Aircraft Initial Airworthiness Certifications in a Virtual Setting: An Assessment of European Union Law's Ability to Accommodate the Technological Advances in Aviation

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Abstract

The thesis explores the integration of artificial intelligence (AI) and virtual testing in the aircraft manufacturing process, particularly in the context of airworthiness certification. It investigates the extent to which aircraft manufacturers can conduct the construction and testing of new aircraft in a virtual setting with the use of AI, satisfying EU regulatory requirements for airworthiness certifications before the aircraft is physically built. The current EU legislative and regulatory framework, primarily designed for traditional methods of aircraft certification, is scrutinized for its compatibility with these emerging technologies. The thesis proposes amendments to the EU legislative framework, particularly Regulation (EU) 748/2012, to accommodate the complexities introduced by virtual manufacturing and flight-testing. The proposed amendments include redefining 'type-certification' to encompass the certification of software and algorithms used in virtual manufacturing and flight-testing and allowing for compliance demonstration through simulations or virtual tests. The thesis also proposes the implementation of a phased certification process, a VR inspection system, and a collaborative certification framework to enhance the efficiency, robustness, and reliability of the certification process. These proposals aim to facilitate the integration of these technologies into the aviation industry while ensuring that associated risks are adequately managed. The thesis underscores the need for continuous exploration of these issues, stakeholder engagement, and refinement of the proposed solutions to adapt and innovate in the future of aviation.

Keywords: Aviation law, EU law, EASA, certification, airworthiness certification, virtual flight testing, artificial intelligence, machine learning, regulatory compliance

Chapter 1: Introduction

1.1 Background/problem statement

With the explosive popularity of a Metaverse where virtual assets can be gathered, traded, sold or simply displayed, Boeing, the aviation colossus, jumped on the trend and announced that they are planning to construct aircraft in that virtual setting.[1] Boeing is an example of an enterprise that has always been seeking digitalisation, leading to notable increases in value and productivity while also having faced failures such as the tragic 737 Max crisis.[2] Greg Hyslop, Boeing's chief engineer, stated in an interview with Reuters that one of their aims is to 'strengthen engineering' through this digitalisation and virtualisation of aircraft making.[3] This statement opens the door to many different topics for discussion, but the problem which this thesis will deal with is whether aviation companies could conduct the aircraft designing and testing process completely virtually; the process starting from the choice of and experimentation with materials to the engineering, construction, flight and safety simulations all the way to obtaining the necessary certifications before the aircraft has been built. Thus, the plane would have to be legally flight-worthy before it ever got a physical form. This would, potentially, cut down production costs, reduce the negative environmental impact and hopefully lead to a greener and cheaper transportation experience. Additionally, such an initiative by a large company would push for more expertise and foster developments in all the technologies involved that such an innovation would require. These include technologies ranging from commonly used ones like general e-commerce services, 3D-printing and applications for designing aircraft, all the way to complex virtual flight-testing environments and even the use of Artificial Intelligence (AI) to place the aircraft through numerous simulations in order to assess durability of the materials, general integrity and even provide information on the behaviour of the aircraft in various situations.

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[1] Eric M Johnson, Tim Hepher, 'Boeing Wants to Build its next Airplane in the ''Metaverse''' <https://www.reuters.com/technology/boeing-wants-build-its-next-airplane-metaverse-2021-12-17/> (*Thomson Reuters*, 17 December 2021) accessed 13 October 2022.

[2] Eric M Johnson, 'Timeline-Boeing's 737 MAX Crisis' <https://www.reuters.com/article/boeing-737max-timeline-idUSL1N2I417A> (*Thomson Reuters*, 17 December 2021) accessed 13 October 2022; Nick Ismail, 'Boeing's Digital Transformation… it's Cultural' <https://www.information-age.com/boeings-digital-transformation-cultural-123476508/> (*Information Age*, 15 November 2018) accessed 13 October 2022.

[3] Eric M Johnson, Tim Hepher, 'Boeing Wants to Build its next Airplane in the ''Metaverse''' <https://www.reuters.com/technology/boeing-wants-build-its-next-airplane-metaverse-2021-12-17/> (*Thomson Reuters*, 17 December 2021) accessed 13 October 2022.

The virtual setting that includes all the steps for modelling and testing commercial aircraft to assess their airworthiness is constantly reviewed and improved either to conform to airworthiness certifications and later compliance verification or to contribute to the technological advancement of aviation in terms of safety and efficiency (financially and timewise). One of the factors that is already contributing to the progress and strengthening of the aviation industry is AI. The application of AI in the aircraft-making process is not a topic often discussed due to its specialized character, yet it is a core feature for the future of aviation. This can be deduced by the documents that the European Union Aviation Safety Agency (EASA) has dedicated to the operation of AI in all aspects of aviation including obtaining certifications and passing safety tests.[4] Discussing the involvement of AI in this process is essential since both Artificial Intelligence and Machine Learning include a degree of unpredictability in their results that can often make or break things. The consideration of implementing them in virtual testing, therefore, requires an assessment of the risks and benefits it carries and the level of independence or control that should be assigned to them. Unfortunately, the impact of Artificial Intelligence and Machine Learning on this field still lacks in regulation, extent of implementation as well as general and specialised literature. The regulatory gap can be deduced firstly from the lack of a dedicated EU regulatory instrument on the application of these technologies and secondly from the omission to address in any substantial degree the manner in which AI and ML should be regulated and how they should be implemented in the industry. [5] One of the very few mentions in the relevant legislation that remotely address these technologies can be found in Recital 12 and Article 1(2) of the Regulation (EU) 2018/1139 which, although it does not explicitly mention AI and ML, it instead allows and even promotes any subsequent legislation that will foster innovation in all fields of aviation.[6] The EASA acknowledges this flexibility and identifies the gap in the legislation regarding AI which it demonstrates in the AI Roadmap as well as through the recent launch of EU funded research projects on this topic.[7] One such example is the KIEZ4.0 AI

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[4] European Union Aviation Safety Agency, 'Research Projects' <https://www.easa.europa.eu/en/research-projects?search=artificial+intelligence&date_filter%5Bmin%5D=&date_filter%5Bmax%5D=> (*European Union Aviation Safety Agency*) accessed 17 December 2022.

[5] See Appendix A for a quick reference table of relevant legislation.

[6] Parliament and Council Regulation (EU) 2018/1139 of 4 July 2018 on Common Rules in the Field of Civil Aviation and Establishing a European Union Aviation Safety Agency, and Amending Regulations (EC) No 2111/2005, (EC) No 1008/2008, (EU) No 996/2010, (EU) No 376/2014 and Directives 2014/30/EU and 2014/53/EU of the European Parliament and of the Council, and Repealing Regulations (EC) No 552/2004 and (EC) No 216/2008 of the European Parliament and of the Council and Council Regulation (EEC) No 3922/91.

[7] European Union Aviation Safety Agency, *Artificial Intelligence Roadmap: A Human-Centric Approach to AI in Aviation* (European Union Aviation Safety Agency 2020) 7, 11, 12.

which aims to investigate what classes of AI could be used for certain certifications.[8] These projects, like a few others, are still ongoing, illustrating a gap in literature. There are, however, several sources that will be introduced in the literature review touching either individually or in combination on the topics of AI and ML and its engagement in the aircraft-making process, which appear to be sufficient material for a thesis to examine and still leave room for criticism, review, arguments and original proposals.

The next step for this thesis would be to assess the extent to which the existing legal framework can accommodate this AI infused process. From a legal standpoint, getting a plane certified for flight is no simple task. A lot of requirements must be met for the durability of the components of the aircraft, its safety certifications and its behaviour during actual flight. Such things are regulated by authorities like the US's Federal Aviation Administration following a series of tests listed in their lengthy 481-page long handbook.[9] Similarly, the EASA has its own set of regulations and test points for new aircraft that can be found among their numerous general and specialised handbooks and guides.[10] Some of these certifications require hundreds of hours of flight time before an aircraft can be deemed flight-worthy which circles back to the intriguing query on whether and how it would be possible to certify an aircraft with either no or significantly reduced physical flight hours.

Finally, the goal of this thesis is to extend its role from a piece of academic work to a consultation tool that could potentially probe enough discussion and trigger action that would lead to notable reductions in negative impact on the environment and production costs through a regulated but promoted innovation.[11]

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[8] European Union Aviation Safety Agency, 'KIEZ4.0 AI: Artificial Intelligence for European Certification Actions with Industry 4.0 Aspects' <https://www.easa.europa.eu/en/research-projects/kiez40-ai> (*European Union Aviation Safety Agency*, 29 Jul 2021) accessed 13 October 2022.

[9] Federal Aviation Administration, 'AC 25-7D - Flight Test Guide for Certification of Transport Category Airplanes: Document Information' (*Federal Aviation Administration*, 4 May 2018) accessed 13 October 2022.https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/1033309> (*Federal Aviation Administration*, 4 May 2018) accessed 13 October 2022.

[10] European Union Aviation Safety Agency, 'Easy Access Rules for Airworthiness and Environmental Certification (Regulation (EU) No 748/2012)' (*European Union Aviation Safety Agency*, 18 May 2022) accessed 13 October 2022.https://www.easa.europa.eu/en/document-library/easy-access-rules/easy-access-rules-airworthiness-and-environmental-certification (*European Union Aviation Safety Agency*, 18 May 2022) accessed 13 October 2022. See also Commission Regulation (EU) No 748/2012 of 3 August 2012 laying down implementing rules for the airworthiness and environmental certification of aircraft and related products, parts and appliances, as well as for the certification of design and production organisations (recast) [2012] OJ L224/1.

[11] Placeholder footnote for data that will be compiled later

1.2 Research question and sub-questions

The preceding introduction leads to the following research question. To what extent is it possible for aircraft manufacturers to conduct the construction and testing of new aircraft in a virtual setting with the use of Artificial Intelligence in view of satisfying the EU regulatory requirements in place to achieve airworthiness certifications before the aircraft is ever physically built?

1. What does the current sphere of virtual-testing entail? In what manner is AI involved in the aircraft manufacturing process and what is its potential to further assist in that process in view of obtaining the necessary airworthiness certifications? What are the risks that such dependence on AI on this process carries?
2. What is the EU regulatory framework in place for assessing whether aircraft are airworthy and to what extent does it currently facilitate certification while in the virtual manufacturing and simulation stage?
3. Should the current legislative and regulatory framework be amended in order to accommodate the virtual manufacturing and flight-testing process so that planes can be certified as flightworthy before ever taking a physical form? What proposals could make this process possible?

1.3 Literature review

The literature on aviation technologies is extensive, yet it falls behind on certain aspects that are either very new or have elements currently under consideration, research and development. One of these areas that are often discussed by policymakers, lawmakers, engineers, pilots and other aviation professionals regards the implementation of virtual means in the different processes of aviation like flight simulation, training, material testing, design, and airworthiness certification.[12] Through the various research papers and discussions two things may be deduced; firstly, the importance of the role of such technologies in reinforcing the field of aviation remains undisputed and secondly, that the need for the production of such literature stems from the question of how reliable and trustworthy are such technologies when

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[12] Dimitris Mourtzis, John Angelopoulos and Nikos Panopoulos, ‘A Virtual Collaborative Platform for Education in the Design and Simulation of Aeronautics Equipment: The Teaching Factory 5.0 Paradigm’ (12th Conference on Learning Factories, Queenstown, April 2022, published 1 April 2022) <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4071869> accessed 30 September 2022; Xiaoqin Liu and others, ‘Research on Airworthiness certification of Civil aircraft based on Digital virtual flight test technology’ (38th Digital Avionics Systems Conference (DASC), San Diego, September 2019, published 30 April 2020) <https://ieeexplore.ieee.org/document/9081641> accessed 13 October 2022.

considering the duty of companies and regulators for safe air transportation as well as liability issues concerning more controversial technologies such as Artificial Intelligence reliance.[13]

The digitalisation of the aircraft manufacturing, certification and operation process, of course, not a one-dimensional topic. For example, some researchers evaluate its merits by comparing the data produced from virtual testing against the data gathered from physical flights to demonstrate the importance of integrating virtual flight testing in the aircraft airworthiness evaluation process arguing that it can lead to reduced production costs, accelerate production of new aircraft or speed-up the recertification process of existing ones which works in the benefit of aviation companies.[14] Apart from the 'corporate friendly' perspective, others look at the issue through the environmental lens and argue that further extending the incorporation of flight simulations and the use of virtual tools in the manufacturing, certification and operation of aircraft and avionics can significantly reduce the environmental footprint of these processes' physical counterparts.[15] Some researchers delve deeper into the digitalisation effort, with an example being the evaluation of virtual testing of material strength in terms of cost reduction and environmental impact.[16] Except from the more specialised character of such research, the differentiation from other works lies in the conclusion that the focus for this digitalisation effort should be assessing and improving the reliability on simulations especially automated and AI based ones.[17]

On the note of the aforementioned discussions and considering the jurisdictional choice for the drafting of this thesis being the EU, the European Union and specifically EASA as the primary institution concerned with the digitalisation of the aircraft manufacturing and certification processes and also the regulating authority. It is important to understand that there

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[13] European Union Aviation Safety Agency, 'Machine Learning Application Approval' <https://www.easa.europa.eu/en/research-projects/machine-learning-application-approval#group-research-project-details> (European Union Aviation Safety Agency, April 2021) accessed 13 October 2022; 'KIEZ4.0 AI: Artificial Intelligence for European Certification Actions with Industry 4.0 Aspects' <https://www.easa.europa.eu/en/research-projects/kiez40-ai> (European Union Aviation Safety Agency, 29 Jul 2021) accessed 13 October 2022.https://www.easa.europa.eu/en/research-projects/machine-learning-application-approval#group-research-project-details> (*European Union Aviation Safety Agency*, April 2021) accessed 13 October 2022; European Union Aviation Safety Agency, 'KIEZ4.0 AI: Artificial Intelligence for European Certification Actions with Industry 4.0 Aspects' <https://www.easa.europa.eu/en/research-projects/kiez40-ai> *(European Union Aviation Safety Agency*, 29 Jul 2021) accessed 13 October 2022.

[14] Ivan Burdun and Alexander Grebenkin, 'Aircraft Virtual Flight Test and Certification Technology: Validation and Application Experience' (SAE 2016 Aviation Technology Forum, Sanghai, June 2016, published 5 October 2016) <https://www.researchgate.net/publication/308886254_Aircraft_Virtual_Flight_Test_and_Certification_Technology_Validation_and_Application_Experience> accessed 13 October 2022.

[15] Clean Aviation, *Clean Sky Highlights 2020* (Clean Sky Joint Undertaking 2021) 7, 8, 11, 14, 16, 18.

[16] Cianettia F and others, 'Virtual qualification of aircraft parts: test simulation or acceptable evidence?' (2019) 24 Procedia Structural Integrity 526, 527, 530, 538.

[17] ibid 528, 529, 538.

are different types of reference to certification that needs to be distinguished. First, there is the certification of technology itself as a tool to be introduced (or updated/upgraded) in any stage of the aviation process, like the assessment of whether an AI system is satisfactory to be a part of this process.[18] Then there is the certification of avionics, aircraft materials and general airworthiness of the aircraft through the use of virtual means, like using an AI system to simulate thousands of flight hours and through various scenarios and produce data that will determine whether the aircraft or part of its equipment can be certified as airworthy. Although there is plenty of discussion regarding the former type of certification, the literature on the latter is limited at best.

With the above discussion in mind, this thesis will revolve around the latter type of certification which is also where the gap in the literature is visible. The thesis will assess the ability of the current EU legislation to accept to certify aircraft as airworthy with the only (or at least the majority) of evidence for the certification process being the results of virtual simulations with an additional point of focus being AI systems. Additionally, there will be proposals for regulatory reforms in order to accommodate (or restrict) the use of virtual means in the certification process. The thesis aims to act as a contributing piece of academic work to the overall effort of the EU (and EASA) to assess the extent to which they can regulate the implementation of AI and ML technologies in aviation since it is a topic that is currently under the lens of researchers, academics and other relevant experts through several EU funded projects and calls for expert contributions.[19]

1.4 Methodology and methods

The aim of this thesis is to produce a substantiated opinion on the extent to which certifications that are normally obtained through physical flight hours can instead be obtained during the virtual stage of aircraft manufacturing and flight testing. In order to achieve that, there are three driving methodological approaches that will be utilised. The doctrinal approach

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[18] Woodrow Bellamy, ‘EASA Expects Certification of First Artificial Intelligence for Aircraft Systems by 2025’ (Aviation Today, 19 February 2020) <https://www.aviationtoday.com/2020/02/19/easa-expects-certification-first-artificial-intelligence-aircraft-systems-2025/> accessed 13 October 2022.

[19] European Union Aviation Safety Agency, ‘EASA to Deepen Partnership with European Universities and Academia: Calling all PhD Students from European Universities & Research Entities’ <> (European Union Aviation Safety Agency, 29 Jul 2021) accessed 13 October 2022.https://www.easa.europa.eu/en/newsroom-and-events/press-releases/easa-deepen-partnership-european-universities-and-academia> (European Union Aviation Safety Agency, 29 Jul 2021) accessed 13 October 2022. See also Eric M Johnson, ‘Timeline-Boeing's 737 MAX Crisis’ <https://www.reuters.com/article/boeing-737max-timeline-idUSL1N2I417A> (*Thomson Reuters*, 17 December 2021) accessed 13 October 2022; Nick Ismail, ‘Boeing’s Digital Transformation… it’s Cultural’ <https://www.information-age.com/boeings-digital-transformation-cultural-123476508/> (*Information Age*, 15 November 2018) accessed 13 October 2022.

is the central methodology as the majority of the thesis will be dealing with the assessment of current regulations of the EU regarding certifications of airworthiness and aviation in general. There will be an investigation of the ability of these regulations to accommodate the virtual testing certifications instead of the physical ones and most importantly there will be proposals of amendments or introduction of new pieces of legislation. The second methodology will be the interdisciplinary approach that must unavoidably be employed due to the technical nature of the research and the gap in the legal (primarily) literature. The legal content will be complemented by a mixture of data gathered from engineering and physics papers, environmental assessments and reports, AI and machine learning research projects focusing on aviation.

1.5 A first overview of the different chapters

The first chapter of the thesis lays out the route that leads to the discovery of the main issue, being the extent to which certification of airworthiness for airplanes can be further obtained through the virtual stage of flight testing. This chapter will provide an overview of the different parameters that will be engaged, a definition of the main ideas, the limitations and the reasoning behind them as well as the general structure of the thesis itself. The second chapter will discuss the technical aspects of virtual testing and simulations for aircraft with a focus on the processes regarding airworthiness certification. It will then introduce the AI involvement in the process. The chapter will first differentiate between certifying AI tools to be used in the process of aircraft's virtual testing and certifications awarded following processes that involve the use of AI. A balancing exercise of the risks and benefits of the use of AI in this process will be conducted. The third chapter will include a doctrinal assessment of the current EU legal framework regarding airworthiness certification and a more precise distinction of the types of certifications that will be discussed in the thesis. The assessment will focus on the extent to which current legislation allows for certification in the virtual stage, the manner in which certification takes place in practice and the practical reasons for legislators not extending the ability to certify virtual processes further. The fourth and final substantive chapter will assess whether there is indeed a regulatory gap that needs to be filled in order to accommodate further certifications during the virtual stage of aircraft manufacturing and testing. Since the thesis does not take a binary (black or white) stance but rather investigates the extent of potential virtual certification, this chapter will argue both why (if any) regulatory instruments should remain unchanged and in what way should other regulatory instruments be amended, or what new legislation should be introduced to allow for the further integration of virtual certification in this process. The fifth chapter will follow the standard course of a thesis conclusion, summarising all the arguments presented in the previous chapters, address the set problem question(s), putting the findings into perspective to display their significance and finally present the potential of this paper to act as a steppingstone for further discussion and continuous investigation as technology progresses and new laws (like the AI Act) are introduced.

Chapter 2: Virtual Flight-Testing Technology

Rapid advances in technology have led to new methods in aircraft design, certification and certification processes. In particular, the use of virtual testing and artificial intelligence has the potential to revolutionize the aviation industry, particularly in the context of airworthiness certification. This chapter aims to explore the current state of virtual testing in aircraft manufacturing and examine the role of AI in facilitating these processes. In this context, AI can become an indispensable tool that has the ability to improve the efficiency of virtual testing by optimizing designs, by predicting failure modes and simulating complex scenarios. However, the increasing reliance on AI in aircraft manufacturing and certification processes also raises concerns about the potential risks that come with it. This chapter will address these concerns by examining the implications of AI-dependence on safety, security, and regulatory compliance.

2.1 Contextual framework

Testing aircraft in a virtual setting can bring about a variety of different categories of the simulations that take place. The distinction that will be made here is a more straightforward and general one. There are simulations of flights where humans will take part in as a tool to train themselves, a prime example being commercial pilots either looking to obtain experience, completing some required flight hours to get certified or test new aircraft.[20] Then there is the virtual flight-testing that takes place when an aircraft manufacturer or other similarly interested companies and authorities wish to design new aircraft and test how said aircraft may act in different scenarios. These tests and the data they generate are ultimately meant to act as evidence that an aircraft satisfies as many requirements as necessary to progress in the certification process for airworthiness. The virtual flight-testing discussed in this thesis is not concerned with the certifications awarded to individuals through the simulated training, but rather the certifications awarded to aircraft through the simulated flights.

The other clarification regards the type of AI that this thesis is concerned with. The distinction between certifying AI tools used in aircraft virtual testing and certifications awarded following processes involving AI is crucial to understanding the aviation certification landscape. The process of verifying AI tools refers to evaluating and validating the AI systems themselves, and ensuring that they comply with safety, performance, and reliability standards. This

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[20] James Comstock and others, *Flight Simulation Scenarios for Commercial Pilot Training and Crew State Monitoring* (National Aeronautics and Space Administration, 2020).

certification step is necessary to guarantee that the AI tools used in virtual testing and other stages of aircraft manufacturing are dependable and fit for purpose.[21] On the other hand, certifications awarded following processes that involve the use of AI refer to the airworthiness and safety approvals awarded to aircraft after successful completion of tests and evaluations that utilise AI tools. These certifications prove that the aircraft has undergone a thorough inspection, including virtual testing aided by AI, and has met the necessary regulatory standards to be deemed airworthy and safe for operation. Thus, the former focuses on the trustworthiness of AI tools themselves, while the latter emphasizes the aircraft's compliance with safety and performance standards through AI-assisted testing and evaluation processes.

2.2 Virtual flight-testing technology

In order to better understand the sphere of virtual flight-testing, it is important to possess at least a basic understanding of its technicalities. There are several technologies involved in these simulated flights, but 4 of them can be considered central (especially for this thesis) since newly introduced methods are generally based on them. The first one is Computational Fluid Dynamics (CFD). Versteeg and Malalasekera offer a long but solid explanation of this method describing it as the process where code is created with the aim of solving heavily numerical problems to simulate fluid flow.[22] Among other fields, engineers have been employing CFD for decades in aviation to analyse the aerodynamics of aircraft to calculate forces like lift and drag and use that data to optimise the overall design to improve the aircraft’s performance.[23] CFD has seen use as early as the 1960s, yet the complexity of the calculations in combination with the lack of hardware that could take on such tasks made it less desirable, until the late 1990s since when computational power has rapidly increased while also becoming much more affordable and therefore accessible.[24] Even with the technology catching up, the hunt for more efficient designs makes CFD a difficult method to utilise, and Martins, through an array of benchmarks, substantiates his position that a great solution to this has and will be the open-source nature of the code used for the process.[25]

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[21] Norbert Kroll and others, ‘DLR project Digital-X: towards virtual aircraft design and flight testing based on high-fidelity methods’ (2016) 7(1) CEAS Aeronautical Journal 3, 4.

[22] Henk Versteeg and Wije Malalasekera, An Introduction to Computational Fluid Dynamics: The Finite Volume Method (2nd edn, Pearson 2007) 1-4.

[23] ibid 1; Joaquim Martins, ‘Aerodynamic Design Optimization: Challenges and Perspectives’ (2022) 239 Computer and Fluids <https://doi.org/10.1016/j.compfluid.2022.105391> accessed 4 April 2022, p 2, 3.

[24] Henk Versteeg and Wije Malalasekera, An Introduction to Computational Fluid Dynamics: The Finite Volume Method (2nd edn, Pearson 2007) 1, 2.

[25] Joaquim Martins, ‘Aerodynamic Design Optimization: Challenges and Perspectives’ (2022) 239 Computer and Fluids <https://doi.org/10.1016/j.compfluid.2022.105391> accessed 4 April 2022, p 8, 10, 13.

The second key technology is the Finite Element Analysis (FEA). In simple terms, this is (also) a heavily numerical method used to predict the behaviour of materials and more generally whole structures to external forces like stress and deformation.[26] This technique is used in conjunction with CFD, as it takes the data of loads that impact the frame of an aircraft to calculate the stress applied to its various parts and identify what adjustments may need to be made.[27] The 'Finite Element' nature of this method comes from the process used to divide the problem at hand into a finite number of groups (called elements) to avoid the complexity of trying to conduct the same calculation with an infinite number of (infinitely) smaller elements.[28]

The third key technology is Flight Control System Simulations (FCSS). This regards simulations that test how an aircraft's flight control systems respond to various situations. Flight control systems include the autopilot, the various physical moving parts that control the aircraft's movement such as the rudder and the flaps and the fly-by-wire, a system that replaces the conventional manual flight controls of an aircraft with an electronic interface. These simulations can be split into 3 categories. A pilot-in-the-loop simulation, which is useful for scenarios too dynamic and therefore complicated for a computer to recreate that a human can instead emulate the desired action.[29] A hardware-in-the-loop simulation refers to the process where one (or more) of the several pieces of physical equipment being tested in the real world is replaced by a software that is still connected to the rest physical equipment making it able to interact with the environment.[30] Lastly, an all-digital simulation, as the name suggests, refers to the testing of flight controls taking place in a completely virtual environment.[31] The latter type of simulation is the focus of this thesis as it is the one with the most potential for reducing costs and time of the aircraft manufacturing and testing process. It is also the most scalable option given its lack of restrictions for real time synchronisation efforts that the other two options suffer from, thus benefitting the most from computational power.

The fourth method is multi-physics simulations. This is the simulation of a wide array of physical phenomena at the same time creating overly complex and, therefore, computationally demanding scenarios. Multi-physics simulations essentially refers to the

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[26] Jacob Fish and Ted Belytschko, A First Course in Finite Elements (1st edn, Wiley 2007) 1, 2.
[27] ibid 4.
[28] Figure 1, Appendix B.
[29] Ivan Djokic and Zarko Barbaric, 'Flight Control System Development Using Simulation: An Integrated Approach' (2012) 19(2) Tehnicki Vjesnik 287, 290.
[30] ibid.
[31] ibid.

combination of aircraft-testing methods (like the 3 used before) that individually have a relatively narrow set of parameters but together can produce a more comprehensive and result that is often truer to reality.[32] The literature on multi-physics simulations is vast and examines the interactions between the various virtual-testing methods in an effort to discover and prove which ones work the best in a relevant situation.

2.3 AI in virtual testing

The application and integration of Artificial Intelligence is becoming progressively more prevalent in many scientific sectors and aviation is no exception. EASA, in their AI Roadmap, notes the significant impact that AI, and in particular its Machine Learning aspect, already has and will have on a lot of fields of modern aviation.[33] One such proposed application is in the aircraft design process, where EASA suggests it can help select the most appropriate non-regression tests.[34] Non-regression tests are a type of software testing that ensures that previously developed and tested software still performs as expected after changes or modifications are made. This use of ML can result in a more optimal validation of a system's performance and reliability to avoid redundancies or overlaps when a new set of tests is introduced. When ML is employed in the selection of such non-regression sets involving large datasets, it has been proven that it fares better than more conventional methods in finding the shortest way possible to an answer by avoiding as many overlapping features as necessary to achieve its goal.[35]

Another important application of AI is in the physics simulations during virtual flight-testing. As explained earlier, running physics simulations and especially when it comes to fluids, requires enormous computational power and the traditional methods like CFD and FEA are successful mainly because they smooth down the processed data to compensate for the complexity of the otherwise 'infinite' elements. One of the most promising propositions is supporting these traditional methods with ML methods.[36] An experiment conducted on the application of AI to calculate turbulent fluid flow – arguably one of the most complicated phenomena to simulate due to its chaotic and everchanging nature – had the ML programme

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[32] Marc Errera and others, 'Multi-Physics Coupling Approaches for Aerospace Numerical Simulations' (2011) 2 Aerospace Lab 1, 2.

[33] European Union Aviation Safety Agency, Artificial Intelligence Roadmap: A Human-Centric Approach to AI in Aviation (European Union Aviation Safety Agency 2020) 7-11.

[34] ibid 8.

[35] Mariana Silva, 'Reduction of Non-Regression Time Through Artificial Intelligence' (Universidade Do Porto 2020) 25-37.

[36] Dmitrii Kochkov and others, 'Machine Learning–Accelerated Computational Fluid Dynamics' (2021) 118(21) Proceedings of the National Academy of Sciences.

produce an immense number of much more accurate equations (instead of averaging the equations like FEA models do) achieving this feat 80 times quicker than the non-ML-optimised process would take.[37] It is worth mentioning that while the simulation of turbulence is a part of the design process, it also serves as a form of testing. The AI model is tested against the chaotic and everchanging nature of turbulence to see how well it can predict and handle such conditions. EASA also suggests that ML can be used to optimise certain qualification processes that require the demonstration of physical phenomena such as electromagnetic related phenomena that can be disruptive to avionics.[38] ML technology could, once again, provide more efficient techniques to mitigate any undesirable interactions between the aircraft and such physical phenomena, by simulating and analysing said interactions and providing the most optimal solutions or developing protective measures.[39]

2.4 AI dependency

Implementing AI in any field comes with risks that need to be accounted for and EASA recognises these in their AI strategy. This part groups them into two central ones so it must be noted that there are several risks that can be equally important yet, they are often co-dependent. One of the risks that is common across most of the fields where AI sees ample use is algorithmic bias and inaccuracies due to the data quality or quantity and human (lack of) supervision. AI works with whatever data it is fed and in areas like healthcare, welfare, insurance and banking it is expected and has been the case that the result of its decision-making process sometimes produces unwanted and unintended results like racial, social and economic profiling. The famous Dutch SyRI welfare detection case stands as an example of how questionable training data quality in combination with lack of transparency of the route that an ML system took to make a decision can have a negative and unforeseeable impact.[40] This does not fall far from how unrefined datasets and a black-box AI can affect the aircraft and the stakeholders during virtual flight testing. Depending on the datasets that the algorithm is fed it can create excellent results that achieve its optimisation goals but could also produce errors which may lead to more

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[37] ibid (pdf pages) 1, 2.

[38] European Union Aviation Safety Agency, Artificial Intelligence Roadmap: A Human-Centric Approach to AI in Aviation (European Union Aviation Safety Agency 2020) 8.

[39] Simon De Ridder and others, ' Machine-Learning-Based Hybrid Random-Fuzzy Uncertainty Quantification for EMC and SI Assessment ' (2020) 62(6) IEEE Transactions on Electromagnetic Compatibility 2538, 2543, 2546.

[40] — —, ‘Profiling and SyRI’ (The Public Interest Litigation Project, 11 December 2015, updated 23 April 2020) <https://pilpnjcm.nl/en/dossiers/profiling-and-syri/> access 8 April 2023)

wasted time in locating and fixing the issue or worse, it could be overlooked resulting in a more catastrophic scenario when the aircraft is finally physically flown.

Another challenge regarding the ‘human supervision’ element, is determining how much independence will be given to AI. Processes that are totally automated by AI have produced unwanted results with a popular example being Microsoft’s chatbot “Tay” that in the 24 hours of processing data from Twitter users it mimicked their interactions and posted offensive content leading to its swift termination by Microsoft.[41] Equating this to a situation in a physics simulation where a ML tool is left unattended to keep conducting the simulation, analysing the results and finding a more efficient way would lead to a circular and arguably restricted use of the algorithm. In such a process, it is very unlikely that something detrimental will occur given the set limitations and human intervention could happen every (x) number of cycles. On the other hand, ML could be less restricted and instead of that limited and exclusive repetition of the simulations, it may be left to use the data of each simulation to proceed with the next steps such as running non-regression tests, revamping and finishing the design of the aircraft, creating safety protocols and after finishing all that work, could potentially begin looking for more efficient ways to complete these tasks by creating shortcuts between the different stages and even altering its own algorithm to optimise it. These shortcuts could become difficult at tracking down and interpreting, an issue known as the black box problem.[42] In this scenario, the AI is left almost completely unsupervised and a human would only receive the final product, that being the virtual model of the finished aircraft with all the flight-test results required for the certifications of airworthiness. Although that element of independence surrendered to the AI would definitely be a tremendous time saver for the aircraft manufacturing and certification process, the problem that may have become obvious is that when the first human intervention occurs, they will either have to trust that the AI has not made any errors or go through a vigorous verification process of the produced data that may end up more time consuming than having intervened during one or more of the flight-testing tests. Therefore, complete reliance on AI, at least at the current stage of the available technology, does not seem reasonably justifiable and instead a middle ground needs to be found. EASA provides a rounded plan on how they will tackle all of these matters within the next decade and

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[41] Elle Hunt, ‘Tay, Microsoft's AI chatbot, gets a crash course in racism from Twitter’ (The Guardian, 24 March 2016) <https://www.theguardian.com/technology/2016/mar/24/tay-microsofts-ai-chatbot-gets-a-crash-course-in-racism-from-twitter> accessed 12 April 2023.

[42] Dwivedi YK and others, ‘Artificial Intelligence (AI): Multidisciplinary Perspectives on Emerging Challenges, Opportunities, and Agenda for Research, Practice and Policy’ (2021) 57 International Journal of Information Management (pdf) 6.

expresses their desire to implement AI and ML in aviation in all stages with the appropriate care without unnecessary hindrances.[43]

2.5 Conclusion

This chapter explored the current state of virtual flight-testing and manufacturing of aircraft by discussing the 4 key technologies of the process: Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA), Flight Control System Simulations (FCSS), and multi-physics simulations. AI and ML in particular has demonstrated potential to seriously improve the efficiency of virtual testing through design optimisation, error prediction and of course the simulation of complex and computationally demanding scenarios. The integration of ML tools in the traditional virtual testing technologies has produced promising results paving the way for AI for more extensive AI integration. Consequently, AI seems to be a great candidate for streamlining the certification process for new aircraft since it can utilise and analyse much larger and complex datasets that traditional methods struggle with. Although progress appears inevitable, and with EASA being a frontrunner in AI integration in aviation, the risks that come with AI were presented. The two general categories that encompass most of the associated risks are algorithmic, data and machine bias, including issues of data quality, and overreliance on AI. This chapter set the foundations for the central issue that virtual testing and AI carry when it comes to the certifications of airworthiness of the aircraft, being the regulatory obstacles, which will be discussed in the next chapters.

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[43] European Union Aviation Safety Agency, *Artificial Intelligence Roadmap: A Human-Centric Approach to AI in Aviation* (European Union Aviation Safety Agency 2020) 22.

Chapter 3: Current State of EU Legal Framework

3.1 Introduction

The combination of all the various methods for virtual testing and simulation in aviation and the introduction of AI in the blend demands an evaluation of the relevant regulatory framework. This chapter examines the current EU regulations on aircraft airworthiness and its approach to virtual manufacturing and flight-testing. The goal is to understand how EU law accommodates technological advancements for the initial airworthiness certification for commercial aircraft. This process will contribute to identifying and assessing both the opportunities and pitfalls of integrating virtual testing in the airworthiness certification process.

At this stage, a brief discussion regarding the problem of regulatory disconnection is essential. As Brownsword explains, technologies (and especially fast advancing ones) can outpace regulation and based on the nature of the disconnection he labels them as descriptive or normative.[44] Descriptive disconnection regards situations where the regulatory framework and its scope no longer aligns with the technological advancements.[45] In this context, the rapid advancements of AI and machine learning in aircraft simulations may outpace the existing regulations, as these regulations may be referring to an earlier and much different version of the technology and would instead result in absence of clarity, potentially hindering innovation in the industry. On the other hand, normative disconnection refers to the incompatibility of a new technology with the set of values on which the regulators relied upon when drafting the regulation.[46] In the case of AI in aircraft virtual testing, this would regard the ethical issues in various fields like transparency or biases that come from AI-driven decision-making suggesting that regulators may have to either amend or introduce new regulatory frameworks to cover these issues.

3.2 Initial airworthiness certification process and requirements

The initial certification of airworthiness for aircraft falls under the responsibilities of EASA and it is a complicated process that branches extensively to cover all the multitude of

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[44] Roger Brownsword, Rights, Regulation, and the Technological Revolution (Oxford University Press 2008) 162, 165.

[45] ibid 166.

[46] ibid.

requirements that ensure an aircraft is safe to be flown.[47] EASA has regulations, standards, and procedures in place that aircraft manufacturers must follow to acquire the initial certification (type-certificate). The process can be divided into five stages:

1. **Pre-application:** under Part 21.A.14 of Regulation 748/2012 any entity that wishes to apply for a type-certificate (TC) must demonstrate their capability to handle the relevant project by either holding a Design Organisation Approval (DOA) according to Subpart J or, if exempted, submit a statement of their intention to apply to EASA.[48] This statement must include an overview of all the substantial parts of their project to convince EASA that they are competent enough to carry it out.[49]
2. **Application:** the applicant will submit a formal application to EASA under Part 21.A.15 of Regulation 748/2012 which will contain details of the aircraft's design along with all the necessary documents that EASA requires to verify compliance with the relevant certification specifications (CSs).[50] EASA classifies these CSs in small airplanes, large airplanes and small rotorcrafts but the main focus will be the large airplanes covered by CS-25.[51]
3. **Compliance Demonstration:** the applicant needs to demonstrate that the aircraft complies with all relevant certification specifications.[52] They must present proof in the form of data collected from the various tests measuring aspects like structural integrity, controllability and manoeuvrability, performance of avionics, safety systems and several more.[53] The results of these tests must be recorded and systematically submitted to EASA while the applicant actively refines the aircraft itself as well as the employed

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[47] Parliament and Council Regulation (EU) 2018/1139 of 4 July 2018 on Common Rules in the Field of Civil Aviation and Establishing a European Union Aviation Safety Agency, and Amending Regulations (EC) No 2111/2005, (EC) No 1008/2008, (EU) No 996/2010, (EU) No 376/2014 and Directives 2014/30/EU and 2014/53/EU of the European Parliament and of the Council, and Repealing Regulations (EC) No 552/2004 and (EC) No 216/2008 of the European Parliament and of the Council and Council Regulation (EEC) No 3922/91 [2018] OJ L212/1, art 1(e).

[48] Commission Regulation (EU) No 748/2012 of 3 August 2012 Laying Down Implementing Rules for the Airworthiness and Environmental Certification of Aircraft and Related Products, Parts and Appliances, as well as for the Certification of Design and Production Organisations (recast) [2012] OJ L224/1, pt 21.A.14, 21.A.231-21.A.265.

[49] ibid, pt 21.A.14(b), 21.A.14(c).

[50] ibid, pt 21.A.15; European Union Aviation Safety Agency, Easy Access Rules for Airworthiness and Environmental Certification (Regulation (EU) No 748/2012) (European Union 2023) 94-98.

[51] European Union Aviation Safety Agency, Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes (CS-25) (European Union 2021).

[52] Commission Regulation (EU) No 748/2012 of 3 August 2012 Laying Down Implementing Rules for the Airworthiness and Environmental Certification of Aircraft and Related Products, Parts and Appliances, as well as for the Certification of Design and Production Organisations (recast) [2012] OJ L224/1, pt 21.A.14.

[53] ibid, pt 21.A.20.

tests in order to satisfy the demanding standards set under the CSs.[54] In this continuity lies the distinction of the Compliance Demonstration stage from the Application stage with the latter referring instead to the initial one-and-done instance of submitting a form to EASA.

4. **Compliance Verification:** EASA continuously reviews the applicant's documentation and assesses the aircraft's compliance with the certification specifications. This process can involve independent tests, inspections, or analyses conducted by EASA experts, as well as other specialist entities.[55] EASA is expected to perform the review (and any other task within its power) in line with the principle of proportionality and decide based on a risk and performance assessment.[56]
5. **Issue of the Type-Certificate (TC):** once EASA determines that an aircraft satisfies the necessary certification specifications and other requirements it may move to issue a TC showing that the aircraft is airworthy. With the TC, the applicant will be able to manufacture and operate the aircraft within the EU. For this part, it is worth mentioning that there are 3 main certificates; Type-Certificate, Restricted Type-Certificate and Supplemental Type-Certificate.[57] TC is the main and most relevant certificate for the present discussion as the other two allow only restricted operations of an aircraft or regard some later modification to the original design respectively.[58]

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[54] European Union Aviation Safety Agency, Easy Access Rules for Airworthiness and Environmental Certification (Regulation (EU) No 748/2012) (European Union 2023) 104-107; European Union Aviation Safety Agency, Easy Access Rules for Acceptable Means of Compliance for Airworthiness of Products, Parts and Appliances (AMC-20) (European Union 2021).

[55] Commission Regulation (EU) No 748/2012 of 3 August 2012 Laying Down Implementing Rules for the Airworthiness and Environmental Certification of Aircraft and Related Products, Parts and Appliances, as well as for the Certification of Design and Production Organisations (recast) [2012] OJ L224/1, pt 21.A.33; Parliament and Council Regulation (EU) 2018/1139 of 4 July 2018 on Common Rules in the Field of Civil Aviation and Establishing a European Union Aviation Safety Agency, and Amending Regulations (EC) No 2111/2005, (EC) No 1008/2008, (EU) No 996/2010, (EU) No 376/2014 and Directives 2014/30/EU and 2014/53/EU of the European Parliament and of the Council, and Repealing Regulations (EC) No 552/2004 and (EC) No 216/2008 of the European Parliament and of the Council and Council Regulation (EEC) No 3922/91 [2018] OJ L212/1.

[56] Parliament and Council Regulation (EU) 2018/1139 of 4 July 2018 on Common Rules in the Field of Civil Aviation and Establishing a European Union Aviation Safety Agency, and Amending Regulations (EC) No 2111/2005, (EC) No 1008/2008, (EU) No 996/2010, (EU) No 376/2014 and Directives 2014/30/EU and 2014/53/EU of the European Parliament and of the Council, and Repealing Regulations (EC) No 552/2004 and (EC) No 216/2008 of the European Parliament and of the Council and Council Regulation (EEC) No 3922/91, arts 4(1)(e), 4(2), recital 12.

[57] Commission Regulation (EU) 748/2012 of 3 August 2012 Laying Down Implementing Rules for the Airworthiness and Environmental Certification of Aircraft and Related Products, Parts and Appliances, as well as for the Certification of Design and Production Organisations (recast) [2012] OJ L224/1, art 1(a).

[58] ibid, parts 21.A.21, 21.A.23, 21.A.111-21.A.115.

The process described above is, for the most part, the standard process that any aircraft will need to obtain an initial airworthiness certification. However, it is important to note that different classes of aircraft, specific technologies, designs and other factors can make the process a lot more complicated. Fortunately, EASA consolidates these extensive sets of requirements in the comprehensive “Easy Access Rules” and CSs.

3.3 EU regulations governing aircraft airworthiness

The EU body of aviation law covers in detail the requirements for an aircraft’s initial and continued classification as airworthy to the highest safety and environmental standards. The foundation of the EU's regulatory framework for aircraft airworthiness is Regulation 2018/1139 establishing the common rules for civil aviation and the EASA itself.[59] This legislation establishes the fundamental principles and requirements for certifying, maintaining, and operating aircraft in the EU. It also defines the powers and responsibilities of EASA and the national aviation authorities of Member States. The next key piece of legislation is Regulation 748/2012, which directly addresses specifics of obtaining airworthiness and environmental certifications for aircraft and certifications for the involved organisations that carry out aviation projects.[60] This regulation delves into the technical and procedural requirements that all aircraft stakeholders must adhere to and demonstrate their conformity to EASA in order to obtain the necessary certification of airworthiness.

Both aforementioned key pieces of legislation are supplemented by various regulations that cover additional airworthiness requirements, administrative procedures, stakeholder responsibilities and maintenance related instructions. Regulations 2020/1159 and 2015/640 lay down such additional airworthiness standards, provide administrative procedures and address newly emerging risks regarding continuing airworthiness.[61] Furthermore, Regulations 2021/1963 and 1321/2014, apart from technical requirements, also establish administrative

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[59] Parliament and Council Regulation (EU) 2018/1139 of 4 July 2018 on Common Rules in the Field of Civil Aviation and Establishing a European Union Aviation Safety Agency, and Amending Regulations (EC) No 2111/2005, (EC) No 1008/2008, (EU) No 996/2010, (EU) No 376/2014 and Directives 2014/30/EU and 2014/53/EU of the European Parliament and of the Council, and Repealing Regulations (EC) No 552/2004 and (EC) No 216/2008 of the European Parliament and of the Council and Council Regulation (EEC) No 3922/91 [2018] OJ L212/1.

[60] Commission Regulation (EU) 748/2012 of 3 August 2012 Laying Down Implementing Rules for the Airworthiness and Environmental Certification of Aircraft and Related Products, Parts and Appliances, as well as for the Certification of Design and Production Organisations (recast) [2012] OJ L224/1.

[61] Commission Regulation (EU) 2020/1159 of 5 August 2020 Amending Regulations (EU) No 1321/2014 and (EU) No 2015/640 as Regards the Introduction of New Additional Airworthiness Requirements [2020] OJ L257/14; Commission Regulation (EU) 2015/640 of 23 April 2015 on additional airworthiness specifications for a given type of operations and amending Regulation (EU) No 965/2012 [2015] OJ L106/18.

procedures to ensure that maintenance and continued airworthiness checks take place while.[62] Initial airworthiness falls outside of the scope of these regulations, which makes them not directly relevant to the objective of this thesis.

3.4 Supporting legislation

Among these numerous EU statutory instruments that are currently in place, one of the aims of the thesis is to locate what parts accommodate virtual flight-testing, manufacturing and similar simulations for a new aircraft to obtain its initial airworthiness certification before having been physically created. A great starting point for this discussion is Regulation 2018/1139, which, as explained earlier, gives EASA its status as the regulating and overseeing authority of civil aviation in the EU. Article 86 of this regulation constitutes an explicit promotion of innovation as it requires EASA to facilitate research and development for the introduction of new technologies in aviation.[63] This facilitation translates in EASA initiating research projects, provide financial or expert guidance to other institutions carrying out research and experimentation of any new technologies.[64] This initiative is evidently already taking place in the field of AI-driven systems in aircraft simulations for certification with projects like KIEZ4.0 AI which aims to assess the suitability of different classes of AI for certification process of commercial aircraft.[65] EASA is also expected to work closely with stakeholders (mainly EU institutions but also third parties) to review, propose amendments and implement regulations on all aviation related fields meaning that adapting to the integration of new technologies for a more virtual certification process is not just within their power but it is a prerequisite for the smooth cooperation of aviation law and any technological advancement.[66] Additionally, the risk and performance-based approach that EASA adopts allows for a dynamic regulatory system with the flexibility to adapt to technological changes while focusing on

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[62] Commission Regulation (EU) 1321/2014 of 26 November 2014 on the Continuing Airworthiness of Aircraft and Aeronautical Products, Parts and Appliances, and on the Approval of Organisations and Personnel Involved in these Tasks [2014] OJ L 362/1; Commission Regulation (EU) 2021/1963 of 8 November 2021 Amending Regulation (EU) No 1321/2014 as Regards Safety Management Systems in Maintenance Organisations and Correcting that Regulation [2021] OJ L 400/18.

[63] Parliament and Council Regulation (EU) 2018/1139 of 4 July 2018 on Common Rules in the Field of Civil Aviation and Establishing a European Union Aviation Safety Agency, and Amending Regulations (EC) No 2111/2005, (EC) No 1008/2008, (EU) No 996/2010, (EU) No 376/2014 and Directives 2014/30/EU and 2014/53/EU of the European Parliament and of the Council, and Repealing Regulations (EC) No 552/2004 and (EC) No 216/2008 of the European Parliament and of the Council and Council Regulation (EEC) No 3922/91 [2018] OJ L212/1, art 86

[64] ibid, arts 75(2)(j), 86(2), 86(3).

[65] European Union Aviation Safety Agency, 'KIEZ4.0 AI: Artificial Intelligence for European Certification Actions with Industry 4.0 Aspects' <https://www.easa.europa.eu/en/research-projects/kiez40-ai> (European Union Aviation Safety Agency, 29 Jul 2021) accessed 15 May 2023.

[66] ibid, arts 1(2), 75(2)(b), 75(2)(c), 75(2)(j), recitals 36, 40.

achieving certain safety or environmental results rather than simply enforcing prescribed rules.[67]

The next piece of legislation which addresses the specifics of airworthiness certification is Regulation 748/2012. According to this regulation, ground and flight tests are required for the aircraft to be certified and physical tests are presented as the intended method while it allows for “Acceptable Means of Compliance” (AMC) and “Certification Specifications” (CS) to be drafted by EASA.[68] AMCs and CSs represent a non-binding set of standards by which compliance with the regulatory requirements can be demonstrated. EASA acknowledges these as a way to demonstrate compliance with a regulatory requirement. Part 21 of the regulation calls for CSs to be created and followed for the demonstration of compliance.[69] For example, CS-25 permits as proof of compliance for a wide range of flight related tests to be either the data obtained from physical tests or any other tests of similar accuracy.[70] This can essentially translate to data emanating from simulated flights being acceptable means of compliance with the prerequisite that said tests can produce similarly accurate results to physical flight tests. Another similar instance of the flexibility that the regulation provides comes from EASA’s AMC 21.A.15(b) which on the one hand lists the type of tests (physical or virtual) the results of which need to be presented but, on the other hand, also explicitly requires that the applicant stipulates any deviation from said AMCs.[71] The European Aviation Safety Agency (EASA) acknowledges AMCs as a valid means of compliance, as evidenced by one of their past changes in certification rules.[72] These changes have seen a shift from prescriptive design requirements to performance-based standards, with many of the AMCs being transferred out of the rules and into consensus standards. This shift was informed by the experience gained with the Light Sport Aircraft (LSA) structure, where the use of consensus standards as a means of compliance was considered acceptable.[73] The consensus standards, developed by ASTM International

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[67] ibid, arts 4(1)(e), 4(2), recital 12.

[68] Commission Regulation (EU) 748/2012 of 3 August 2012 Laying Down Implementing Rules for the Airworthiness and Environmental Certification of Aircraft and Related Products, Parts and Appliances, as well as for the Certification of Design and Production Organisations (recast) [2012] OJ L224/1, art 10, part 21.A.18(c).

[69] ibid, parts 21.A.17, 21.A.18.

[70] European Union Aviation Safety Agency, Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes (CS-25) (European Union 2021), CS 25.21(a)(1).

[71] European Union Aviation Safety Agency, *Easy Access Rules for Airworthiness and Environmental Certification* (Regulation (EU) No 748/2012) (European Union 2023) 98.

[72] European Union Aviation Safety Agency, Easy Access Rules for Normal-Category Aeroplanes (CS-23) (CS Amendment 5, AMC/GM Issue 1) (European Union 2017).

[73] Nicholas K Borer, ‘Development of a New Departure Aversion Standard for Light Aircraft’ (17th AIAA Aviation Technology, Integration, and Operations Conference, Denver, June 2017).

Committee F37 on Light Sport Aircraft, include input from producers, users, and general interest members, including regulators.[74] This process allows for the standards to be maintained, modified, updated, and improved, providing a dynamic and adaptable framework for AMCs and CSs. This infers that such deviations are acceptable, but need to be reviewed and approved by EASA also meaning that if EASA ends up approving a new method, process or technology for the testing and the demonstration of compliance, then that method would not be far from becoming an "acceptable means of compliance.

In the context of determining the functional equivalence of virtual and physical tests, it is crucial to consider the role of numerical simulation in aircraft design. As highlighted in the paper by Kroll et al, high-fidelity methods are increasingly being used in the design and flight testing of aircraft.[75] These methods involve the implementation of different aircraft disciplines for multidisciplinary analysis and optimisation of realistic aircraft configurations.[76] To establish functional equivalence, the criteria could include the accuracy of these numerical methods in predicting the performance of the aircraft under various conditions, the efficiency of reduced order methods for load analysis, and the effectiveness of the multidisciplinary optimisation process based on a multi-level/variable-fidelity approach. However, these criteria also present challenges. For instance, developing accurate numerical methods and integrating different aircraft disciplines may require significant expertise and computational resources.[77] Moreover, the use of reduced order methods for load analysis and a multi-level/variable-fidelity approach for optimisation introduces additional complexities in the certification process. These approaches comprise simplified versions of the actual full physics engaged and thus ensuring these simplified models accurately represent real-world systems is challenging due to inherent assumptions. Furthermore, these models can act as "black boxes," complicating the certification process due to a lack of transparency. Lastly, incorporating these methods into existing certification processes may require significant procedural changes and updates to regulatory guidelines. The solution to these challenges could involve updating the AMCs to explicitly include these high-fidelity methods and criteria for determining functional

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[74] ibid.

[75] Norbert Kroll and others, 'DLR project Digital-X: towards virtual aircraft design and flight testing based on high-fidelity methods' (2016) 7(1) CEAS Aeronautical Journal 3.

[76] ibid, 4.

[77] ibid, 15.

equivalence, and providing clear guidance on how these methods should be evaluated in the certification process.

All these different provisions provide an overall degree of flexibility in the certification process that allows alternative methods to be used if it can be proven that an equivalent level of safety is achieved for the new aircraft. However, the legislation lacks explicit guidelines describing the type, manner and extent to which particular new technologies can produce a level of simulation with data quality equivalent (or better) to that of physical flight and part testing.

3.5 Conclusion

The evaluation of the EU legislative framework reveals an effort to accommodate technological advancements in aviation, specifically in the context of virtual flight-testing, manufacturing, and simulations (with or without AI in the mix) in the initial airworthiness certification process. The current regulatory framework in combination with EASA’s comprehensive guidelines and specifications, provides avenues for the integration of such innovations. Notably, EASA's responsibility to promote innovation paired with its risk and performance-based approach facilitate the potential application of virtual testing methodologies, presenting a flexible system capable of evolving with technological advancements.

However, the lack of explicit guidelines creates ambiguities that point towards a potential descriptive disconnection. The question of how simulated testing data quality can match or supersede that of physical tests is not addressed. In order to draw the full potential of virtual testing certification of airworthiness and the implementation of machine-learning algorithms a discussion must take place on possible legislator amendments or other alternatives that may sufficiently regulate these new methods without unnecessarily hindering innovation. The next chapter delves into how any such amendments of propositions can be created to ensure that EU law can properly adapt to allow aircrafts to obtain their initial airworthiness certification by avoiding as many physical tests as possible.

Chapter 4: Bridging the Gap

4.1 Introduction

In the context of the rapidly evolving landscape of aviation technology, particularly with the advent of artificial intelligence and virtual testing, it becomes imperative to scrutinise the adaptability of existing regulatory frameworks. These technological advancements raise the prospect of significant shifts in the processes of aircraft certification, introducing concepts such as virtual manufacturing and flight-testing. While these innovations have the potential to transform the sector, they also challenge the current understanding and regulations of aircraft airworthiness certification.

The previous chapter investigated the current EU legislative and regulatory framework’s capacity to accommodate these virtual testing methodologies. Although there are elements within the regulations that could be interpreted to accommodate virtual testing, it was clear that these provisions were not originally designed with such concepts in mind. This raises the pertinent question of whether the current framework is fully equipped to manage the complexities and risks associated with these advanced technologies and if amendments are needed. This chapter, therefore, aims to provide a deeper analysis of the current framework's compatibility with virtual manufacturing and flight-testing, exploring the potential need for amendments, suggesting specific changes, and proposing new policies that could facilitate the smooth integration of these emerging technologies within the realm of EU airworthiness legislation.

4.2 Regulatory incompatibility

The existing legislative and regulatory framework for aircraft certification in the European Union, as outlined in Regulation 748/2012 and guided by EASA, was designed to ensure the safety and airworthiness of aircraft through rigorous physical testing and inspection processes.[78] However, the advent of advanced technologies such as artificial intelligence (AI), virtual manufacturing, and flight-testing has challenged the adequacy of this framework. The existing framework does not explicitly recognise or accommodate virtual manufacturing and flight-testing processes as certification methods (at least not to any significant extent). The

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[78] Commission Regulation (EU) 748/2012 of 3 August 2012 Laying Down Implementing Rules for the Airworthiness and Environmental Certification of Aircraft and Related Products, Parts and Appliances, as well as for the Certification of Design and Production Organisations (recast) [2012] OJ L224/1, art 10, part 21.A.18(c).

regulations are heavily grounded in traditional, physical methods of aircraft construction and testing. This raises questions about the legal validity of virtual processes and the certification of aircraft produced through these methods.

Ritter et al have published a conference paper on the particular matter of virtual certifications which provides an insightful example of this issue.[79] It discusses the use of high-fidelity multidisciplinary simulations for virtual flight tests, which can significantly reduce the time and cost associated with traditional flight tests.[80] However, the current EU regulatory framework does not provide clear guidance on how these virtual tests should be conducted, evaluated, or recognised in the certification process. The paper further elaborates on the concept of a virtual flight test, which is a “multidisciplinary numerical simulation where aerodynamics, flight mechanics, and structural dynamics are coupled in space and time.”[81] This process is part of a comprehensive model known as Flying the Equations (FTE) and Flying Through the Database" (FTD), which are used to generate a Virtual Aircraft Model.[82] This model is then used in a full-flight simulator to evaluate specific aspects of an aircraft.[83] However, the current EU regulatory framework does not provide clear guidance on how these virtual flight tests should be conducted, evaluated, or recognised in the certification process.

The current legislative and regulatory framework may not be equipped to adequately assess the risks associated with AI and virtual processes. For instance, algorithmic bias is a new type of risk that is not addressed in the existing regulations. According to a study by Nishant et al, algorithmic bias in AI systems can lead to skewed results, which can have significant implications in the aviation industry.[84] For example, if an AI system used in virtual manufacturing or flight-testing is trained on biased data, it could produce results that favour certain conditions over others, leading to potential safety risks.

Another risk is the overreliance on AI. As discussed in the article by Corsello and Santangelo, overreliance on AI could lead to complacency among human operators, potentially resulting in overlooked errors or oversights in the virtual manufacturing and flight-testing

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[79] Markus Ritter and others, ‘Virtual Aircraft Technology Integration Platform: From Virtual Flight Testing towards Simulation-Based Certification’ (AIAA Scitech 2021 Forum, virtual, January 2021) <https://doi.org/10.2514/6.2021-1203> accessed 18 June 2023.

[80] ibid, p 2.

[81] ibid, p 5.

[82] ibid, p 3, 4.

[83] ibid, p 4.

[84] Rohit Nishant, Dirk Schneckenberg and MN Ravishankar, ‘The Formal Rationality of Artificial Intelligence-based Algorithms and the Problem of Bias’ (2023) 0(0) Journal of Information Technology 1.

processes.[85] This is particularly concerning in the aviation industry, where safety is paramount and human oversight is crucial in identifying and addressing potential issues.

While the current EU legislative and regulatory framework has served well in the era of physical manufacturing and testing, it appears to be ill-equipped to accommodate the emerging virtual processes. This incompatibility poses significant challenges to the integration of advanced technologies in aviation and calls for a thorough review and amendment of the existing framework.

4.3 Need for amendment of the current framework

Although it may lack on certain aspects, the current framework is not entirely incompatible with these new technologies, but it may rather require amendments to better align with the unique needs and challenges that these technologies present. One of the key areas where the current framework may fall short is in its provisions for testing and certification. As per the EU Regulation 748/2012, aircraft are required to undergo rigorous testing to ensure their airworthiness. However, these provisions were established with traditional manufacturing and testing processes in mind and may not fully account for the complexities and nuances of virtual processes. As such, there may be a need to amend these provisions to better accommodate virtual manufacturing and flight-testing. The descriptive disconnect can be addressed by updating the regulations to explicitly recognize and accommodate the use of AI and machine learning in virtual testing and certification. This could involve defining new standards for virtual testing, establishing guidelines for the use of AI and machine learning in this context, and creating mechanisms for the validation and certification of virtual testing results. Creating mechanisms for the validation and certification of virtual testing results could involve establishing a set of criteria that virtual tests must meet to be considered valid. These criteria could be based on the principles outlined in the AI Act, such as transparency, accountability, and robustness.[86] For example, a valid virtual test might need to provide clear documentation of the testing process, demonstrate that it can reliably produce accurate results, and include mechanisms for identifying and correcting errors. The AI Act also emphasises the

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[85] Antonio Corsello and Andrea Santangelo, ‘May Artificial Intelligence Influence Future Pediatric Research? The Case of ChatGPT’ (2023) 10 Children 757, 758.

[86] Parliament, ‘Proposal for a Regulation of the European Parliament and of the Council Laying Down Harmonised Rules on Artificial Intelligence (Artificial Intelligence Act) and Amending Certain Union Legislative Acts’ (2021) COM 206 final.

importance of human oversight, which could be incorporated into the certification process by requiring that virtual tests be reviewed and approved by a human expert.[87]

Addressing the normative disconnect, on the other hand, could involve a more fundamental reassessment of the values and principles underlying the regulations. This could involve engaging in a broader societal dialogue about the ethical implications of AI and machine learning, and developing new regulatory principles that reflect a consensus on these issues. Consider the case of the Titan Submersible, a real-world example of the consequences of gross disregard of certification and its purpose. The director of OceanGate, which built Titan, ignored expert warnings about the submersible's flaws and its unsuitability for deep dives.[88] They also refused to seek any form of certification for it. This disregard for the certification process and the principles it upholds led to a tragic accident. This example illustrates the dangers of a normative disconnect, where the values and principles underlying the regulations are not respected. Addressing this disconnect could involve a more fundamental reassessment of the values and principles underlying the regulations, emphasizing their importance in ensuring safety and mitigating risks, even in the face of advanced technologies like AI and virtual testing. These technologies also introduce new complexities and risks that the current legislative and regulatory framework may not be fully equipped to manage. This could involve establishing mechanisms for ongoing monitoring and assessment of these technologies, and for updating the regulations as needed to address emerging issues..

The work by Xie et al provides a compelling argument for these amendments.[89] They propose an approach to incorporate certification considerations into early design stages using virtual certification techniques.[90] They developed a certification analysis module that transforms regulations from textual documents to quantitative constraint functions, ensuring the certification constraint check of the design through physics-based analysis.[91] Essentially, they created a tool that takes the rules for aircraft certification, which are usually written in legal documents, and turns them into mathematical equations. These equations can then be used to check if an aircraft design meets all the necessary requirements, using computer

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[87] ibid, ch 1.2, 2.3 (Explanatory Memorandum).

[88] Nicholas Bogel-Burroughs, Jenny Gross and Anna Betts, 'OceanGate Was Warned of Potential for 'Catastrophic' Problems with Titanic Mission' (New York Times, 20 June 2023) <https://www.nytimes.com/2023/06/20/us/oceangate-titanic-missing-submersible.html> accessed 4 July 2023,

[89] Xie J and others, 'A Model-Based Aircraft Certification Framework for Normal Category Airplanes' (AIAA Aviation 2019 Forum, Dallas, June 2019).

[90] ibid.

[91] ibid, 3-11.

simulations and analysis.[92] This makes the certification process more efficient and precise, especially for aircraft that was designed and tested using virtual means. Therefore, this approach could mitigate potential risks of increased costs due to necessary redesigns for compliance with certification requirements. The authors also note that the current certification process is conducted at a later stage when there is little design freedom left.[93] If any necessary redesign has to be made for the compliance of certification requirements at this stage, the associated cost could be significantly high. This further justifies the need for amendments to the current framework to allow for certification considerations in the early stages of aircraft design.

The ESWIRP project, highlighted in Boyet's publication, serves as a significant case study demonstrating the potential integration of virtual methodologies within the aviation sector.[94] The project's objective was to enhance the operational efficiency of three key wind tunnels across Europe by creating a universal virtual wind tunnel model.[95] This innovative model offered operators the ability to evaluate the impact of various control parameters on test conditions, thereby equipping the user community with a more effective tool for putting their novel concepts to trial.[96] This instance accentuates the advantages of virtual techniques and underscores the necessity for the existing legislative and regulatory framework to evolve in response to these novel technologies.

If the current framework is not amended to accommodate these new technologies, it could potentially hinder the development and implementation of innovative ideas in the aviation industry. The potential implications of this could be far-reaching, affecting not only the industry itself but also the broader economy and society. For instance, if the current framework is unable to accommodate virtual manufacturing and flight-testing, it could potentially slow down the development of more efficient and environmentally friendly aircraft, which could in turn have implications for the EU's climate goals.

4.4 Proposed legislative amendments

The EU legislative framework, particularly Regulation (EU) 748/2012, is primarily designed for traditional methods of aircraft certification. However, the advent of virtual

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[92] ibid, 11.
[93] ibid, 2.
[94] Guy Boyet, ‘ESWIRP: European Strategic Wind Tunnels Improved Research Potential Program Overview’ (2018) 9 CEAS Aeronautical Journal 249.
[95] ibid, 250.
[96] ibid, 263-266.

manufacturing and flight-testing introduces complexities that the existing regulations may not fully address. A key area for amendment is the definition of 'type-certification' in Article 3 of Regulation (EU) 748/2012.[97] Currently, type-certification is granted based on the assessment of an aircraft's design. With virtual manufacturing, the 'design' extends beyond physical attributes to include the algorithms and software controlling virtual components. Therefore, an amendment to the definition of 'type-certification' is proposed to encompass the certification of software and algorithms used in virtual manufacturing and flight-testing. Requiring new standards for their evaluation would ensure their reliability and accuracy, and promote innovation and safety in aviation.

Another amendment pertains to the demonstration of compliance in Article 21 of Regulation (EU) 748/2012.[98] The current regulation stipulates that compliance should be demonstrated through tests or analysis. In the context of virtual manufacturing and flight-testing, compliance may also involve simulations or virtual tests.[99] Thus, it is proposed that Article 21 be amended to explicitly allow for compliance demonstration through simulations or virtual tests including AI and ML driven tests.

The integration of these techniques into the EU legislative and regulatory framework would require amendments to existing regulations. Specifically, provisions related to the design and certification process in Regulation (EU) 748/2012 would need to be revised to explicitly allow for the integration of certification considerations in the early stages of aircraft design. Similarly, the provisions related to the demonstration of compliance would need to be amended to allow for the use of quantitative constraint functions and physics-based analysis in the demonstration of compliance. This would create a flexible environment to facilitate the integration of these technologies into the aviation industry while ensuring that associated risks are adequately managed.

4.5 Additional proposals for regulating the process

4.5.1 Phased Certification Process

The implementation of a phased certification process specifically designed for virtual manufacturing and flight-testing could revolutionise the aircraft design and development process. This process would allow for the progressive validation of virtual testing results at

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[97] Commission Regulation (EU) 748/2012 of 3 August 2012 Laying Down Implementing Rules for the Airworthiness and Environmental Certification of Aircraft and Related Products, Parts and Appliances, as well as for the Certification of Design and Production Organisations (recast) [2012] OJ L224/1, art 3.

[98] ibid, art 21.

[99] ibid, arts 21.A.17, 21.A.18.

different stages of the aircraft design and development process, even before the aircraft takes a physical form. The phased certification process could be divided into early stage, mid-stage, and final stage certifications, each validating different aspects of the aircraft's design and its performance under a range of simulated conditions. The three stages of the phased certification process - early, mid, and final - are proposed to align with the progressive nature of aircraft design and development. In the early stage, preliminary design concepts can be validated. The mid-stage allows for validation of more detailed design and performance aspects as the aircraft design evolves. The final stage serves to validate the complete design under a range of simulated conditions. A follow-up post-production validation phase could be conducted to confirm that the physical aircraft performs as expected based on the virtual testing results.

The phased certification process aligns well with the approach discussed in the paper by Denham et al which emphasises the use of flight dynamics models and non-deterministic simulations to predict the performance of modified aircraft configurations.[100] This approach could be integrated into the phased certification process, where these models and simulations could be used to validate the aircraft's design and performance at different stages of development. As an additional benefit, the paper's focus on estimating performance and associated uncertainty could be particularly relevant for the post-production validation phase of the phased certification process.[101] Here, the predictions made by the flight dynamics models and simulations could be compared with the actual performance of the physical aircraft, providing a robust method for validating the effectiveness of the virtual testing process. This could enhance the reliability and credibility of the phased certification process, promoting its acceptance within the aviation industry and regulatory bodies. The phased certification process, complemented by the methodologies discussed by Denham et al, could contribute to a comprehensive and robust framework for the certification of aircraft developed through virtual manufacturing and flight-testing.

4.5.2 VR Inspection System

The use of virtual reality technology could transform the aircraft certification process. A VR inspection system would allow inspectors to conduct a detailed inspection of the virtual aircraft in a simulated environment, examining every part of the aircraft in detail, simulating various conditions, and even conducting inspections remotely.

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[100] Denham CL, Patil M, Roy CJ and Alexandrov N, ‘Framework for Estimating Performance and Associated Uncertainty for Modified Aircraft Configurations’ (2022) 9 Aerospace 490; In simple terms the approach uses computer models and simulations to predict how changes to an aircraft's design might affect its performance.

[101] ibid, 491.

A paper by Vora et al provides empirical evidence on how VR technology can enhance the accuracy and efficiency of aircraft inspection.[102] In the context of the proposed VR inspection system, these findings could be particularly relevant and despite the considerations posed in this publication dating back to 2001, the current technology only further supports these claims.[103] The detailed inspection enabled by VR technology could significantly improve the accuracy of the certification process, reducing the likelihood of errors or oversights. Furthermore, the ability to simulate various conditions could provide inspectors with a comprehensive understanding of the aircraft's performance under different scenarios, enhancing the robustness of the certification process. VR can aid in the inspection of real components by providing a detailed, three-dimensional representation of the aircraft and its components. This allows for thorough and precise inspections without the need for physical access to the aircraft. Through VR various conditions and scenarios can be simulated that may not be feasible to replicate in a conventional physical inspection, providing a more comprehensive assessment of the aircraft's performance and safety. The potential for remote inspections would also address logistical challenges, making the certification process more efficient and flexible. Remote inspections, facilitated by technologies like VR, can address logistical challenges by eliminating the need for physical presence at the aircraft location. This can significantly reduce travel time and costs and allows for inspections to be conducted more quickly and frequently. In addition, remote inspections can be performed by experts located anywhere in the world, ensuring that the most qualified individuals are able to contribute to the certification process regardless of geographical constraints. This could be particularly beneficial in the current global context, where remote operations have become increasingly important.

A more recent study by Wu and Vu presents an Aircraft Maintenance Virtual Reality (AMVR) system for aviation industry maintenance and training.[104] The system, designed for a Dornier-228 aircraft, included a walk-around visual inspection in a virtual environment. The study found the AMVR system effective in improving students' aircraft maintenance skills, further supporting the potential of VR technology in aircraft inspection processes.[105] Improving

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[102] Jeenal Vora and others, ‘Using Virtual Reality Technology to Improve Aircraft Inspection Performance: Presence and Performance Measurement Studies’ (2001) 45(27) Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 1867, 1870.

[103] ibid, 1869, 1870.

[104] Wen-Chung Wu and Van-Hoan Vu, ‘Application of Virtual Reality Method in Aircraft Maintenance Service - Taking Dornier 228 as an Example’ (2022) 12 Applied Sciences, 7283.

[105] ibid, 7286.

students' aircraft maintenance skills through VR training can contribute to the certification process by enhancing the overall quality and reliability of aircraft maintenance through these virtual means. Well-trained maintenance personnel would be better equipped to detect and correct issues that could impact the aircraft's compliance with certification requirements. In the context of airworthiness certification, this study further emphasises the potential of VR technology in transforming the initial aircraft certification process. A VR inspection system, as proposed, could leverage the advancements in VR technology to enable detailed and efficient inspections of virtual aircraft models, thereby enhancing the overall efficiency and effectiveness of the aircraft certification process, thus facilitating the integration of virtual manufacturing and flight-testing into the aviation industry as a means for initial airworthiness assessment.

4.5.3 Collaborative Certification Framework

A collaborative certification framework involving multiple stakeholders in the certification process could enhance the robustness of the process and ensure that all relevant expertise is utilised. This framework could include a shared responsibility between all stakeholders, a peer review process, and a continuous improvement mechanism.

Bendarkar et al present a model-based framework for managing certification artifacts, which could be adapted to a collaborative certification framework. The paper emphasizes the use of a Model-Based System Engineering (MBSE) approach to manage the complexity of the certification process. This approach could be particularly beneficial in a collaborative certification framework, as it would provide a structured and systematic way of managing the various inputs and outputs from different stakeholders. The paper also discusses the use of a Type Certification Compliance Checklist, which could serve as a valuable tool in a collaborative framework to ensure all necessary compliance showings have been made. This approach aligns with the EASA’s emphasis on a risk and performance-based regulatory approach, which encourages collaboration and data sharing among stakeholders.

These proposals could complement the proposed amendments to the current framework by introducing progressive validation, leveraging VR technology, and fostering collaboration among stakeholders. They represent innovative approaches to aircraft certification that could enhance the efficiency, robustness, and reliability of the process.

4.6 Conclusion

The integration of virtual technologies into the realm of EU airworthiness legislation presents both opportunities and challenges. The potential benefits are significant, including increased efficiency, reduced costs, and the ability to test and validate designs under a wide range of conditions. However, these technologies also introduce new complexities and risks that the current legislative and regulatory framework may not be fully equipped to manage.

The phased certification process, VR inspection system, and collaborative certification framework proposed in this chapter represent innovative approaches to addressing these challenges. They align with the EU's emphasis on a risk- and performance-based regulatory approach and leverage the capabilities of virtual technologies to enhance the efficiency, robustness, and reliability of the certification process. However, the successful integration of these technologies will require careful consideration and amendment of the current legislative and regulatory framework. The proposed amendments to Regulation (EU) 748/2012, including the definition of 'type-certification' and the demonstration of compliance, are critical steps towards this goal. Moving forward, it will be crucial to continue exploring these issues, engaging with stakeholders, and refining the proposed solutions. The future of aviation depends on our ability to adapt and innovate, and the integration of virtual technologies into the EU airworthiness legislation represents a significant step in this direction.

Chapter 5: Conclusion

This conclusion serves as the culmination of the exploration into the integration of AI and ML in the virtual testing and initial airworthiness certification of aircraft within the European Union's legislative and regulatory framework. The thesis has navigated through a complex landscape of technological advancements, regulatory challenges, and potential solutions. The aim is to encapsulate the key findings, address the research questions, discuss the limitations, and propose recommendations for future research and practical implications. The conclusion also provides an opportunity to reflect on the broader implications of this research in the rapidly evolving field of aviation technology.

5.1 Gap in the literature

The literature review revealed a significant gap in the understanding of how AI and ML, as applied in virtual testing and certification of aircraft, interact with the existing EU legislative and regulatory framework. While there is a wealth of research on the technical aspects of AI and ML, and their applications in various industries, there is a dearth of comprehensive studies that specifically address their use in the aviation industry, particularly in the context of virtual testing and certification. The literature lacks a detailed analysis of how the current EU regulatory framework can adapt to these technological advancements. This gap underscores the need for this research, which seeks to bridge the divide between technological innovation and regulatory adaptability in the aviation sector.

5.2 Addressing the research question

The main research question of this thesis sought to understand how the European Union's legislative and regulatory framework for aircraft initial airworthiness certification can accommodate the use of artificial intelligence (AI) and machine learning (ML) in virtual testing and certification. This broad question was further dissected into three sub-questions, each addressed in a separate chapter of the thesis.

The first sub-question explored the current EU legislative and regulatory framework for aircraft certification and its capacity to accommodate AI and ML in virtual testing. The analysis revealed that while the current framework has provisions that could potentially accommodate virtual testing, these were not explicitly designed with such advanced technologies in mind. The framework is heavily grounded in traditional, physical methods of aircraft construction and testing, raising questions about the legal validity of virtual processes and the certification of aircraft produced through these methods.

The second sub-question delved into the risks and challenges posed by the use of AI and ML in virtual testing and certification. The findings highlighted several risks, including algorithmic bias and overreliance on AI, which the current legislative and regulatory framework may not be fully equipped to manage. These risks underscore the need for a robust regulatory approach that can effectively manage the complexities introduced by these advanced technologies.

The third sub-question examined potential amendments to the current framework and proposed new policies to facilitate the integration of AI and ML in virtual testing and certification. The analysis proposed several amendments to the existing EU Regulation 748/2012, including changes to the definition of 'type-certification' and the demonstration of compliance. Additionally, innovative approaches such as a phased certification process, a VR inspection system, and a collaborative certification framework were proposed to enhance the efficiency, robustness, and reliability of the certification process.

In summary, the research questions guided a comprehensive exploration of the intersection between AI and ML in virtual testing and certification and the EU's legislative and regulatory framework for aircraft certification. The findings underscore the need for regulatory adaptability in the face of rapid technological advancements in the aviation industry. This appears to be achievable through partial regulatory amendments combined with certain processes to assist the law in regulating the virtual methods for the initial airworthiness certification.

5.3 Importance of findings

The findings of this research are significant as they provide a comprehensive understanding of the intersection between advanced technologies and the existing regulatory frameworks in the aviation industry. The exploration of the current EU legislative and regulatory framework for aircraft certification revealed that it is not entirely incompatible with these new technologies. Instead, it may require specific amendments to better align with the unique needs and challenges that these technologies present.

The identified risks and challenges associated with the use of AI and ML in virtual testing and certification underscore the need for a robust regulatory approach that can effectively manage these complexities. However, the potential for algorithmic bias and overreliance on AI, among other risks, are not insurmountable. They can be effectively managed within the existing framework with the right adjustments and considerations.

The proposed amendments and innovative approaches to the certification process, including a phased certification process, a VR inspection system, and a collaborative certification framework, represent a significant step towards the wider reliance of virtual testing methods for certification. These proposals could enhance the efficiency, robustness, and reliability of the certification process, facilitating the integration of these technologies into the aviation industry while ensuring that associated risks are adequately managed. The findings of this thesis thus contribute to the ongoing discourse on the future of aviation in the era of AI and ML, suggesting that the current regulatory framework can be adapted to accommodate these advancements with careful and considered amendments.

5.4 Limitations of the research

This research, while comprehensive, is not without its limitations. The primary constraint is the rapidly evolving nature of the technologies under study. Artificial Intelligence and Machine Learning are fields that are advancing at an unprecedented pace. As such, the findings and recommendations of this research are based on the current state of these technologies and the existing regulatory framework. Future advancements in AI and ML could introduce new complexities and challenges that are not addressed in this thesis. Additionally, the research is focused on the EU legislative and regulatory framework, and the findings may not be fully applicable to other jurisdictions with different regulatory environments. Furthermore, the proposed amendments and innovative approaches to the certification process would require further empirical testing and validation to assess their effectiveness and feasibility in practice.

5.5 Recommendations for future research

Future research in this area could take several directions. Firstly, empirical studies could be conducted to test the proposed amendments and innovative approaches to the certification process. This could involve developing prototypes of the phased certification process, VR inspection system, and collaborative certification framework, and testing them in real-world scenarios. Secondly, comparative studies could be undertaken to examine how different jurisdictions are adapting their regulatory frameworks to accommodate AI and ML in aviation. This could provide valuable insights into best practices and potential pitfalls. As demonstrated earlier, EASA already has theoretical and practical research projects on the topic but they have yet to be concluded, meaning that these propositions could even be considered (if they have not already) by the specialists conducting these projects.

5.6 Concluding remarks

The exploration of the integration of AI and ML in virtual testing and certification within the EU's legislative and regulatory framework for aircraft certification has been a journey through a complex landscape of technological advancements, regulatory challenges, and potential solutions. The findings of this research have significant practical implications for the aviation industry. The proposed amendments to the legislative and regulatory framework and the introduction of innovative certification processes such as a phased certification process, a VR inspection system, and a collaborative certification framework could lead to significant cost and time savings. They could also enhance the efficiency, robustness, and reliability of the certification process, facilitating the integration of AI and ML in virtual testing and certification.

However, these advancements also require industry adaptation to new technologies and processes. The aviation industry, regulatory bodies, and other stakeholders will need to navigate the challenges and complexities introduced by these technologies. This includes managing risks such as algorithmic bias and overreliance on AI and ensuring that safety and efficiency remain paramount in the face of rapid technological change.

Moreover, the broader implications of this research extend beyond the aviation industry. The integration of AI and ML in virtual testing and certification could have far-reaching impact on the EU's climate goals, economic growth, and technological innovation. As such, this research contributes to the ongoing discourse on the future of aviation in the era of AI and ML along with more typical virtual methods, suggesting that with careful and considered amendments, the current regulatory framework can be adapted to accommodate these advancements.

The future of aviation depends on our ability to adapt and innovate. The findings of this research underscore the need for regulatory adaptability in the face of rapid technological advancements. While challenges lie ahead, the potential benefits of integrating AI and ML in virtual testing and certification are significant. As we continue to explore this new frontier, it is our hope that this research will serve as a guidepost, illuminating the path towards a future where technology and regulation work hand in hand to advance the field of aviation.

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Appendix A

Table 1: List of Abbreviations

Abbreviation	Definition
AI	Artificial Intelligence
AMC	Acceptable Means of Compliance
AMVR	Aircraft Maintenance Virtual Reality
CFD	Computational Fluid Dynamics
CS	Certification Specification
DOA	Design Organisation Approval
EASA	European Union Aviation Safety Agency
ESWTIRP	European Strategic Wind Tunnels Improved Research Potential Program
FAA	Federal Aviation Administration
FCSS	Flight Control System Simulations
FEA	Finite Element Analysis
FTD	Flying Through the Database
FTE	Flying the Equations
MBSE	Model-Based System Engineering
ML	Machine Learning
TC	Type-Certificate
VR	Virtual Reality

Table 2: Quick Reference of Relevant Legislation

Description	Regulation
General Regulation	Regulation (EU) 2018/1139
Initial Airworthiness	Regulation (EU) 748/2012
Additional Airworthiness Specifications	Regulation (EU) 2020/1159
Continuing Airworthiness	Regulation (EU) 2021/1963

Appendix B

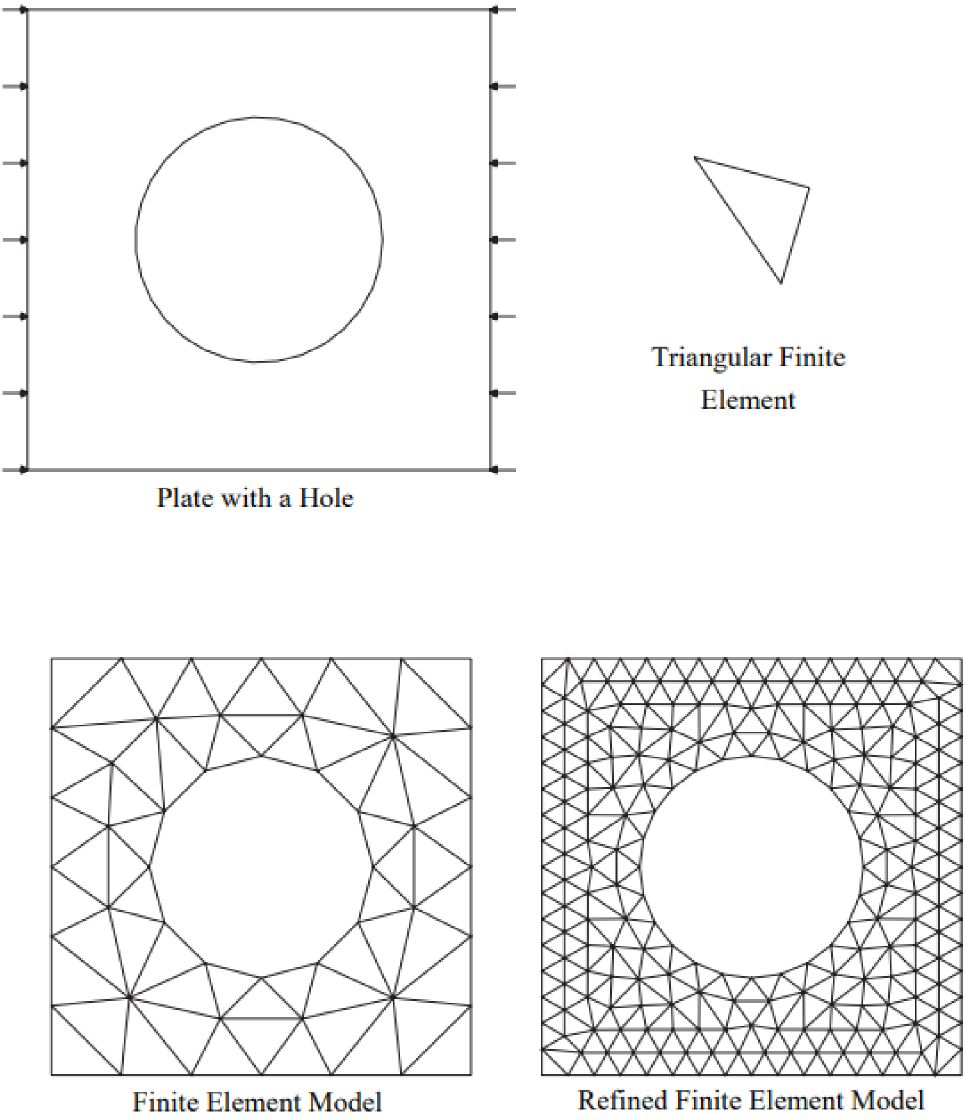

Plate with a Hole

Triangular Finite Element

Finite Element Model

Refined Finite Element Model

Figure 1: A visualisation of the effect of the Finite Element Analysis method. It demonstrates how in view of achieving a result as accurately as possible (represented by the "hole") a mesh is generated comprising of several Finite Elements making a "Finite Element Model". The more of these can be generated, the finer or rounder (term for visualisation purposes) the hole will be and therefore, a more accurate result can be produced which is referred to as a "Refined Finite Element Model".