “level of specificity” is introduced, which will also be one of the main dimensions for the analysis of documents within the survey, as it will be seen in Section 4.1. This concept relates to the level of detail provided within the requirements specified by the regulation; therefore, it is linked to the ease of generating design specifications from them. For instance, a paragraph in the code stating that the stalling speed may not exceed 83 km/h provides a high level of specificity, since it establishes a value that can enter a quantitative method. On the other hand, a paragraph stating that the aircraft should have stability and control characteristics that allow for safe operation does not allow a direct and unequivocal derivation of a detailed specification but could be used as a qualitative criterion.

As mentioned beforehand, aircraft design follows an incremental approach, where the design space is explored more broadly in the first stages but more in depth in later ones. Therefore, it is expected that, before the onset of further stages, the design space is narrowed down to the most promising configurations in order to avoid employing excessive time and resources in the later phases. During this process, it is relevant to avoid the aircraft from converging to undesired alternatives when narrowing down the design space. Related to this, it is also critical that the design convergence ensures that the remaining aircraft concepts are certifiable, at least within the scope of certification that is being studied at the design stage being considered. Although the restrictions that may result from airworthiness regulations could reduce the design space, thus eliminating potential candidates, they do so while providing in compensation an increase in confidence of the certifiability of the remaining designs, which is crucial for the designer and facilitates that the process converges in designs which are airworthy and safe.

Linking with the previous concept of the design space constraints associated with regulations, when requirements have a high level of specificity, they establish “hard restrictions” in the design space that limit its boundaries, but in compensation, the confidence in the certifiability of the remaining design space is high. When dealing with low specificity requirements, the designer might have to derive design restrictions based on qualitative guidelines, so the constraints are not “clear-cut” and may thus provide certain flexibility to the design; on the other hand, the level of confidence in the certifiability of the designs is lower, as a clear and detailed criterion was not given by the Authority. Therefore, it can be seen that the level of specificity of regulatory requirements can have a significant effect on how they are integrated in an aircraft design methodology, and also on their potential effect in the design space. The above concepts regarding the differences that can result in a constrained design space when considering requirements with differing levels of specificity are illustrated in Figure 3.

These concepts are relevant to the paper since, as it will be seen, RPAS regulations present varying levels of specificity not only amongst outstanding documents but even between different requirements given within the same document. This highlights the need to develop procedures that aid the designer in navigating regulatory requirements with different characteristics so as to aid their effective integration within RPA design. Furthermore, the idea of certain certification requirements acting as constraints to the design space will be more clearly seen in the two case studies that are conducted in Section 6.3.

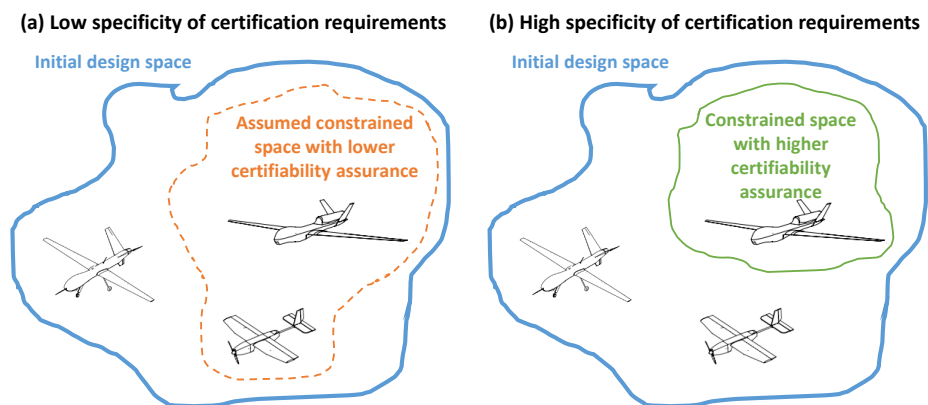


Figure 3. Conceptual representation of difference in breadth and certification assurance of constrained design spaces according to requirements of differing levels of specificity. Some candidate designs may be left out in the case of a higher specificity level but, as a trade-off, the assurance in certifiability can be expected to be higher.

2.2. RPAS Initial Airworthiness and Operations Regulatory Paradigm Highlights

As mentioned in the introduction, the particularities of RPASs when compared to aircraft piloted on-board demand a novel regulatory paradigm with respect to that of traditional manned aviation [8]. These singular aspects shall affect within this work both the definition of the criteria for the analysis of airworthiness documents, which should consider the main features of the regulatory paradigm, as well as the documents themselves that are to be evaluated. A brief account is given below of those aspects within the RPASs regulatory paradigm which are more relevant within the scope of this work:

- **Risk-based and operations-centric approach:** The concept of developing regulations in accordance to the proportionality of risk of the object for which these rules are being developed is not new and has been present in manned aviation for a long time [41]. However, as the regulatory initiatives for RPASs have developed and matured, there has been a redirection from a traditional approach, which is “aircraft-centric”, to an “operation-centric” approach, based on an analysis of the risks resulting from the combined consideration of the aircraft and its operation—in line with previous research in this area [4]. In the framework of EASA, different operational categories (open, specific and certified) have been defined, where regulatory requirements increase in correlation with risk—from minimal regulatory oversight in the first case to a very similar model to manned aircraft in the third, in which initial airworthiness and operators are certified, amongst other aspects [42,43];
- **Tight coupling between airworthiness and operational considerations:** In relation to the previous point, one of the most innovative aspects of current RPAS regulations is that a very tight coupling between airworthiness and operation considerations can be seen, with aspects related to these areas often appearing side-to-side in the same regulations [8]. This is coherent with the risk-based approach, which considers aspects inherent to the aircraft in combination with those of the operational scenario, often with both aspects in combination determining the regulations that apply to the aircraft under consideration.
- **Performance-based approach to airworthiness codes:** The reorganisation and change in spirit of the Part/CS-23 regulations [44] has had a notable impact in the field of RPAS regulations. This activity sought to regulate through “objective oriented” requirements, seeking to provide flexibility to applicants in the way that they demonstrate compliance with the regulation specifications, and at the same time intending to reduce both regulatory time and costs, both for the industry and for the regulator [44]. In summary, and in relation with the previously mentioned concept of “level of specificity”, the requirements provided in the code have a lower level of specificity

and are less prescriptive in nature. The applicant can opt to demonstrate compliance with them through use of Acceptable Means of Compliance (AMC) and Guidance Material (GM), which, in the case of the reorganisation of manned aircraft regulations, can include references to previous versions of the regulations and also to consensus standards. Through consulting these other references, a higher level of specificity can be achieved. This approach has been supported in the area of RPASs in works previous to its implementation, such as [17]. This concept has been implemented, for instance, in the CS-UAS by JARUS [45], where the specific requirements that the designer can find outside the main document are called Airworthiness Design Standards (ADS). However, contrary to the Part/CS-23 approach, there is no clear correspondence here between each requirement of the regulation and the corresponding ADS recognised by the Authority, which can be regarded as an additional challenge to establish the initial certification basis and to guarantee certifiability assurance in advance to making specific consultations with the Authority.

In the introduction, it was mentioned that the field of RPAS regulations has undergone a noteworthy harmonisation effort in the past few years. Regulatory alignment is also relevant from a design standpoint, as seen earlier in Section 2.1. Thereby, a few comments with respect to the harmonisation efforts and challenges in the field of RPAS airworthiness are commented below.

Firstly, it should be noted that regulatory harmonisation can be evaluated at different levels of granularity: for instance, it can be analysed at an international level (harmonisation between EASA and FAA) or, rather, at a national level within a certain context (for example, harmonisation between applicable regulations in EU member states). Regulatory alignment presents a particular series of challenges, with many possible factors contributing to heterogeneity, some of which are not directly linked to aviation technical aspects. Some of these may include the differing philosophies of each regulator, the development of the market in each country, previous experience with the technology to be regulated, geographical and urban aspects, and even sociopolitical factors that affect the regulatory development [10].

A particular case of interest can be seen in the EU region, as the scenario has changed significantly in the past few years. Before the year 2018, according to previous EASA Basic Regulation (216/2008), EASA only had legal remit in RPASs over 150 kg, and the rest of the cases fell under the scope of the regulations of each Member State NAA. During this time, as previous research pointed out [10,17], there were many discrepancies amongst the NAA regulations in the EU region, leading to a paradigm in clear need of harmonisation. One of the main premises of the EU is the free circulation of people and goods within the context of the European Single Market; thereby, it was seen that in order to foster the development of RPASs following the premises of the EU, a harmonised approach through the use of Community Law was necessary. The main change came with the update to the EASA Basic Regulation in 2018 (2018/1139), which established that all RPAS operations, irrespective of weight, would fall under the unified scope of the EASA, only leaving state aircraft and operations within the scope of NAA regulations as well as similar concepts. From this point onward, EASA has published numerous regulations, as will be seen in further detail in Section 5, which nowadays provide a uniform and harmonised paradigm within the majority of RPAS operations for the EU. Thereby, it can be considered that the update to the Basic Regulation was a fundamental step that has resulted in the harmonisation of regulations in the EU for the majority of RPAS operations.

However, as anticipated in the introduction, it will be seen that, when comparing the EU regulatory paradigm to that of the FAA, there are significant differences both in the main guiding principles of the regulations as well as within the regulatory material itself. These heterogeneous aspects shall be analysed in detail in Section 5. Thereby, it can be seen that in the international scenario, there is still work to be conducted towards harmonisation. Furthermore, outside the scope of the EU, other national regulations might present significant differences, as evaluated in the previous works of [10,17,18], including the information of countries such as China, India and Malaysia, amongst many others. As the scope of this

research is focused on the main international civil and military entities already commented in Section 1.1, an analysis of further regulatory heterogeneity would be out of the scope of this paper. Nevertheless, it is clear that achieving regulatory harmonisation across different jurisdictions is a key issue towards RPAS design and certification.

Finally, it should also be noted that the RPAS regulatory paradigm is still not fully developed, as various areas of regulation are still in progress, such as the development of the certified category, and there is still room for improvement with respect to harmonisation. In view of the trends followed in recent years, it can be argued that these aspects will continue to develop in the near future.

3. Literature Review and Research Gap Analysis

In this section, a state-of-the-art analysis of topics related to the scope of this research shall be conducted. This will allow us to point out the main research gaps found in the relevant topical areas and, thus, select those aspects that the current research seeks to cover.

3.1. Previous Reviews of RPAS Regulatory Paradigm

Since one of the main objectives of this research is to conduct an up-to-date analysis of RPAS regulations within the topics of the paper, firstly, an analysis is conducted of previous works that have performed similar studies—that is, previous research studies that have conducted surveys of RPAS regulations in different topical areas. Searching within the open literature and also in some textbooks related to the field, the main works that have been found correspond to references [3,6–8,10,14,16–18,46,47]. The main characteristics of these works are summarised and compared in Table A2 within Appendix B. The following text provides a brief overview on the main trends of these previous research efforts.

It can be seen that the field of RPAS airworthiness has attracted significant research effort in recent times, as mentioned previously in the introduction. Each of the surveys that has been found in the literature has analysed different regulatory areas and topics, which is according to the dynamic evolution of regulations in all of these areas. With respect to the Authorities object of study, it is seen that there has been significant effort in studying national regulations in previous research [10,17]. However, few works have analysed and compared the regulations of various Regulators with international influence. Thereby, the international scope of the present work would constitute one of the highlights of this research. With respect to the areas of initial airworthiness and design, only two previous works, those of [6,8], have focused on these areas. However, taking into account the regulatory changes since the years in which those works were conducted, as seen in Figure 1, a significant research gap can be seen in this area, which this work seeks to cover. Previous works have not considered military codes; therefore, a further research gap is sought to be covered in this research by incorporating NATO standards, which are military airworthiness codes within the international domain, which is within the scope of this paper. Furthermore, albeit the works of [6,8] have analysed aspects related to initial airworthiness and design, the current research has considered specific characteristics of the regulations that deal with the capacity of integrating them within design methodologies and processes, which have not been covered in previous surveys and would constitute one of the novel contributions of this research. This is one of the key aspects of this research, as it allows, when developing the DECEX procedure in Section 6, the leveraging and integration of aspects from the analysed regulations into certification-driven methodologies for RPASs.

3.2. Previous Works in Design and Initial Airworthiness Integration

Having seen the previous works that have conducted surveys on the regulatory paradigm of RPASs, the next stage is an overview of research within the state-of-the-art that has tackled the issues of RPAS design and airworthiness aspects, since these two topical areas intersect at various points within this paper. In this subsection, several works are analysed from the fields of manned aviation and RPAS design, some of which have integrated airworthiness aspects within the design continuum. The main text contains an

overview of these works and the main trends of this line of work within the state-of-the-art. The interested reader can find more thorough information of each work within Table A3 in Appendix C.

Within the field of traditional manned aviation aircraft design, many works have considered the requirements of certification regulations in the design process, starting from well-established textbook methodologies such as the ones in [19,25,36], which integrate FAR and CS requirements in aircraft conceptual and preliminary design procedures; moving on to recent works that have developed certification-driven analytical and optimisation methodologies considering various certification paradigms and requirements, such as certification analysis of general aviation aircraft [37], noise regulations [48] and even hydrogen-fuelled aeroplanes [49]; to research seeking to include certification considerations within MDO frameworks including computerised design environments [26,50]. It should be noted that the systematic process of extracting design requirements for their integration in design methodologies has been given significant attention in these previous works [26,37,50], as it was mentioned in Section 2.1 that this is one of the main ways to include airworthiness aspects during the first stages of design. This approach is also employed in works where the main aircraft architecture has already been decided, along with the use of safety assessment methodologies, in the context of certification of disruptive technologies, such as in the work of [40], or in the development of aircraft systems with a safety perspective such as in [51]. Aside from the applications in aircraft design, it is also clear that the broader area of airworthiness of manned aviation is notably dynamic, with recent works such as those of [52–55] covering different dimensions of this field, discussing some challenges in airworthiness and certification considering the evolution of the aviation paradigm, and showing a continuous interest in it.

Moving on to design methodologies for RPA, as already mentioned beforehand, their design presents several challenges that are different to that of manned aircraft, requiring specifically tailored design approaches to account for their particularities [24]. The field of research of design methodologies for RPA is considerably prolific: from textbook-based approaches such as those of [21,33]; moving on to statistical methodologies for initial sizing [22,56,57]; design approaches based on design restrictions and optimisation, such as in [35,58]; and even computerised design environments [59]. In contrast, and in spite of the recognised relevance of considering certification aspects in the design process, there are currently very few works within the field of RPASs that have dealt with the combination of the disciplines of airworthiness and aircraft design simultaneously, and on how airworthiness requirements might impact the design of the RPA. For instance, the work of [33] supports the relevance of integrating airworthiness aspects in RPA design, and explains the main structure and contents of NATO Standard AEP-83, recommending the designer to check various typical design constraints related to certification. However, these are not integrated in a design workflow per se, and their effect on key design parameters is not demonstrated. On the other hand, the work of [27] is remarkable in that there is an extraction of regulatory requirements, demonstrated through a particular case of considering lightning protection aspects, to integrate them at an optimisation stage of the RPA design; however, in this case, the requirements were obtained from Part/CS-25 regulations, thereby not employing RPAS-specific rules. Moving on to the works of [6,28], they developed design approaches using RPAS regulations in their specific areas (systems weight estimation and structural weight estimation, respectively) upon extracting specific requirements within their scope. However, many years have passed since these works were conducted; thus, the regulations employed therein have since been repealed.

In view of this, there is a gap in research work covering and analysing the current RPAS regulation paradigm with a focus on the impact of regulations on aircraft design. Therefore, the current scenario motivates us to update current certification-based design approaches for RPA, and also to develop and research novel design strategies that take into account up-to-date RPA regulations and that can aid the designer in navigating this complex legal landscape. In order to accomplish this, our work firstly conducts a survey

of the outstanding regulations that are currently in effect, evaluating them attending to characteristics that are relevant both from the airworthiness and the aircraft design viewpoints. The objective is to assess their potential impact not only on the design of a particular RPAS, as could be the case of an ad-hoc design process,; but also to study the feasibility of integrating them on systematic design methodologies developed taking those regulations into account. We consider, for both cases, the DECEX procedure that will be expounded in Section 6 seeks to be an encompassing and flexible approach to extract certification aspects to integrate them in a variety of design methodologies or in particular design cases.

3.3. Emerging Technologies in RPAS and Prospective Influences in Certification and Design

The field of RPASs presents a high level of innovation, as can be seen in the application of numerous technological advances pertaining to different areas, ranging from new materials, to communication and sensing technologies, and also covering the potential applications of Artificial Intelligence (AI) and autonomy [17,23]. Considering the paramount objective of the safe integration of RPASs within the aviation system, these technological aspects should be accounted for within the regulatory paradigm in order to ensure their safety. However, the development of airworthiness standards for these novel aspects presents a series of challenges, owing both to the novelty of the technological concepts as well as to the accelerated pace in the evolution of their capabilities [60]. Technological progress is often conducted at a faster pace than rulemaking, which might leave temporary regulatory gaps [17]. In this section, an overview is provided of previous research covering new technologies in RPASs, as well as considerations with respect to possible influences in future regulations and design approaches.

The areas of technological breakthroughs and potential applications in RPASs are very broad and varied. Some outstanding areas of technological advancement, with comments on related regulatory aspects, are covered in the works of [17,23,60,61], including but not limited to morphing technologies, new materials, AI and autonomy, novel control algorithms, disruptive powerplant architectures, advances in energy storage and propulsion technologies, 5G network applications, imaging and sensing technology advancements and cybersecurity, amongst many others. Each of these technological areas has differing peculiarities with respect to possible integration in design methodologies and certification prospects, which would require a profound analysis for each of them. As a detailed analysis of these aspects would be outside the scope of this research, in this subsection, two areas are prioritised: (a) AI and autonomy, which is one of the main areas of regulatory concern [9]; (b) new materials and possible structural applications, which link tightly with the areas of structural design and airworthiness structural requirements.

In the field of automation and AI, it should be noted that the current state of aviation regulations regarding this topic is still at the conceptual level. For instance, EASA has been working on an AI Roadmap [62], developing the top-level vision of the Agency in this regard and proposing an action plan for future rulemaking activities, which are still in the process of being undertaken. A research work that has conducted a review of relevant standards and regulatory material towards the certification of AI-based autonomous systems can be found in [63]. In general, the regulatory status quo for autonomy and AI aviation regulations is yet under development, requiring greater maturity for further development and implementation prospects [9,64]. One of the main challenges towards certifying these systems comes from the the black-box and non-deterministic nature of several AI algorithms and applications, which demand novel approaches towards airworthiness assurance. One of the main approaches being investigated is to have a Run-Time Assurance (RTA) system, which has a deterministic function that acts as a safety monitor, controlling the outputs from the non-deterministic algorithm and issuing warnings or activating recovery measures [9,63,64]. Another relevant challenge in the rulemaking field is the development of a spectral approach towards autonomy-related requirements [65]. This would be more coherent with the fact that it has been regarded that there are dif-

ferent possible levels of autonomy [66], and each would have a distinct risk level, which also depends on the context. A regulatory system considering different safety assurance approaches depending on autonomy level and operation context would provide a much more flexible solution than current practice [65]. DAA can be considered to be one of the main enablers of autonomous operations, as well as a potential application of AI for its fruition [64], with control algorithms being another outstanding area of implementation of AI and autonomy, as seen in the work of [67], where the gap in current regulatory material is also highlighted.

In the area of new materials and their application to RPASs, a recent study has conducted an analysis of advanced materials and processes for Advanced Air Mobility (AAM) and RPA [68]. One of the main key issues that was identified, linked with airworthiness and certification, is that there are few guidelines for design and manufacturing using next-generation materials such as thermoplastics, which are not certified for their use in primary structure. A technology roll-out process is proposed to accelerate the development of guidelines and standards. In the meantime, the RPAS industry usually employs material systems from public databases. Interest in design methodologies for RPA structure considering new materials can be seen in recent research works, with a particular interest in additive manufacturing elements, such as the empennage [69], aerodynamic surfaces [70] and fittings [71] amongst other elements. There is also interest in the development of design approaches for morphing elements for RPA, as seen in the work of [72], and also in structures made of meta-materials [73]. It should be highlighted that many of the previously cited works have employed manned aviation regulations for structural design instead of the corresponding structural criteria of available RPAS regulations, such as the NATO Standard codes. Therefore, there would be room for comparison between the results of designing with manned and RPA certification criteria, which is an aspect that could be covered with the DECEX procedure developed in this research.

From this overview, and as seen in the cited research works, it is clear that there is a need for further advancement in regulations for both autonomy and novel materials that can allow for airworthiness assurance and further practical application of these technological advancements. The previous references discuss some of the challenges that have been outlined here in greater detail. Some of these works have also discussed regulatory gaps and have proposed prospective changes to regulations, such as that of [17], which developed a methodology in this regard. In contrast, the research developed in this paper is focused on existing regulations for RPA, since the designer necessitates the integration of approved requirements in the design methodology so as to ensure the certifiability of the RPA to be developed. Nevertheless, as it is clear that the regulatory paradigm of RPASs is very dynamic and is expected to evolve in the following years, particularly in lines related to the technological advancements commented here, this has been taken into account in the development of the DECEX procedure, which has been conceived to be flexible so it can adapt to regulatory changes and provide easy integration of new requirements in the design continuum as new regulations are developed.

4. Materials and Methods

The objectives of this study are to perform a survey on initial airworthiness documents for RPA and to develop a flexible procedure that can aid the designer to navigate this complex airworthiness paradigm in order to extract requirements relevant to the scope of the design approach which is to be populated with airworthiness aspects, and to integrate them in those design activities. In order to achieve both prospects, a set of dimensions that are to be analysed in the survey for the different documents should be defined to allow for comparison between them and to aid the designer in having a means to evaluate and select those that are more relevant to integrate in design activities. This process of defining the characteristics of the regulations to be evaluated, attending to the scope and priorities of the survey, is in a similar vein to that of previous regulatory reviews [10,17,18]. Furthermore, the search process for finding the regulatory documents is outlined below.

4.1. Criteria for the Review of Design-Related Airworthiness Regulations

As it was seen in Figure 2 of the workflow of the research, there will be two stages of the regulations survey. In the first, the broader scope of documents of the initial airworthiness of RPASs shall be analysed, and the second stage will focus on documents that are more relevant to the integration of airworthiness requirements within design methodologies and processes, thereby focusing more on the second of the main topical areas of this research.

With respect to the dimensions of the regulations to be evaluated in the first stage, these should be relevant from the viewpoint of both airworthiness and design, and they should also aid in selecting those documents more relevant for design aspects towards the second stage of the survey. In contrast with previous works, one of the novel contributions of this paper is that the criteria here have been selected considering both airworthiness aspects and design considerations affecting their potential integration and influence in design methodologies. It should be noted that some of these criteria can not only be evaluated at a regulation level but also at a requirement level, which is one of their essential applications in the DECEX procedure to be expounded in Section 6. The dimensions are the following:

- **Level of Regulatory Document Tier (LRD Tier):** Usually, regulators organise the taxonomy of their documents according to “levels of regulatory material”, such as EASA, which has a hierarchical structure of its regulations. For instance, the Basic Regulation is at a higher hierarchical position than the CS codes, and so on. In this work, documents from entities with differing criteria to organise their material are being studied. Therefore, the present LRD Tier concept is applied in a broader sense, allocating the same Tier to documents with a similar nature in their breadth and scope. Tier 1 is for high-level documents laying out essential requirements and covering a broad scope, including implementing regulations. At the same time, their level of depth and detail is usually low, as the intention is to provide general governing guidelines and not specific criteria. For example, the EASA Basic Regulations, in the Essential Requirements for Airworthiness, lay out general qualitative criteria for structures and materials; however, one must consult the lower-tier CS codes to find specific quantitative limit load factor values [29]. Tier 2 is for more detailed documents giving specific provisions for aspects that are not covered within Tier 1 ones, in the vein of Certification Specifications (e.g., Part/CS-23). Tier 3 documents have more detail and focus, such as FAA Advisory Circulars (ACs), and EASA AMC and GM. Tier 4 is reserved for consensus standards and similar documents.
- **Legal applicability:** Refers to the nature of the document with respect to its legally-binding status or otherwise. This dimension is not exclusively dependent on the document itself but also on the scope of application that is considered (countries affected by the legislation, civil/military paradigm). Within this work, this shall be evaluated within the main civil framework of each regulation. For instance, the legal applicability of FAA Part 107 is evaluated for the USA, whereas the legal applicability for EASA regulations is assessed for the EU Member States.
- **Topical focus:** Brief summary related to the main subjects covered by the document.
- **Level of specificity:** This concept was explained in Section 2.1. Three levels are considered: low, when only general qualitative criteria are given; medium, where no detailed quantitative specifications are provided but more specific aspects to be taken into account or calculated by the applicant are provided; and high, where specific values or limits are given. Within Appendix D, some examples are provided of excerpts of regulatory documents of RPASs corresponding to each of these levels in order to further illustrate the criteria employed within this dimension. From a design perspective, and in relation with the discussion of Section 2.1, requirements with a high level of specificity could be integrated in a more straightforward way within design methods as quantitative restrictions. On the other hand, those with a low or medium level of specificity could be integrated as qualitative criteria or can serve to highlight variables of interest to be defined within the design approach;

- Streamlined or ad-hoc requirements: Streamlined procedures are those that are relatively straightforward in that the requirements to comply with are mostly laid out in advance (such as in classical certification specification codes). However, in the field of RPASs, there are cases, mostly pertaining to specific category operations [43], where requirements or mitigations are laid out depending on the result of a prior operational risk assessment. An example is the Specific Operations Risk Assessment (SORA) methodology by JARUS, where the number of barriers, as well as their integrity, depend on the result of a prior operational risk assessment. In these cases, the requirements are a function of the outputs of this risk assessment study; therefore, depending on the case of application, the set of conditions that must be complied with are different. These are considered ad-hoc procedures, and they do not provide a pre-established certification basis; rather, it is dependent both on the aircraft and the operation to be conducted. From a design perspective, these approaches could hinder the integration of requirements within design methodologies due to various reasons: (a) as they are dependent on the operational scenario, different operations might demand differing requirements, and also not all operational scenarios might be envisioned in the first stages of the design project; (b) the safety assessment might demand analysis on certain aspects of the aircraft that might not be known at the first stages of the design, such as systems architecture or reliability estimations, which is in line with the reasons for the application of more advanced risk analysis techniques being usually left for later design stages, as commented in Section 2.1; (c) the case-by-case basis approach of determining the certification basis for each combination of aircraft and operational scenario can complicate the definition and integration of a unique set of certification aspects. There may be some alternative ways to conduct the safety evaluation by the Authority depending on the regulatory paradigm, such as acquiring a Light UAS Operator Certificate (LUC) in the EASA paradigm. However, these options would be outside the scope of this paper.
- Scope: Aircraft type (fixed-wing, rotary-wing) and operational category (open specific, certified).

With respect to the dimensions for the second stage of the survey, in this case, as the focus is set on providing the designer with a rapid evaluation of the main applicability characteristics of the documents in order to aid them in selecting the documents that can be used in the design approach, the characteristics to be analysed here shall be the applicability criteria of the codes with respect to design aspects and operational characteristics. An analysis of specific characteristics for each code such as the criteria for structural airspeeds or limit load manoeuvring factors would be outside the scope of this paper, as the paragraphs that would have to be studied are highly dependent on the scope of the design methodology. Furthermore, the objective of DECEX is to provide a flexible approach that can aid the designer in identifying those paragraphs of the regulations that are applicable to the design approach under study, and this task of identifying the applicable regulatory requirements is within the steps of the DECEX procedure. Nevertheless, within the application case studies of DECEX conducted in Section 6.3, the relevant paragraphs with specific criteria that are relevant to their scopes shall be identified as a demonstration of application of the DECEX workflow.

4.2. RPAS Regulatory Document Search Process

An overview of the search process of the RPAS regulatory documents to be included in the survey is outlined here. These documents shall be selected according to the scope of the research, which, as it has been anticipated and will be seen in Section 5, focuses on entities with marked international influence in the rulemaking paradigm—more specifically, ICAO, EASA, FAA, JARUS and NATO—representing both the civil and military domains. Other aspects of the main scope to be considered are the focus on initial airworthiness aspects and also on fixed-wing aircraft, as laid out in Section 1.1.

Previous surveys of RPAS regulations employed three distinct approaches to the document search process: (a) an in-depth analysis of the original sources of information, which are mainly the websites of the different Authorities, as performed for instance in [6,8]; (b) the use of pre-compiled lists and overviews of regulations, such as in [10]; (c) a combined approach, as seen in [18]. The first procedure is less streamlined as it requires navigation in the specific websites of the different Authorities, which usually employ quite different structures to their contents and documents, but it provides certainty that the documents are official (of particular interest to the aircraft designer) and current (which is important in view of the rapid evolution of the regulatory landscape). The second approach is more streamlined and allows for greater reproducibility but the sources of information are not the original ones; furthermore, upon checking many of the pre-compiled lists cited in previous research, these are no longer available, which also affects the third approach on the part of the databases. Thereby, the first procedure was selected for the current work. In order to search for relevant documents within each entity's website, two approaches were followed:

1. The search engines of the entities' websites have been used with keywords related to the area of study, including, amongst others: 'RPA', 'RPAS', 'UAV', 'UAS', 'drone', 'unmanned aircraft', etc. The search results were then sorted so as to keep those related to the scope of the study;
2. With previous knowledge of the websites' site map and of the hierarchy and organisation of documents from different entities [29,74], the areas related to RPAS regulations and rulemaking processes were examined so as to find documents relevant to this research.

These two methods complement each other, as some documents, such as the EASA SC-RPAS.SubpartB-01, could not be found directly with the second procedure within the Unmanned Aircraft area of the website but were found through the search engine. Rule-making documents such as Terms of Reference (ToR) and Notices of Proposed Amendments (NPAs) were found through the second method by following the thread of relations of these documents with each other. Overall, this search process yielded an extensive database of documents, which will be analysed in Section 5 within the survey.

5. Analysis of Regulations Regarding RPAS Initial Airworthiness and Operational Restrictions

This section contains the two-stage survey mentioned in the Introduction. In the first stage, a broader set of stakeholders and regulations are reviewed to provide a wide overview of the current RPAS regulatory landscape related to initial airworthiness, and the criteria defined in Section 4.1 are employed to analyse and compare the relevant documents. This step is more focused in initial airworthiness from a general perspective. In view of the results of this stage, and employing the aforementioned criteria for review, only the most promising documents from a design standpoint are kept for the second stage in order to conduct a further analysis of their applicability criteria relative to design and operational restrictions. Therefore, this second stage shall be more focused on design aspects. In this way, both of them cover the main topical areas of the research presented in this paper.

In addition to the scope of the work, as established in Section 1.1, it should be highlighted that—attending to the bibliographic sources available during the research—access to regulatory documents has been limited to those that are publicly available in the open domain. Furthermore, albeit some regulations allow for waivers or exemptions to certain requirements, these particular cases, which have to be evaluated in a case-by-case basis for each design and operational scenario, have not been included in this review.

The written discussion in both stages of the review shall be more focused in expounding the main contextual aspects of the documents that shall be analysed, whereas the main results of evaluating the different criteria for the review of the documents are contained within Table 1 for the first stage of the review and in Table 2 for the second one. The main

text shall also develop the foremost aspects of discussion and comparison between the regulations attending to the aforementioned criteria.

5.1. Stage 1: Broad Review of Current Regulatory Landscape

The following text offers some context and general comments on the regulatory paradigm related to the initial airworthiness documents of each entity, whereas the results complementing this exposition can be seen in summarised form in Table 1.

5.1.1. ICAO

It could be considered that the first deliverable of ICAO with respect to RPAS rulemaking was Circular 328 [75], stating general policy and objectives for rulemaking activities and considerations for ICAO Standards and Recommended Practices (SARPs) amendments. This document, as is usual of ICAO Circulars, has a broad scope and is of high-level nature. The next main deliverable could be considered to be the Manual on Remotely Piloted Aircraft Systems [76], which is more detailed than the Circular, while still remaining at a high level, as is usually the case of this type of ICAO document, which seeks to provide guidance to Contracting States on technical and operational issues. It should be noted that the airworthiness paradigm proposed here is the traditional one consisting of Type Certificates, Certificates of Airworthiness and approved organisations for design and production. In both cases, no specific design-related provisions are provided; so, these documents are not particularly suited to direct integration in design methodologies, albeit having great importance in the international initial airworthiness paradigm of RPAS and ICAO further developments, thus they are included here.

Even though before the publication of the RPAS Manual some Chicago Convention Annexes had already been amended, including some relatively straightforward aspects related to RPASs (such as the amendment of Annex 13, which included a new definition of “accident” applicable to RPASs), it was from the time of publishing of the RPAS Manual onward when ICAO started the very ambitious task of amending the Chicago Convention Annexes to include more thorough aspects related to RPAS airworthiness and operations. This activity is still ongoing, with some of the key Amendments envisaged for applicability in 2026 [77]. Chicago Convention Annexes are documents requiring payment, but some information was found through other references covering the potential changes such as [8], and also in the ICAO document [77].

Another relevant source of ICAO material is the ICAO UAS Toolkit, the main web page of which can be found in [78]. This resource is directed foremost to regulators in the Contracting States, providing the main perspectives and guidelines of ICAO to aid in their rulemaking. Of particular interest are the documents provided in the form of ICAO Model UAS Regulations, issued in 2020, the main purpose of which is to serve as an example and template for Contracting States to develop their own RPAS regulations. These include the following: Part 101 [79], dealing with operations in the open category; Part 102 [79], dealing with operations in the specific category and also other aspects such as operator certification; and Part 149 [80], which tackles organisation approvals. It should be noted that the operational categorisation employed by ICAO has a similar basis to that used by EASA and JARUS [43], as it will be seen later. These model regulations have seldom been the object of academic analysis, so their inclusion can be considered one of the main contributions of this research.

5.1.2. EU/EASA

The development of regulations for the field of RPASs within the EU framework has followed a long process, with many changes in direction in the first stages of the rulemaking progress. This survey focuses on the currently applicable paradigm and documents, which has resulted from a series of rulemaking tasks from 2015 onward. A detailed account on the historical perspective and the previous paradigm can be found in the works of [8,47].

The current regulatory framework is markedly operations-centric, and the main “hard law” Regulations approved by the EU Commission are the following:

- Commission IR 2019/947 [81]: Focuses on aspects related to rules and procedures for the operation of RPASs, laying out the principles for the three main categories of operations: open, specific and certified. It also covers topics such as remote pilot licensing and instructions related to conducting operational risk assessments for the specific category.
- Commission DR 2019/945 [82]: Deals with the applicable requirements for RPASs in the different categories of operations with respect to manufacturer’s obligations and markings and documentation for commercial RPASs. The Appendix expounds the specific limitations for the classes of RPASs from C0 to C6, mainly intended for open and specific operations.
- Commission DR 2024/1108 [83] and IR 2024/1110 [84]: These recently approved regulations integrate RPAS aspects within the classical framework of the EU Implementing Regulation for initial airworthiness IR 748/2012, allowing RPASs as well as their equipment and control stations to be included within the paradigm of type certificates, establishing the certification basis, airworthiness certificates, etc.

While provisions for the open and specific categories are already mostly laid out, the certified category of operations is still under development. As commented in the rulemaking documents [85,86], detailed certification codes for RPASs such as CS-UAS and CS-Light UAS are expected for 2025. It should be highlighted that the current concept of EASA with respect to the use of CS for RPASs is laid out in [86] and illustrated in Figure 4 below. The main idea is that a classical certification code adequate to the type and risk of the RPA will be selected (for instance, CS-23), and the requirements will be complemented with RPAS-specific aspects contained in CS-UAS. On the other hand, for the case of Light UAS, the future CS-Light UAS would contain all the applicable requirements.

Aside from this, currently and until the new CS landscape is established, there are some RPAS special conditions available. In this work, due to their relation to the airframe of fixed-wing aircraft and the research scope in general, SC-RPAS.SubpartB-01 [87] and SC Light-UAS for Medium and High Risk [88] have been included, and their main characteristics can be seen in Table 1. The authors have not found that these references being considered in previous works; therefore, their consideration here would constitute one of the novel aspects of this survey.

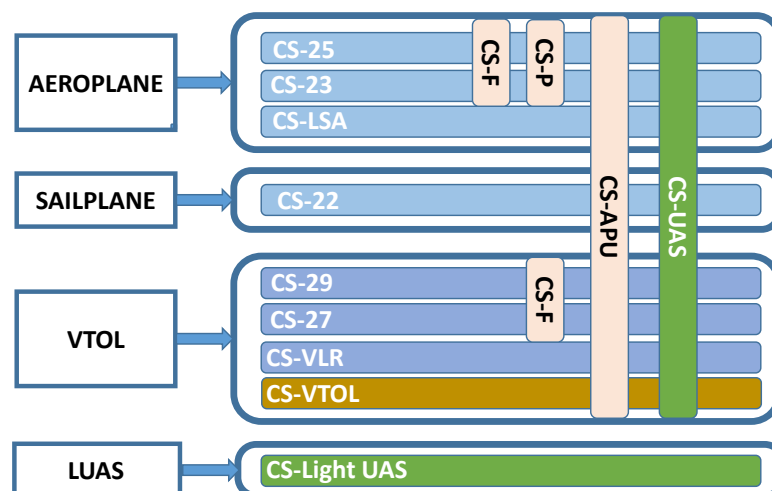


Figure 4. Representations of the organisation and interrelations amongst CS codes within the future EASA RPAS framework. Figure adapted from [86].

5.1.3. USA/FAA

Within the FAA framework, there are also different applicable regulations depending on the characteristics of the operation and of the air vehicle. Albeit the categories of operation of open, specific and certified are not employed here, some parallels can be drawn. The main applicable regulations and paradigms are briefly commented below:

- Part 107 [89]: This is the main regulation in the FAA paradigm for flying RPASs below 55lb with commercial and professional purposes and is also an option for public operations that fall within the restrictions of this regulation. It lays out requirements with respect to pilot licensing, operational restrictions, registration of aircraft, etc. Four different operational categories are established for operations over human beings, with differing requirements and restrictions with respect to the aircraft and operation characteristics. Waivers can be requested for many of the limitations, which are evaluated by the FAA on a case-by-case basis.
- 49 USC 44809 Exception for limited recreational operations of unmanned aircraft [90]: Provides a limited set of requirements for recreational activities of RPASs, being also the current area where model aircraft fall into. One of the main aspects is that the user must fly according to guidelines and safety standards of FAA-recognised Community-Based Organization (CBO). The AC 91-57C establishes guidelines with respect to these organisations and their required safety standards.
- 49 USC 44807 Special Authority for certain unmanned aircraft systems [91]: This approach is envisioned for RPAS operations presenting characteristics that are not an option for waiver through Part 107. Here, the applicant conducts a safety risk analysis, which is checked by the Administrator on a case-by-case basis, and measures are established according to the safety analysis results; therefore, it is an ad-hoc approach.
- In the case of public operations, one option is to fly under Part 107 if the aircraft and operation comply with their requirements. A second option is through a Certificate of Authorization (COA), which requires an application containing mainly operational information, which is reviewed by the FAA. A third option is provided through 49 USC 40102 (a) (41) or 49 USC 40125, which is intended for public aircraft operations. The latter two procedures are markedly ad-hoc and limited to public operations; thus, they are not included in the Table 1 evaluation.
- Certification of advanced operations: Another way for RPAS operations is to follow the traditional options to aircraft certification, including alternatives for special airworthiness certificates and flight permits. In the case of RPASs, as no specific codes are yet available, one of the recommended options is through an experimental airworthiness certificate employing the FAA Order 8130.34D for Airworthiness Certification of Unmanned Aircraft Systems and Optionally Piloted Aircraft [92]. However, it should be noted that this document is not a detailed airworthiness code; rather, it employs an approach consisting of an initial evaluation and the calculation of a risk index in order to determine the criteria with which the applicant has to comply and the level of the safety evaluation considered by the FAA, therefore being again markedly ad-hoc.

5.1.4. JARUS

JARUS is an organisation of experts, with no legal remit, that proposes recommendations for rulemaking, some of which have been adopted by EASA.

With respect to the certified category, within the scope of this research, the CS-LUAS [93] and CS-UAS [45] codes have been analysed. It should be stated that the first was developed following the principles of the legacy Part/CS-23, and therefore contains more detailed requirements; whereas CS-UAS, which is intended for larger RPASs, follows a performance-based approach inspired by the new Part/CS-23 regulations. This explains the difference in level of specificity seen in Table 1. It should also be noted that CS-UAS employs the concept of ADS, commented beforehand in Section 2.2, and proposes regulations (such as CS-LUAS) or consensus standards to complement the design-independent design criteria found here with more detailed guidelines. However, no direct correspondence of

which consensus standard or external document can be used to substantiate the different requirements is provided, in contrast to CS-23 within the manned aviation paradigm, which does provide these connections explicitly. In contrast to the envisioned future framework for CS codes in EASA, here, each CS code contains all requirements, both for the air vehicle as well as for other equipment and the control station.

Regarding the specific category, very recently, JARUS has updated the SORA methodology to version 2.5 [94]. This is the main approach, which has been adopted by EASA with some modifications, for operations in this category. It consists of a safety assessment to be conducted attending to aspects of the RPAS and its operation. Depending on the results of the safety assessment, several possible requirements—that can affect, amongst other aspects, the design assurance of the RPAS—are established, thereby constituting an ad-hoc procedure.

5.1.5. NATO

Two detailed certification codes related to RPAS initial airworthiness were found in the document search:

- NATO Standard AEP-4671 [95]: This document consists of a very thorough and detailed code, with high level of specificity, based on that of the legacy CS-23, with additions in certain points related to RPAS-specific aspects. It is intended primarily for heavyweight fixed-wing RPASs.
- NATO Standard AEP-83 [96]: This code is focused on lightweight fixed-wing RPASs and is therefore associated with a lower risk of aircraft operations. It has a particular form not seen in other instances, where requirements are laid out in a table with three columns. The first column contains the high-level airworthiness essential requirements, the second one provides detailed arguments that add a layer of specificity upon the relatively broad guidelines of the first, and the third contains directions with respect to the means of evidence.

5.1.6. Overall Discussion and Conclusions of Stage 1 of the Survey

In view of the previous text and of the results of Table 1, containing the evaluation of the key characteristics for the aforementioned documents, several aspects related to the set of documents that were analysed and of the overall RPAS international initial airworthiness paradigm can be extracted.

First of all, common concepts and ideas can be found through the different regulatory contexts, which can be expected taking into account the harmonisation efforts. The aforementioned risk-based approach and the concurrent consideration of design and operational aspects to establish the applicable regulations, as mentioned in Section 2.2, can be seen in all paradigms. This is in accordance to previous research, which proposed a paradigm where the certification requirements should depend on both dimensions [4]. From an RPA design standpoint, this can be seen as an added challenge, as a coupling is added between the operational scenario and the applicable regulations. Even though the design of an aircraft always starts from a set of design missions, not all possible operational scenarios are considered at this stage, which in this case could result in uncertainties regarding the regulatory requirements to integrate in the design stage. Furthermore, these operational aspects do not only cover aspects such as operational airspeeds or cruise altitude but also whether the operation is above people and the population density or the distance to aerodromes, as it will be seen in the second stage of the survey, where this issue is commented in more detail.

Table 1. Summary of findings from the first stage of the survey. The table footer contains the meaning of the different symbols employed.

Entity	Regulation	LRD Tier	Legally Binding?	Topical Focus	Lvl. of Specificity	Streamlined or Ad-Hoc	Availability	Scope	
								Aircraft Type	Operation Category
ICAO	Circular 328 [75]	Tier 1	No	Varied	Low	Streamlined	Public	All	-
	RPAS Manual [76]	Tier 1	No	Varied	Low	Streamlined	Public	All	-
	Chicago Convention Annexes	Tier 1	Yes ^a	Varied	Low-Medium	Streamlined	Payment required	All	Certified
	Part 101 and 102 [79]	Main doc: Tier 1 ACs: Tier 3	No	Operations	Medium	101: Streamlined 102: Ad-hoc	Public	All	101: Open 102: Specific
	Part 149 [80]	Tier 1	No	Organisation approvals	Low	Streamlined	Public	All	Open and specific
EASA	IR 2019/947 [81], DR 2019/945 [82]	Main doc: Tier 1 AMC and GMs: Tier 3	Yes	Operations, design	Medium	Open category: Streamlined Specific category: ad-hoc	Public	All	All
	DR 2024/1108 [83], IR 2024/1110 [84]	Tier 1	Yes	Initial airworthiness certification framework	Medium	Streamlined	Public	All	Specific and certified
	SC-RPAS.SubpartB-01 [87]	Main doc: Tier 2 AMC and GMs: Tier 3	No	Initial airworthiness, design	High	Streamlined	Public	Fixed wing	See footnote ^b
	SC Light UAS [88]	Tier 2	No	Initial airworthiness, design	Medium	Streamlined ^c	Public	All	Specific

Table 1. Cont.

Entity	Regulation	LRD Tier	Legally Binding?	Topical Focus	Lvl. of Specificity	Streamlined or Ad-Hoc	Availability	Scope	
								Aircraft Type	Operation Category
FAA	USC 44809 [90]	Main doc: Tier 1 ACs: Tier 3	Yes	Varied	Low-Medium	Depends on guidelines of organisation	Public	All	-
	Part 107 [89]	Tier 1	Yes	Varied	Medium	Streamlined	Public	All	-
	USC 44807 [91]	Tier 1	Yes	Assessment of special operations	Low	Ad-hoc	Public	All	-
	Order 8130.34D [92]	Tier 3	No	Experimental certification process	Medium	Ah-hoc	Public	All	-
JARUS	CS-LUAS [93]	Main doc: Tier 2 AMC and GMs: Tier 3	No	Initial airworthiness, design	High	Streamlined	Public	Fixed wing	Certified
	CS-UAS [45]	Main doc: Tier 2 AMC and GMs: Tier 3	No	Initial airworthiness, design	Medium	Streamlined ^d	Public	All	Certified
	SORA [94]	See footnote ^e	No	Risk assessment of operations	Medium-High	Ad-hoc	Public	All	Specific

Table 1. Cont.

Entity	Regulation	LRD Tier	Legally Binding?	Topical Focus	Lvl. of Specificity	Streamlined or Ad-Hoc	Availability	Scope	
								Aircraft Type	Operation Category
NATO	AEP-4671 [95]	Main doc: Tier 2 AMC and GMs: Tier 3	No ^f	Initial airworthiness, design	High	Streamlined	Public	Fixed wing	Certified
	AEP-83 [96]	Tier 2 and 3	No ^f	Initial airworthiness, design	Medium-High	Streamlined	Public	Fixed wing (mainly)	Certified

^a Albeit the Chicago Convention Annexes satisfy the definition of “standard” according to ICAO, it is permitted in special cases that Contracting States do not comply with some aspects, as long as they notify differences. ^b The SC was developed attending to the previous paradigm of EASA as established by the Policy E.Y013-01, and it is applicable for RPASs for which the kinetic energy assessment according to this Policy results in an initial certification basis according to CS-VLA, so it can be considered to be associated to the certified category. ^c Albeit the content is streamlined, the regulation is applicable to RPASs with a resulting SAIL of III or more within the specific category, which does depend on a prior safety assessment. ^d Due to heavy emphasis on performance-based requirements, and the need to complete certain requirements with ADS, establishing a certification basis might tend towards a slightly ad-hoc approach. ^e SORA is a particular case as it does not follow the typical structure or spirit of certification regulations. ^f Not legally binding in the civil field; however, it is legally binding in NATO Signatory States that have adopted it.

Another common aspect that can be seen in the different paradigms is that, for medium risk operations (such as specific category operations or, in the USA paradigm, operations not yet in the certified paradigm but also outside Part 107 applicability), a safety assessment-based process towards airworthiness assurance is proposed. All of these require a risk analysis to be conducted, and upon the results, a series of mitigating measures with respect to various aspects, including those related to the design assurance of the airframe, are established. This is what has been called an ad-hoc approach in the characteristics for analysis proposed in Section 4.1. As the main high-level approach for the safety assurance of these type of operations is already similar in the different paradigms, a possible further step for regulatory harmonisation could be that the same systematic safety assessment approach (such as the SORA approach by JARUS) could be accepted by the different Authorities. Moving on to aspects related to design, due to the nature of these type of approaches, the possibility of including aspects from these regulations in systematic design procedures that seek to be applicable to a variety of RPASs is hindered. This is due to the precise requirements to be complied with not being established until the end result of the risk assessment, which usually involves a relatively specific knowledge of the aircraft. This, in turn, is not usually available in early design stages where the level of knowledge and definition of the design are low, as commented in Section 2.1. As a further challenge, and in relation to the previous paragraph, the result of the safety assessment is highly dependent on aspects related to the operational scenario (for instance, population density on ground or distance to aerodromes); so, for the same aircraft, and depending on purely operational aspects, requirements related even to the design and components of the aircraft depend on the operational scenario. As an example, following the SORA methodology, an aircraft with a maximum characteristic dimension of over 8m, flying over an unpopulated area with low air risk, is expected to have a Specific Assurance and Integrity Level (SAIL) that does not require specific design criteria for systems and equipment. However, the same aircraft flown over a populated area results in a higher SAIL level, which demands that ADS such as CS-LUAS or EASA SC-Light UAS are employed for the design of components. This further increases the coupling between design aspects and those related to the operational scenario. Taking all of this into account, those approaches following an ad-hoc perspective are particularly challenging to be included in the first stages of design.

It can be seen from the text above that the certified category is the one that still requires more thorough development through most of the regulatory paradigms, with the exception of NATO, which already has well-established detailed certification codes. It is understandable that this category has seen the least development, as the largest volumes of operations are expected within open and specific categories. From a design standpoint, certification codes usually have a high level of specificity, providing the designer with a more straightforward manner to integrate their requirements in design activities, as expounded in Section 2.1. Furthermore, the certification of the aircraft allows a certain decoupling from the operational limitations and safety assessments dependent on the particular operational scenario, which are established in open and specific categories, therefore allowing more flexible use of the aircraft, which can be a competitive advantage. On the other hand, the design space is expected to become more limited, as seen in Section 2.1, and the designer has to deal with certification activities, demonstrations and costs.

For open category operations or similar paradigms, such as that of FAA Part 107, it is seen that the level of specificity is generally lower than that of the certified category. This is in accordance with the aforementioned risk-based philosophy, where regulatory prescriptions are reduced to avoid hindering operations of low risk [8]. In contrast, those documents that are more similar in nature to CS codes, such as the NATO standards, tend to have a higher level of specificity. However, it must be mentioned that there is a particular case in the JARUS codes, the CS-LUAS, which is intended for lighter RPASs, and has a higher level of specificity than the CS-UAS, which is intended for larger aircraft, thereby with a higher associated risk. This particularity can be explained since the first code was developed according to the perspective of the legacy Part/CS-23, whereas the second one

was developed accounting for the new Part/CS-23 performance-based paradigm, therefore resulting in less prescriptive requirements [44]. From a designer's perspective, the positive and negative aspects of having either less prescriptive requirements with lower specificity or more prescriptive ones with a higher level were already discussed in Section 2.1.

At this point, it should be noted that the possible negative aspects of having a lower level of specificity, which are mainly related to a lower assurance on the certifiability of the design, could be offset by the use of AMC and GM with a higher level of specificity. The result of this would be that the designer could have the option to follow more prescriptive requirements with a higher specificity level if desired, but this would not be a mandatory process, thereby leveraging the advantages of performance-based regulations of allowing for a larger feasible design space and not constraining the design process and the ways of demonstrating airworthiness compliance. However, for this to be in effect, a clear correspondence is needed between the performance-based requirements and the applicable lower-Tier but more specific documents. This is not currently the case in the field of RPASs within the few certified category documents available, particularly in CS-UAS, where—albeit CS-LUAS and CS-LURS are recognised as possible ADS to the aforementioned regulation—no detailed provisions or other alternatives are provided, which makes the selection of ADS a relatively ad-hoc process. Also related to this issue, it should be noted that no Tier 4 documents have been found in the survey within the scope of the review. Several entities have developed standards for RPASs, such as ASTM [97–99], ISO [100,101], EUROCAE or the Flight Safety Foundation (BAR standards). However, these documents could not be accessed without payment, therefore leaving them outside the scope of this work. Future documents within the public domain dealing with specific aspects of RPAS design that could be employed as ADS could constitute a paramount advantage to the field.

In contrast with the relatively vague ADS selection process in RPASs, CS-23 does offer an unambiguous correspondence between each requirement and the applicable consensus standards or past regulations that can be used if the designer seeks a higher level of specificity. Should future editions of the aforementioned RPAS documents, or the future EASA certified category paradigm, be more aligned with the organisation of the new CS-23, along with the aforementioned development and proposal of standards in the public domain, it can be argued that this would be advantageous for the aircraft designer, allowing for greater flexibility in certification basis selection while also providing detailed guidelines to which they can adhere. It should be noted that this standpoint of having high-level flexible requirements with low specificity complemented by lower-level alternatives to show compliance with the first ones can be considered to have been explored, within the same document, in the AEP-83 [96], as seen in the text above.

5.2. Stage 2: Design and Operational Applicability of Selected Documents

As mentioned beforehand, and with a more design-oriented perspective, in this section, some more aspects of the documents that may be more relevant to the aircraft designer are analysed. In particular, the design and operational applicability aspects of the documents are considered. These are of particular relevance to the designer as they aid in selecting the proper certification basis for the aircraft being designed. The documents that have been omitted from the previous survey are as follows: those that followed ad-hoc approaches, due to the limitations they offer for integration in design activities as mentioned beforehand; those that are not focused in the airframe design or operational constraints, such as ICAO Part 149 or EU DR 2024/1108 and IR 2024/1110; and also those documents whose content is not yet definitive or could not be accessed, namely, the Chicago Convention Annex amendments.

Two main dimensions have been evaluated with respect to document applicability: design limitations, which are related to the RPA airframe characteristics, and operational considerations. These two dimensions link with the coupling of design and operational characteristics in the field of RPAS that was mentioned previously. It should be noted that certain operational aspects, such as operational constraints or design mission objective

criteria, can have a critical influence in design and are therefore considered in design methodologies. In fact, in some cases, design requirements such as completing a certain mission over complicated terrain can constitute critical restrictions to the RPAS design, as seen in [102,103]. The results from this analysis can be seen in Table 2.

One of the foremost conclusions that can be extracted in view of Table 2 is that, even having excluded from the analysis particular cases of the regulations such as waivers and special procedures, there are many particularities to consider even for the operational restrictions, as can be seen in the table footnotes. Therefore, it can be concluded that a specialised level of knowledge in the regulations is required so as to fully cover all considerations. However, it is expected that a designer that wishes to develop an aircraft with a relatively broad operational spectrum would opt for the main processes that are less ad-hoc, which are the ones that have been included here.

With respect to the applicability of the different regulations, and firstly attending to design aspects, it can be seen that, with the current paradigm, the spectrum of MTOM values is broadly covered but there are some overlaps between regulations, particularly within the certified category. While the criteria for separating CS-LUAS and CS-UAS has been mostly based in the difference between CS-VLA and CS-23, the NATO standards establish a different threshold. With respect to operational considerations, except perhaps for the max speed, most of the other aspects are related to the specific operational scenario rather than to performance characteristics of the airframe; thereby, they are of more use to the operator than to the aircraft designer. Overall it can be seen that, even regarding the applicability of regulations, the scenario is notably heterogeneous, in spite of the advances in recent times towards a more homogeneous framework.

A remarkable aspect, which is related both to airworthiness and design considerations, is that operational restrictions only appear within regulations of the open category, whereas in the certified category no such limitations are present. This is tightly related to the methods used by the Authorities for safety assurance in each of the categories. In the case of open category, as it is not intended that combinations of aircraft and operational scenarios with overall low associated risk have to go through the lengthy and expensive process of certification, which could hinder the development and usage of RPASs, and would not be according to the principle of proportionality as mentioned in Section 2.2, the safety assurance is achieved instead through operational limitations that allow control of the risk—that is, there are few restrictions on the design but relevant limitations in the operational scenario. On the other hand, for the certified category, which is usually related to aircraft and operational scenarios with a higher combined risk, the most emphasis is placed on the design, through compliance with detailed certification codes, in order to reach the desired safety assurance level—that is, if a large RPAS has to be flown over a populated area, as the concept of operation itself includes a high level of risk, then the safety assurance is achieved through a certification process for the RPAS, which allows to control the overall risk to an acceptable level and in turn provides larger operational flexibility. This explains that the certified category documents included in Table 2 contain no operational limitations, as the risk to be managed through the safety assurance has been absorbed through certification.

Table 2. Summary of findings from the second stage of the survey. The table footer contains the meaning of the different symbols employed.

Entity	Regulation	Design Applicability			Operational Restrictions				
		Mass (MTOM)	Aircraft Type	Operation Category	Impact Energy	Max. Speed	Max. Height	Distance to Aerodromes	Proximity to People
ICAO	Part 101 [79]	<25 kg ^a	All	Open	-	-	<120 m AGL	>4 km	>30 m
EASA	Subcategory A1 [81]	C0: <0.25 kg C1: <0.9 kg ^b	C0, C1: electric powered	Open	C1: <80 J terminal velocity	C0, C1: <19 m/s	<120 m AGL ^c	See note ^d	No overflight of assemblies
	Subcategory A2 [81]	C2: <4 kg	Electric powered	Open	-	-	<120 m AGL ^c	See note ^d	>30 m
	Subcategory A3 [81]	C2: <4 kg C3, C4: <25 kg ^b	All	Open	-	-	<120 m AGL ^c	See note ^d	>150 m
	SC-RPAS. SubpartB-01 [87]	See note ^e	Fixed-wing	See note ^f	Unpremeditated descent: <0.003 MJ, LOC: <0.02 MJ	-	-	-	-
	SC Light UAS [88]	See note ^g	All	Specific	See note ^g	See note ^g	See note ^g	See note ^g	See note ^g
FAA	Part 107 [89]	<25 kg	All	-	See note ^h	<44.8 m/s	<122 m AGL ^c	See note ⁱ	Generally no overflying ^e
JARUS	CS-LUAS [93]	<750 kg	Fixed wing	Certified	-	-	-	-	-
	CS-UAS [45]	Non-VTOL: <8618 kg VTOL: <3175 kg	All	Certified	-	-	-	-	-
NATO	AEP-4671 [95]	Mainly 150–20,000 kg	Fixed wing	Certified	-	-	-	-	-
	AEP-83 [96]	<150 kg	Fixed wing	Certified	>66 J ^j	-	-	-	-

AGL: Above Ground Level, LOC: Loss of Control, MJ: Mega Joules. ^a Additional requirements must be met for RPA between 15 kg and 25 kg. ^b Some privately built and legacy RPA can also operate in these subcategories. ^c Can be exceeded to overfly an obstacle. ^d No detailed provisions are given in the Regulations or their AMC and GM, but it is expected that most aerodromes are considered as “restricted geo-zones” for the operation of RPASs, therefore restricting operations in their vicinity save for prior authorisations. ^e Applicability depends on kinetic energy, combining mass and velocity. ^f As per footnote b in Table 1. ^g Characteristics resulting from the safety assessment conducted prior to employing the Special Condition. ^h Different types of operation depending on impact energy and proximity to people are established. ⁱ No specific distance given, but Air Traffic Control (ATC) permission is required to operate within lateral boundaries of the surface area of Class E airspace designated for airports. ^j An Appendix of the regulation includes a reduced and higher-level set of requirements for impact energy below 66 J.

Finally, an aspect which—albeit not compiled by Table 2—has been observed within this second stage of the survey, is that the level of specificity at the requirement level when comparing similar topics on different regulations can vary greatly, even for codes sharing a significant MTOM interval. As mentioned in Section 4.1, the level of specificity can be evaluated at regulation level but a detailed analysis at requirement level is essential for the designer to extract certification-driven restrictions for design, as will be one of the main topics of the DECEX procedure to be expounded in Section 6. For instance, regarding the topic of operational airspeed definitions (such as V_{MO} or V_{NE}), NATO AEP-4671 provides detailed definitions and their requirements and relationships between them. However, CS-UAS, with which it shares a significant applicability overlap in MTOM range, only contains broad guidelines stating that the applicant must determine relevant structural airspeeds. This could be expected since the level of specificity of CS-UAS is lower than that of AEP-4671. Other discrepancies amongst the main certified category codes considered in this study can be observed for different topics, such as stall, climb, manoeuvring and gust requirements. A detailed review of differences between requirements of this regulation is outside the scope of this survey, which is at a higher level; in any case, the certification requirements to be integrated in a design methodology would depend on its design stage and scope, as commented in Section 2.1. The effect of these discrepancies between specificity at requirement level shall be commented in the next section within two cases of study, as the DECEX procedure proposed therein intends to solve some of these issues faced by the designer when navigating this regulatory paradigm.

6. Flexible Procedure for Design Criteria Extraction (DECEX)

Having covered the first of the main objectives of the research in the previous section, in this one, the second and main point of the investigation shall be tackled—that is, the investigation of new procedures to aid the designer in navigating the complex regulatory landscape of RPASs and integrating airworthiness considerations in the design continuum, particularly within its first stages. The developed procedure has been named DECEX (DEsign Criteria EXtraction), and it tightly links with the previous points of the paper. The survey of Section 5 not only constitutes the main body of text that can be used with the procedure but also revealed key challenges that the designer must face when navigating the regulatory paradigm and integrating airworthiness aspects in design. Precisely, the DECEX approach has been developed taking those findings into account. Furthermore, the characteristics that were defined in Section 4.1 and used in the review shall also be employed here.

6.1. Rationale for the Development of the DECEX Procedure

The review conducted in the previous section not only focused on airworthiness aspects but also on how the characteristics and content of the different regulations, and the paradigm as a whole, might impact the RPA designer and the integration of certification aspects in RPA design methodologies. As mentioned in the introduction and in the literature review, there is still work to be conducted in the general area of RPA design, and more particularly, in certification-driven RPAS design. Considering the current regulatory paradigm, which is more developed and harmonised than some years ago, and the relevance of integrating certification aspects in design, as already discussed in Section 2.1, there would be remarkable potential in the development of new RPA design methodologies integrating airworthiness considerations that are up-to-date within the current paradigm and even in updating previous methodologies with the new requirements. It should be noted that the focus here is not on developing a specific design methodology or the integration of certification aspects in a particular design process. Rather, it is on the development of the design methodologies themselves, as this can potentially have a farther reach, as multiple possible future airworthiness-driven approaches could benefit from it rather than only one design methodology, which in the end is developed with a particular scope with respect to the design stage and the disciplines considered. This can be considered one of the novel aspects of this work in that the objective is to define a procedure that can be applied

to populate different design methodologies with airworthiness aspects, augmenting its applicability and reach.

The main rationale behind the development of DECEX is that, if a designer seeks to develop a new airworthiness-based design methodology for RPASs, or when conducting the design of a specific RPA accounting for certification aspects, they face many issues in the process of navigating the regulatory landscape and extracting the desired requirements from the regulations to integrate them in the design continuum. Some of the outstanding challenges, as anticipated in the discussions presented along the survey, are summarised below:

- Firstly, the designer requires a common reference of all the potential applicable regulations, the requirements of which might be extracted. Albeit in the field of manned aviation the potential regulations are clearer and well-established; in this case, as seen in the aforementioned sections, the material is more spread out. It could be said that this point has been tackled, at least within the scope of this work, through the survey conducted beforehand in this paper.
- There is a notable heterogeneity not only in the main characteristics of the regulations as evaluated with the criteria proposed in Section 4.1, but also in their content related to specific topics (such as the definitions and requirements with respect to airspeeds, as commented in Section 5.2), which is in contrast with the comparatively more homogeneous manned aviation paradigm.
- There is a general lack of publicly available high-specificity regulations and standards for the certified category of RPASs. As commented in Section 2.1, detailed provisions are the ones that can be most easily integrated in quantitative procedures, and they also provide larger certifiability confidence.
- Adding to the above issues, even if detailed consensus standards were accessible to complement low-specificity requirements in the main texts, there are no detailed directions for the correspondence of the requirements in the main regulation with the applicable standards to demonstrate compliance with that particular requirement.
- As seen before, the RPAS regulatory paradigm is very dynamic. Therefore, design approaches that are not flexible and cannot easily adapt to changes in the regulations through the integration of new requirements could risk becoming obsolete in a few years.

It should be noted that some of these challenges are similar to those found in the work of [37] when developing their framework for design-airworthiness integration for manned general aviation design. These challenges were commented in Section 2.1. However, in the field of RPASs, these issues (for instance, the differences between the requirements established by differing documents) have been found to be of greater magnitude due to the characteristics of the paradigm. It could be argued that the issue commented in the first point within the list above is in part covered by the survey developed in this work; however, the challenges related to the extraction of the requirements from the regulations and their integration in design methodologies remain. Seeking to mitigate these issues that the RPA designer is expected to find in view of the current regulatory paradigm, a procedure is proposed to aid both in the extraction of design criteria from this complex landscape as well as in their integration to design methodologies. The scope and nature of the DECEX procedure presented here is not that of a design methodology per se, as mentioned beforehand. Rather, it is a procedure that accounts for the previously analysed issues in the RPA regulatory landscape in order to aid the designer to extract the applicable criteria that can be integrated into RPAS design methodologies. Therefore, the nature of DECEX is that of a procedure that aids in the comparison and extraction of certification criteria from a set of applicable regulations so as to integrate certification-based aspects into existing or novel design methodologies according to their scope, which can then employ these regulatory criteria to perform the sizing of aircraft, improving their certifiability. The nature of the procedure and its connection with design activities can be more clearly seen in Figure 5, which will be commented shortly.

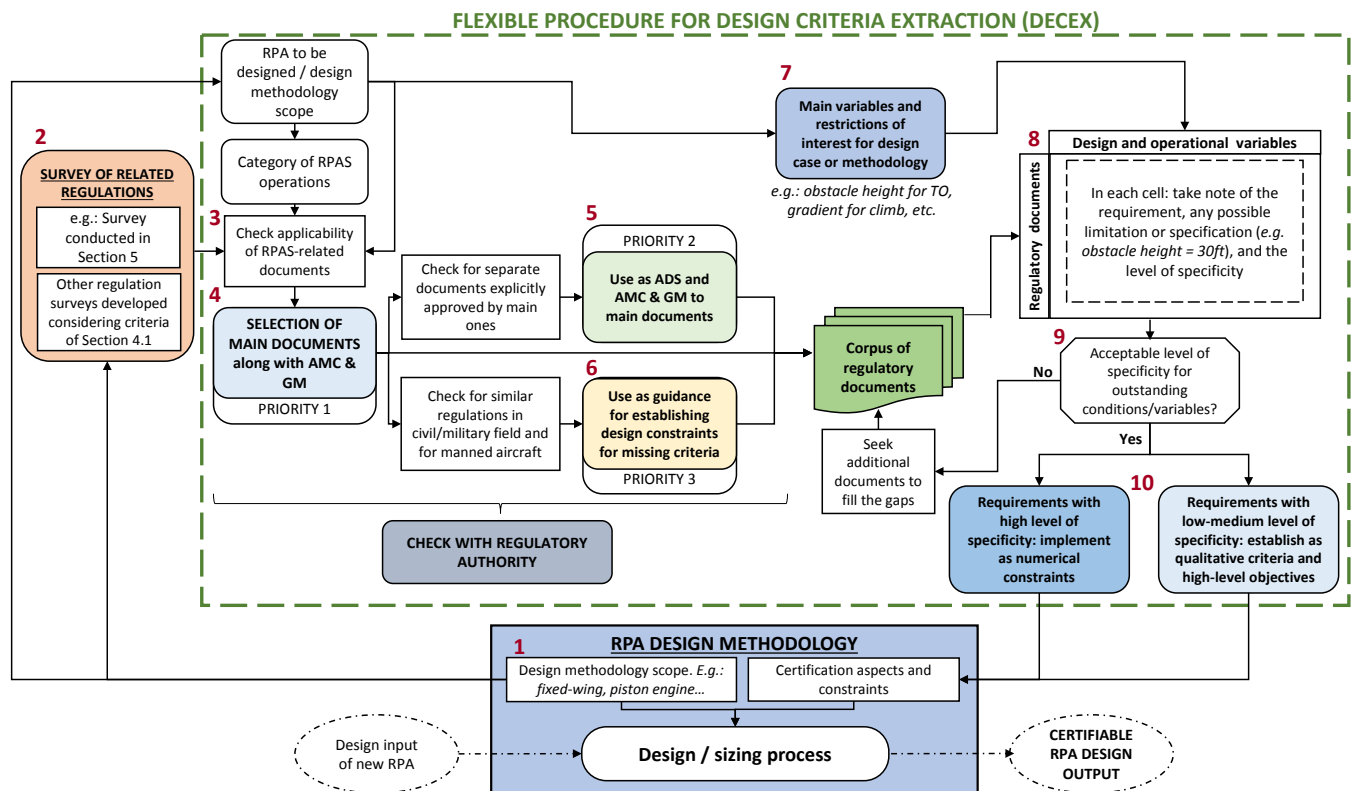


Figure 5. DECEX procedure workflow. This schema has assumed that a design methodology is being populated with airworthiness requirements; however, it can also be applied directly to a design process, accounting for its scope in step 1. The numbers indicate the main workflow highlights and are commented in the main text.

This process of transforming regulatory requirements into design criteria, which is the main focus of DECEX, was already commented in Section 2.1 as presenting a series of challenges, has already been tackled by previous works within the manned aviation paradigm [37,48], and automatic procedures for conducting this process have even been integrated in computational design environments and MDO frameworks [26,50]. However, no such work has been developed for the field of RPASs, accounting for their particularities and considering the current regulatory paradigm; thus, this constitutes one of the novel contributions of this research to the state-of-the-art. It should be highlighted that, in order to prepare for future possible changes in RPAS regulations (which are to be expected, as it was seen for instance in Section 3.3 that rulemaking is still ongoing in areas of AI and new materials, amongst others), and also for cases where different regulations than those analysed in this survey are considered, the procedure was developed so as to be flexible and adaptable. These characteristics of flexibility and adaptability are not only considered with respect to the regulations that can be integrated but also from the viewpoint of the design approach to be populated with airworthiness requirements, as different design stages and methodologies may place emphasis on certain disciplines (such as structures, or stability and control) and have different objectives with respect to the level of detail of the requirements to be integrated, as commented in Section 2.1. Therefore, DECEX has been conceived to be applicable to a variety of types of design methodologies in order to further improve its usability, which is a desirable characteristic for certification-driven procedures, as highlighted in previous work [37], and can be considered one of the main contributions of the methodology. This flexibility also lends itself to future work in extending the DECEX approach to further design stages, such as preliminary design or systems engineering approaches, which also employ the airworthiness criteria

extraction and integration perspective along with other safety modelling approaches, as commented beforehand.

6.2. DECEX Application Workflow

The main workflow of the DECEX procedure is illustrated in Figure 5 and is explained below, following the main steps highlighted in the schema:

1. As the objective is to integrate airworthiness aspects within a design methodology or process, the first stage, in accordance with the theoretical background commented in Section 2.1, is to establish the topical scope of the design activity. This mainly includes the design stage of interest and potential disciplines of consideration.
2. Then, a search is conducted to find the main applicable regulatory documents, accounting for the aforementioned scope. It should be noted that the survey conducted in Section 5 can constitute this step for design activities mainly related with the RPA airframe and dealing with early design stages. If the scope is different, other documents can be reviewed here for integration in the procedure. If the regulations change, this step can be modified to integrate the new applicable documents, in order to update the design approach according to the novel regulations by following the procedure from here.
3. At this point, and in view of the documents that have been reviewed, the ones applicable to the design methodology scope are selected for the next stages. This will also be dependent on the category of operations associated to the expected output design and the operational scenario. Tables 1 and 2 provided in this work can be consulted for this stage. Only those documents that are applicable continue on the next step.
4. In the next steps, the corpus of documents from which regulatory requirements will be extracted shall be selected, with different priority levels depending on the degree of correspondence to the scope of the design activity. The main idea behind this is to have, aside from the main ones, other documents to attend to in case the foremost ones have a low level of specificity such that it is preferred to seek clearer and quantitative requirements in others, and also to compare the restrictions set by the different ones. This process of selecting alternative regulatory documents to use when the main ones do not achieve the desired characteristics, or to complete their gaps with requirements from others, has been used in previous works [37,40] within the manned aviation paradigm to great effect. Firstly, those documents that are directly aligned in applicability (as in the results of stage 2 of the survey in Section 5.2) to the scope of the design activity, are labelled as “Main documents” along with their AMC and GM.
5. Having selected the main documents, and as the issue of low level of specificity is widespread in the field of RPAS regulations, as it was seen in the review, a second group of documents is selected. These will be those that are explicitly referred to in the main documents, which can serve as ADS or complimentary material to the main ones. For instance, CS-UAS explicitly recommends the use of CS-LUAS as ADS for cases where the latter is applicable within the CS-UAS paradigm. It has been noted in Section 5.1.6 that the correspondence between main documents and their ADS is seldom stated in a direct way in the field of RPASs, which complicates this step, and this is the reason for considering a third group of documents.
6. The third group of documents are potential documents that, even if not directly applicable to the design case, are other reputable references that may aid in filling the gaps from the first and second groups. For instance, if the RPA is being designed within the civil domain, military RPAS regulations can be considered here or even manned aviation documents applicable to a similar MTOM range. Even outside the design process, upon seeking approval by the Authority of the certification basis, these other documents can be useful to seek for alternative and more detailed proof of compliance approaches for those points in which the applicable main documents are

- not detailed. All of this generates a corpus of documents where the potential specificity gaps of the primary ones can be covered by the secondary and tertiary references.
7. For the next step, it is necessary to define with more detail the relevant variables related to design aspects that are related to the scope of the methodology: geometric, performance, structural, etc. Specific variables should be defined, such as climb gradient, stall speed, obstacle height for Take-Off, etc. This will serve for the next step, where specific requirements will be sought within the documents in relation to the design aspects of interest.
 8. Now, having both the corpus of documents and the regulatory documents of the three levels, the next step consists of examining each of those references for the applicable requirements for each design variable of interest. These are compiled in a table, as seen in Figure 5, in such a way that for each variable, the applicable aspects from each document are compiled. At this point, the specificity would be evaluated at requirement level, instead of for the whole document, which was anticipated in Section 4.1 when defining the level of specificity criterion. Furthermore, this allows a direct comparison of the similarity and differences in the content of the requirements, allowing to detect, for instance, heterogeneous limit values for certain restrictions.
 9. Once the table has been crafted, the level of specificity for each variable is evaluated for the group of documents. If any gaps are identified, for instance no high level of specificity requirement having been found for certain variable, more regulatory material can be sought to achieve the desired level. Once the results are satisfactory, the next step is undertaken.
 10. Considering the results from the table, these are translated to the design methodology in one of two forms. For those variables for which a high level of specificity has been found, the requirement can enter the design activity as a quantitative constraint in the relevant equations or in the optimisation process. Those variables for which this condition is not achieved are not discarded; rather, they can also be integrated as qualitative criteria. For instance, a requirement such as “the aeroplane should present desirable stability and control characteristics”, even if not providing a quantitative limit, can be taken into account so the designer can generate objective values attending to this criterion, or as a general design guideline.

6.3. Example Application Cases

In order to better illustrate the aforementioned procedure of the DECEX approach, two brief case studies are conducted in this subsection. These examples of application shall focus on the main scope of the research, which is on conceptual design aspects for RPA. In particular, it is proposed that a design methodology is sought to be derived, using regulations from international stakeholders, for two distinct categories of RPA: in the first case study, a civil tactical RPA, and in the second one, a High-Altitude Long Endurance (HALE) RPA. This allows to provide different perspectives on the regulations required for each of the categories and the effect of certification constraints in the design space, tying with the aspects of airworthiness influence in the design space discussed in Section 2.1.

In both cases, it is sought to investigate the development of a procedure to select the wing loading at Take-Off (W_{TO}/S_w) and the Take-Off Power-To-Weight ratio (P_{TO}/W_{TO}) for propeller aircraft or the Take-Off Thrust-to-Weight ratio (T_{TO}/W_{TO}) for turbofan and turbojet aircraft. This design approach shall be based on the use of a matching diagram that compares both variables. In this diagram, restrictions of certain point performances (such as cruise, climb, landing and stall) are represented to identify the feasible region that complies with all requirements. Some of the restrictions, such as those related to Take-Off, landing and cruise conditions, are mostly based on performance requirements—for instance, the maximum landing run distance is usually provided as an initial specification, whereas others such as climb and stall constraints can have a more direct influence of certification requirements. The matching diagram is a classical step of conceptual design methodologies, such as those of [19,20,25], and it has also been employed in recent research

for RPASs [33,58,104], albeit without considering certification aspects, which is the main gap that the DECEX procedure would seek to cover. As the design methodology itself is not the main scope of this work, rather the procedure to populate it with airworthiness aspects, the reader is referred to the previous references for a further description of the matching diagram design approach, where the mathematical basis and typical constraints are detailed.

6.3.1. Case Study 1: Tactical RPA

The first case study focuses on the initial sizing through a matching diagram of a civil fixed-wing single-piston engine RPAS within the tactical category. The expected MTOM range varies amongst references. Here, the classification of [21] is considered; therefore, the aircraft would have approximately between 150 and 500 kg of MTOM.

Starting with the DECEX workflow expounded in the previous section, the scope of the design approach has already been commented above, which is step 1. For step 2, the results from the survey conducted in this paper would be directly applicable due to the focus on international entities and the scope of the design approach being focused on the airframe itself. In step 3, it can be seen from the characteristics of the type of aircraft to be designed as well as its envisioned missions that the certified category would be the applicable one. Even if some operational scenarios could be conducted within the specific category, since it is envisioned that certain missions would require certification, the most conservative case is selected. Moving on to step 4, and being within the certified category, Tables 1 and 2 are used to seek the main documents. In this case, the main certification code available for civil RPASs of this type would be CS-UAS from JARUS, as the EASA paradigm is still under development. Thereby, this reference is selected as the main document. Then, for step 5, CS-UAS explicitly recommends the use of CS-LUAS as ADS. Since that document is applicable for below 750 kg, it can be used for this type of design methodology, so it is integrated as a priority 2 document. As no further specific documents are referenced by CS-UAS, step 6 is undertaken next. Here, the selection of documents is much more flexible as it is not required that it is explicitly stated by the main one. In order to complete the set of documents, it is decided to include, from the civil RPAS domain, SC-RPAS.SubpartB-01 on the side of EASA, and from the military RPAS domain, NATO AEP-4671, which is explicitly applicable to the MTOM range of interest. Finally, in order to compare the results with the manned aviation domain and to account for a reference from that field, which is much more established and mature than that of RPA, the legacy CS-VLA of EASA, which has a high level of specificity and also fits within the weight range, is also considered.

Moving on to step 7, the main variables of interest of the design methodology are defined. Attending to typical constraints for the matching diagram approach and, for this example, focusing particularly on certification-driven aspects, the following aspects shall be analysed: stall/minimum speed (V_{so}), climb gradient, rate of climb, positive limit load manoeuvring factor (n_{lim+}) and gust intensity at design cruising speed (U_c). All of these can be represented in the aforementioned matching diagram as restrictions in order to determine the feasible regions of (W_{TO}/S_w) and (P_{TO}/W_{TO}). Considering these variables, and now proceeding to examine the regulatory documents for requirements related to them, this would constitute step 8, which results in the information presented in Table 3 in which the level of specificity of each requirement has been indicated.

One of the first conclusions that can be deduced from the table is the necessity of evaluating the level of specificity at the requirement level and not only at the document-level. For instance, CS-LUAS, within Table 1, was quoted as having an overall high level of specificity. However, it can be seen that, depending on the requirement, a high level of specificity is not always found at the requirement level. Furthermore, one aspect that was mentioned in Section 5.2 but was not demonstrated there is that the level of specificity at the requirement level for similar aspects, but within different regulations, can be significantly different. This can be seen, for instance, for the climb gradient, where for CS-UAS and CS-LUAS the specificity is medium and no particular limitation is declared, but for the

NATO AEP-4671, a high level can be found. Through the DECEX approach, by checking the different variables of interest through various documents, the gaps can be filled with higher specificity requirements. For instance, in CS-UAS, for stall speed, the regulation states that “The minimum safe speed must be determined...”, but no specific threshold is established. The applicant, upon checking CS-VLA, could select that value as a design standard, and it can be proposed as a means to demonstrate compliance with the guidelines of CS-UAS by establishing a quantitative limit that is substantiated by another regulation. This can also provide aid when meeting the Authority to validate the certification basis and proof of compliance methods.

Table 3. Results summary of DECEX procedure application for the first case study, focused on a tactical RPA.

Code	Stall Speed (V_{so})	Climb Gradient γ	Rate of Climb (V_a)	Load Factor n_{lim+}	Gust Intensity U_c
CS-UAS	2110: M	2120: M	2120: M	N/A (refers to ADS)	N/A (refers to ADS)
CS-LUAS	N/A	53: M ^a	N/A	337: $n_{lim+} \geq 3.8$	333: 15.24 m/s
SC-RPAS. SubpartB-01	49: M	N/A	65: ≥ 2 m/s	N/A	N/A
AEP-4671	49: M	65: $\geq 5\%$	N/A	337: $n_{lim+} \geq 3.8$	333: ≥ 15.24 m/s
CS-VLA	49: $V_{so} \leq 83$ km/h	N/A	65: ≥ 2 m/s	337: $n_{lim+} \geq 3.8$	333: 15.24 m/s

N/A: not available, M: Medium specificity. For High level of specificity, the limit values are declared. ^a: Limit values to be determined in accordance with the Authority, but none stated directly in the regulation.

As the table has resulted in a high level of specificity being obtained for each requirement through the use of the different regulations, in step 9 it can be assumed that the objectives have been attained; therefore, when moving on to step 10, all of them can be integrated as quantitative restrictions in the design methodology. At this point, it is sought to demonstrate the relevance of the certification constraints, and thus of the DECEX procedure, in the determination of the feasible design space within the scope of this design case, when compared with the same case study but without accounting for these airworthiness aspects. On the one hand, some restrictions that are mainly focused on performance requirements instead of certification requirements are defined. These shall be Take-Off, landing and cruise restrictions. On the other hand, the restrictions related with the relevant airworthiness variables, with the limit values provided by the DECEX applications, are also represented. These shall be climb, gust and stall restrictions. A manoeuvring restriction has not been plotted, as tactical RPA typically develop surveillance and reconnaissance missions where no high-performance manoeuvres are expected to be performed. Again, the mathematical procedure as well as typical values can be found in the previously cited references. The resulting matching diagram is represented in Figure 6.

As it can be seen from the results of the case study, and coinciding with the discussion on the influence of certification constraints in the design space of Section 2.1, there is a noteworthy reduction in the design space when seeking to address the airworthiness restrictions extracted with DECEX, particularly through the climb and gust constraints. The great effect of the climb requirements can be explained through the use of a fixed landing gear of most tactical RPASs, which results in high drag, thus greatly penalising climb performance. Some of these restrictions were taken from codes that are not within the main level of priority of the DECEX corpus of documents—for instance, CS-VLA, which is a code for manned aviation. However, by applying these restrictions as ADS, the designer can have a greater assurance in the certifiability of the system, rather than if an arbitrary value for the climb gradient, for instance, is decided by the applicant in view

of the low level of specificity of the main applicable regulations (CS-UAS and CS-LUAS), which do not set a specific limitation. Constraining the design to the region considering airworthiness constraints leaves less design flexibility and might result in a more costly design (for instance, due to the higher power loading required); however, it provides the advantages of certifiability and safety, which are the main topics covered in this research, and the main advantages provided by the use of DECEX in the development of design methods, as demonstrated here.

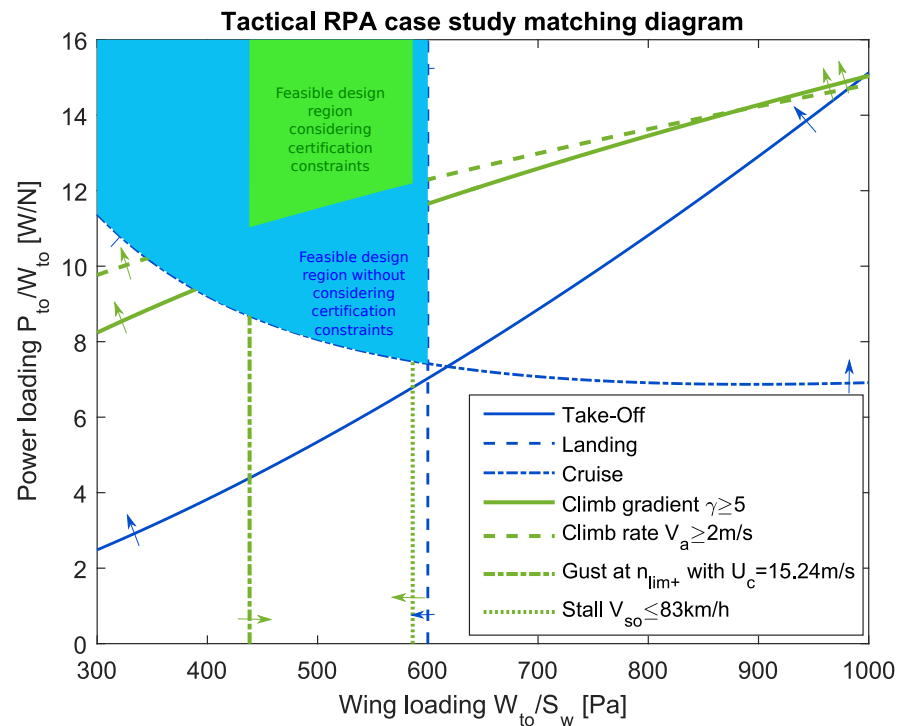


Figure 6. Matching diagram for the first case study, considering the restrictions mentioned in the main text. Constraints mainly related with performance initial specifications are in blue, and those related to certification aspects are in green. The arrows indicate where the feasible design region lies for each of the constraints. The feasible design regions with and without considering certification constraints are identified.

6.3.2. Case Study 2: HALE RPA

The second case study focuses on the initial sizing through a matching diagram of a fixed-wing single turbofan engine RPAS within the HALE category. These aircraft usually operate at very high altitudes over 50,000 ft (12,000 m) [21]. A typical example is the Global Hawk, with an MTOM of around 13,000 kg, resulting in very different characteristics from those of the previous case study.

As the workflow of the DECEX methodology has already been followed in more detail in the first case study, in the current one, these explanations are omitted in order to directly discuss the results. Firstly, the table resulting from step 8 in the workflow is provided in Table 4. It should be noted that, in this case, due to the aircraft's characteristics, it is only compatible with the applicability scope of very few regulations. It should be noted that the Part/CS-25 regulations have been considered here, which is according to the manned aviation regulation equivalency provided in the EASA Policy E.Y013-01 for typical HALE RPASs, including the Global Hawk [6]. However, in these cases, a certain tailoring of the code would be required to adapt it to the characteristics of the RPAS, according to the aforementioned Policy. For instance, in this case, the original Part/CS-25 requires a minimum of two engines, so this aspect would have to be adapted to the RPA of study, which has only one engine but—according to the impact energy criterion of the Policy—

would be certified with Part/CS-25. In any case, the primary regulation here would be the NATO AEP-4671.

Table 4. Results summary of DECEX procedure application for the second case study, focused on a HALE RPA.

Code	Climb Gradient γ (LG Retracted)	Climb Gradient γ (LG Extended)	Load Factor n_{lim+}	Gust Intensity U_c
AEP-4671	65: $\geq 5\%$	65: $\geq 2.5\%$	337: $n_{lim+} \geq 2.72^a$	333: $\geq 10.29 \text{ m/s}^b$
Part/CS-25	See note ^c	119: $\geq 3.2\%^d$	337: $n_{lim+} \geq 2.72^a$	See note ^e

^a: As obtained from the mathematical expression given in the regulations for an MTOM of 13,000 kg. ^b: As obtained from the gust intensity values accounting for a strategic surveillance mission altitude of 12,000 m. ^c: The conditions for LG retracted provided in different paragraphs of the regulation pertaining to the flight path and climb conditions depend on the number of engines, and no explicit option is provided for one engine. Nevertheless, they are all much less restrictive than the one provided by AEP-4671. ^d: The only condition provided by the regulation for All Engines Operating and LG extended is that of balked landing, which has been considered here. ^e: Not applicable, as the gust envelope is not present in amendments to the regulations after the year 2000, and the method for complying with gust requirements is not directly comparable to that of the gust envelope, as provided in AEP-4671, which is the main code in this application of DECEX.

First of all, it should be noted that in this example, contrary to the previous case study, there are no issues of low level of specificity in the requirements, mainly due to both regulations being very detailed codes for aircraft with a comparatively high risk, which tend to have more specificity. Some of the conditions evaluated in the previous case study, such as stall speed and rate of climb, were not found in the codes of the current application case, thereby no airworthiness restrictions are considered for them here. Another difference of this case is that here some of the regulatory requirements when contrasting the different regulations present differing limit values, particularly the climb gradient with LG extended. These shall be compared in the matching diagram, which is presented in Figure 7.

In this case study, it is seen that the influence of airworthiness restrictions in the design space, albeit present, is not as noteworthy as in the tactical RPA case, particularly since the design point is usually selected at high wing loadings and low thrust-to-weight ratios [19,25]. This highlights that the relative influence of certification constraints in the design space can be very dependent on the scope of the design method, which not only includes the type of aircraft but also, through the application of DECEX, the considered regulations. This underlines the relevance of making the DECEX procedure flexible and adaptable to different scopes of design methodologies, as it can be seen that the influence of certification aspects can differ depending on the case. For this application example, and going back to the aforementioned discrepancies in the values of the LG down climb restrictions, it is seen that the one provided by Part/CS-25 is more restrictive than the others. This can be explained not only by the gradient being more demanding than the one provided by NATO AEP for LG down but also since it is a balked landing condition; thus, full thrust is not available from the start, which has been accounted for in the calculations. In any case, as these are not the primary regulations considered within the DECEX workflow, and the NATO AEP code already provides a high level of specificity, this restriction could be ignored, depending on the certification prospects that are sought by the designer. Nevertheless, it still provides a relevant case of comparison between the manned and RPA airworthiness requirements and how they compare to each other.

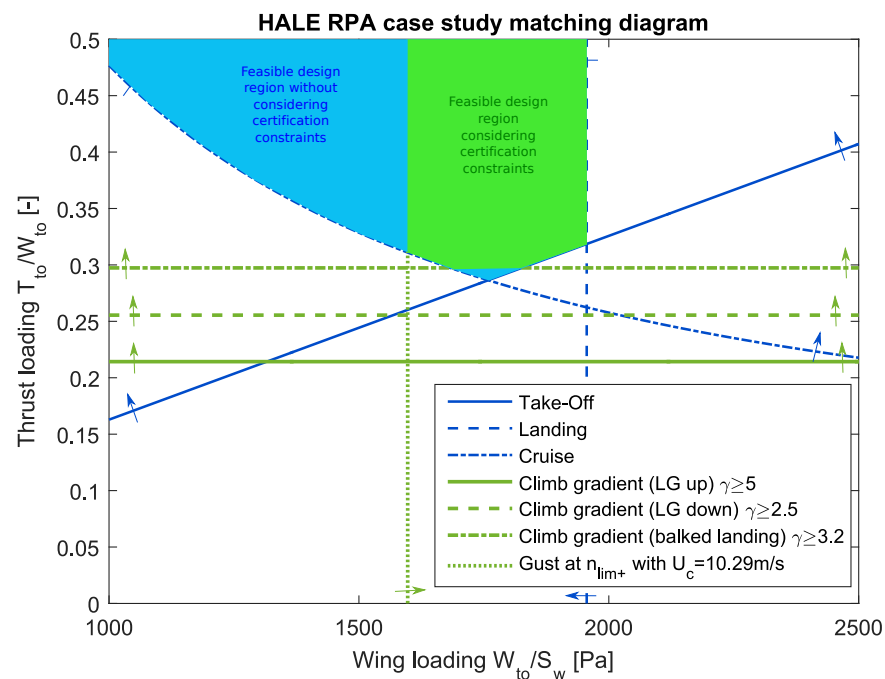


Figure 7. Matching diagram for the second case study, considering the restrictions mentioned in the main text. Constraints mainly related with performance initial specifications are in blue, and those related to certification aspects are in green. The arrows indicate where the feasible design region lies for each of the constraints. The feasible design regions with and without considering certification constraints are identified.

7. Conclusions

The research presented in this paper has analysed the current international landscape of RPAS initial airworthiness regulations from the perspectives of airworthiness and of the integration of these requirements in design methodologies and processes. In view of the gap detected in the lack of integration of airworthiness aspects within design methodologies for RPA, and considering the main challenges to accomplish this as seen in the findings of the survey, the DECEX procedure has been developed as a tool to aid the designer in extracting, comparing and implementing certification constraints in design methodologies for an RPAS according to their scope.

The most noteworthy contributions of the research are the following:

- The definition of the criteria proposed in this paper in Section 4.1 to scrutinise the regulations, which consider both airworthiness and design–integration aspects.
- The up-to-date survey, considering both design and airworthiness characteristics, which has been conducted on the international paradigm of RPAS initial airworthiness, having analysed some documents that are particularly recent and, thus, were not considered in previous works.
- The synthesis of DECEX: a flexible, adaptable and systematic approach for the integration of airworthiness aspects in design, which is broadly applicable to design approaches with different scopes, allowing to populate them with relevant certification considerations.

With respect to the results of the survey, one of the main findings is that there is a significant heterogeneity between regulations for similar aircraft and operational categories across different international entities, as seen in Section 5, which can lead to difficulties towards designing RPASs for global market access. Furthermore, RPA regulations generally present a lower level of specificity compared to traditional manned ones. On the one hand, this can be regarded as negative, resulting in a lower certifiability assurance and streamlining when designing and certifying RPA. On the other hand, it can be regarded that the low level of specificity provides benefits in avoiding highly prescriptive requirements

and procedures that could hinder expansion and innovation within the field of RPASs. The possible balanced approach proposed here that could satisfy both viewpoints might be achieved through the concept of ADS proposed by JARUS: the main, legally applicable regulations would be performance-based and with lower specificity but having a clear and unambiguous correspondence of each requirement with publicly available consensus standards or AMC and GM that can raise the level of specificity and, being approved by the Authority, provide certifiability assurance following more streamlined processes that are easier for the designer. In order to accomplish this, it would be needed that (a) more ADS be developed to cover the design variety of RPASs with higher specificity alternatives and (b) that an unambiguous correspondence between main regulation requirements (such as those of CS-UAS) with the ADS is formalised, in a similar way to the new Part/CS-23 in the field of manned aviation, so the designer can know with certainty which procedures are accepted to demonstrate compliance with each requirement.

Regarding the DECEX procedure, the foremost benefits that can be leveraged from its use can be summarised as follows:

- The procedure provides a streamlined way to compare the similarities and differences amongst regulatory requirements from different regulations within the scope of the design method, as it was demonstrated particularly in the second case study when contrasting conditions and values for climb gradient were found.
- It allows users to solve specificity gaps in main regulations by evaluating other, more detailed regulations from different entities and aviation paradigms. This was demonstrated particularly in case study 1, where a limit value for rate of climb was found in SC-RPAS.SubpartB-01 and CS-VLA, whereas the other regulations provided no explicit restrictions.
- Its flexibility allows to populate design methodologies that have different scopes with regulatory requirements from diverse regulations. This was seen through the two case studies, each for a different category of RPA (tactical and HALE), thus resulting in distinct regulations to be considered.
- It enables contrasting the effect of airworthiness restrictions on the design space when compared to the case of only considering initial specification requirements. In both case studies, the design space is reduced when considering certifiability, albeit the impact of airworthiness aspects was different in each of them.
- The characteristics of flexibility and adaptability of DECEX allow it to be applied to a variety of regulatory landscapes and design methodology scopes, which is a necessity in the field of RPASs due to the aforementioned heterogeneity in regulations, the fact that rulemaking is still in progress and regulations are to be updated, and the novel design concepts that are usually developed in this area.

With respect to future work, albeit the review has focused on the main international, EU and USA regulations of RPASs, the market of RPASs is expanding worldwide. As such, the tools and procedures proposed in this research could be used for future analyses in other contexts, such as the thriving RPAS markets of Asia or Africa, or even to compare different national regulations as in previous works, but using the novel criteria for consideration of design integration aspects. The authors outline that the criteria for review employed here and the results can serve as a basis for future comparative work between other regulatory documents, which can further highlight the challenges in this area. Finally, the flexibility of the DECEX procedure could lend itself to further application, not only in different regulatory paradigms but also for design approaches with differing scope. For instance, for the preliminary design stage, a more detailed review of structural considerations in the international paradigm could be evaluated in order to integrate them in an optimisation process. This application case could leverage the CS-LUAS Appendix for simplified structural design criteria, amongst other options. Another possible future application, which could be more directed towards further design phases, could be for a systems engineering approach once the main airframe has been sized. Other documents, more specific to systems engineering and safety analysis, could be integrated and compared

through the procedure. The authors expect that this procedure can be employed in future work along with its capability to be coupled with the results of alternative surveys in order to further explore the joint airworthiness and design challenges in the area of RPASs.

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Abbreviations

The following abbreviations are used in this manuscript:

AAM	Advanced Air Mobility
AC	Advisory Circular
ADS	Airworthiness Design Standard
AGL	Above Ground Level
AI	Artificial Intelligence
AMC	Acceptable Means of Compliance
ASTM	American Society for Testing and Materials
ATC	Air Traffic Control
ATM	Air Traffic Management
CBO	Community-Based Organization
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
COA	Certificate of Authorization
CONOPS	Concept of Operations
CS	Certification Specification
DAA	Detect And Avoid
DECEX	DEsign Criteria EXtraction
DR	Delegated Regulation
EASA	European Union Aviation Safety Agency
EU	European Union
EUROCAE	European Organisation for Civil Aviation Equipment
FAA	Federal Aviation Administration
FEM	Finite Element Methods
GM	Guidance Material
HALE	High-Altitude Long Endurance
ICAO	International Civil Aviation Organization
IR	Implementing Regulation

ISO	International Organization for Standardization
JAA	Joint Aviation Authorities
JARUS	Joint Authorities for Rulemaking of Unmanned Systems
LRD	Level of Regulatory Document
LG	Landing Gear
LUC	Light UAS Operator Certificate
MALE	Medium-Altitude Long Endurance
MDO	Multidisciplinary Design Optimisation
MTOM	Maximum Take-Off Mass
NAA	National Aviation Authority
NPA	Notice of Proposed Amendment
NATO	North Atlantic Treaty Organization
OML	Outer-Mold Line
RA	Resolution Advisories
RPA	Remotely Piloted Aircraft
RPAS	Remotely Piloted Aircraft System
RTA	Run-Time Assurance
SARP	Standard and Recommended Practice
SC	Special Condition
SORA	Specific Operations Risk Assessment
TCA	Time of Closest Approach
ToR	Terms of Reference
UAS	Unmanned Aircraft Systems
UAV	Unmanned Air Vehicle
USA	United States of America
USC	United States Code
VLA	Very Light Aircraft

Appendix A. Table of Overview of Literature References from RPASs' Four Main Dimensions towards Safe Integration in the Aviation Paradigm

As commented in the introduction, four key dimensions were identified in previous works towards the safe integration of RPASs within the current aviation framework: (1) airworthiness certification, (2) ATM integration, (3) interaction with other aircraft and (4) flight crew certification. At that point in the introduction, some example works dealing with each of these dimensions were referenced. Albeit the research presented in this article is mainly focused in the first dimension, and more references pertaining to it are analysed in further detail within the literature review section, a brief overview of the cited references pertaining to those four dimensions in the introduction is provided here to further aid in contextualising each of them and to provide further information in the usual scopes and characteristics of research conducted in each of them.

Table A1. Overview of main characteristics of selected works within the state-of-the-art pertaining to the four key dimensions commented in the main text. References have been organised according, firstly, to topical dimension, and secondly, with respect to the year of publication.

Reference	Year	Topical Dimensions	Scope	Analysed Characteristics and Parameters	Limitations
Dalamagkidis et al. [7]	2008	- Airworthiness certification	International RPAS regulations landscape and RPAS rulemaking characteristics and perspectives	Evaluation of manned aviation airworthiness aspects and discussion of possible applicability and adaptations for rulemaking of RPASs. Parameters include RPAS mass and flight altitude, expected fatalities in case of accident, etc.	Scope mainly focused on prospective regulatory aspects, as the RPAS regulatory paradigm was incipient by that time
Cuerno-Rejado, Martínez-Val [6]	2011	- Airworthiness certification	Analysis of international initial airworthiness regulatory landscape and evaluation of applicability in existing RPA	Evaluation of airworthiness code applicability through a case study focused on load requirements. Parameters include impact kinetic energy, lethal crash area, gust load factor, etc.	Case study scope limited to manned aircraft code tailoring to RPASs according to EASA Policy E.Y013-01
Cook [9]	2018	- Airworthiness certification	Identification and discussion of main trends in airworthiness regulations of RPASs	Evaluation of aspects related to safety targets, influence of CONOPS in regulations and implementation of aspects such as DAA and AI. Parameters include safety probability objectives, RPA MTOM, etc.	Scope focused on the five overall trends of airworthiness regulations identified in the paper
Stöcker et al. [10]	2018	- Airworthiness certification - Flight crew certification	Global overview of worldwide national RPAS regulations, including evaluation and comparison of pilot qualifications	Analysis of statements and requirements on technical, operational and pilot licensing requirements from different regulations. Parameters include year of regulation release, regulation weight limits, requirements of competency and/or licensing depending on aircraft mass and operation characteristics, etc.	Regulatory information limited to those provided by secondary regulation databases. Consideration of political and social acceptance aspects outside the scope of the paper

Table A1. Cont.

Reference	Year	Topical Dimensions	Scope	Analysed Characteristics and Parameters	Limitations
Massuti and Tomasello [8]	2018	<ul style="list-style-type: none"> - Airworthiness certification - Flight crew certification 	International airworthiness and operations regulations for RPASs. Legal basis for personnel qualification, pilot requirements and operator responsibility	RPAS classifications towards regulatory applicability. Personnel requirements and considerations in different paradigms and operation categories. Parameters include safety probability objectives, RPA MTOM, pilot age, required tests, medical requirements, etc.	Scope mainly covers ICAO, EASA and FAA paradigms, with a few specific countries such as Italy. Military regulations outside the scope of the work
Karyotakis et al. [3]	2021	<ul style="list-style-type: none"> - ATM integration - Airworthiness certification 	Safety assessment and assurance of advanced and specific operations of RPASs, considering ATM aspects	Influences of ATC, pilot and air vehicle in safety analysis results. Two types of operations: transport of people and of goods. Parameters include RPAS accident rate, ground risk, RPA weight, SORA SAIL level, etc.	Scope focused on specific category of operations. Open and certified categories fall outside of the scope of the research
Ferreria et al. [11]	2018	<ul style="list-style-type: none"> - ATM integration - Interaction with other aircraft 	Risk analysis of integration of RPASs in non-segregated airspace, considering ATM, C2 link and security aspects amongst others	Quantitative risk analysis of two hazardous scenarios: mid-air collision and ground collision. Parameters include C2 link reliability, initial and residual risk of hazards, conflict probability, etc.	Model limited to remotely piloted aircraft, without conventional aircraft in the airspace. Design aspects and reliability of other systems from C2 link outside the scope of the paper
Pérez-Castán et al. [5]	2020	<ul style="list-style-type: none"> - ATM integration - Interaction with other aircraft 	Challenges of RPAS integration in non-segregated airspace attending to traffic volume and conflict simulations	Analysis of air conflicts in an example airspace zone attending to the number of RPA. Parameters include number of conflicts, conflict duration, No. of RPASs, etc.	Model limited to one flight level with no climb or descent manoeuvres
Stroeve et al. [12]	2023	<ul style="list-style-type: none"> - ATM integration - Interaction with other aircraft 	ACAS Xu simulations of RPASs evaluating loss of separation considering response of remote pilot	Definition of model of remote pilot considering stochastic variations in pilot and aircraft aspects. Parameters include remote pilot response delay, strength, mode, stochastic models of onboard sensors and communication systems, etc., with output metrics such as TCA and RA percentages	Simplified encounter geometry only two aircraft, straight original trajectories with short duration when compared to ACAS validation studies

Table A1. Cont.

Reference	Year	Topical Dimensions	Scope	Analysed Characteristics and Parameters	Limitations
Peukert et al. [13]	2024	- Interaction with other aircraft	Development of traffic display system for RPAS pilots towards improving traffic avoidance	Evaluation of existing traffic display models and responses of RPAS pilots to novel questionnaire. Parameters include display units, conflict depiction, symbols for display elements, etc.	No experimental comparison of implemented display effectiveness compared to previous alternatives
Janke and de Haag [14]	2022	- Flight crew certification	Survey of status quo of adoption of new EU regulations within Member States in terms of operators and registration	Analysis of number of Remote Pilot licences within the current framework of the EU. Parameters include no. of A1/A3 licences per country, no. of LUC per country, no. of operators per country, etc.	Missing data from certain Authorities that did not respond to the survey. Data on individual aircraft unavailable
Maier et al. [15]	2024	- Flight crew certification	Proposal of new RPAS pilot training plan for RPA of high MTOM	Crew requirements and training plan for rotary wing RPASs of high MTOM. Parameters include required flight hours, licence test manoeuvres, training requirements and periodicity, etc.	Scope limited to the development of a pilot training plan for a specific rotary wing RPASs

Appendix B. Table of Literature Review Evaluation of Surveys and Analyses on RPAS Regulations

In Section 3.1, a literature review analysis of works that have conducted regulatory surveys within the field of RPAS airworthiness was performed. Here, a table is provided that presents an overview on the main characteristics of these previous research works, which supports the text found in the main body of the article that discusses the current gaps within the state-of-the-art as well as the role of the current research in covering some of those points.

Table A2. State-of-the-art overview of surveys and analyses on RPAS regulations, and comparison with the survey conducted in this paper.

Reference	Year	Regulatory Focus	Topical Focus	Analysed Characteristics and Parameters
Dalamagkidis et al. [7]	2008	Main international RPAS framework and certain National regulations	Rulemaking activities, airworthiness certificates and RPAS classifications	Possible classifications of RPASs towards certification and potential regulatory road map. Parameters include RPAS mass and flight altitude, minimum time between ground impact accidents, etc.
Cuerno-Rejado, Martínez-Val [6]	2011	International civil and military regulations: EASA, FAA and others	Airworthiness and design: focus on impact energy and load requirements	Practical evaluation of applicability of manned aircraft codes using impact energy criterion. Parameters include impact kinetic energy, gust load factor, structural weight, etc.
Valavanis, Vachtsevanos [17]	2015	EU National RPAS regulations	Technical and operational requirements	Comparison of restrictions to evaluate harmonisation challenges and perspectives. Parameters include MTOW limitations and LOS conditions per regulation, number of operators and manufacturers per region, etc.
Stöcker et al. [10]	2017	Worldwide National RPAS regulations	Technical, operational and administrative requirements	Applicability and main limitations of regulations within selected topics. Parameters include MTOW limitations, distance to aerodromes, distance to people, LOS conditions, etc.
Masutti and Tomasello [8]	2018	International civil regulations, mainly ICAO, EASA and FAA	Varied topics: airworthiness, security, personnel licensing, etc.	Air Law perspective. Scope of regulations, main topics, applicability, etc. Parameters include MTOW limitations, mission radius, probability of failure, etc.
Bassi [16]	2019	EU/EASA civil framework	Privacy, cybersecurity and remote identification	Air Law perspective. Competences of the organisations and open issues. Parameters include regulations and articles related with security, liability, privacy, remote identification, etc.

Table A2. Cont.

Reference	Year	Regulatory Focus	Topical Focus	Analysed Characteristics and Parameters
Srivastava et al. [18]	2020	Worldwide National RPAS regulations	Operations, registration, licensing, data protection and privacy	Operational restrictions and requirements with respect to the analysed topics. Parameters include MTOM limitations, maximum height, lateral distance, etc.
Xu et al. [46]	2020	Worldwide National RPAS regulations	Operations, airspace design and ATM for low altitude operations	Operational restrictions, ATM technologies and airspace architectures. Parameters include maximum flight height, geo-fencing volume characteristics, etc.
Karyotakis et al. [3]	2021	EU and FAA civil paradigms for advanced operations	Airspace integration and ATM for RPASs in relation to specific operations	Comparison of the requirements for advanced/specific operations in both frameworks. Parameters include RPAS mass and height, maximum dimension of RPA, impact kinetic energy, etc.
Alamouri et al. [47]	2021	EU/EASA civil regulations	Rulemaking activities, technical properties, operational prospects and risk assessment approach	Operational category applicability and application of the SORA methodology. Impact of regulations on RPAS use and economic potential. Parameters include RPAS mass and height, maximum dimension of RPA, ground risk class, etc.
Janke, de Haag [14]	2022	EU/EASA civil framework	Personnel licensing and RPAS registration	Requirements towards personnel licensing and registration marks for operation categories. Parameters include EASA open subcategories, no. of operators for specific operations, etc.
This research	2024	International civil and military regulations: ICAO, EASA, FAA, JARUS, NATO	Airworthiness aspects related to aircraft (conceptual) design	Airworthiness aspects and design considerations affecting the potential integration and influence of requirements in design methods. Parameters include document regulatory tier, topical focus of regulations, level of specificity *, scope, RPA MTOM, etc.

* Some of these characteristics have been devised within this research in order to evaluate relevant aspects of the regulatory documents related with their integration in design methodologies. These dimensions are elaborated and explained in Section 4.1.

Appendix C. Table of Literature Review Evaluation of Previous Research on Airworthiness and Design Integration

In Section 3.2, several works related to the integration of airworthiness aspects in aircraft design activities were analysed. The main conclusion resulting from this overview was that, until now, few RPAS design methods have been developed considering airworthiness aspects. The following table summarises the main characteristics from the works cited in the aforementioned section, highlighting the design and airworthiness integration aspects where applicable.

Table A3. Overview of main characteristics of selected works within the state-of-the-art pertaining to airworthiness and design aspects, with a main focus on the integration of airworthiness aspects within aircraft design activities. The column “Design Stage Focus” evaluates references attending to the aircraft design stage taxonomy expounded in Section 2.1. References are organised attending to citation order within the main text.

Reference	Aircraft Type	Design Stage Focus	Research Scope	Airworthiness Regulations and Integration in Design Activities
Torenbeek [19]	Manned	Conceptual and preliminary: rapid, low-fidelity methods	Full concept synthesis and initial sizing of subsonic aircraft. Encompassing design approach covering performance, aerodynamics, structures, stability and control, powerplant aspects, etc.	Integration of FAA and CAA regulations in many aspects and sizing procedures. For instance, requirements for performance in matching diagram, structural requirements in manoeuvring envelope, stability and control requirements for tail sizing, etc.
Roskam [25]	Manned	Conceptual and preliminary: rapid, low-fidelity methods	Full concept synthesis and initial sizing of civil and military aircraft. Encompassing design approach covering performance, aerodynamics, structures, stability and control, powerplant aspects, etc.	Integration of FAA regulations and certain military standards in many aspects and sizing procedures. For instance, requirements for performance in marching diagram, cabin layout, stability and control requirements for tail sizing, etc.
Stinton [36]	Manned	Conceptual and preliminary: rapid, low-fidelity methods	Full concept synthesis and initial sizing of aircraft, with a focus on light aircraft. Encompassing design approach covering performance, aerodynamics, structures, stability and control, powerplant aspects, etc.	Various considerations: FAA, JAA and CAA certification categories and applicability ranges; analysis of main paragraphs regarding flying qualities and performance; evaluation of impact in design areas and relation with relevant variables; limits for pilot effort when sizing control surfaces, etc.
Tyan et al. [37]	Manned	Conceptual and preliminary: rapid methods and optimisation	Initial OML layout sizing and optimisation of general aviation aircraft attending to regulatory requirements	FAR 23 and KAS 23 regulations. Dedicated procedure for elaboration of certification database and requirement extraction. Consideration of variable constraints attending to regulatory restrictions within optimisation procedure and final compliance check
Nöding and Bertsch [48]	Manned	Preliminary: simulation framework with multiple disciplinary modules	Evaluation of transport aircraft noise in relation to take-off and approach trajectories and design parameters, such as fuselage geometry and MTOM. Sensitivity studies evaluating contributions of engines and airframe	Aircraft noise metrics as well as take-off and approach trajectories according to ICAO Annex 16 regulations are evaluated for the design concepts analysed with the simulation framework

Table A3. Cont.

Reference	Aircraft Type	Design Stage Focus	Research Scope	Airworthiness Regulations and Integration in Design Activities
Spencer [49]	Manned	Preliminary: systems architecture, engineering and safety	Evaluation of current airworthiness codes limitations towards certifying hydrogen-fuelled aeroplanes, considering the main aspects of hydrogen power systems	Analysis of current CS-25 certification requirements affecting the propulsion system (crashworthiness, explosion prevention, etc.) and discussion on gaps in their application to the certification basis and design of hydrogen aeroplanes
Schmollgruber et al. [26]	Manned	Conceptual and Preliminary: MDO framework	Development of a dedicated certification module within the design package FAST. The module allows to manage the certification constraints established by the regulations and their integration in an MDO process	The certification module allows a formal representation of the relationships between CS-25 regulatory requirements and key design variables in UML format, standardising their representation and integration into design MDO workflows as optimisation constraints
Xie et al. [50]	Manned	Preliminary: MDO framework	Proposal of a certification-driven environment for the integration of certification constraints in multi-objective airframe optimisations. Case study of horizontal tail refinement attending to flight mechanics requirements	The flight characteristics module checks, for the input aircraft geometry, a series of characteristics extracted from the regulations, mainly requirements from CS 25 Subpart B and Subpart C to check both flight mechanics and structural compliance
Travascio et al. [40]	Manned	Preliminary: systems engineering	Once a system architecture for a disruptive concept such as a hybrid propulsion system) has been defined, a procedure is proposed to identify certification basis gaps from existing regulations in order to propose modifications or introduction of new requirements through a safety assessment process	Regulations such as CS-25, CS-E and CS-P are analysed for potential requirements considering the system architecture of study. The gaps in the requirements are covered by generating a proposal of means of compliance that are obtained through a safety assessment of the system design
Jeyaraj et al. [51]	Manned	Preliminary: systems engineering and MDO	Development of a methodology to introduce safety assessment earlier in the design continuum, focusing on system architecture and safety analysis, towards seamless integration in MDO approaches	Regulatory requirements for systems, such as those of Part 23 or Part 25 (as stated in an application example), are included through a safety filtering method that analyses proposed architectures and keeps those that comply with the requirements
Insley and Turkoglu [52]	Manned	Not applicable	Analysis of commercial air transport accidents and serious incidents related to maintenance, supplemented with opinions gathered from experts, in order to identify main factors and high-risk areas	No regulatory requirement integration in design methodologies
Habib and Turkoglu [53]	Manned	Not applicable	Study of general and commercial aviation accidents and serious incidents in the context of Nigeria, complemented with a survey from subject matter experts, to identify root causes and main areas of concern	No regulatory requirement integration in design methodologies

Table A3. Cont.

Reference	Aircraft Type	Design Stage Focus	Research Scope	Airworthiness Regulations and Integration in Design Activities
Rötger et al. [54]	Manned	Not applicable	Review of current regulations applicable to supersonic transport aircraft and current rulemaking activities. Discussion on prospective regulatory aspects to be covered in future rules	No regulatory requirement integration in design methodologies
Kusmieriek et al. [55]	Manned	Not applicable	Survey of opportunities and challenges of hybrid propulsion systems considering the demands of emission regulations and objectives. Evaluation of different system architectures and trends of aircraft equipped with these powertrains	No regulatory requirement integration in design methodologies
Sóbester et al. [24]	RPASs	Conceptual and preliminary	Development of a geometry service to produce and modify both the OML and the structural layout of RPA. Evaluation of weight, wing loading and power loading trends for RPA	No regulatory requirement integration in design methodologies
Gundlach [21]	RPASs	Conceptual and preliminary: rapid, low-fidelity methods	Full concept synthesis and initial sizing of RPASs. Covers many aspects of RPAS design, not only including those of the air vehicle: aerodynamics, performance, structures, powerplant aspects, payload and communications, command and control, etc.	As the regulatory framework of RPASs was still incipient, the regulatory considerations considered in the method have mainly been adapted from manned aircraft regulations
Keane et al. [33]	RPASs	Conceptual, preliminary and detailed design	Full coverage of the different stages of RPAS design, mainly focused on small RPA. Conceptual design methods are mainly focused on rapid approaches such as the matching diagram, preliminary methods usually employ optimisation, and detailed design aspects are mainly focused on final geometry definition for manufacturing	The relevance of integrating airworthiness aspects in RPA design is supported, and the main structure and contents of NATO Standard AEP-83 are explained, recommending checking various typical design constraints towards certification
Gómez-Rodríguez et al. [22]	RPASs	Conceptual: statistical approach	Evaluation of main design trends of H-tail RPA by employing factor analysis on an RPA database. Development of a rapid sizing method based on the results of the factor analysis approach	No regulatory requirement integration in design methodologies
Gómez-Rodríguez et al. [56]	RPASs	Conceptual: statistical approach	Analysis of a database of RPASs, evaluating general design trends with respect to layout and powerplant, and development of a rapid sizing method for H-tail RPA based on correlations obtained from the database	Thresholds for MTOM towards design trend analysis established in part attending to regulations at the time of research; however, some of these are no longer applicable
Mitridis et al. [57]	RPASs	Conceptual: statistical approach	Analysis of a database of RPAS attending to the NATO classification, analysing key categorisation aspects and design parameters through correlations, dot plots and box plots	No regulatory requirement integration in design methodologies

Table A3. Cont.

Reference	Aircraft Type	Design Stage Focus	Research Scope	Airworthiness Regulations and Integration in Design Activities
Champasak et al. [35]	RPASs	Preliminary: multiobjective optimisation	Development of a metaheuristic-based optimisation framework for RPA design incorporating reliability aspects. Four case applications are conducted based on pre-defined value ranges for optimisation variables	No regulatory requirement for integration in design methodologies
Tyan et al. [58]	RPASs	Conceptual and preliminary: rapid, low-fidelity methods and optimisation	Initial sizing of a hybrid fixed-wing VTOL small RPA using rapid sizing procedures and a matching diagram constraint approach. Further optimisation and resizing of the vehicle starting from the initial concept	Maximum flight height of Part 107 regulations is considered as the cruising altitude of the RPA
Aliaga-Aguilar and Cuerno-Rejado [59]	RPASs	Conceptual and preliminary: rapid methods towards integration in MDO	Development of aerodynamic and performance modules towards their integration within an MDO-driven computerised design environment for small RPA	No regulatory requirement integration in design methodologies
Torrigiani et al. [27]	RPASs	Preliminary: MDO framework with multiple disciplinary modules	Starting from an initial MALE RPA concept, it is optimised through the use of the AGILE framework comprising multiple modules, from geometry definition to aerodynamic calculations including systems engineering	Consideration of CS-25 regulatory requirements, particularly particular lightning protection, with respect to systems engineering in the requirements definition and optimisation process, accounting for systems interaction
Casarosa et al. [28]	RPASs	Conceptual: rapid weight estimation method	Analysis of RPAS onboard system requirements and trends towards developing a rapid weight estimation method for the take-off weight of a certifiable RPA. Use of statistical data of onboard equipment to develop the estimation approach	Definition of the minimum equipment required and redundancies attending to airworthiness design requirements available for civil RPASs at the time of publication, particularly safety targets. This information is employed to estimate the required equipment and, from the statistical data, the weight
Cuerno-Rejado and Martínez-Val [6]	RPASs	Conceptual: rapid, low-fidelity methods	Development of a rapid approach towards estimating RPA required structural weight to withstand gust and manoeuvre loads prescribed by applicable regulations. Evaluation in a case study of various existing RPA to compare the structural weight required to comply with the regulations with the actual one	Considering the EASA Policy E.Y013-01, which allows to derive requirements for RPA through the tailoring of manned aviation certification codes, the corresponding applicable codes are obtained for various existing RPA, and from the requirements, for each of them, the gust and manoeuvring requirements are derived

Appendix D. Level of Specificity Examples

In this appendix, an example excerpt of RPAS regulations corresponding to each of the three main levels of specificity considered for the survey, as commented in Section 4.1, is provided to illustrate the differences between them when classifying documents and requirements:

Appendix D.1. Low Level of Specificity

“CS-UAS.2115 Take-Off and minimum performance

- (a) *The applicant must determine the UA minimum performance required for take-off,*
 (b) *If the most critical flight phase is other than take-off, the applicant in addition to (a) must determine the UA minimum performance for this flight phase.” [45].*

According to the criteria given in Section 4.1, this requirement only establishes broad aspects that the applicant must determine, but no specific guidance on what aspects of performance are required are given, nor is any numerical constraint provided.

Appendix D.2. Medium Level of Specificity

“CS-LUAS.53 Flight Performance

The following information must be determined and provided in the approved Flight Manual:

- (a) *In take-off configuration at maximum weight within the operational flight envelope established for take-off:*
 (1) *The rotation speed VR, except for catapult assisted or rocket assisted take-off and hand launched RPA*
 (2) *The obstacle clearance height, agreed by the authority*
 (3) *The distance required to take-off and climb to the obstacle clearance height*
 (4) *The minimum speed at the obstacle clearance height.” [93].*

More detail is provided than in the previous case regarding the variables and parameters that the applicant must determine, albeit no numerical constraint is prescribed.

Appendix D.3. High Level of Specificity

“USAR.65 Climb: All Engines Operating

- (a) *Each UA must have a steady gradient of climb at sea level of at least 5% with:*
 (1) *Not more than maximum continuous power on each engine;*
 (2) *The landing gear retracted (if such a configuration is designed);*
 (3) *The wing flaps in the take-off position(s); and*
 (4) *A climb speed not less than the greater of 1.1 V_{MC} and 1.2 V_{S1} for multi-engine UA and not less than 1.2 V_{S1} for single-engine UA.” [95]*

In this case, not only are requirements prescribed in relation to specific variables, but quantitative values are also provided by the regulation.

References

1. Available online: <https://ec.europa.eu/docsroom/documents/19184?locale=en> (accessed on 6 September 2023).
2. Gertler, J.; Zoretich, T. 2022/2023 World Civil Unmanned Aerial Systems Market Profile & Forecast; Market report; Teal Group Corporation: Fairfax, VA, USA, 2023.
3. Karyotakis, M.; Panagiotakopoulos, D.; Braithwaite, G.; Tsourdos, A. Aspects and Challenges of Unmanned Aircraft Systems Safety Assurance and Certification for Advanced Operations. In Proceedings of the AIAA Aviation 2021 Forum, Virtual Event, 2–6 August 2021; AIAA 2021-2397. [CrossRef]
4. Clothier, R.; Palmer, J.; Walker, R.; Fulton, N. Definition of an airworthiness certification framework for civil unmanned aircraft systems. *Saf. Sci.* **2011**, *49*, 871–885. [CrossRef]
5. Pérez-Castán, J.; Gómez-Comendador, F.; Rodríguez-Sanz, A.; Valdés, R.A.; Alonso-Alarcón, J. Safe RPAS integration in non-segregated airspace. *Aircr. Eng. Aerosp. Technol.* **2020**, *92*, 801–806. [CrossRef]
6. Cuerno-Rejado, C.; Martínez-Val, R. Unmanned Aircraft Systems in the Civil Airworthiness Regulatory Frame A case study. *J. Aircr.* **2011**, *48*, 1351–1359. [CrossRef]
7. Dalamagkidis, K.; Valavanis, K.P.L. A Survey of Unmanned Aircraft Systems Regulation Status and Future Perspectives. In Proceedings of the 16th Mediterranean Conference on Control and Automation, Ajaccio, France, 25–27 June 2008. [CrossRef]

8. Masutti, A.; Tomasello, F. *International Regulation of Non-Military Drones*; Edward Elgar Publishing Limited: Chentelham, UK, 2018; ISBN 978-1-78536-757-1.
9. Cook, S.P.; King, L. Trends in Remotely Piloted Aircraft Systems Airworthiness. In Proceedings of the 2018 AIAA Information Systems-AIAA Infotech @ Aerospace, Kissimmee, FL, USA, 8–12 January 2018; AIAA 2018-1723. [\[CrossRef\]](#)
10. Stöcker, C.; Bennett, R.; Nex, F.; Gerke, M.; Zevenbergen, J. Review of the Current State of UAV Regulations. *Remote Sens.* **2017**, *9*, 459. [\[CrossRef\]](#)
11. Ferreira, R.; Baum, D.; Neto, E.P.; Martins, M.; Almeida, J.; Cugnasca, P.; Camargo, J. A Risk Analysis of Unmanned Aircraft Systems (UAS) Integration into non-Segregate Airspace. In Proceedings of the 2018 International Conference on Unmanned Aircraft Systems (ICUAS), Dallas, TX, USA, 12–15 June 2018; pp. 42–51. [\[CrossRef\]](#)
12. Stroeve, S.; Villanueva-Cañizares, C.J.; Dean, G. Remote pilot modelling for evaluation of ACAS Xu. In Proceedings of the SESAR Innovation Days 2023, Seville, Spain, 27–30 November 2023.
13. Peukert, M.; Santel, C. Tactical Conflict Avoidance of Manned Traffic-Display Concepts for UAV Pilots. *CEAS Aeronaut. J.* **2024**, *15*, 315–324. [\[CrossRef\]](#)
14. Janke, C.; de Haag, M. Implementation of European Drone Regulations-Status Quo and Assessment. *J. Intell. Robot. Syst.* **2022**, *106*, 33. [\[CrossRef\]](#)
15. Maier, L.; Hosseini, S.; Sax, F.; Rhein, J.; Barth, A.; Holzapfel, F.; Hajek, M.; Yavrucuk, I. Evaluation of the Pilot Training Concept for Flying a Helicopter UAV. In Proceedings of the AIAA SCITECH 2024 Forum, Orlando, FL, USA, 8–12 January 2024; AIAA 2024-1720. [\[CrossRef\]](#)
16. Bassi, E. European Drones Regulation: Today's Legal Challenges. In Proceedings of the International Conference on Unmanned Aircraft Systems (ICUAS 2019), Atlanta, USA, 11–14 June 2019; pp. 435–442. [\[CrossRef\]](#)
17. Valavanis, K.P.; Vachtsevanos, G. *Handbook of Unmanned Aerial Vehicles*; Springer: Dordrecht, The Netherlands, 2015; ISBN 978-90-481-9706-4.
18. Srivastava, S.; Gupta, S.; Dikshit, O.; Nair, S. A Review of UAV Regulations and Policies in India. In Proceedings of the 1st International Conference on Unmanned Aerial System in Geomatics (UASG 2019), Roorkee, India, 6–7 April 2019; pp. 315–325.
19. Torenbeek, E. *Synthesis of Subsonic Airplane Design*; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1982; ISBN 978-90-481-8273-2.
20. Gudmundsson, S. *General Aviation Aircraft Design*, 1st ed.; Butterworth-Heinemann: Oxford, UK, 2014; ISBN 978-0-12-397308-8.
21. Gundlach, J. *Designing Unmanned Aircraft Systems: A Comprehensive Approach*, 1st ed.; American Institute of Aeronautics and Astronautics (AIAA): Reston, VA, USA, 2012; ISBN 978-1-60086-843-6.
22. Gómez-Rodríguez, A.; Sanchez-Carmona, A.; García-Hernández, L.; Cuerno-Rejado, C. Remotely Piloted Aircraft Systems Conceptual Design based on Factor Analysis. *Aerosp. Sci. Technol.* **2019**, *90*, 368–387. [\[CrossRef\]](#)
23. Karakoc, T.H.; Özbek, E. *Unmanned Aerial Vehicle Design and Technology*; Springer Nature: Cham, Switzerland, 2024; ISBN 978-3-031-45320-5.
24. Söbester, A.; Keane, A.; Scanlan, J.; Bressloff, N. Conceptual design of UAV airframes using a generic geometry service. In Proceedings of the Infotech @ Aerospace Conferences, Arlington, VA, USA, 26–29 September 2005; AIAA 2005-7079. [\[CrossRef\]](#)
25. Roskam, J. *Airplane Design*; Parts I–VIII; Design, Analysis and Research Corporation (DARcorporation): Lawrence, KS, USA, 1985; ISBN 978-1-884885-42-6/43-3/56-3/53-2/50-1/52-5/54-9/2-42.
26. Schmollgruber, P.; Bartoli, N.; Bedouet, J.; Defoort, S.; Gourinat, Y.; Benard, E.; Lafage, R.; Sgueglia, A. Use of a certification constraints module for aircraft design activities (FAST). In Proceedings of the 17th AIAA Aviation Technology, Integration, and Operations Conference, Denver, CO, USA, 5–9 June 2017; AIAA 2017-3762. [\[CrossRef\]](#)
27. Torrigiani, F.; Deinert, S.; Fioriti, M.; Fede, F.D.; Jungo, A.; Pisu, L.; Sanchez, F.; Liscouet-Hanke, S.; Ciampa, P.; Nagel, B. MBSE certification-driven design of a UAV MALE configuration in the AGILE 4.0 design environment. In Proceedings of the AIAA Aviation 2021 Forum, Virtual Event, 2–6 August 2021; AIAA 2021-3080. [\[CrossRef\]](#)
28. Casarosa, C.; Galatolo, R.; Mengali, G.; Quarta, A. Impact of safety requirements on the weight of civil unmanned aerial vehicles. *Aircr. Eng. Aerosp. Technol.* **2004**, *76*, 600–606. [\[CrossRef\]](#)
29. Cuerno Rejado, C. *Aeronavegabilidad y Certificación de Aeronaves*, 1st ed.; Ediciones Paraninfo: Madrid, Spain, 2008; ISBN 978-84-2833-183-8.
30. Pittini, M.; Kourousis, K. Harmonising and standardising military airworthiness in Europe: A review of key aspects and achievements. *Aeronaut. J.* **2023**, *128*, 911–927. [\[CrossRef\]](#)
31. Gómez-Rodríguez, Á. On the Certification Aspects of RPAS and Their Relation with Design Strategies. Master's Thesis, Cranfield University, Bedford, UK, 2024.
32. Torenbeek, E. *Advanced Aircraft Design: Conceptual Design, Analysis and Optimization of Subsonic Civil Airplanes*; John Wiley & Sons Ltd: Chichester, UK, 2013; ISBN 978-11-1856-811-8.
33. Keane, A.; Söbester, A.; Scanlan, J. *Small Unmanned Fixed-Wing Aircraft Design*; John Wiley & Sons Ltd.: Chichester, UK, 2017; ISBN 978-11-1940-629-7.
34. Gómez-Rodríguez, A.; Sanchez-Carmona, A.; García-Hernández, L.; Cuerno-Rejado, C. Assessment of aircraft conceptual design tools towards the synthesis of Remotely Piloted Aircraft platforms. In Proceedings of the 8th European Conference for Aeronautics and Space Sciences (EUCASS), Madrid, Spain, 1–4 July 2019.

35. Champasak, P.; Panagant, N.; Pholdee, N.; Vio, G.; Bureerat, S.; Yildiz, B.; Yildiz, A. Aircraft conceptual design using metaheuristic-based reliability optimisation. *Aerosp. Sci. Technol.* **2022**, *129*, 107803. [CrossRef]
36. Stinton, D. *The Design of the Airplane*, 2nd ed.; AIAA: Reston, VA, USA, 2001; ISBN 978-1-56347-514-6.
37. Tyan, M.; Yoon, J.; Nguyen, N.V.; Lee, J.W.; Kim, S. Design-airworthiness integration method for general aviation aircraft during early development stage. *Aircr. Eng. Aerosp. Technol.* **2019**, *91*, 1067–1076. [CrossRef]
38. Bleu-Laine, M.H.; Bendarkar, M.; Xie, J.; Briceno, S.; Mavris, D. A Model-Based System Engineering Approach to Normal Category Airplane Airworthiness Certification. In Proceedings of the AIAA Aviation 2019 Forum, Dallas, TX, USA, 17–21 June 2019; AIAA 2019-3344. [CrossRef]
39. Nicolosi, F.; Marco, A.D.; Vecchia, P.D. Stability, flying qualities and longitudinal parameter estimation of a twin-engine CS-23 certified light aircraft. *Aerosp. Sci. Technol.* **2013**, *24*, 226–240. [CrossRef]
40. Travascio, L.; Buzzo, G.; Pascarella, D.; Baldizzone, M.; Gily, M.; Casagrande, C.; Martina, V.; Quarona, E. Disruptive Technologies Certification Standard Approach. *Aerospace* **2023**, *10*, 637. [CrossRef]
41. International Civil Aviation Organization. Good Regulatory Practices. 2016. Available online: https://www.icao.int/sustainability/Pages/regulatory_practices.aspx (accessed on 27 July 2024).
42. European Union Aviation Safety Agency (EASA). *Concept of Operations for Drones. A Risk Based Approach to Regulation of Unmanned Aircraft*; Brochure; EASA: Cologne, Germany, 2015. Available online: <https://www.easa.europa.eu/en/document-library/general-publications/concept-operations-drones> (accessed on 27 July 2024).
43. Joint Authorities for Rulemaking on Unmanned Systems (JARUS). UAS Operational Categorization. Document Identifier: Jar-del-wg7-uasoc-d.04, JARUS. 2019. Available online: http://jarus-rpas.org/wp-content/uploads/2023/06/jar_10_doc_UAS_Operational_Cat.pdf (accessed on 27 July 2024).
44. Federal Aviation Administration (FAA), Department of Transportation (DOT). Revision of Airworthiness Standards for Normal, Utility, Acrobatic, and Commuter Category Airplanes. 81 fr 96572, Federal Register, USA. 2016. Available online: <https://www.federalregister.gov/d/2016-30246> (accessed on 27 July 2024).
45. Netherlands, 2015; Chapter 87, pp. 2117–2133.
46. Joint Authorities for Rulemaking on Unmanned Systems (JARUS). CS-UAS. Document Identifier: Jarus-del-wg3- cs-uas-d.04, JARUS. 2019. Available online: http://67.217.59.217/jarus/wp-content/uploads/2023/06/jar_13_doc_CS_UAS-1.pdf (accessed on 27 July 2024).
47. Xu, C.; Liao, X.; Tan, J.; Ye, H.; Lu, H. Recent Research Progress of Unmanned Aerial Vehicle Regulations Policies and Technologies in Urban Low Altitude. *IEEE Access* **2020**, *8*, 74175–74194. [CrossRef]
48. Alamouri, A.; Lampert, A.; Gerke, M. An Exploratory Investigation of UAS Regulations in Europe and the Impact on Effective Use and Economic Potential. *Drones* **2021**, *5*, 63. [CrossRef]
49. Nöding, M.; Bertsch, L. Application of noise certification regulations within conceptual aircraft design. *Aerospace* **2021**, *8*, 210. [CrossRef]
50. Spencer, R. Certification considerations for the configuration of a hydrogen-fuelled aeroplane. *Aeronaut. J.* **2023**, *127*, 213–231. [CrossRef]
51. Xie, J.; Sarojini, D.; Cai, Y.; Corman, J.; Mavris, D. Certification-Driven Platform for Multidisciplinary Design Space Exploration in Airframe Preliminary Design. *J. Aircr.* **2022**, *59*, 329–349. [CrossRef]
52. Jeyaraj, A.K.; Liscouët-Hanke, S. A Safety-Focused System Architecting Framework for the Conceptual Design of Aircraft Systems. *Aerospace* **2022**, *9*, 791. [CrossRef]
53. Insley, J.; Turkoglu, C. A Contemporary Analysis of Aircraft Maintenance-Related Accidents and Serious Incidents. *Aerospace* **2020**, *7*, 81. [CrossRef]
54. Habib, K.A.; Turkoglu, C. Analysis of Aircraft Maintenance Related Accidents and Serious Incidents in Nigeria. *Aerospace* **2020**, *7*, 178. [CrossRef]
55. Rötger, T.; Eysers, C.; Fusaro, R. A Review of the Current Regulatory Framework for Supersonic Civil Aircraft: Noise and Emissions Regulations. *Aerospace* **2024**, *11*, 19. [CrossRef]
56. Kuśmierk, A.; Galiński, C.; Stalewski, W. Review of the hybrid gas-electric aircraft propulsion systems versus alternative systems. *Prog. Aerosp. Sci.* **2023**, *141*, 100925. [CrossRef]
57. Gómez-Rodríguez, A.; Sanchez-Carmona, A.; García-Hernández, L.; Cuerno-Rejado, C. Preliminary Correlations for Remotely Piloted Aircraft Systems Sizing. *Aerospace* **2018**, *5*, 5. [CrossRef]
58. Mitridis, D.; Kapsalis, S.; Terzis, D.; Panagiotou, P. An Evaluation of Fixed-Wing Unmanned Aerial Vehicle Trends and Correlations with Respect to NATO Classification, Region, EIS Date and Operational Specifications. *Aerospace* **2023**, *10*, 382. [CrossRef]
59. Tyan, M.; Nguyen, N.V.; Kim, S.; Lee, J.L. Comprehensive preliminary sizing; resizing method for a fixed wing- VTOL electric UAV. *Aerosp. Sci. Technol.* **2017**, *71*, 30–41. [CrossRef]
60. Aliaga-Aguilar, H.; Cuerno-Rejado, C. Development and validation of software for rapid performance estimation of RPAS. *Adv. Eng. Softw.* **2017**, *110*, 1–13. [CrossRef]
61. Clothier, R.A.; Williams, B.P.; Coyne, J.; Wade, M.; Washington, A. Challenges to the Development of an Airworthiness Regulatory Framework for Unmanned Aircraft Systems. In Proceedings of the 16th Australian Aerospace Congress (AIAC16), Melbourne, Australia, 23–24 February 2016; pp. 87–98; ISBN 978-90-481-9706-4.

61. Banafaa, M.; Pepeoglu, Ö.; Shayea, I.; Alhammadi, A.; Shamsan, Z.A.; Muneef, A.R.; Alsagabi, M.; Al-Sowayan, A.S. A Comprehensive Survey on 5G-and-Beyond Networks with UAVs: Applications, Emerging Technologies, Regulatory Aspects, Research Trends and Challenges. *IEEE Access* **2024**, *12*, 7786–7826. [\[CrossRef\]](#)
62. European Union Aviation Safety Agency (EASA). *EASA Artificial Intelligence Roadmap 2.0: A Human-Centric Approach to AI in Aviation*; EASA: Cologne, Germany, 2023. Available online: <https://www.easa.europa.eu/en/document-library/general-publications/easa-artificial-intelligence-roadmap-20> (accessed on 30 August 2024).
63. Costello, D.; Adams, R. A Framework for Airworthiness Certification of Autonomous Systems within United States Naval Aviation. *J. Aviat.* **2023**, *7*, 7–16. [\[CrossRef\]](#)
64. Matalonga, S.; Black, J.; Riordan, J. Verification and Validation for a Digital Twin for Augmenting Current SORA Practices with Air-to-Air Collision Hazards Prediction from Small Uncooperative Flying Objects. *J. Intell. Robot. Syst.* **2024**, *110*, 109. [\[CrossRef\]](#)
65. Nawaz, S.A. Regulating Autonomy in Civilian Drones: Towards a Spectral Approach. *J. Intell. Robot. Syst.* **2024**, *110*, 46. [\[CrossRef\]](#)
66. Angelov, P. *Sense and Avoid in UAS: Research and Applications*; Wiley: Chichester, UK, 2012; ISBN 978-0-470-97975-4.
67. Aibin, M.; Aldiab, M.; Bhavsar, R.; Lodhra, J.; Reyes, M.; Rezaeian, F.; Saczuk, E.; Taer, M.; Taer, M. Survey of RPAS Autonomous Control Systems Using Artificial Intelligence. *IEEE Access* **2021**, *9*, 167580–167591. [\[CrossRef\]](#)
68. Ravi, A.K.; Olivares, G.; Gomez, L.; Bhasin, A.; Roberson, M.; Huberty, W.; Bounds, C. *A53 A11L.UAS.93 Advanced Materials and Processes Survey for AAM and UAS Aircraft*; Report; Alliance for System Safety of UAS through Research Excellence (ASSURE): Starkville, MS, USA, 2022.
69. Battaglia, M.; Acanfora, V.; Garofano, A.; Maisto, G.; Riccio, A. An innovative approach to a UAV tails structural design for additive manufacturing. *Polym. Compos.* **2024**, *45*, 11149–11161. [\[CrossRef\]](#)
70. Mieloszyk, J.; Tarnowski, A.; Goetzendorf-Grabowski, T. Designing aerodynamic devices for UAV-lessons learned. *Aircr. Eng. Aerosp. Technol.* **2024**, *96*, 73–83. [\[CrossRef\]](#)
71. Mieloszyk, J.; Tarnowski, A.; Kowalik, M.; Perz, R.; Rządowski, W. Preliminary design of 3D printed fittings for UAV. *Aircr. Eng. Aerosp. Technol.* **2019**, *91*, 756–760. [\[CrossRef\]](#)
72. Elelwi, M.; Pinto, F.S.; Botez, R.M.; Dao, T.-M. Multidisciplinary Optimization for Weight Saving in a Variable Tapered Span-Morphing Wing Using Composite Materials—Application to the UAS-S4. *Actuators* **2022**, *11*, 121. [\[CrossRef\]](#)
73. Song, J.; Yan, J.; Yi, B. Design, fabrication, and characterization of hierarchical mechanical metamaterials. *Front. Mech. Eng.* **2024**, *19*, 3. [\[CrossRef\]](#)
74. De Florio, F. *An Introduction to Aircraft Certification and Operations*, 3rd ed.; Butterworth-Heinemann: Saint Louis, MO, USA, 2016; p. 552, ISBN 978-00-8100-888-1.
75. International Civil Aviation Organization (ICAO). *Circular 328. Unmanned Aircraft Systems (UAS)*; Circular; ICAO: Montréal, QC, Canada, 2011; ISBN 978-92-9231-751-5. Available online: https://www.icao.int/Meetings/UAS/Documents/Circular%20328_en.pdf (accessed on 27 July 2024).
76. International Civil Aviation Organization (ICAO). *Manual on Remotely Piloted Aircraft Systems (RPAS)*, 1st ed.; Manual; Doc 10019; ICAO: Montréal, QC, Canada, 2015.
77. International Civil Aviation Organization (ICAO). *State Letter AN 11/61-22/70. Proposed New Annex 6, Part IV, and Consequential Amendments to Annexes 1, 2 and 8 Related to International Remotely Piloted Aircraft Systems (RPAS) Operations in Controlled Airspace/Aerodromes Arising from the Eighteenth Meeting of the Remotely Piloted Aircraft Systems Panel (RPASP/18)*; State letter; ICAO: Montréal, QC, Canada, 2022.
78. International Civil Aviation Organization (ICAO). *The ICAO UAS Toolkit*; Web resources; ICAO: Montréal, QC, Canada, 2024. Available online: <https://www.icao.int/safety/UA/UASToolkit/Pages/default.aspx> (accessed on 27 July 2024).
79. International Civil Aviation Organization (ICAO). *ICAO Model UAS Regulations: Part 101 and Part 102*; Model Regulations; ICAO: Montréal, QC, Canada, 2020. Available online: <https://www.icao.int/safety/UA/Documents/Model%20UAS%20Regulations%20-%20Parts%20101%20and%20102.pdf> (accessed on 28 July 2024).
80. International Civil Aviation Organization (ICAO). *ICAO Model UAS Regulations: Part 149*; Model Regulations; ICAO: Montréal, QC, Canada, 2020. Available online: <https://www.icao.int/safety/UA/Documents/Model%20UAS%20Regulations%20-%20Part%20149.pdf> (accessed on 28 July 2024).
81. European Union (EU). Commission Implementing Regulation (EU) 2019/947 of 24 May 2019 on the Rules and Procedures for the Operation of Unmanned Aircraft. Oj L 152, 11.6.2019, pp. 45–71, Official Journal of the European Union. 2019. Available online: http://data.europa.eu/eli/reg_impl/2019/947/oj (accessed on 27 July 2024).
82. European Union (EU). Commission Delegated Regulation (EU) 2019/945 of 12 March 2019 on Unmanned Aircraft Systems and on Third-Country Operators of Unmanned Aircraft Systems. Oj L 152, 11.6.2019, pp. 1–40, Official Journal of the European Union. 2019. Available online: http://data.europa.eu/eli/reg_del/2019/945/oj (accessed on 27 July 2024).
83. European Union (EU). Commission Delegated Regulation (EU) 2024/1108 of 13 March 2024 Amending Regulation (EU) No 748/2012 as Regards the Initial Airworthiness of Unmanned Aircraft Systems Subject to Certification and Delegated Regulation (EU) 2019/945 as Regards Unmanned Aircraft Systems and Third-Country Operators of Unmanned Aircraft Systems. Oj L, 2024/1108, 23.5.2024, Official Journal of the European Union. 2024. Available online: http://data.europa.eu/eli/reg_del/2024/1108/oj (accessed on 27 July 2024).

84. European Union (EU). Commission Implementing Regulation (EU) 2024/1110 of 10 April 2024 Amending Regulation (EU) No 748/2012 as Regards the Initial Airworthiness of Unmanned Aircraft Systems Subject to Certification and Implementing Regulation (EU) 2019/947 as Regards the Rules and Procedures for the Operation of Unmanned Aircraft. Oj L, 2024/1110, 23.5.2024, Official Journal of the European Union. 2024. Available online: http://data.europa.eu/eli/reg_impl/2024/1110/oj (accessed on 27 July 2024).
85. European Union Aviation Safety Agency (EASA). *Terms of Reference for Rulemaking Task RMT.0230. Introduction of a Regulatory Framework for the Operation of Unmanned Aircraft Systems and for Urban Air Mobility in the European Union Aviation System, Issue 4; Tor rmt.0230—issue 4*; EASA: Cologne, Germany, 2024. Available online: <https://www.easa.europa.eu/en/document-library/terms-of-reference-and-rulemaking-group-compositions/tor-rmt0230> (accessed on 27 July 2024).
86. European Union Aviation Safety Agency (EASA). *EASA Concept Paper: Certified Category Operations of UAS, Certification of UAS and UAM Operations, Issue 2.1*; Concept paper; EASA: Cologne, Germany, 2019.
87. European Union Aviation Safety Agency (EASA). *Proposed Special Condition RPAS.SubpartB-01, RPAS Subpart B—Flight*; Doc. no.: Sc-rpas.subpartb-01; EASA: Cologne, Germany, 2016. Available online: <https://www.easa.europa.eu/en/document-library/product-certification-consultations/proposed-special-condition-rpassubpartb-01> (accessed on 27 July 2024).
88. European Union Aviation Safety Agency (EASA). *Special Condition Light UAS*; Special Condition; EASA: Cologne, Germany, 2020. Available online: <https://www.easa.europa.eu/en/document-library/product-certification-consultations/special-condition-light-uas> (accessed on 27 July 2024).
89. Federal Aviation Administration (FAA), Department of Transportation (DOT). 14 CFR Part 107. Code of Federal Regulations, 81 FR 42209. Regulation, Federal Register, USA. 2016. Available online: <https://www.ecfr.gov/current/title-14/part-107> (accessed on 27 July 2024).
90. United States Code (USC). 49 USC 44807: Special Authority for Certain Unmanned Aircraft Systems. Regulation, USA. 2019. Available online: <https://uscode.house.gov/view.xhtml?req=granuleid:USC-prelim-title49-section44807&num=0&edition=prelim> (accessed on 27 July 2024).
91. United States Code (USC). 49 USC 44809: Exception for Limited Recreational Operations of Unmanned Aircraft. Regulation, USA. 2019. Available online: <https://uscode.house.gov/view.xhtml?req=granuleid:USC-prelim-title49-section44809&num=0&edition=prelim> (accessed on 27 July 2024).
92. Federal Aviation Administration (FAA). *Order 8130.34D—Airworthiness Certification of Unmanned Aircraft Systems and Optionally Piloted Aircraft*; Faa order; FAA: Washington, DC, USA, 2017.
93. Joint Authorities for Rulemaking on Unmanned Systems (JARUS). CS-LUAS. Document Identifier: Jar_del_wg3_d.04, JARUS. 2017. Available online: http://jarus-rpas.org/wp-content/uploads/2023/06/jar_07_doc_CS_LUAS.pdf (accessed on 28 July 2024).
94. Joint Authorities for Rulemaking on Unmanned Systems (JARUS). JARUS Guidelines on Specific Operations Risk Assessment (SORA) v2.5 package. Document Identifier: Jar-del-srm-sora-mb-2.5, JARUS. 2024. Available online: http://jarus-rpas.org/wp-content/uploads/2024/06/SORA-v2.5-Main-Body-Release-JAR_doc_25.pdf (accessed on 28 July 2024).
95. NATO Standard AEP-4671; Unmanned Aircraft Systems Airworthiness Requirements (USAR). Edition b version 1. NATO: Brussels, Belgium, 2019.
96. NATO Standard AEP-83; Light Unmanned Aircraft Systems Airworthiness Requirements. Edition b version 1. NATO: Brussels, Belgium, 2016.
97. F2910-22; Standard Specification for Design and Construction of a Small Unmanned Aircraft System (sUAS). ASTM: West Conshohocken, PA, USA, 2022.
98. F3298-19; Standard Specification for Design, Construction, and Verification of Lightweight Unmanned Aircraft Systems (UAS). ASTM: West Conshohocken, PA, USA, 2019.
99. F3563-22; Standard Specification for Design and Construction of Large Fixed Wing Unmanned Aircraft Systems. ASTM: West Conshohocken, PA, USA, 2022.
100. ISO 21384-2:2021; Unmanned Aircraft Systems Part 2: UAS Components. ISO: Geneva, Switzerland, 2021.
101. ISO 21384-3:2023; Unmanned Aircraft Systems Part 3: Operational Procedures. ISO: Geneva, Switzerland, 2023.
102. Goetzendorf-Grabowski, T.; Rodzewicz, M. Design of UAV for photogrammetric mission in Antarctic area. *Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng.* **2016**, *231*, 1660–1675. [CrossRef]
103. Pranoto, F.; Budiyanata, A.; Prabowo, G. *Small to Medium UAVs for Civilian Applications in Indonesia*, 2nd ed.; IntechOpen Limited: London, UK, 2018; pp. 9–28; ISBN 978-1-78923-284-4.
104. Rodzewicz, M.; Goraj, Z.; Tomaszewski, A. Design and testing of three tailless unmanned aerial vehicle configurations built for surveillance in Antarctic environment. *Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng.* **2018**, *232*, 2598–2614. [CrossRef]

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