drones

Review

Towards Safe and Efficient Unmanned Aircraft System Operations: Literature Review of Digital Twins' Applications and European Union Regulatory Compliance

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Abstract: Unmanned aerial system/unmanned aircraft system (UAS) operations have increased exponentially in recent years. With the creation of new air mobility concepts, industries use cutting-edge technology to create unmanned aerial vehicles (UAVs) for various applications. Due to the popularity and use of advanced technology in this relatively new and rapidly evolving context, a regulatory framework to ensure safe operations is essential. To reflect the several ongoing initiatives and new developments in the domain of European Union (EU) regulatory frameworks at various levels, the increasing needs, developments in, and potential uses of UAVs, particularly in the context of research and innovation, a systematic overview is carried out in this paper. We review the development of UAV regulation in the European Union. The issue of how to implement this new and evolving regulation in UAS operations is also tackled. The digital twin (DT)'s ability to design, build, and analyze procedures makes it one potential way to assist the certification process. DTs are time- and cost-efficient tools to assist the certification process, since they enable engineers to inspect, analyze, and integrate designs as well as express concerns immediately; however, it is fair to state that DT implementation in UASs for certification and regulation is not discussed in-depth in the literature. This paper underlines the significance of UAS DTs in the certification process to provide a solid foundation for future studies.

Keywords: digital twin (DT); unmanned aerial system/unmanned aircraft system (UAS); unmanned aerial vehicle (UAV); drone; urban air mobility (UAM); advanced air mobility (AAM); European Union (EU) regulation; regulatory framework

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1. Introduction

In recent years, new innovative technologies, such as unmanned aerial vehicle (UAVs) and vertical take-off and landing (VTOL) aircraft, have led to the creation of new air mobility concepts [1]. UAVs operate in various sectors: agriculture, inspection, media, and entertainment. UAVs' operational and technological capabilities have evolved. They are expected to gain greater freedom of use and enter the area of commercial flights in the near future. Currently, most UAV civil operations are conducted in low-level uncontrolled or segregated controlled airspace due to safety concerns [2]. Operations in high-risk environments set higher requirements to overcome related risks: collisions with civil aircraft, injuries, and accidents due to UAV operation errors. The prevailing measures in UAS management necessitate the thorough consideration and addressing of concerns pertaining to scalability, compliance, cybersecurity, privacy, limitations in real-time monitoring, and the intricate regulatory landscape, which often entail significant investments of time and resources. One of the possible solutions is to leverage digital twin (DT) technology to map the physical space during UAV operation into the virtual space to assess the risk related to the operation beforehand. The utilization of DT has become an engaging subject today [3]. A DT is a virtual replica of real-world entities or processes. DTs develop models to simulate future scenarios and employ historical as well as real-time data to illustrate the past and present [4]. DTs can gain new and unexpectedly detailed insights into how machines and operations work in addition to how to improve them using sensors, cost-efficient and more secure data storage, powerful computers to analyze data, and artificial intelligence [5]. DT allows engineers to check, analyze, and integrate designs as well as express concerns immediately [6]. For example, DT helps anticipate when a machine may fail based on data analysis, which allows the boosting of productivity through preventive maintenance [7]. DTs' application is mainly grouped into the manufacturing [8], aviation, automotive, education and research [9], and healthcare and medicine fields [10]. DT technology is expected to change the "rules of the game" in aviation manufacturing in the future [11]. The aviation community is fostering an aspiration to offer air mobility as an alternative for everyday transportation needs, commonly known as urban air mobility (UAM) and advanced air mobility (AAM) [12]. AAM encompasses a broad concept that enables individuals to access on-demand air mobility, cargo and package delivery, healthcare applications, and emergency services through an interconnected multimodal transportation network [13]. Achieving this system necessitates the seamless integration of air traffic management systems, ground control systems, and communication networks to facilitate effective communication between AAM vehicles and ground systems to ensure safe and efficient operations. As a result, the aviation industry is actively working towards developing an innovative aerospace framework that promotes shared aerospace practices, ensuring the safety, sustainability, and efficiency of air traffic operations [14]. A wide range of literature has been published to explore operational strategies and expectations in the context of AAM [15–28]. Currently, NASA, in collaboration with the FAA, other federal partner agencies, industry, and academia, is actively engaged in research and development efforts to establish the infrastructure, information architecture, concepts of operation, operations management tools, software functions, and other functional components of AAM [29]. Nevertheless, several challenges have the potential to affect the growth of AAM. These challenges include autonomous flight capabilities, the availability of necessary infrastructure for take-off and landing, integration into existing airspace as well as other transportation modes, and competition with shared automated vehicles [30].

UAM, a subset of AAM, is anticipated to yield substantial economic benefits while posing notable developmental challenges. UAM necessitates the development of sophisticated urban-capable vehicles and the establishment of an airspace system capable of efficiently managing high-density operations [12]. According to the European Union Aviation Safety Agency (EASA), UAM is defined as "a new safe, secure and more sustainable air transportation system for passengers and cargo in urban environments, enabled by new technologies and integrated into multimodal transportation systems. The transportation is performed by electric aircraft taking off and landing vertically, remotely piloted or with a pilot on board" [31]. The EASA further predicts that, by 2030, approximately 340 million people residing in EU cities will experience UAM [31]. The concept of urban aerial transportation is not novel, as historical examples of UAM services date back to the 1940s [32]. A notable instance of these historical examples is New York Airways, which operated commercial helicopter-based passenger transport services from 1953 to 1979. However, due to a series of fatal accidents and crashes, New York Airways ultimately ceased operations and filed for bankruptcy. Although this particular chapter of urban aerial mobility concluded abruptly, modern-day congested metropolises have witnessed the resurgence of diverse helicopter transport services [33]. Similar to other transportation systems, UAM necessitates the establishment of infrastructure encompassing the physical ground infrastructure for vehicles as well as the implementation of digital technology and telecommunications for effective traffic management. An essential element for the successful introduction of UAM is the development of appropriate regulations, including the definition of certification standards and policies that govern UAM operations. Addressing these regulatory aspects is crucial to ensure the safe and efficient integration of UAM into existing transportation frameworks [34].

A wide range of literature has been published to answer the research question of how to safely integrate unmanned aircraft systems (UASs) into UAM and AAM within the context of regulation. Studies have addressed key concerns about privacy, the operation of civilian drone regulations, and the social as well as ethical implications of this integration. Winkler et al. [35] highlighted the concerns and needs for privacy and the operation of civilian drone regulations. Clarke investigated the impacts of civilian drone regulation on behavioral privacy [36] and public safety [37]. Thomasen [38] evaluated the impact of robots (including drones) and their regulation on public spaces. In this paper, the authors also examined the technology's impacts on women's privacy and related regulations [39]. Merkert et al. [40] used a theoretical road pricing framework to analyze drone operators' willingness to pay for low-altitude airspace management (LAAM). West et al. [41] reviewed the public's opinions on drone policy. Li and Kim [42] studied the dynamics of local drone policy adoption in California. Nelson and Gorichanaz [43] investigated the emergence of drones and evolving regulation in 20 cities in Southern California. However, in the available literature and official documentation, there was no agreed and consolidated definition of UAM in Europe until recent years, when the EASA introduced the UAM concept as "The safe, secure and sustainable air mobility of passengers and cargo enabled by new generation technologies integrated into a multimodal transportation system conducted in to, within or out of urban environments" [1]. The EASA is also establishing a regulatory framework addressing the safety, security, and environmental aspects of UASs to ensure their acceptance and adoption by European citizens. Some elements of this regulatory framework have already been established; for example, Regulation (EU) 2019/947, Regulation (EU) 2019/945, Regulation (EU) 2021/664, Regulation (EU) 2021/665, and Regulation (EU) 2021/666 [1].

In parallel with the establishment of regulatory frameworks, the potential of [5,8–11] DT utilization in the aviation industry has been explored and documented in numerous pieces of the scientific literature [44–49]. DTs can be used in any stage of the aircraft life cycle [50–60], such as design, manufacturing, operations, and maintenance. DTs can also be implemented on components as well as systems [61–70] that provide a comprehensive view of an aircraft and its individual parts. It allows for monitoring and analysis at different levels, enabling engineers to assess the performance and health of specific components as well as understand the overall behavior and interactions within the system. Various research efforts have been conducted to use DT in UASs [3,71–90], addressing challenges and opportunities of UASs within this dynamic and evolving field. However, despite the significant discussion of DTs in the general aviation literature, especially in relation to manufacturing and maintenance, more effort and attention need to be devoted to the application of DTs in UASs [71].

Overall, the aviation industry is subjected to an international framework, yet it requires additional efforts to establish a similar framework for UAS operations [91]. Considering the strong ongoing developments in this domain, the approach to UAS certification does not evolve with the same dynamic [6], and the UAS European Union (EU) regulatory framework was fragmented before 2020, mainly considered in quite local and regional contexts. However, some significant steps have recently been made in this aspect, particularly since 2020, and the EU legal framework of UASs is undergoing changes to provide uniform regulation. One of the aims of this paper is to also bring these developments to the closer attention of the research community in order to support strongly evolving research efforts, as this aspect has so far been generally understated across the scientific literature. Understanding the appropriate operational category presented by the EASA for UASs helps to gain more insights into the requirements of authorizations and certification. However, when developing a product that requires regulatory certification, this is only one half of the matter. The separation between design and analysis activity is one of the critical gaps in the certification process. DTs facilitate engineering and manufacturing teams to design and build products better and faster. It also helps them to check, analyze, and integrate designs as well as express concerns instantly [6]. This paper provides a comprehensive overview of the developed UAS regulation in the European Union provided by the EASA and examines the potential of DTs to assist the certification process. This paper aims to make a bridge between DTs, UASs, and the EU regulatory framework to present a reliable basis for future studies. The structure of the paper is as follows: Section 2 is structured into three subsections. The first subsection provides an overview of the research methodology. The second subsection introduces the current and upcoming European regulatory framework for UASs. The third subsection illustrates the concept and applications of DTs. Section 3 provides a valuable resource by analyzing the existing relevant literature and highlighting important trends as well as developments. Section 4 presents the links and potential to use DTs to assist the certification by drones' EU regulatory framework. forming an outlook for future studies and applications. Section 5 presents the conclusion, where some key lessons learned based on the existing body of literature are presented.

2. Materials and Methods

One of the essential steps toward determining the potential of DTs in the certification process is specifying the related regulation in the context of operational robustness and airworthiness. Airworthiness concerns the safety standards in all construction aspects: structural strength, safeguard provisions, design requirements relating to aerodynamics, performance, and electrical as well as hydraulic systems [92]. Robustness refers to the characteristic of mitigation measures resulting from combining the improvements in safety provided by mitigation measures and the levels of assurance as well as integrity in attaining the desired safety enhancement [93]. In general, international and national regulations are focused on safety. However, small drones avoid many of these requirements, as they pose fewer risks [91]. UAV operations are a relatively new concept and have significant potential in combination with new technologies, resulting in new applications (with their required regulations). DTs are also a relatively new concept accepted in various industries and have great potential for UAV operations. A DT is a description of a component, product, or system providing a series of interconnected relevant digital models containing engineering data, operation data, and behavior descriptions obtained from simulations. It can be modified as a real-world system can be developed through its life cycle. A DT is used to develop solutions that are applicable to actual systems in addition to describing the behavior. It can be applied to testing and simulation, enabling users to observe how new behaviors are exhibited and find answers to their problems [94].

In the legal context, it is essential to acknowledge and understand the distinct terminology used when referring to drones, as they may carry different legal implications. The term "drone" was first used in 1935 and is nowadays quite accepted by both the media and the general public [95]. Alongside "drone", the most frequently used terms are "unmanned aerial vehicle" (UAV) and "unmanned aircraft system/unmanned aerial system" (UAS). The terms "drone" and "unmanned aerial vehicle" (UAV) stand out as referring only to a flying platform (the airplane and its payload). The phrase "unmanned aerial system" (UAS) is the most well known term for an entire system (a flying platform and ground station). "Unmanned aircraft system" (UAS) is widely used by the Federal Aviation Administration (FAA), European Aviation Safety Agency (EASA), and International Civil Aviation Organization (ICAO). Hence, it is better to utilize the term "unmanned aircraft systems" when referring to UASs in this study. It is essential to utilize the correct terminology in order to deliver the concepts in the debate properly [95].

Official documents and legislations mainly use the terms "UAV" and "UAS". While professional drone users are familiar with these terms and use them, the terms "UAV" and "UAS" are less familiar to the public, especially when abbreviated [95]. People might therefore have few or no associations with these terms, so the term "drone" is occasionally used in conjunction with these terms for simpler demonstration in documents. In this work, we make an effort to use the terminology accurately, considering the references to prevent misconception.

This section is divided into two subsections: The first subsection introduces the existing and upcoming European regulatory framework for UASs. The second subsection illustrates different DTs' methodologies.

2.1. Research Methodology

To answer the research question of how DT can assist the certification process, we provide a detailed and comprehensive analysis of the state of the art through the following source databases: Google Scholar, Scopus, Springer, Science Direct, and the European Union Aviation Safety Agency. We instigated a data search by combining the keywords "Unmanned Aerial Vehicle", "Unmanned Aircraft System", "Unmanned Aerial System", "UAV", "UAS", and "drone" in combination with "digital twins", "DT", "certification", "regulation", "European Union (EU) regulation", "regulatory framework", "Urban Air Mobility", "UAM", "Advanced Air Mobility", and "AAM". In the literature search, we identified relevant articles according to the title and context of the study. A total of 121 references, which were best-aligned with the scope and objectives of our research, were selected, of which 20 articles were directly relevant to the scope of DT applications for UASs. The results sections of the selected references were analyzed to gain valuable insights in this domain.

The first step to answering the identified research questions is to investigate the existing and upcoming European regulatory framework for UASs and to understand the concept, methodologies, and applications of DTs.

2.2. European Union Regulatory Framework

Until 2020, the Member States regulated civil drones with an operating mass of less than 150 Kg, and the EASA handled civil drones with an operating mass of over 150 Kg. The fragmentation in the extent, content, and level of national detail led to unreached conditions for the joint recognition of operational authorization between the EU Member States [91]. Fortunately, the EASA is providing uniform regulation for the EU legal framework of UASs since 2020 [96]. Figure 1 presents an overview of European Union regulatory framework progress over time.

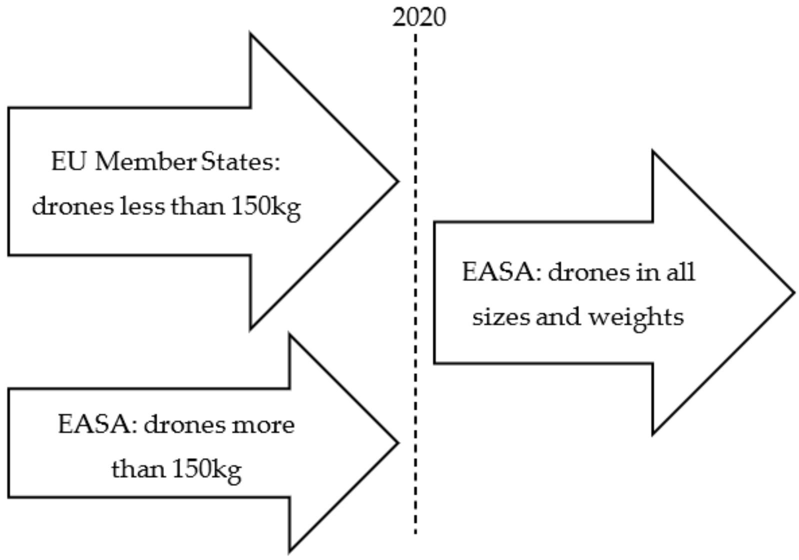

Figure 1. Chronological evolution of the European Union regulatory framework.

2.2.1. Access Rules for Unmanned Aircraft Systems (Regulations (EU) 2019/947 and 2019/945)

The operational framework for civil drones in the Europian Union (EU) is Regulations 2019/947 and 2019/945. These regulations conduct a risk-based approach, considering the weight, specifications, and intended operation of civil drones [97]. Regulation 2019/947 was expected to be implemented on 1 July 2020; however, due to the COVID-19 crisis, it was delayed to 31 December 2020 [96].

Civil Drone Operation Categories in the European Union Regulatory Framework

Regulation 2019/947 presents three risk-based categories for civil drone operations, shown in Figure 2: the open, specific, and certified categories [97]. The definition of each category is as follows:

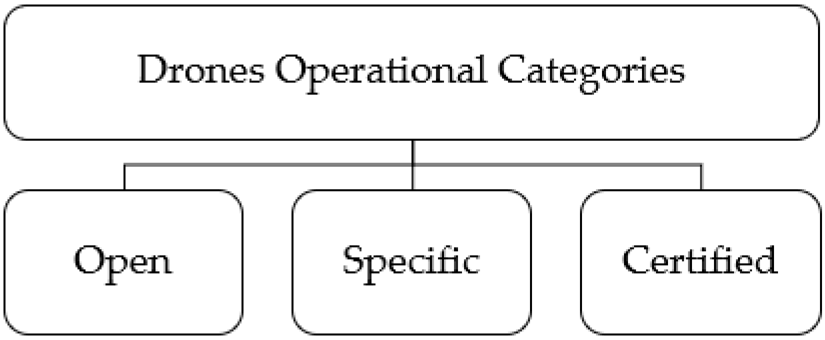

Figure 2. Categorization of UAS operations under EU regulation.

1. The open category (low-risk): Drones in low-risk operations (e.g., leisure drone activities and low-risk commercial activities) are in the open category. This category is specified by three subcategories: A1, flying over people but not over assemblies of people; A2, flying close to people; and A3, flying far from people. Each subcategory has requirements based on UAS's weight (the operational weight is less than 25 Kg) [98].
2. The specific category (medium-risk): Operations that carry more risks and are not in the scope of the open category's operations are in the specific category. In this category, operational authorization (issued by the competent authority of registration) is required based on the risk assessment outcome conducted under Article 11 of Regulation (EU) 2019/947, unless the operation is a standard scenario (STS): a predefined operation described in the appendix of EU Regulation 2019/947 [99].
3. The certified category (high-risk): UAS high-risk operations and future drones onboard passenger flights (e.g., air taxis) are in the certified category. These UASs must always be certified, the UAS operator will need air operator approval issued by the competent authority, and the remote pilot must hold a pilot license. In the future, drone automation will reach fully autonomous UAS operations. The safety approach of these flights will be very similar to manned aviation. Almost all aviation regulations will need to be amended, and the EASA decided to conduct this major task in multiple phases [100].

Overall, drone operations with any of the below conductions are certainly in the certified category:

- A UAS with a dimension of 3 m or more flying over assemblies of people (operation of a less than 3 m UAS flying over assemblies of people may be in the specific category unless the risk assessment outcome indicates that is in the certified category).
- Transport of people.
- Transport of dangerous goods (the payload is not in a crash-protected container) [93].

Operational Risk Assessment for Drones in Specific Category

UAS operational risk assessment is divided into three categories: standard scenarios (STSs), predefined risk assessment (PDRA), and specific operation risk assessment (SORA) [93]. The definition of each category is as follows:

1. Standard scenario (STS): Due to the lower risks in UAS operations in STSs listed in Table 1, a declaration may be submitted.

Table 1. List of standard scenarios (STSs) [93.].

STS#	Edition/ Date	UAS Characteristics	BVLOS/VLOS [2]	Overflown Area	Maximum Range from Remote Pilot	Maximum Height	Airspace
STS-01	June 2020	Bearing a C5 class marking (maximum characteristic dimensions of up to 3 m and MTOM [1] of up to 25 kg)	VLOS	Controlled ground area that might be located in a populated area	VLOS	120 m	Controlled or uncontrolled, with a low risk of encounter with manned aircraft
STS-02	June 2020	Bearing a C6 class marking (maximum characteristic dimensions of up to 3 m and MTOM of up to 25 kg)	BVLOS	Controlled ground area that is entirely located in a sparsely populated area	2 km with an AO [3] 1 km, if no AO	120 m	Controlled or uncontrolled, with a low risk of encounter with manned aircraft

[1] Maximum take-off mass. [2] Beyond visual line of sight/visual line of sight. [3] Airspace observer.

2. Predefined risk assessment (PDRA): PDRA is considered the most common operation in Europe, and instead of conducting a full risk assessment, an authorization request may be submitted based on the PDRAs listed in Table 2. PDRAs are described in a generic way to provide flexibility, while STSs are detailed. The two types of PDRAs are PDRAs derived from STSs (a UAS operator conducts similar operations without the UAS class label mandated in STSs) and generic PDRAs. A PDRA with the letter "G" is a generic PDRA, and those with an "S" are PDRAs derived from STSs [93].

Table 2. List of predefined risk assessments (PDRAs) [93].

PDRA#	Edition/ Date	UAS Characteristics	BVLOS/VLOS	Overflown Area	Maximum Range from Remote Pilot	Maximum Height	Airspace	AMC# [1] Article 11
PDRA-S01	1.0/July 2020	Maximum characteristic dimension of up to 3 m and MTOM of up to 25 kg	VLOS	Controlled ground area that might be located in a populated area	VLOS	120 m	Controlled or uncontrolled, with a low risk of an encounter with manned aircraft	AMC4
PDRA-S02	1.0/July 2020	Maximum characteristic dimension of up to 3 m and MTOM of up to 25 kg	BVLOS	Controlled ground area that is entirely located in a sparsely populated area	2 km with an AO, 1 km if no AO	120 m	Controlled or uncontrolled, with a low risk of an encounter with manned aircraft	AMC5
PDRA-G01	1.1/July 2020	Maximum characteristic dimension of up to 3 m and typical kinetic energy of up to 34 kJ	BVLOS	Sparsely populated area	If no AO, up to 1 km	150 m (operational volume)	Uncontrolled, with a low risk of an encounter with manned aircraft	AMC2

Table 2. *Cont.*

PDRA#	Edition/ Date	UAS Characteristics	BVLOS/VLOS	Overflown Area	Maximum Range from Remote Pilot	Maximum Height	Airspace	AMC# [1] Article 11
PDRA-G02	1.0/July 2020	Maximum characteristic dimension of up to 3 m and typical kinetic energy of up to 34 kJ	BVLOS	Sparsely populated area	N/a	As established for the reserved airspace	As reserved for the operation	AMC3

[1] Acceptable means of compliance.

3. Specific operation risk assessment (SORA): SORA evaluates the UAS operation risks, considering any class, size, and type of operation [93]. Figure 3 demonstrates the SORA methodology.

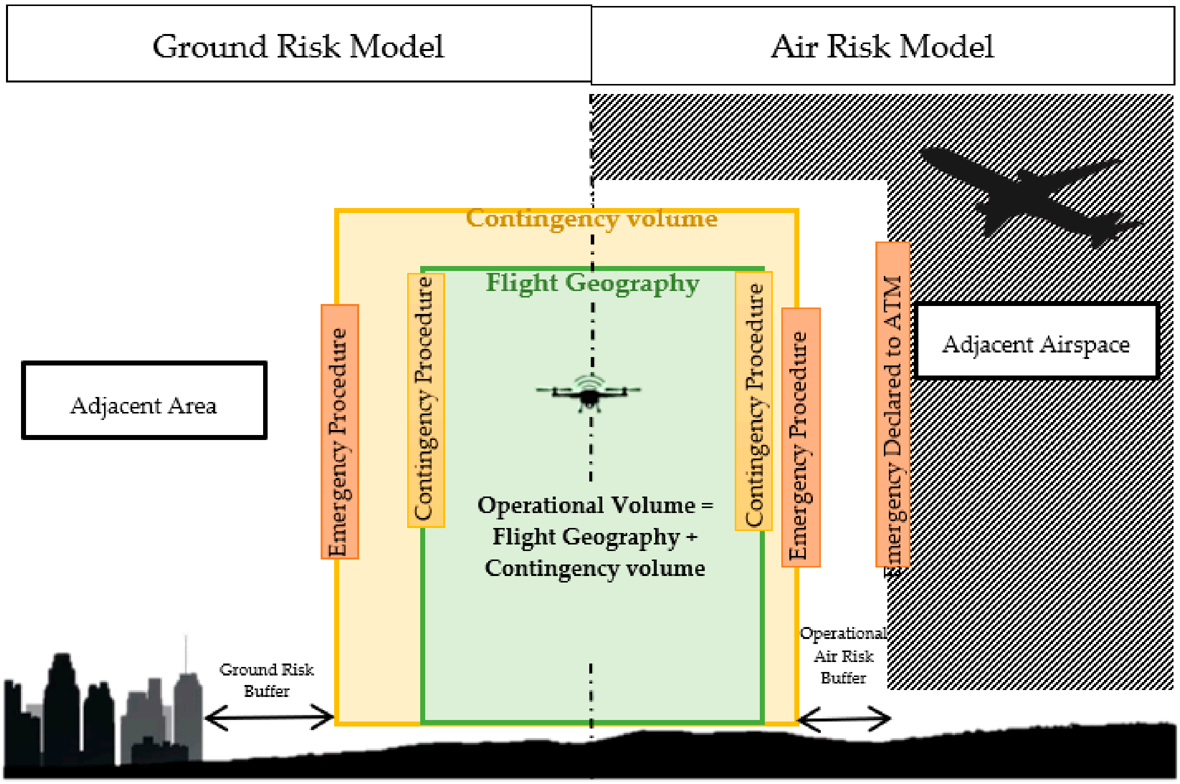

Figure 3. Graphical representation of SORA [93].

SORA defines risk as "the combination of the frequency (probability) of an occurrence and its associated level of severity". Risk mitigations and operational safety objectives (OSOs) can be demonstrated at different robustness levels presented by SORA: low, medium, and high. SORA focuses on the assessment of air and ground risks. Figure 4 presents the required workflow to conduct SORA. Ten steps are required to conduct SORA, and some of these steps may be repeated in different environments [22]. It is important to verify the operational feasibility before starting SORA. The operation must not be categorized as the open category or certified category, must not be covered by an STS or a PDRA, and not be subjected to a specific NO-GO from the competent authority [93].

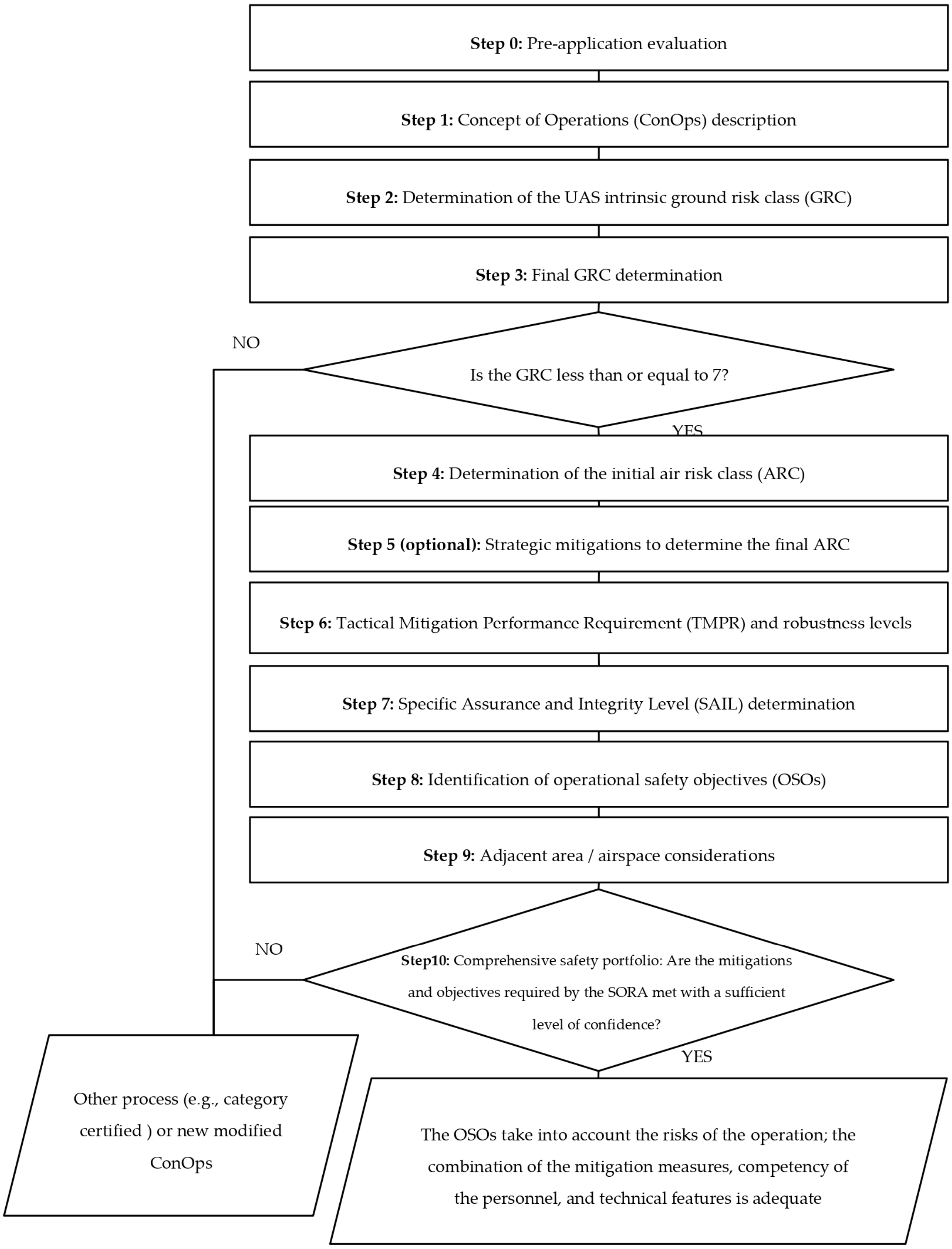

Figure 4. Workflow for conducting SORA: ten steps and iterations [93].

To ensure safety in UAS operations, especially in populated areas, the design verification of drones by the EASA is needed depending on the risk level of operations [101]:

- In high-risk operations (i.e., SAIL V and VI according to SORA), the EASA will issue a type certificate according to Part 21 (Regulation (EU) 748/2012). Easy Access Rules for Airworthiness and Environmental Certification (Regulation (EU) No. 748/2012) contains the applicable 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 organizations [102].

- In medium-risk operations (i.e., SAIL III and IV according to SORA), a design verification report will be applied [101].

2.2.2. Commission Implementing Regulation (EU) in U-Space (Regulations (EU) 2021/664, 2021/665, and 2021/666)

U-space is a set of services and procedures to ensure safe and efficient airspace accessibility for a large number of UAS operations, with the purpose of achieving automated UAS management and integration. The European Commission adopted and published a regulatory framework for U-space in April 2021. This regulatory package is going to implement three regulations as of January 2023 [103]:

1. Regulation (EU) 2021/664 regulates the technical and operational requirements for the U-space system [104].
2. Regulation (EU) 2021/665 amends Regulation (EU) 2017/373 to establish requirements for air traffic management and air navigation service providers in the U-space designated in controlled airspace [105].
3. Regulation (EU) 2021/666 modifies Regulation (EU) 923/2012 to establish the rules for the presence and requirements for manned aviation operating in U-space airspace [106].

2.2.3. EASA Artificial Intelligence Roadmap (Autonomous and Automatic UASs)

Autonomous and automatic UASs are reaching a level of complexity and development such that they are expected to conduct safe operations in urban air mobility (UAM). Automatic UAVs operate on predetermined routes, and remote pilots intervene in the case of unforeseen events. In autonomous UAVs, artificial intelligence (AI) must conduct a safe flight (without a pilot's intervention) and cope with unforeseen conditions as well as unpredictable emergencies. Automatic UAV operations are allowed in all categories. Autonomous UAVs only operate in the specific category and certified category (where the Regulation includes more flexible tools to verify requirements and the level of robustness); they are not allowed in the open category [107].

One of the key research questions is how these operations can safely be used in UAM [108]. In 2020, the EASA published a human-centric approach for the safe use of AI in aviation, entitled "EASA AI roadmap". Figure 5 presents the trustworthy AI building blocks: AI trustworthiness analysis, learning assurance, AI explainability, and AI safety risk mitigation [109]. The EASA AI roadmap's deliverables timeline foresees the first approvals of AI in 2025 [110].

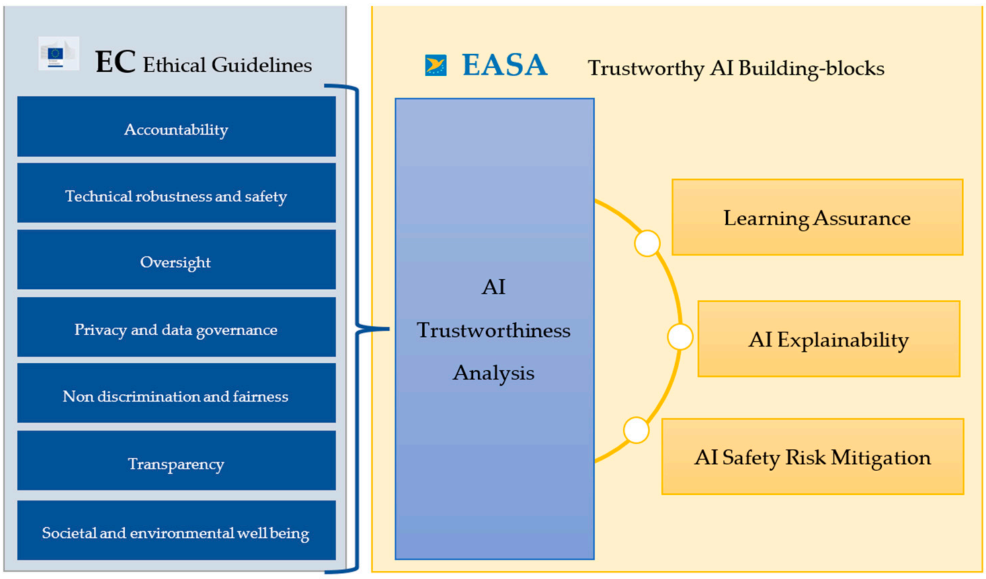

Figure 5. EASA trustworthy AI building blocks [109].

2.3. Digital Twins

The digital twin concept was first used in the manufacturing literature in 2010 as "a digital representation of an asset (e.g., physical objects, processes, devices) containing the model of its data, its functionalities and communication interfaces" [111], providing the elements and dynamics of asset operation throughout its life cycle [112]. Various DT definitions exist in the current literature depending on the domains and industries [113]. A list of DT definitions based on domains is as follows:

1. Aerospace industry: "A Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin. The Digital Twin is ultra-realistic and may consider one or more important and interdependent vehicle systems, including airframe, propulsion and energy storage, life support, avionics, thermal protection, etc." [114].
2. Manufacturing industry: "The Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin" [112].
3. Construction industry: "Digital twin construction (DTC) is a new mode for managing production in construction that leverages the data streaming from a variety of site monitoring technologies and artificially intelligent functions to provide accurate status information and to proactively analyze and optimize ongoing design, planning, and production" [115].
4. Service infrastructure: "a dynamic virtual representation of a physical object or system across its lifecycle, using real-time data to enable understanding, learning and reasoning" [116].
5. Healthcare: "A digital twin is a digital representation of a physical asset reproducing its data model, its behavior and its communication with other physical assets. Digital twins act as a digital replica for the physical object or process they represent, providing nearly real-time monitoring and evaluation without being in close proximity" [111].

DTs in various industries have approximately the same features and application purposes. The main components for generating DT models are physical elements/assets, linked data, and virtual models [113]. DTs can be categorized as follows:

1. Static DT: A static DT is developed (with the design information in a digital format) before the manufacturing process [117].
2. Dynamic DT: With the help of real-time sensors mounted on a product, a dynamic digital is obtained. These sensors allow us to access real-time information. The data obtained from the physical machine by the sensors are transferred to a virtual machine. The virtual machine uses trained simulation- and data-driven models on the received data to present the needed information about the physical machine [118]. With the help of artificial intelligence and data analytics, the DT gains the potential to reach autonomous decision making [113].

Static DT is the simplest way of implementing DT, and dynamic DT is the most complex one. As the level of details and information increases, the complexity and cost of DTs increase. Figure 6 presents the relationship between DTs and business value. Code green is simple design data, code yellow is the design and manufacturing data, and red is the dynamic DT that also includes operational field data [117].

Figure 7 illustrates the DT complexities (three main complexity levels) and time horizon approximations (three main life cycle stages of a physical system with the related DT applications) [119].

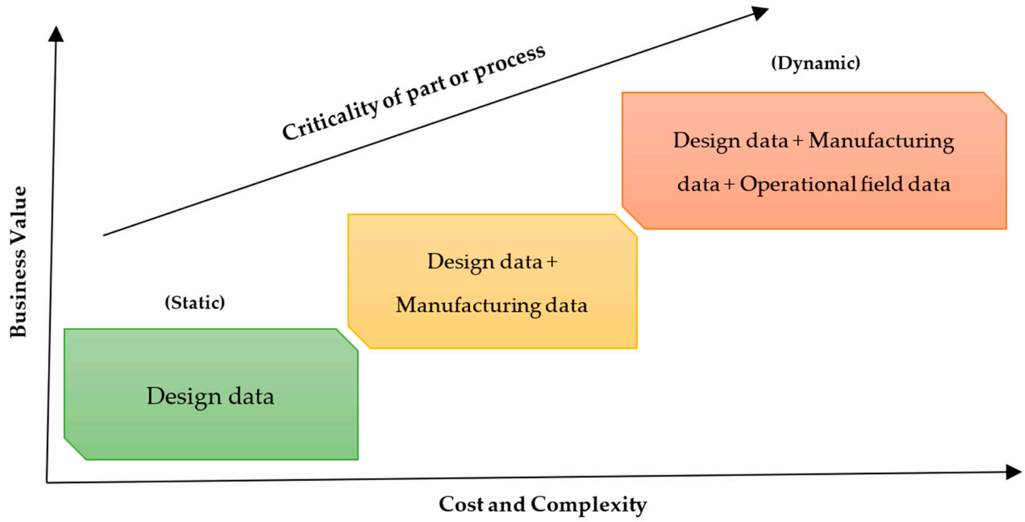

Figure 6. Types of digital twins and business value [117].

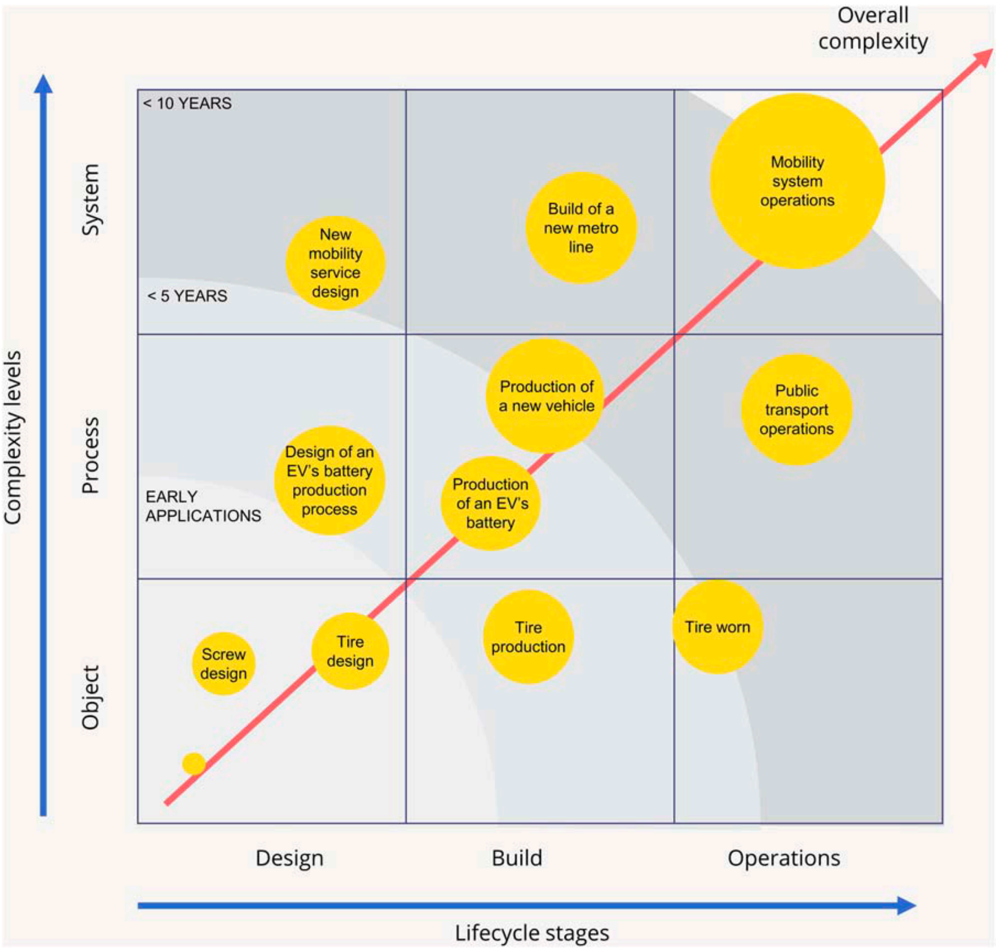

Figure 7. Digital twin complexities and time horizon approximations [119].

Before developing and implementing the DT, various research questions must be answered. Semeraro et al. [120] presented Table 3 to summarize the key research questions of DTs answered by the literature so far.

Table 3. List of digital twin research questions [120].

Research Question	Answers
"What is a Digital Twin?" Definition	"A set of adaptive models that emulate the behaviour of a physical system in a virtual system getting real time data to update itself along its life cycle. The digital twin replicates the physical system to predict failures and opportunities for changing, to prescribe real time actions for optimizing and/or mitigating unexpected events observing and evaluating the operating profile system"
"Where is appropriate to use a Digital Twin?" Contexts and use cases	1. Healthcare Improving operational efficiency of healthcare operations 2. Maritime and Shipping Design customization 3.Manufacturing Product development and predictive manufacturing 4. City Management Modeling and simulation of smart cities 5. Aerospace Predictive analytics to foresee future aircraft problems
"Who is doing Digital Twins?" Platforms	GE Predix; SIEMENS PLM; Microsoft Azure; IBM Watson; PTC Thing Worx; Aveva; Twin Thread; DNV-GL; Dassault 3D Experience; Sight Machine; and Oracle Cloud
"When and Why has a Digital Twin to be developed?" Life cycle and functions	1. In the design phase The digital twin is used to help designers to configure and validate product development quicker, accurately interpreting market demands and the customer preferences 2. In the production phase The digital twin shows great potential in real-time process control and optimization, as well as accurate prediction 3. In the service phase The digital twin can monitor the health of a product and perform diagnoses as well as prognoses
"How to design and implement a Digital Twin?" Architecture and components	The physical layer involves various subsystems and sensory devices that collect data and working parameters The network layer connects the physical to the virtual, sharing data and information The computing layer consists of virtual models emulating the corresponding physical entities

It is important to distinguish between the concepts "digital twin", "digital shadow", and "digital model". Figure 8 highlights the differences in these concepts by focusing on the data transfer among physical and virtual twins [119].

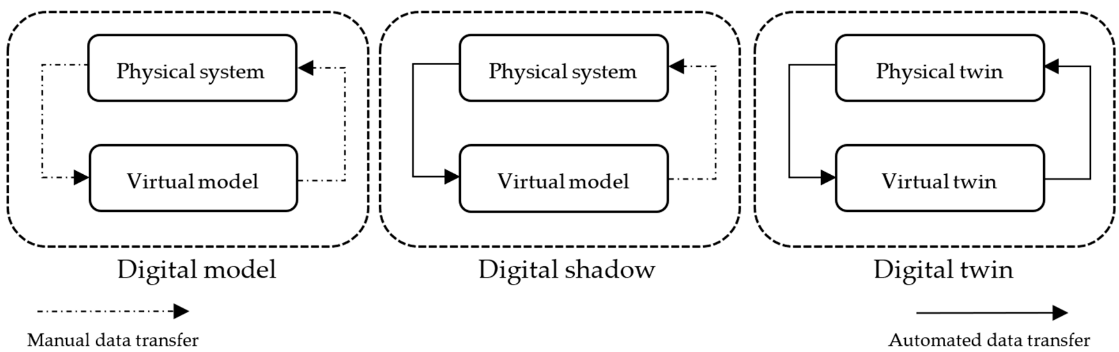

Figure 8. Data transfer comparison between physical systems and virtual models in a digital twin, digital shadow, and digital model [119].

Figure 9 demonstrates the important risks and challenges when developing DTs [117]. Modeling a digital copy of a physical system to perform real-time validation and optimization is a complex task as it involves sensors, multifunctional models, multisource data, services, etc. A DT requires an accurate model of reality and a large amount of data. It can potentially be used in life cycle assessments; however, the development of standards-based interoperability is important and challenging for evaluating DT applications along the entire life cycle. A few contributions also focused on DT applications for improving sustainability performance [120].

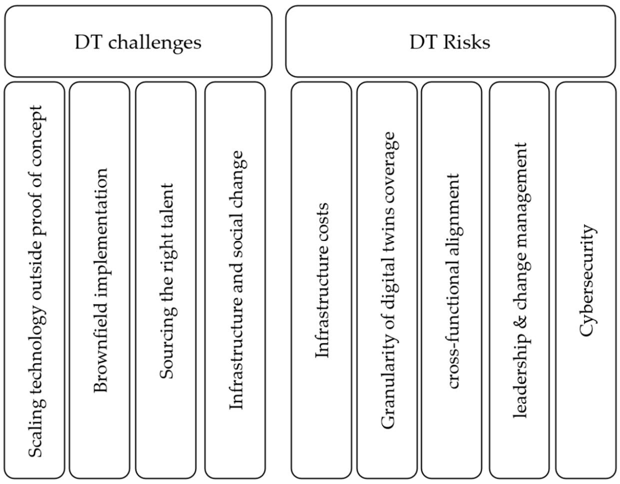

Figure 9. Digital twins' risks and challenges [117].

To comprehensively understand the state of knowledge on the application of DTs in UASs, as well as their benefits and challenges, a synthesis of the literature that integrates various subtopics is crucial. The implementation of DTs has been widely explored in aviation-related scientific literature. For example, the EU-funded project Secure Urban Air Mobility for European Citizens (AURORA) is planning to develop and integrate safety-critical technologies to support autonomous UAS flights in urban environments. Figure 10 presents examples of DT applications in this project [121].

(**a**)

(**b**)

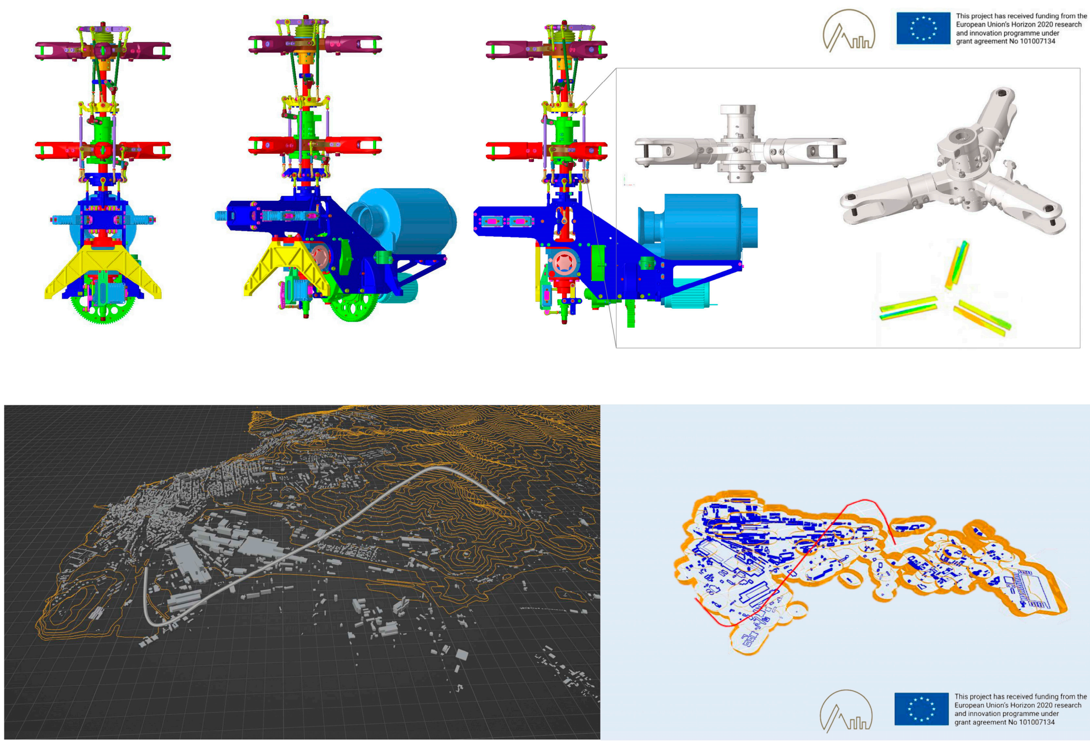

Figure 10. The EU-funded AURORA project: (**a**) digital representation of the rotor (digital twin for manufacturing and digital certification) and (**b**) digital representation of the flight path (digital twin for solutions testing) [121].

The German Aerospace Center (DLR) has also established an internal project to identify techniques, technologies, and processes for DTs [44]. Liu et al. [45] reviewed the overall framework for creating a DT in combination with the industrial Internet of things (IIoT) to enhance the autonomy of aerospace platforms. Liao et al. [46] presented the findings of research conducted at the National Research Council of Canada (NRC), which included a review and evaluation of DT concepts and digital threads, particularly the airframe digital twin (ADT) framework used by the United States Air Force (USAF), as well as a feasibility and adaptability study of the ADT for use with Royal Canadian Air Force (RCAF) aircraft. Aydemir et al. [47] reviewed the available approaches, technologies, and challenges of DTs for aircraft applications. Mendi et al. [48] evaluated DT applications and their advantages in military aviation. Ibrion et al. [49] presented DTs' risks and challenges in the marine industry by learning from the aviation industry. DTs can be effectively utilized in any stage of the aircraft life cycle, encompassing the design, manufacturing, operation, and maintenance phases. DTs enable engineers to create virtual prototypes and simulate various scenarios, allowing for the efficient optimization of aerodynamic performance, structural integrity, and overall aircraft functionality in the design stage. DTs can facilitate real-time monitoring and quality control, ensuring that components are produced to precise specifications and tolerances during manufacturing. DTs, based on their level of complexity, have the potential for real-time data collection and analysis, offering insights into the operation phase, including aircraft performance, fuel efficiency, and operational safety. DTs can also support predictive maintenance by continuously monitoring the health of aircraft systems and components, as well as detecting potential issues before they lead to failures or disruptions. Leveraging DTs throughout the aircraft life cycle can enhance decision making, improve safety, reduce costs, and ultimately maximize the overall performance and lifespan of the aircraft. For instance, Tuegel et al. [50] proposed the airframe DT structural modeling concept to design and maintain airframes (which has the potential to improve US Air Force aircraft management over the life cycle) by creating a tail number computational model and structural management plans for each aircraft. Seshadri et al. [51] suggested employing DTs to manage the structural health of damaged aircraft using guided wave responses. A genetic algorithm (GA) optimization evaluates the cumulative signal responses at preselected sensor locations to estimate the size, position, and orientation of the damage. Mandolla et al. [52] implemented a DT for additive manufacturing in the aerospace industry by utilizing blockchain solutions. This work highlights how businesses utilizing the blockchain can create secure and connected manufacturing infrastructure and provides a conceptual solution to securing and organizing the data generated by an end-to-end additive manufacturing process in the aerospace industry. Zhang et al. [53] established a digital-thread-based modeling digital twin (DTDT) framework for an aircraft assembly system, enhancing the controllability and traceability of the manufacturing process and product quality through improved data management. Tyncherov et al. [54] proposed DT modeling of aircraft operational life cycle by presenting aircraft systems' DTs with operational and maintenance environments as a cloud of data considering machine learning (ML) methods to improve prediction and planning accuracy. Tuegel et al. [55] reengineered the aircraft structural life prediction process to high-performance digital computing, presenting a conceptual model of DTs for predicting aircraft structure life and assuring its structural integrity. Ríos et al. [56] discussed an aircraft avatar implication through an industrialization-focused perspective while reviewing the various topics involved in an aircraft's digital counterpart development (i.e., product identification, product life cycle, and product information). Strelets et al. [57] created a DT in a uniform information environment of the product life cycle, which, as the virtual copy of a product, is convenient to use at all stages of the life cycle. Liang et al. [58] presented a real-time displacement detection DT in aircraft assembly. Zhang et al. [59] proposed an effective simulation and optimization containing heuristic algorithms and applied them to a DT-based aircraft part production workshop. Singh et al. [60] presented an information management (IM) framework for DTs in aircraft manufacturing, with a case study for aircraft structure damage tolerance, demonstrating the different phases of IM (from identification to retrieval and retention).

The existing body of aviation-related scientific literature extensively explores the potential of DTs and highlights their versatile applications, including their effectiveness not only in system-level implementation but also at the individual-component level. Employing DTs at these different levels can unlock new insights and ultimately advance the state of knowledge in the field. For example, Lei et al. [61] modeled a DT for tooth surface grinding, considering the low-risk transmission performance of non-orthogonal aviation spiral bevel gears. Zakrajsek et al. [62] developed a DT for a specific aircraft tire at touchdown to improve tire touchdown wear prediction. Xu et al. [63] suggested DT optimization with several DT modules for a system to virtually simulate as well as optimize the parameters, performance, and manufacturing. The DT modules make corrections during the optimization using real-time feedback data from manufacturing measurements and performance testing. Borgo et al. [64] presented a DT of a ground steering system and systematically analyzed the effect of uncertainties and sensor faults with estimation algorithms (least squares estimation and soft computing approach) under several scenarios. Hu et al. [65] developed a DT decision-making approach to generate reconfigurable fixturing schemes optimization for the trimming operation of aircraft skins. Peng et al. [66] provided an online fault diagnosis system for the TFE-731 turbofan engine and used model-based and data-driven approaches to create DTs of the engine parameters. Li et al. [67] used the concept of dynamic Bayesian networks (DBNs) to develop a health monitoring model for aircraft. An example of the proposed method is also illustrated on an aircraft wing's fatigue crack growth [68]. Kosova et al. [69] developed a DT and used ML for a health-monitoring system (limited to aircraft hydraulic systems) to diagnose system failures in the early stages using 20 failure scenarios. Laukotka et al. [70] implemented DTs for civil aviation, aircraft, and aircraft cabins, based on modular product family design and model-based systems engineering.

Various research efforts have been diligently conducted to explore and harness the potential of DTs in UASs. The application of DTs in UASs has emerged and prompted researchers to utilize the benefits of this technology, aiming to enhance design, operation and mission planning, and maintenance practices, leading to more reliable, efficient, and capable UASs. However, after reviewing DTs throughout the entire life cycle of the aviation system, Xiong et al. [71] concluded that while aviation DTs are frequently utilized in manufacture and maintenance, more effort and attention are required for UAV DT applications. Lv et al. [72] also reviewed AI applications in DTs in aerospace, intelligent manufacturing, unmanned vehicles, and smart city transportation. Salinger et al. [73] presented a hardware testbed for a self-aware UAV to advance dynamic data-driven application system (DDDAS) development. Self-awareness refers to a vehicle's ability to collect information about itself and utilize that knowledge to complete missions through dynamic decision making on board. Kapteyn et al. [74] combined reduced-order models with Bayesian estimation to create a data-driven DT for a 12 ft wingspan UAV to enable the aircraft to adjust its mission plan in the event of structural damage or deterioration. The authors further advanced the methodology using interpretable ML [75]. Alaez et al. [76] modeled a DT of a VTOL UAV using the Gazebo robotics simulator, compared the UAV's take-off, hovering, and landing operation with and without a wind physics model, and tested it in different wind speeds and directions. Yang et al. [77] proposed a DT for a multirotor UAV with a simulation system, a physical UAV, and a service center for advanced capability training as well as algorithm verification. The authors also demonstrated a DT simulation platform for verification that further simulates and tracks the life cycle of a multirotor UAV [78]. Lv et al. [3] analyzed the effects and limitations of UAVs in 5G/B5G wireless communication and developed a UAV DT 5G communication channel model using deep learning (DL) to further reduce UAV limitations. Moorthy et al. [79] designed a UAV network simulator focusing on high-fidelity UAV flight control by using two simulators they developed in prior years: UBSim (a Python-based event-driven simulator) and UB-ANC (a simulation framework used to design, implement, and test various UAV networking applications). Wu et al. [80] addressed the security concerns that arise when a drone system is attacked and investigated the computational intelligence of drone information systems and DTs of drone networks based on DL. Shen et al. [81] proposed a DT with deep reinforcement learning (DRL) (in which a DT of a multi-UAV system is built into a central server to train a DRL model) to solve the flocking motion problem of multi-UAV systems. Lv et al. [82] developed a UAV DT to provide medical resources quickly and accurately to analyze the feasibility of UAV DTs during COVID-19 prevention and used DL algorithms to construct a UAV DT information forecasting model. Fraser et al. [83] used DT and data-driven approaches to investigate the general susceptibilities of UAVs against contemporary cyber threats. Kapteyn et al. [84] suggested a probabilistic graphical model representing the DT and its physical asset for a UAV using experimental data to calibrate the DT. The UAV encounters an in-flight damage event and the DT is updated using sensor data. Riordan et al. [85] presented a DT to evaluate UAS-mounted LiDAR ability to detect small-object air collision risks, considering the Hamburg port with its aerial hazards (e.g., birds, drones, helicopters, and low-flying aircraft). Iqbal et al. [86] presented a DT with a runtime trust assessment for an autonomous food delivery drone system to evaluate the trusted execution of intelligent agents (autonomous drones or other vehicles). Grigoropoulos et al. [87] employed DTs and simulations to support offline validation and runtime checking in a platform as a service (PaaS) system for drone applications. Lee et al. [88] proposed a DT with a model-based system engineering methodology for a UAS capable of route selection in a military case study, where the route optimization module suggests an optimal path based on inputs such as potential damage. Lei et al. [89] created a DT to define the physical entity of a UAV swarm and track its life cycle. The UAV swarm's behaviors are investigated using an ML-based decision model. Wang et al. [90] combined DTs and convolutional neural networks (CNNs) for a UAV autonomous network to explore the airspace structure and safety performance of the UAV system. The presented literature emphasizes the significance of exploring and utilizing DTs in UASs. These case studies highlight the significance of DTs in addressing various challenges and opportunities of UASs associated with topics such as driving technological advancements, decision-making processes, and operational efficiency within this dynamic and evolving field. Digital twin technology has the potential to address some of these challenges and complement existing measures in UAV management. By modeling a digital copy of UASs and their operational environment, DTs can provide real-time monitoring, analyses, and optimization of UAS operations. This can enhance situational awareness, enable predictive maintenance, improve traffic management, and support decision-making processes. DTs can also facilitate data integration and interoperability across different systems, enabling a more comprehensive and coordinated approach to UAV management. However, it is important to note that DTs are not a standalone solution but should be integrated into a holistic framework that considers regulatory, technical, and operational aspects. Overall, the unique role of using a DT to facilitate UAV certification and regulation lies in the ability to model a digital copy of a physical system for real-time validation and optimization. However, this task is inherently complex and presents several challenges, as depicted in Figure 9, which offers an overview of the risks and challenges associated with the overall DT process. One challenge is the requirement for an accurate model of reality, which necessitates a deep understanding of the physical system and its operational characteristics. Additionally, as demonstrated in Figure 8, the creation of DTs necessitates the transfer of data between a physical system and a virtual model. Depending on the complexity level of a DT, this process involves handling a large amount of data from various sources, including sensors and sometimes even multifunctional models. Ensuring the accuracy and reliability of these data is crucial for the effectiveness of a DT. Furthermore, integrating a DT into UASs to assist the certification process requires careful consideration of legal and regulatory requirements. These challenges highlight the need for careful planning, robust data management, and close collaboration between experts in UAV certification and DT technology to successfully utilize DT in the context of UAV certification.

3. Results

UAVs are becoming popular. Autonomous (artificial intelligence applications) and automatic UAVs are expected to conduct safe operations, and they will enter UAM to transport goods and individuals in the near future. A wide range of literature is published to answer the research questions of "how to adapt UAV applications to regulations" and "how to adapt DT applications to UAV". However, it is fair to state that there is not much literature considering the use of DT applications in UAVs for certification and regulation. This lack of literature is inevitable in the early stages of new, emerging concepts. In order to fill this gap, we conducted a literature review considering a total of 121 references. Table 4 provides a comprehensive collection of references along with the keywords that are closely aligned with our research concepts. They serve as concise descriptors that capture the essence of the paper's content and help identify its key focus areas. The inclusion of these relevant keywords allows for a focused exploration and clear navigation of the existing literature, facilitating the identification of common themes, connections, and relationships across the literature. By including associated keywords in the table, we aimed to provide additional information and context about the content of each reference. We have systematically identified and classified the references into key focus areas: DTs, general aviation, UAVs/UASs, UAM/AAM, and regulation. By organizing the references under these categories, the table allows for a clear understanding of the primary themes and topics covered in each reference, enhancing the clarity and structure of our research with a more organized exploration. While the references consider multiple topics and overlap across the key focus areas, we have made an effort to present the primary purpose of each paper and provide associated keywords to highlight key themes and connections that contribute to a more comprehensive understanding of our research concepts and emphasize the various aspects explored in the literature.

Table 4. Compilation of references and their associated keywords relevant to our research concepts.

Reference Number	Year	Type	Key Focus	Related Keywords
[1]	2022	Regulatory document	Regulation	EASA regulations, operation of air taxis in cities
[2]	2021	Journal article	UASs/UAVs	Airspace organization and management, air traffic control, air traffic management, air traffic service provision, unmanned aircraft system, UAS traffic management
[3]	2021	Journal article	DT, UASs/UAVs	Unmanned aerial vehicles, deep learning, digital twins
[4]	2022	Other	DTs	Digital twins
[5]	2023	Other	DTs	Digital twins
[6]	2022	Other	General aviation	Aerospace certification, digital twins
[7]	2020	Other	DTs	Digital twins
[8]	2019	Journal article	DTs	Artificial intelligence, digital twins, human–computer interaction, machine learning
[9]	2018	Conference proceeding	DTs	Digital twins, learning theories, situational awareness
[10]	2021	Journal article	DTs	Digital twins, manufacturing system design, smart manufacturing
[11]	2020	Conference proceeding	DTs	Digital twin concept, digital twin application
[12]	2021	Journal article	UASs/UAVs	eVTOL, rotorcraft, design, advanced air mobility, urban air mobility

Table 4. *Cont.*

Reference Number	Year	Type	Key Focus	Related Keywords
[13]	2022	Journal article	UAM/AAM	Advanced air mobility, urban air mobility, emergency response, air ambulance, electric vertical take-off and landing, VTOL, eVTOL
[14]	2023	Journal article	UAM/AAM	Advanced air mobility, connected eVTOL, operations, infrastructure, communications, sustainability
[15]	2021	Conference proceeding	UAM/AAM	Surveillance, traffic control, aircraft navigation, safety, air traffic control, active appearance model
[16]	2020	Conference proceeding	UAM/AAM	Urban air mobility, aircraft performance, flight trajectory, autonomous systems, flight control, flight operation, detect and avoid
[17]	2022	Conference proceeding	UAM/AAM	Urban air mobility, aerial photography, conventional takeoff and landing, airspace management, short take-off and landing, federal aviation regulation, commercial aircraft
[18]	2021	Conference proceeding	UAM/AAM	Urban air mobility, autonomous systems, human automation interaction, ground control station, air transportation, national aeronautics and space administration, small unmanned aircraft systems
[19]	2021	Conference proceeding	UAM/AAM	Safety management, urban air mobility, airspace management, unmanned aircraft systems, supersonic aircraft, national airspace system, flight operations quality assurance, aeronautical information service
[20]	2022	Conference proceeding	UAM/AAM	Urban air mobility, aeronautics, special-use airspace, federal aviation administration, heliports, aviation, take-off and landing
[21]	2022	Conference proceeding	UAM/AAM	Flight testing, aviation, urban air mobility, propeller blades, true airspeed, flight path angle, vertical take-off and landing
[22]	2021	Conference proceeding	UAM/AAM	Urban air mobility, airspace class, air transportation, vertical take-off and landing, rotorcrafts, airspace system, helicopters, fixed-wing aircraft
[23]	2023	Conference proceeding	UAM/AAM	Urban air mobility, landing lights, flight testing, flight management system, flight control system, flight vehicle
[24]	2023	Conference proceeding	UAM/AAM	Urban air mobility, image registration, Federal Aviation Administration, vision-based navigation, heliports, instrument landing system
[25]	2021	Conference proceeding	UAM/AAM	Urban air mobility, airspace, software architecture, aeronautics, Federal Aviation Administration, aviation, unmanned aerial vehicle, aerospace industry
[26]	2022	Conference proceeding	UAM/AAM	Air mobility, Federal Aviation Administration, guidance system, sensor fusion, landing lights
[27]	2023	Conference proceeding	UAM/AAM	Air mobility, optical sensor, aviation, radar measurement, detect and avoid, take-off and landing
[28]	2022	Conference proceeding	UAM/AAM	Airspace, urban air mobility, near-mid-air collision, target level of safety, air traffic controller, helicopters, air traffic management, flight planning

Table 4. *Cont.*

Reference Number	Year	Type	Key Focus	Related Keywords
[29]	2021	Journal article	UAM/AAM	Advanced air mobility, cost–benefit analysis, ARIMA forecasting, electric vertical take-off and landing aircraft, small unmanned aircraft system, green transportation
[30]	2021	Journal article	UAM/AAM	Advanced air mobility, urban air mobility, on-demand air mobility, air taxi, vertical take-off and landing
[31]	2023	Other	UAM/AAM	Urban air mobility
[32]	2021	Journal article	UAM/AAM	Urban air mobility, air taxi, electric vehicle, autonomous vehicle, ride hailing, carsharing
[33]	2020	Book		On-demand mobility, transport modeling, urban air mobility, vertical take-off, landing
[34]	2020	Journal article	UAM/AAM	Urban air mobility, vehicle concepts, policy, transport simulation, infrastructure
[35]	2018	Journal article	Regulation	Drones, aircraft, atmospheric modeling, guidelines, FAA, government policies
[36]	2014	Journal article	Regulation	Remotely piloted aircraft (RPA), UAV
[37]	2014	Journal article	Regulation	Co-regulation, self-regulation, aviation safety, drone, RPA, UAV
[38]	2020	Journal article	Regulation	Drone, regulation
[39]	2016	Journal article	Regulation	Privacy regulation, drone privacy
[40]	2021	Journal article	UASs/UAVs	WTP for drone flying, road pricing for drone airspace
[41]	2019	Journal article	Regulation	Drone, regulation
[42]	2022	Journal article	Regulation	Drone regulation, local policy adoption
[43]	2019	Journal article	Regulation	Drones, regulation, policy
[44]	2020	Other	General aviation	Digital twin, data management
[45]	2018	Conference proceeding	DTs	Digital twin
[46]	2020	Journal article	General aviation	Airframe digital twin, digital thread, individual aircraft tracking
[47]	2020	Conference proceeding	General aviation	Commercial aircraft, machine learning, airspace, artificial intelligence, neural networks, aircraft production, aviation
[48]	2022	Journal article	DTs	Digital twins, military aircraft, aircraft propulsion
[49]	2019	Conference proceeding	DTs	Digital twins, aviation industry
[50]	2012	Conference proceeding	DTs	Aircraft structures, high-performance computing structural modeling, air forces, flight dynamics
[51]	2017	Conference proceeding	General aviation	Aircraft structures, genetic algorithm, structural damage
[52]	2019	Journal article	DTs	Digital technology, digital twin, aircraft industry
[53]	2022	Journal article	General aviation	Digital twin, digital thread, aircraft assembly
[54]	2020	Conference proceeding	General aviation	Aircraft maintenance, aircraft life cycle, digital twin
[55]	2011	Journal article	General aviation	Aircraft structural life prediction, digital twin
[56]	2015	Conference proceeding	DTs	Product avatar, digital twin, digital counterpart, aircraft avatar
[57]	2020	Conference proceeding	DTs	Product life cycle, digital twin, aircraft

Table 4. *Cont.*

Reference Number	Year	Type	Key Focus	Related Keywords
[58]	2020	Journal article	General aviation	Aircraft manufacture, digital twin
[59]	2022	Journal article	DTs	Digital twin shop floor, large-scale problem optimization, simulation
[60]	2021	Conference proceeding	General aviation	Digital twin, aircraft manufacturing
[61]	2022	Journal article	General aviation	Non-orthogonal aviation spiral bevel gears, free-form tooth surface grinding, digital twin modeling
[62]	2017	Conference proceeding	General aviation	Flight data, flight operation, flywheels, structural health monitoring
[63]	2021	Journal article	General aviation	Optimization, digital twin, virtual modules
[64]	2020	Conference proceeding	General aviation	Digital twin, virtual sensing, aircraft ground-steering system
[65]	2022	Journal article	General aviation	Aircraft skin, digital twin, layout optimization
[66]	2022	Journal article	DTs	Autoregressive moving average (ARMA) model, turbofan engine modeling
[67]	2017	Conference proceeding	DTs	Aircraft wings, stochastic crack growth models, surrogate model, mathematical models
[68]	2017	Journal article	General aviation	Aircraft wings, stochastic crack growth models, fatigue cracking, airframes
[69]	2022	Journal article	General aviation	Digital twin, aircraft hydraulics, ensemble learning
[70]	2021	Conference proceeding	General aviation	Digital twin, aviation, aircraft cabins
[71]	2022	Journal article	General aviation	Digital twin, aviation industry
[72]	2021	Journal article	DTs	Digital twin, artificial intelligence, autonomous driving
[73]	2020	Conference proceeding	DTs	Digital twin, self-aware unmanned vehicle
[74]	2022	Journal article	DTs, UASs/UAV	Digital twin, model updating, unmanned aerial vehicle
[75]	2020	Conference proceeding	DTs, UASs/UAVs	Machine learning, unmanned aerial vehicle, recurrent neural network
[76]	2022	Journal article	DTs, UASs/UAVs	VTOL, UAV, digital twin, aerodynamic coefficients, gazebo, wind model
[77]	2021	Conference proceeding	DTs, UASs/UAVs	Digital twin, UAV, virtual and real interaction
[78]	2020	Conference proceeding	DTs, UASs/UAVs	UAV, digital twin, simulation
[79]	2022	Conference proceeding	DTs, UASs/UAVs	Unmanned aerial vehicle (UAV), multifidelity simulation
[80]	2022	Conference proceeding	DTs, UASs/UAVs	Unmanned aerial vehicle, deep learning, digital twins
[81]	2022	Journal article	DTs, UASs/UAVs	Deep reinforcement learning (DRL), digital twin (DT), multi-UAV systems
[82]	2021	Journal article	DTs, UASs/UAVs	Unmanned aerial vehicles, digital twins, deep learning
[83]	2021	Conference proceeding	DTs, UASs/UAVs	Digital twin, machine learning, UAV, UAS, cybersecurity
[84]	2021	Journal article	DTs, UASs/UAVs	Digital twin
[85]	2021	Conference proceeding	DTs, UASs/UAVs	Unmanned aerial systems, detect and avoid, data-driven simulation
[86]	2022	Conference proceeding	DTs, UASs/UAVs	Modeling, autonomous drones, digital twin
[87]	2020	Conference proceeding	DTs, UASs/UAVs	Drones, simulation environment, digital twin
[88]	2021	Journal article	DTs, UASs/UAVs	Digital twin, model-based systems engineering

Table 4. *Cont.*

Reference Number	Year	Type	Key Focus	Related Keywords
[89]	2021	Journal article	DTs, UASs/UAVs	data models, unmanned aerial vehicles, integrated circuit modeling, digital twin, computational modeling, machine learning algorithms, real-time systems
[90]	2022	Journal article	DTs, UASs/UAVs	unmanned aerial vehicles, safety, aircraft, aircraft navigation, security, monitoring
[91]	2018	Book	Regulation, UASs/UAVs	European policies, civil drones, safety, security
[92]	2012	Book	General aviation	Aircraft structures
[94]	2018	Conference proceeding	DTs	Digital twin, simulation, cyber-physical system
[95]	2016	Book	Regulation, UASs/UAVs	Drone laws, RPAS, UAS, UAV, commercial drones, autonomous aviation
[96]	2023	Other	Regulation	EASA Provisions, EU Regulations 2019/947 and 2019/945
[97]	2023	Regulatory document	Regulation	Civil drones, unmanned aircraft
[98]	2023	Regulatory document	Regulation	Open category of civil drones
[99]	2023	Regulatory document	Regulation	Specific category of civil drones
[100]	2023	Regulatory document	Regulation	Certified category of civil drones
[93]	2022	Regulatory document	Regulation	Rules For Unmanned Aircraft Systems, Regulation (EU) 2019/947, Regulation (EU) 2019/945
[101]	2021	Regulatory document	Regulation	EASA guidelines, The Design Verification of Specific Category Drones
[102]	2023	Regulatory document	Regulation	Rules for Airworthiness and Environmental Certification, Regulation (EU) No 748/2012
[103]	2021	Other	Regulation	EU regulatory for U-space
[104]	2021	Regulatory document	Regulation	Regulation (EU) 2021/664
[105]	2021	Regulatory document	Regulation	Regulation (EU) 2021/665
[106]	2021	Regulatory document	Regulation	Regulation (EU) 2021/666
[107]	2023	Other	Regulation	Autonomous drones, automatic drones
[108]	2022	Conference proceeding	UAS/UAV	Adversarial machine learning, aviation, urban air mobility, pilot, convolutional neural network, unmanned aircraft system, cyber–physical system
[109]	2020	Regulatory document	Regulation	EASA AI roadmap, AI in aviation
[110]	2022	Conference proceeding	Regulation	Reinforcement learning, aviation, European Aviation Safety Agency, artificial intelligence, neural networks, urban air mobility, unmanned aircraft system, air traffic management, continuing airworthiness
[111]	2020	Journal article	DTs	Digital twin
[112]	2017	Other	DTs	Digital twin
[113]	2021	Conference proceeding	DTs	Digital twin technologies
[114]	2012	Conference proceeding	General aviation	Digital twin, air forces, NASA Goddard Space Flight Center
[115]	2020	Journal article	DTs	Digital twin
[116]	2018	Journal article	DTs	Digital twin
[117]	2022	Other	DTs	Digital twin

Table 4. *Cont.*

Reference Number	Year	Type	Key Focus	Related Keywords
[118]	2022	Book	DTs	Digital twin, digital manufacturing, digital technologies in manufacturing, digital image processing
[119]	2023	Book	DTs, UASs/UAVs	Digital twin, smart urban mobility, UAV
[120]	2021	Journal article	DTs	Digital twin, cyber–physical systems
[121]	2023	Other	DTs, UASs/UAVs	Intelligent urban air mobility, digital twin, autonomous flight

A time frame of two decades was chosen for conducting the literature review, since the term "digital twin" was first introduced in 2010 [111]. However, in this section, as we discussed in the research methodology in Section 2.1, we only analyzed articles within the scope of DT applications for UASs. DT applications in UASs are relatively new, resulting in the majority of the relevant literature having been published within recent years. Although research on DTs in UAS applications has recently gained momentum, there remains a substantial amount of work to be undertaken toward the further exploration and understanding of the potential value and significance that DTs can bring to the field of UAS applications. Figure 11 provides a word cloud visualization that depicts the frequency of selected keywords (DT, UAV, AI, drone, UAS, certification, regulation, and VTOL) within publications related to the applications of DTs in UASs. These specific keywords were carefully selected during the research process, and the word cloud offers a concise representation of the pathway to the literature review scope.

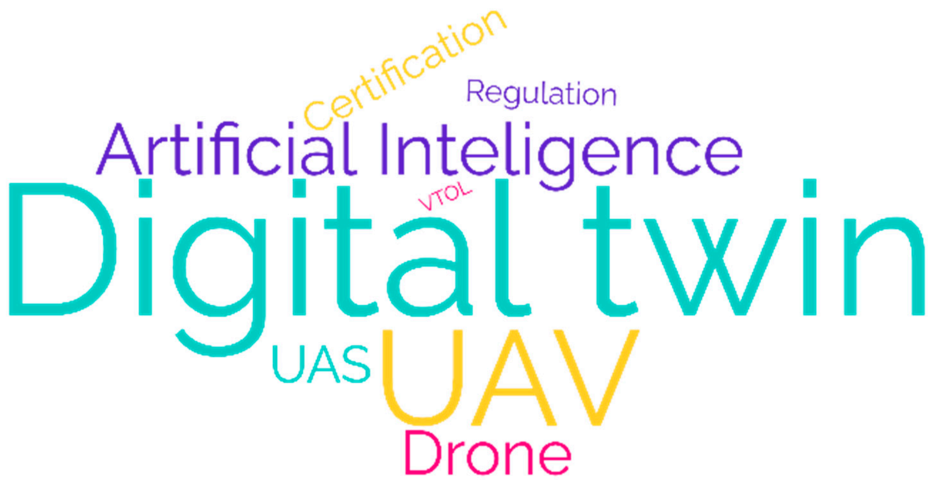

Figure 11. Keyword analysis word cloud for DT applications in publication on UASs.

While the complexity of UASs is fast evolving, only 40% of the publications briefly mentioned certification and regulation when using DTs in UASs, and not many scientific literature efforts focus on the use of DT applications in UASs for certification and regulation, as shown in Figure 12. DTs facilitate designing, building, and analyzing procedures. DTs are very good and relatively time- as well as cost-efficient tools to assist the certification process, since they help engineers check, analyze, and integrate designs as well as express concerns instantly.

Autonomous (with the help of AI and without a pilot's intervention) UAVs are expected to conduct safe operations and cope with unforeseen conditions. As presented in Figure 13, half of the publications considering the use of DT applications in UASs mentioned autonomous flight operations, and 38% of these publications also discussed the use of AI, which leads to the key research question of how these operations can be safely conducted. In UASs' EU operational scope, the EASA published the "EASA AI roadmap" as a human-centric approach to the safe use of AI in aviation.

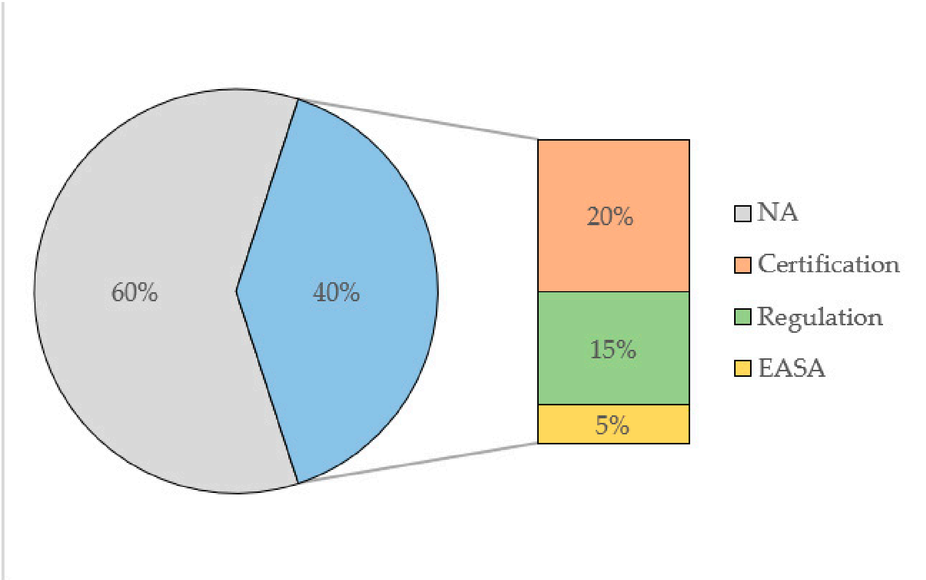

Figure 12. Keyword analysis focused on certification and regulatory frameworks for DT applications in publication on UASs.

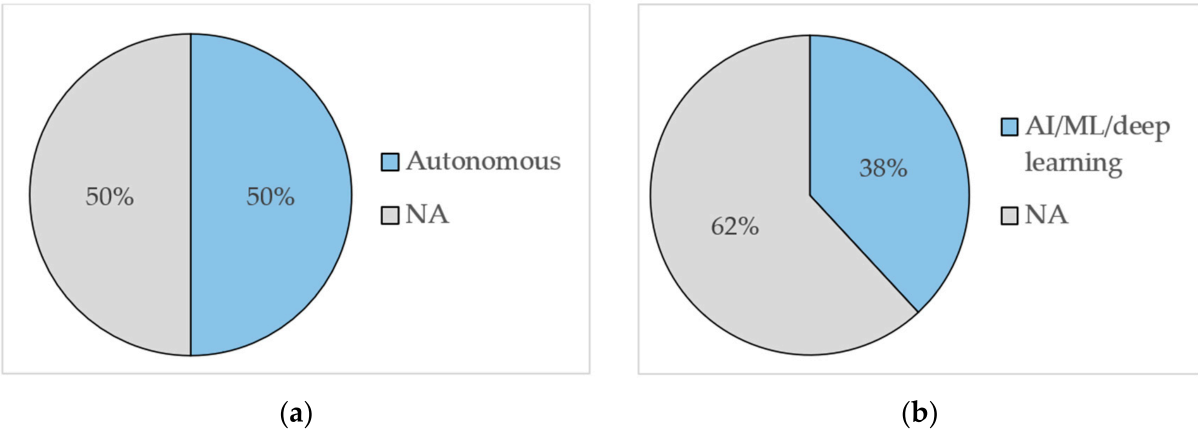

Figure 13. Keyword analysis focused on (**a**) autonomous flights and (**b**) the use of AI/ML/deep learning approaches for DT applications in publications on UASs. (**a**) Autonomous flights mentioned in publications. (**b**) AI/ML/deep learning approaches mentioned in publications.

4. Discussion

Flying cars and aerial transportation systems are some of the distinctive features of the future cities described in science fiction films and books. This is one of the basic concepts accepted by society when imagining the future, and with today's technological advancements we wonder if conducting safe automatic and autonomous flights for metropolitan areas is a few steps away in the near future. The establishment of a socially acceptable regulatory framework is necessary to transform this vision into a reality.

The regulatory framework for UASs in the European Union was fragmented before 2020, as shown in Figure 1, with each EU Member State being responsible for drones with a maximum take-off mass (MTOM) of less than 150 kg while the EASA was in charge of drones with an MTOM exceeding this weight. The transition to new regulations began in 2020, and the EASA is now responsible for drones of all weights and size. Nonetheless, this regulatory framework is still in its early stages, and further developments are expected.

Implementing this evolving regulatory framework presents a significant challenge in UAS operations. DTs can potentially offer a solution by facilitating the design, construction, and analysis processes. They are time- and cost-efficient tools to assist the certification process, since they help engineers check, analyze, and integrate designs as well as express concerns instantly. However, only a limited number of publications (40%) briefly mentioned certification and regulation when discussing the application of DTs in UASs, as shown in Figure 12. Therefore, efforts need to be carried out to emphasize the importance of DTs in assisting the certification process within UAS operations.

In Figure 13, it is notable that autonomous flight operations were mentioned in 50% of the papers examining the use of DTs in UASs, and AI applications were discussed in 38% of the publications. Autonomous and automatic UASs are expected to conduct safe operations in UAM. A quick comparison of autonomous and automatic flights can show that there is no human safety net present during an autonomous flight in the event of unforeseen circumstances. Therefore, precise regulations must be created in the context of AI to ensure autonomous flights are safely conducted. In 2020, the EASA also published the first guidance, the EASA AI roadmap, for the safe use of artificial intelligence in aviation. However, we are still a long way from the dream of having science fiction flying transport systems coming true, as the timeline outlined in the EASA AI roadmap document predicts the first approvals of AI in 2025.

The research subject of how to adapt UASs with UAM and regulation is studied in a wide range of the literature from across the world. However, the implementation of DTs in UASs for assisting the certification process and considering regulation, especially within the context of the EU regulatory framework, remains relatively unexplored. The concept of drone regulation, particularly in relation to EU legislation and the integration of UAM for cargo and passenger transport, is still relatively new. The development of regulations, as well as applying these regulations to UAS operational categories, requires the consideration of numerous criteria and parameters to ensure a robust level of safety and seamless flight operations. Moreover, due to safety concerns and ongoing regulation development, UAV autonomous flights are not currently being carried out in most European countries. The lack of literature and documents is inevitable in the early stages of a new concept's development. Consequently, one of the challenges lies in staying informed about evolving regulations and keeping track of the developments and changes that emerge in this field.

Overall, this paper highlights the necessity of further research on and the exploration of DT applications in UASs, particularly concerning certification and regulation. It is essential to recognize that DTs cannot function as standalone solutions but should be seamlessly integrated into a comprehensive framework that takes into account regulatory, technical, and operational aspects. The distinct advantage of employing DTs to facilitate UAS certification and regulation lies in their ability to create a digital replica of a physical system, enabling real-time validation and optimization. Nonetheless, this task is inherently complex and presents several challenges, such as the necessity of an accurate model of reality and handling a large amount of data from various sources. Furthermore, utilizing DTs to assist the certification process requires careful consideration of legal and regulatory requirements. It is crucial to address these challenges and associated complexities to pave the way for the successful implementation of UASs in UAM.

5. Conclusions

The popularity of UAV operations has increased, and new air mobility concepts have emerged over the past years. It is essential to develop regulations in this new technological context that effectively address the challenges and opportunities presented by UASs. There are various levels of ongoing activities and recent advances in UAS regulatory frameworks, especially in the domain of European Union (EU) regulations. Due to the growing demands, advancements, and possible applications of UASs, particularly in research and innovation, there is a need for a systematic overview. To bridge this gap, we present a comprehensive overview of the developed UAS regulations in the European Union and explore the concept of DTs as well as their potential applications in the UAS domain. We aimed to conduct a systematic review to provide a structured methodology that synthesizes multiple studies to offer a comprehensive and unbiased assessment of DTs' applications in UASs with EU regulatory compliance. Despite limited scholarly focus on the implementation of DTs in UASs considering certification and regulation, we analyzed the existing literature to identify and emphasize the important trends and developments. The overall challenges and the importance of UAS DTs are highlighted to provide a robust foundation for future studies on UAS DTs and their compliance with the EU regulatory framework.

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