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Current Trends in the Application of Polymer 3D Printing in Aircraft Engineering and Methodological Approaches to Design Optimization

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This article analyzes the latest trends in the application of polymer 3D printing technologies in aircraft engineering, with a particular focus on methodological approaches to design optimization. Polymer-based additive manufacturing methods, including FDM, SLS, SLA, and MJF, are considered as enabling technologies for the production of aircraft components with complex geometries, reduced structural mass, and enhanced functional integration. The increasing adoption of these technologies in aircraft structures, systems, and interior components is driven by the need to improve weight efficiency, shorten development cycles, and support flexible manufacturing across different stages of the product life cycle.

Special attention is given to the role of design-stage optimization in ensuring the mechanical performance, durability, and operational reliability of polymer components manufactured using additive technologies. Key challenges inherent to polymer 3D printing are discussed, including anisotropy of mechanical properties, process-induced defects, sensitivity to printing parameters, and variability in material behavior. These factors significantly affect the repeatability and certification readiness of additively manufactured aircraft components.

The article reviews contemporary optimization strategies applied in aircraft engineering, including design for additive manufacturing, statistical methods (such as Design of Experiments and Taguchi techniques), numerical modeling, and data-driven approaches based on AI. The integration of digital design, experimental validation, and intelligent optimization tools into a unified methodological framework is identified as a critical factor for improving the efficiency and reliability of polymer 3D-printed aircraft components. Based on the analysis of recent studies and industrial practices, existing gaps are identified and prospective directions for further research and development of polymer additive manufacturing in aircraft engineering are outlined. Further investigations should be carried out in the field of comprehensive exper-imental validation of optimized designs.

Keywords: polymer 3D printing; aircraft engineering; additive manufacturing; design optimization; process parameters; artificial intelligence; numerical modeling.

Introduction

Recently, additive manufacturing (AM) experienced evident development and is increasingly regarded as a strategic production technology in modern aircraft engineering [1–3]. Unlike conventional manufacturing routes, additive processes enable the fabrication of components with complex internal architectures, high functional integration, and optimized material distribution [4–6]. These capabilities are especially relevant for the aviation industry, where stringent requirements related to mass reduction, structural efficiency, and lifecycle cost continue to intensify [7, 8].

The application of polymer-based additive manufacturing technologies has gained particular importance within this context [9–11]. Polymer 3D printing offers a combination of low material density, manufacturing flexibility, and reduced lead times, making it suitable for a wide range of aircraft components, especially in low- and medium-volume production scenarios [12–14]. Polymer additively manufactured parts are currently employed for cable management systems, air distribution ducts, brackets,

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housings, and interior elements, where geometric complexity and weight efficiency are critical [15, 16]. Advances in high-performance polymers and fiber-reinforced materials have further expanded the functional scope of polymer components within aircraft structures [17–19].

The growing industrial adoption of AM is supported by extensive research activity and practical implementation by leading aerospace manufacturers. Companies such as Airbus, Boeing, and GE Aviation have incorporated polymer additive manufacturing into multiple stages of the product life cycle, including conceptual design, functional prototyping, serial production of selected components, and maintenance, repair, and overhaul operations [2, 9, 20–22]. Their experience demonstrates that additive technologies are no longer limited to experimental use but are becoming integrated into certified industrial workflows [23–25].

In the Ukrainian aviation sector, the enterprise Antonov is exploring the potential of additive manufacturing for small-batch production, repair applications, and supply chain resilience, although large-scale implementation remains constrained by technological and regulatory factors [4, 26].

A review of recent scientific publications and industrial reports indicates a clear tendency toward the use of polymer 3D printing across the entire life cycle of aircraft components [27–29]. At the design stage, additive technologies enable rapid iteration and early optimization of geometry and functionality [30–32]. During production, they support flexible manufacturing and customization, while in the operational phase they facilitate on-demand part replacement and maintenance solutions [10, 33]. However, despite these advantages, the broader application of polymer additive manufacturing in aircraft engineering is still limited by a number of unresolved challenges.

The lack of standardized and methodically verified approaches for the design of polymer components made with additive technologies is one of the biggest problems [31, 34]. Environmental factors, build orientation, material quality, and process parameters all have a significant impact on the mechanical performance of polymer 3D-printed objects [35–37]. As a result, anisotropy of mechanical properties, process-induced defects, and variability in performance remain common [18, 28, 38]. These factors complicate the reliable prediction of structural behavior and hinder the standardization and certification of polymer additively manufactured aircraft components, as reflected in current regulatory and qualification frameworks [9, 10, 39].

The study' novelty lies in the formulation of a comprehensive methodological perspective on the design optimization of polymer aircraft components manufactured using additive technologies. In contrast to existing works, which predominantly address individual aspects such as material characterization [16, 18], process parameter influence [35–37], or isolated optimization techniques [33, 34], this study systematically integrates statistical methods, numerical modeling, and data-driven approaches within a unified design framework [30, 36, 40].

The proposed approach emphasizes the interdependence between design decisions, manufacturing parameters, and resulting structural performance, thereby addressing a critical gap identified in recent aerospace-oriented additive manufacturing research [11, 27, 29]. By synthesizing industrial experience [2, 9, 20], recent scientific findings [15, 17, 28], and advanced optimization techniques [33, 36, 40], the study contributes to the development of a structured basis for improving the reliability, efficiency, and certification readiness of polymer 3D-printed aircraft components.

Problem Statement. The objective of this study is to analyze current trends in the application of polymer 3D printing technologies in aircraft engineering and to

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substantiate methodological approaches to the optimization of component design under aerospace-specific requirements [7, 11, 29].

To achieve this objective, the following scientific and applied tasks are defined:

- to analyze the implementation of additive manufacturing technologies in aviation based on the experience of leading aircraft manufacturers and recent research results [2, 9, 20–22];
- to examine polymer 3D printing technologies, including FDM/FFF, SLA/DLP, and SLS, with respect to their technological capabilities and limitations in aircraft engineering applications [13, 14, 18, 19];
- to identify core challenges associated with the design and manufacturing of polymer additively manufactured aircraft components [28, 31, 35–38];
- to analyze contemporary design optimization methods, including Design of Experiments, Taguchi techniques, artificial intelligence-based approaches, and topological optimization [30, 33, 36, 40].

The object of the study is polymer aircraft components manufactured using additive technologies.

The subject of the study is the set of design, technological, and optimization methods that determine the structural performance and reliability of polymer 3D-printed components in aircraft engineering.

The research methodology is based on a systematic analysis of latest scholarly publications, industrial implementation reports, and regulatory documentation [9, 10, 39], as well as on comparative analysis, synthesis of experimental data, and evaluation of numerical and data-driven optimization approaches [30, 33, 36].

1. Additive manufacturing in aircraft engineering across the product life cycle

AM has transitioned from a supporting role in rapid prototyping to a strategically important production technology in contemporary aircraft engineering [1–3]. The layer-by-layer fabrication paradigm enables the realization of complex geometries, functional integration, and optimized material distribution, which are increasingly challenging to achieve using conventional manufacturing approaches [4–6]. As aircraft programs face growing pressure to reduce structural mass, shorten development cycles, and improve lifecycle efficiency, additive manufacturing has become a key enabler of advanced design and production concepts [7, 8]. Figure 1 shows schematic overview of AM technologies application at different stages of the aircraft product life cycle, highlighting their role in design optimization, flexible production, and maintenance support.

At the design stage, additive manufacturing provides significant advantages by enabling early validation of geometric concepts and functional layouts. Polymer 3D printing technologies facilitate rapid iteration of design variants, assessment of assembly interfaces, and evaluation of spatial constraints without the need for dedicated tooling [27, 30]. The application of design for additive manufacturing principles allows components to be tailored to process-specific constraints, thereby improving material efficiency and structural performance [31, 32]. These skills are especially important for aircraft engineering, where severe mass and performance criteria depend on iterative optimization [7, 8].

During the production phase, polymer-based additive manufacturing supports flexible and economically viable fabrication of low- and medium-volume components. Aircraft manufacturers increasingly employ polymer 3D printing for serial production of brackets, housings, cable routing elements, and air distribution ducts, where traditional

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manufacturing methods may be associated with high tooling costs and limited adaptability [12–15]. Industrial studies demonstrate that additive manufacturing enables part consolidation, reduces assembly complexity, and shortens supply chains, contributing to overall production efficiency [20–22].

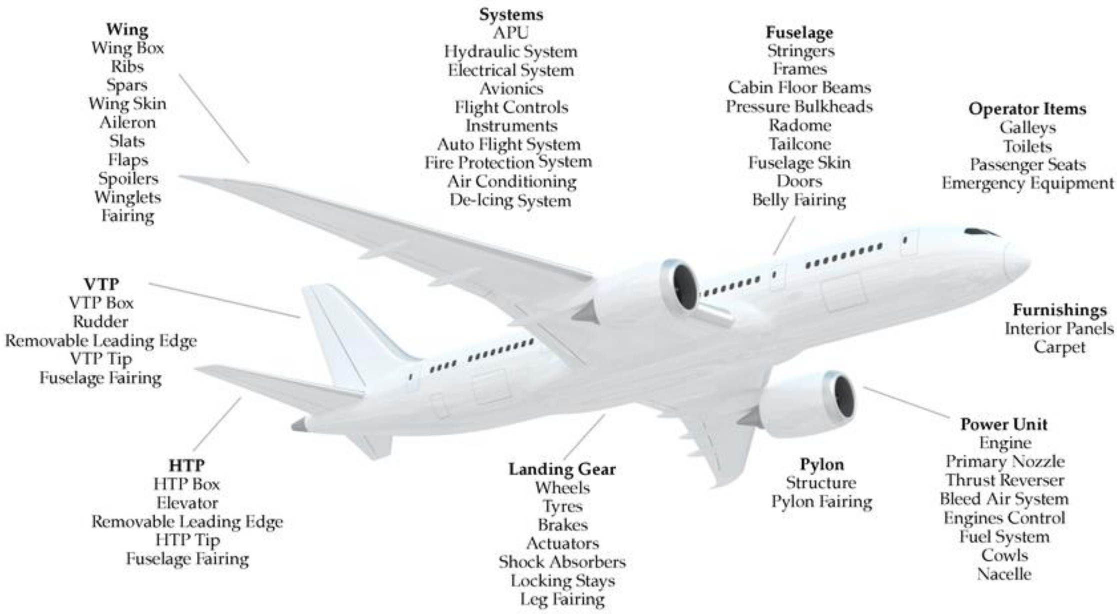

Fig. 1. Application of additive manufacturing technologies across the aircraft product life cycle, including design, production, and maintenance stages

The operational stage of the aircraft life cycle represents another area in which additive manufacturing has demonstrated growing relevance. Polymer additive technologies enable on-demand fabrication of replacement parts and customized components for maintenance, repair, and overhaul operations [10, 33]. This approach is particularly advantageous for aging aircraft fleets and low-volume platforms, where conventional spare part production may be inefficient economically or logistically constrained [23–25]. By reducing inventory requirements and lead times, additive manufacturing contributes to improved aircraft availability and lifecycle cost reduction [24, 25].

Leading aircraft manufacturers have actively integrated additive manufacturing technologies across multiple stages of the product life cycle. Airbus applies polymer additive manufacturing for lightweight interior components and system elements optimized for additive processes, emphasizing mass reduction and functional integration [2, 9]. Boeing employs polymer 3D printing for functional components, tooling, and maintenance applications, with a sound focus on digital continuity and process qualification [20–22]. GE Aviation integrates additive manufacturing within a broader digital engineering framework, combining material qualification, process control, and performance validation [24, 25]. Fig. 2 shows the conceptual integration of digital validation methodologies, additive manufacturing procedures, and design optimization approaches for polymer aircraft components.

In the Ukrainian aviation industry, the enterprise Антонов is exploring the application of polymer additive manufacturing to support small-batch production, repair activities, and import substitution [4, 26]. Although large-scale industrial implementation remains limited, additive technologies offer a promising pathway for

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enhancing manufacturing flexibility and supply chain resilience under constrained conditions.

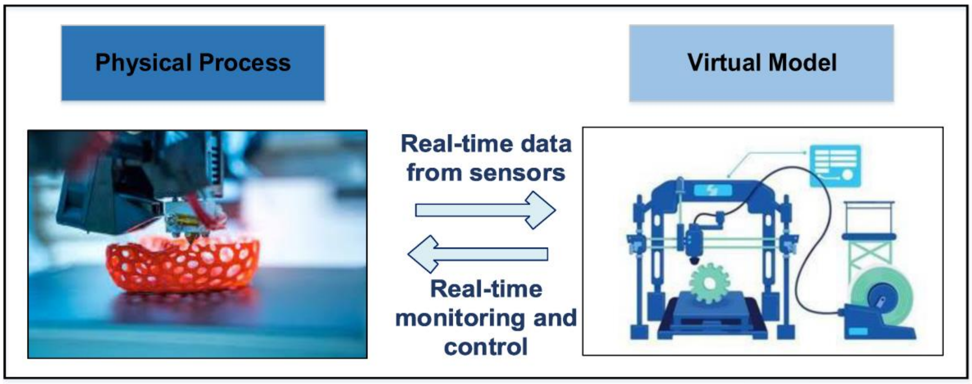

Fig. 2. Conceptual integration of design optimization, AM processes, and digital validation for polymer aircraft components

Despite these demonstrated advantages, the integration of polymer additive manufacturing across the aircraft product life cycle remains uneven. Variability in material properties, sensitivity to process parameters, and limited reproducibility of mechanical performance continue to restrict broader adoption, particularly for safety-critical applications [28, 35–38]. In addition, certification and qualification challenges, driven by the lack of standardized design and validation methodologies, remain a significant barrier to industrial-scale implementation [9, 10, 39].

2. Polymer 3D printing technologies for aircraft applications

Polymer additive manufacturing comprises a group of layer-based fabrication technologies that differ significantly in processing principles, material compatibility, achievable mechanical performance, and suitability for aircraft engineering applications [11–14]. The selection of a particular polymer 3D printing technology is governed by structural requirements, environmental operating conditions, certification constraints, and the targeted stage of the aircraft product life cycle [9, 10, 39]. Among the most widely applied technologies in aviation practice are Fused Deposition Modeling (FDM/FFF), Stereolithography and Digital Light Processing (SLA/DLP), SLS, and AM processes involving fiber-reinforced and hybrid polymer composites [15–19]. Figure 3 illustrates representative examples of polymer additively manufactured aircraft components, demonstrating typical geometries and functional features enabled by these technologies.

Fused Deposition Modeling / Fused Filament Fabrication (FDM/FFF). FDM/FFF is among the most broadly used polymer additive manufacturing technologies in aircraft engineering due to its relative process simplicity, material availability, and cost efficiency [13, 14]. The technology is based on the extrusion of thermoplastic filament through a heated nozzle, followed by layer-by-layer deposition. Commonly used materials include ABS, PETG, and high-performance polymers such as PEEK and ULTEM (PEI), which meet aviation-specific requirements related to flame resistance, smoke density, and toxicity [15–17].

In aircraft applications, FDM/FFF is primarily employed for the production of brackets, cable routing elements, housings, air ducts, and interior components [15, 16]. The ability to fabricate complex geometries without dedicated tooling enables rapid

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adaptation of designs and supports low-volume production strategies [12, 20]. However, the mechanical performance of FDM/FFF parts is strongly influenced by build orientation, layer adhesion, and process parameters, resulting in anisotropic material behavior and variability of properties [28, 35–37].

Fig. 3. Examples of polymer additively manufactured components applied in aircraft engineering, including brackets, air ducts, and interior elements

Recent studies emphasize the significant importance of process parameter optimization and post-processing techniques to enhance structural performance of FDM/FFF components manufactured from high-performance polymers [16–18]. Statistical methods such as Design of Experiments and Taguchi techniques have been shown to significantly reduce variability and improve repeatability [33, 34]. Additionally, data-driven AI-based approaches are increasingly applied to predict mechanical properties and detect process-induced defects [35, 36].

SLA/DLP. These technologies are grounded on the photopolymerization of liquid resins using ultraviolet light, offering high dimensional accuracy and excellent surface quality compared to extrusion-based processes [14, 18]. These characteristics make SLA/DLP particularly suitable for prototyping, aerodynamic testing models, and complex geometries fabrication with fine details [27, 30].

Despite its benefits, most photopolymer materials' comparatively poor temperature stability and long-term durability restrict the use of SLA/DLP in aviation engineering [18, 28]. Material aging, sensitivity to ultraviolet radiation, and reduced mechanical performance under elevated temperatures restrict their use in load-bearing or safety-critical components [31]. Consequently, SLA/DLP technologies are primarily applied at early design stages and for non-structural applications, where geometric fidelity is prioritized over long-term mechanical performance [27, 32]. Figure 4 shows an example of a polymer additively created cutaway model that demonstrates how 3D printing may create intricate aircraft designs.

SLS. SLS enables the fabrication of polymer components without the need for support structures, resulting in greater design freedom and more isotropic mechanical properties compared to FDM/FFF [18, 19]. Common materials include polyamides such as PA11 and PA12, that exhibit favorable mechanical performance and environmental resistance for aircraft applications [29–32].

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Fig. 4. Polymer 3D-printed cutaway model of an aircraft jet engine section illustrating the AM application for complex aerospace geometries

In aircraft engineering, SLS is used widely for manufacturing air ducts, functional housings, and interior components requiring consistent mechanical behavior and geometric accuracy [18, 29]. Lack of pronounced anisotropy and the relatively stable process conditions contribute to enhanced reproducibility and quality control [30, 31]. Nevertheless, factors such as powder reuse, thermal history, and build orientation continue to influence final part properties and require careful process control [32, 34]. SLS applicability for the fabrication of geometrically complex polymer components used in aircraft systems is illustrated by the component demonstrated in Figure 5.

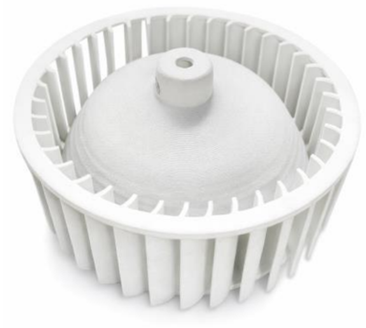

Fig. 5. Polymer component manufactured by SLS, illustrating complex geometry and uniform wall thickness achieved without support structures

Fiber-Reinforced and Hybrid Polymer Composites. Incorporation of reinforcing fibers into polymer matrices represents a promising vector for extending the AM application to structurally demanding aircraft components [17, 19]. Both short-fiber-filled filaments and continuous fiber reinforcement approaches are used to enhance strength, stiffness, and fatigue resistance [24, 38].

Fiber-reinforced polymer AM enables manufacturing lightweight components with ‘customized’ mechanical properties, thus supporting the principles of lightweight design and functional integration [17, 38]. However, challenges related to fiber orientation control, interfacial bonding, and process repeatability remain significant barriers to widespread industrial adoption [31, 39]. Current research focuses on improving material-process compatibility and developing design methodologies that account for anisotropic reinforcement behavior [36, 40]. Representative examples of aircraft brackets manufactured using fiber-reinforced and hybrid polymer composites, illustrating the potential for lightweight design and functional integration, are

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demonstrated in Figure 6.

Fig. 6. Examples of additively manufactured aircraft brackets produced from fiber-reinforced and hybrid polymer composites, demonstrating lightweight design and functional integration

3. Challenges manifesting in the processes of design and manufacturing of polymer additively manufactured aircraft components

Despite the increasing adoption of polymer additive manufacturing technologies in aircraft engineering, their industrial-scale implementation remains constrained by a combination of technological, material, and methodological challenges [9–11]. These challenges occur from the internal characteristics of layer-based fabrication processes, polymer materials sensitivity to manufacturing conditions, and the stringent reliability and certification requirements imposed on aircraft components throughout their service life [28, 39].

A fundamental challenge associated with polymer additive manufacturing is mechanical properties' anisotropy characteristic to layer-by-layer fabrication [28, 35–37]. In extrusion-based processes such as FDM/FFF, insufficient interlayer adhesion and directional dependency of material strength often result in reduced load-bearing capacity in the build direction [16,35]. Although powder-bed-based technologies such as SLS generally exhibit more uniform mechanical behavior, residual anisotropy may still occur as a result of to thermal gradients, scan strategies, and build orientation effects [30–32].

Dimensional inaccuracies, warpage, and residual stresses constitute additional technological limitations, particularly for thin-walled or geometrically complex components [31, 34]. These effects are strongly influenced by process parameters, including temperature distribution, cooling rates, and energy input, as well as by material-specific properties such as thermal expansion and crystallization behavior [18, 29]. As a result, achieving consistent geometric accuracy and dimensional stability remains a critical challenge for functional aircraft components manufactured using polymer additive technologies.

Material degradation and environmental sensitivity further complicate the application of polymer additively manufactured parts in aircraft engineering [26–28].

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Hygroscopic behavior of certain polymers, particularly polyamides used in SLS processes, leads to moisture absorption, which can adversely affect mechanical performance and increase variability of material properties [26, 27]. In addition, prolonged exposure to elevated temperatures, ultraviolet radiation, and cyclic mechanical loading may accelerate material aging and reduce long-term durability and fatigue resistance [28, 38].

Process Variability and Reproducibility. Mechanical and physical properties' reproducibility is a critical requirement for aircraft components, while it remains among the most sound challenges for polymer AM [9, 10, 39]. Variations in raw material quality, including filament or powder batch characteristics, as well as differences in machine calibration and conditions of environment, can lead to substantial scatter of mechanical properties even in case of application of nominally identical process parameters [31, 35–37].

In powder-bed fusion processes such as SLS, powder reuse introduces additional sources of variability, as repeated thermal cycling alters particle morphology and material behavior [30, 32]. Similarly, in FDM/FFF processes, fluctuations in extrusion conditions, nozzle wear, and filament moisture content have been shown to significantly influence interlayer bonding and overall part quality [26, 35]. These elements make it more difficult to create stable process windows and the dependable design allowables needed for certification-oriented design methodologies.

Design and Methodological Limitations. From a design perspective, one of the core limitations consists in the lack of unified and systematically validated methodologies specifically tailored to polymer AM in aircraft engineering [31, 34]. Conventional design approaches and safety factors, originally developed for isotropic materials and traditional manufacturing processes, are often not directly applicable to additively manufactured polymer components [28, 39].

Although design for additive manufacturing principles are widely discussed in the literature, their practical implementation in aircraft engineering remains fragmented and technology-specific [30, 32]. Designers frequently rely on empirical guidelines or limited experimental datasets, which might not fully convey the intricate relationship between geometry, process variables, and material behavior [35–37]. These methodological inconsistencies limit the effective integration of polymer additive manufacturing into certified aircraft structures and systems.

Certification and Standardization Challenges. Certification is among the most crucial obstacles for polymer AM widespread adoption in aviation [9, 10]. Regulatory frameworks require comprehensive evidence of material consistency, process stability, and long-term performance under representative operational conditions [39]. Meanwhile, polymer AM outcomes' strong dependence on process parameters and environmental factors complicates the generation of statistically robust datasets required for certification [31, 39]. Figure 7 presents a structured overview of the core pitfalls in polymer AM, emphasizing the necessity of integrated and optimization-oriented design methodologies.

Current qualification practices often rely on extensive experimental testing and conservative design margins, which might counteract some of additive manufacturing's potential advantages in terms of cost effectiveness and weight reduction [9, 10, 39]. Thus, an increasing need exists for advanced qualification strategies that integrate process monitoring, predictive modeling, and data-driven approaches to reduce uncertainty and support certification efforts [36, 40].

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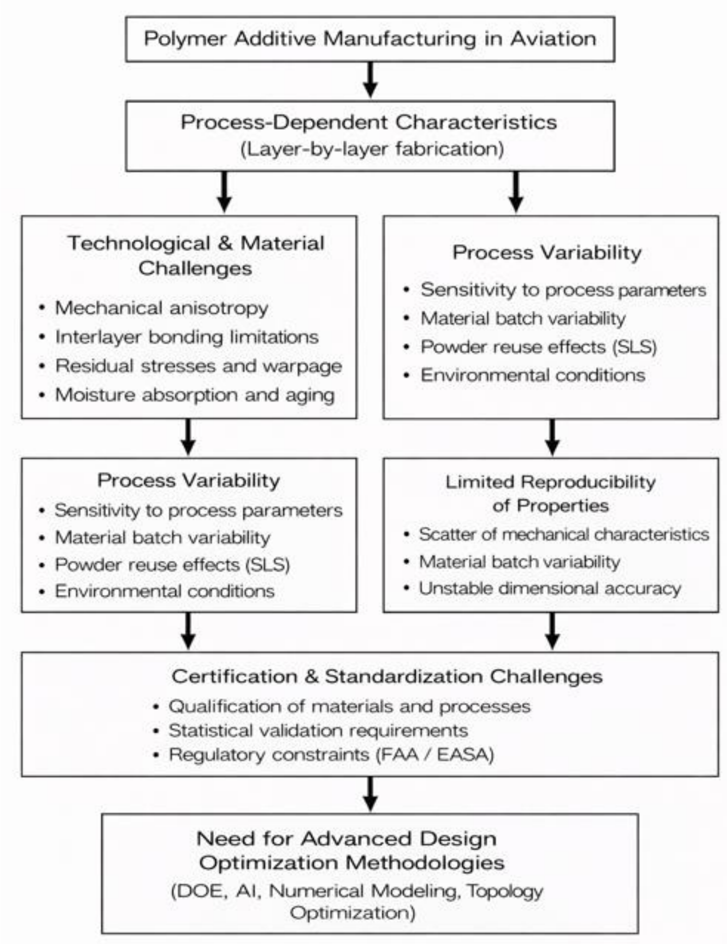

Fig. 7. Core challenges in the design and manufacturing of polymer additively manufactured aircraft components and their implications for design optimization

4. Methods for polymer components design optimization in AM

The performance, reliability, and certification readiness of polymer components manufactured using additive technologies are largely determined at the stage of design, when the patterns of geometry, material distribution, and manufacturing constraints are defined [7, 11, 31]. Unlike conventional manufacturing routes, additive processes require optimization methodologies that explicitly account for layer-based fabrication, anisotropic material behavior, and strong interdependencies between geometry and process parameters [28, 35–37]. Consequently, effective optimization must be performed directly within three-dimensional CAD environments, where design intent, manufacturability, and one can assess structural performance holistically.

In aircraft engineering, the CATIA CAD/CAE platform is widely applied as a unified environment for structural analysis, parametric modeling, and optimization [20-22]. Integrating advanced 3D modeling tools with simulation and optimization modules enables systematic refinement of polymer components intended for additive manufacturing, particularly for brackets, housings, air ducts, and other structurally relevant aircraft elements [12, 15, 30].

Parametric 3D Modeling and Design for AM in CATIA. Parametric 3D modeling constitutes the foundation of design optimization for polymer additively manufactured components [30, 32]. Within CATIA, associative and feature-based modeling allows key geometric parameters – such as wall thickness, fillet radii, rib orientation, lattice

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density, and interface geometry – to be controlled and systematically varied during the optimization process [31, 34]. These parameters have a direct influence on mechanical performance, manufacturability, and mass efficiency of polymer components.

The implementation of Design for Additive Manufacturing (DfAM) principles within CATIA emphasizes early incorporation of process-specific constraints, including minimum feature size, overhang limitations, build orientation, and post-processing requirements [27, 30]. By embedding these constraints into the parametric model, designers can reduce reliance on empirical redesign and improve structural efficiency while maintaining compliance with additive manufacturing limitations [12, 15]. For aircraft applications, such an approach supports both weight reduction and functional integration without compromising reliability.

Finite Element–Based Structural Optimization in a 3D Environment (Figure 8). Structural optimization of polymer components for additive manufacturing is commonly performed using finite element analysis tightly coupled with the 3D design model [28, 35]. In CATIA-based workflows, parametric geometry is directly linked to simulation models, enabling iterative evaluation of stress distribution, deformation, and safety margins under representative loading conditions [20, 22].

Additively manufactured polymers exhibit direction-dependent mechanical properties that should be taken into account in the process of optimization [35–37]. This requirement is addressed by assigning anisotropic material models and evaluating multiple load cases corresponding to different build orientations [31, 36]. This approach enables conducting identification of critical load paths, elimination of non-functional material, and improvement of structural efficiency while accounting for manufacturing-induced anisotropy [28, 39].

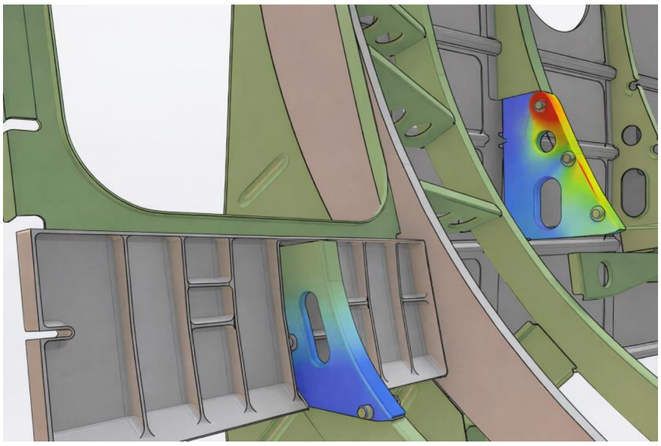

Fig. 8. CATIA-based visualization of a polymer additively manufactured aircraft bracket with stress distribution, illustrating load paths and material efficiency after 3D design optimization

Statistical Optimization of 3D Design Parameters (DOE and Taguchi Methods). Statistical optimization methods, including Design of Experiments and Taguchi techniques, provide a structured framework for optimizing geometric and process-related parameters of polymer additively manufactured components [33, 34]. When applied in conjunction with parametric 3D models in CATIA, these methods enable systematic assessment of the influence of design variables – such as wall thickness, rib spacing, and build orientation – on mechanical performance and dimensional accuracy [30, 33].

By analyzing parameter interactions and sensitivity, DOE-based approaches

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facilitate the identification of robust design configurations with reduced susceptibility to process variability [31, 34]. Particularly, this is of high importance for aircraft components, where reproducibility and consistency represent crucial requirements for the process of certification [9, 10, 39]. Compared to empirical trial-and-error approaches, statistical optimization within a 3D CAD environment provides a transparent and repeatable design methodology aligned with aerospace engineering standards. The main geometric and process-related parameters considered during the 3D design optimization in CATIA are summarized in Table 1.

Table 1

Design and process parameters used for 3D optimization of polymer aircraft components

Parameter	Symbol	Range	Unit	Optimization role
Wall thickness	t	1.5–3.5	mm	Structural stiffness
Rib thickness	tr	1.0–2.5	mm	Load transfer
Fillet radius	R	2–8	mm	Stress reduction
Build orientation	θ	0 / 45 / 90	deg	Anisotropy control
Infill density	ρ	20–60	%	Mass optimization
Layer height	h	0.15–0.30	mm	Interlayer bonding

Topological Optimization and Lightweight Design in CATIA. Topological optimization represents one of the most effective approaches for achieving lightweight and structurally efficient designs in polymer additive manufacturing, particularly for aircraft engineering applications where mass reduction directly influences performance and operational efficiency [17, 38]. Unlike conventional sizing or shape optimization methods, topology optimization focuses on the optimal redistribution of material in frames of a predetermined design space based on applied loads, boundary conditions, and performance objectives [30, 36].

Within the CATIA CAD/CAE environment, optimization of topology is carried out as an integrated process combining parametric 3D geometry, finite element analysis, and iterative material removal algorithms [20–22]. This integration enables designers to perform optimization directly on three-dimensional models, ensuring consistency between design intent, structural simulation, and manufacturability constraints. For polymer components intended for AM, such approach provides special advantages, since it enables complex, non-traditional geometries to be generated and subsequently refined for production. In aircraft engineering, topology optimization in CATIA is commonly applied to brackets, fittings, housings, and support structures that are subjected to multi-axial loading conditions [17, 38]. By defining realistic load cases and constraints, the optimization algorithm identifies load paths and eliminates non-functional material, resulting in organic, load-adapted geometries. These geometries are well suited to additive manufacturing, as they often include internal cavities, variable wall thicknesses, and smooth transitions that are challenging or impossible to accomplish with traditional manufacturing techniques [31,32].

An important aspect of topology optimization for polymer additive manufacturing is the consideration of process-specific constraints during geometry generation. In CATIA-based workflows, these constraints may include minimum feature size, allowable overhang angles, build orientation, and post-processing requirements [27, 30]. Incorporating such constraints at the optimization stage reduces the need for extensive geometric redesign and improves the manufacturability of the optimized component. This is relevant especially for polymer materials, where excessive support

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structures or thin unsupported features can negatively affect quality of surface and mechanical performance [28, 35]. The finite element–based stress distribution in the initial polymer aircraft bracket and the corresponding topology-optimized lightweight design for AM, with stress levels ranging from low to high, are shown in Figure 9.

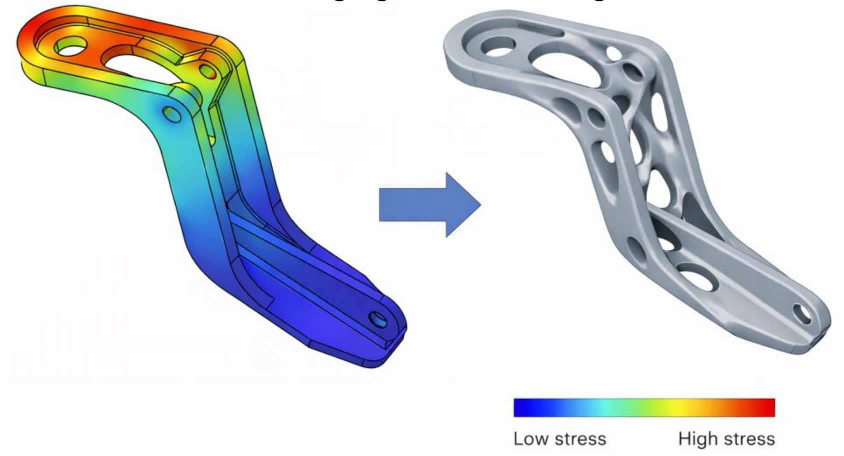

Fig. 9. Finite element–based stress distribution in the initial polymer aircraft bracket and the corresponding topology-optimized lightweight design for additive manufacturing, with stress levels ranging from low to high

Lightweight design principles are closely associated with topology optimization and play a central role in the development of polymer aircraft components [38]. In the CATIA environment, lightweight design is achieved not only through material removal but also through intelligent distribution of stiffness and load-bearing features. The application of ribs, lattice-like structures, and variable wall thicknesses allows designers to tailor the structural response of polymer components while maintaining low mass [17, 31]. Such design strategies are inherently compatible with additive manufacturing and contribute to improved material efficiency.

Following topology optimization, the resulting geometry typically requires interpretation and refinement to ensure compliance with design standards and requirements for certification [31, 39]. In CATIA, this refinement process involves smoothing optimized shapes, reintroducing functional interfaces, and validating the final geometry through additional finite element analyses [20, 22]. This step is essential for translating topology-optimized concepts into practical, certifiable aircraft components manufactured using polymer additive technologies. The results described in Table 2 provide quantifiable evidence of the applied topology optimization approach's efficacy.

Table 2

Comparison of structural performance (before 3D design optimization and after it)

Parameter	Initial design	Optimized design	Change
Mass, g	410	265	−35 %
Maximum von Mises stress, MPa	72	56	−22 %
Maximum displacement, mm	1.30	0.96	−26 %
Safety factor	1.38	1.80	+30 %
Estimated material volume, cm³	320	205	−36 %
Estimated printing time, h	6.5	4.7	−28 %

Data-Driven and AI-Assisted Optimization in a 3D CAD Context. Recent

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research demonstrates the growing role of data-driven and artificial intelligence–based methods in the optimization of polymer additively manufactured components [35, 36, 40]. Machine learning techniques can be used in a CATIA-centered process to evaluate mechanical characteristics and defect generation predictively by applying them to datasets produced by parametric studies and finite element simulations [36, 40].

Correlating 3D geometric parameters with process conditions and performance outcomes, AI-assisted optimization allows reducing the number of simulation required, as well as experimental iterations [35]. This approach justifies the development of digital representations of additive manufacturing processes, linking design geometry, process parameters, and resulting structural behavior [27, 36]. Such integration represents a promising pathway toward more efficient, reliable, and certification-oriented design of polymer aircraft components.

Conclusions

The paper presents the latest trends within the field the application of polymer AM technologies in aircraft engineering, with a particular focus on design-oriented optimization approaches implemented within three-dimensional CAD/CAE environments. The results confirm that polymer-based additive manufacturing has progressed beyond its traditional role in prototyping and has become a technically viable and economically efficient solution for the production of functional aircraft components, especially in those cases when mass reduction, geometric adaptability, and manufacturing flexibility are of primary importance.

Within the scope of this study, the author performed a systematic analysis of aircraft components suitable for polymer additive manufacturing, with particular emphasis on geometrically complex and weight-sensitive parts. Based on this analysis, representative components were selected and reconstructed as fully parametric three-dimensional models. The developed models served as a basis for subsequent numerical analysis and optimization within an integrated CAD/CAE framework.

The comparative assessment of polymer additive manufacturing technologies, including FDM/FFF, SLA/DLP, SLS, and fiber-reinforced polymer processes, demonstrates that their applicability in aircraft engineering is strongly dependent on material behavior, process characteristics, and operational level requirements. The findings demonstrate that no single technology can be deemed universally optimal; rather, a balanced evaluation of mechanical performance, dimensional stability, environmental resistance, as well as manufacturing- and certification-related limitations, must be the basis for choosing an acceptable additive method.

The analysis has identified a set of critical challenges that continue to limit the large-scale industrial adoption of polymer additive manufacturing in aviation. These challenges include anisotropic mechanical properties inherent to layer-based fabrication, variations in part density and residual porosity, sensitivity of material performance to process parameters, variability in reproducibility, warping effects, and the absence of unified, certification-oriented design methodologies. The findings indicate that conventional design practices, originally developed for isotropic materials and traditional manufacturing routes, are insufficient when applied to polymer additively manufactured aircraft components.

A key contribution of this study lies in the systematic examination of design optimization methods implemented directly within the CATIA CAD/CAE environment. For the developed 3D models, representative loading conditions were defined and

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finite element analyses were carried out to evaluate stress distribution and deformation behavior. On the basis of the obtained simulation results, topology optimization procedures were applied to identify efficient load paths and eliminate non-functional material. The results demonstrate that the integration of parametric three-dimensional modeling, finite element–based structural analysis, statistical optimization techniques, and topology-driven lightweight design enables a coherent and effective optimization workflow tailored to polymer additive manufacturing. The aircraft bracket case study presented in this work demonstrates how topology optimization based on finite element stress distribution can yield significant mass savings while maintaining the predefined structural performance criteria and safety margins.

Moreover, the growing role of data-driven and artificial intelligence–assisted approaches in the optimization of additively manufactured polymer components is highlighted. The incorporation of such methods into a three-dimensional design framework supports systematic comparison of design alternatives and enhances the robustness of optimized solutions, thereby partially addressing challenges related to process variability and reproducibility identified in this study.

In summary, the results confirm that the successful implementation of polymer additive manufacturing in aircraft engineering requires a transition from technology-centered adoption toward design-centric optimization strategies embedded within integrated CAD/CAE environments. The CATIA-based optimization framework discussed in this work provides a practical foundation for improving structural efficiency and manufacturability, while supporting preliminary, certification-oriented design assessments rather than replacing formal qualification procedures, of polymer aircraft components manufactured using additive technologies.

Further investigations should be carried out in the field of comprehensive experimental validation of optimized designs, the development of standardized qualification and certification methodologies for polymer AM processes, and the further integra-tion of artificial intelligence techniques with design-stage optimization and in-situ pro-cess monitoring. These efforts are essential for enabling the broader application of polymer additive manufacturing in safety-critical aerospace structures and for ensur-ing its long-term industrial viability.

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Сучасні тенденції застосування 3D-друку полімерних матеріалів в авіаційному машинобудуванні та методологічні підходи до оптимізації проєктування

У цій статті аналізуються сучасні тенденції в застосуванні технологій 3D-друку полімерів в авіаційній інженерії, з особливим акцентом на методологічних підходах до оптимізації конструкції. Методи адитивного виробництва на основі полімерів, включаючи FDM, SLS, SLA та MJF, розглядаються як технології, що дозволяють виробляти авіаційні компоненти зі складною геометрією, зменшеною масою конструкції та покращеною функціональною інтеграцією. Зростаюче застосування цих технологій у конструкціях, системах та внутрішніх компонентах літаків обумовлене необхідністю підвищення

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ефективності ваги, скорочення циклів розробки та підтримки гнучкого виробництва на різних етапах життєвого циклу продукту.

Особлива увага приділяється ролі оптимізації на етапі проектування у забезпеченні механічних характеристик, довговічності та експлуатаційної надійності полімерних компонентів, виготовлених за допомогою адитивних технологій. Обговорюються основні виклики, властиві 3D-друку полімерів, включаючи анізотропію механічних властивостей, дефекти, спричинені процесом, чутливість до параметрів друку та мінливість поведінки матеріалу. Ці фактори значно впливають на повторюваність та готовність до сертифікації авіаційних компонентів, виготовлених за допомогою адитивних технологій.

У статті розглядаються сучасні стратегії оптимізації, що застосовуються в авіаційній інженерії, включаючи проектування для адитивного виробництва, статистичні методи, такі як планування експериментів і методи Тагучі, чисельне моделювання та підходи на основі штучного інтелекту. Інтеграція цифрового проектування, експериментальної валідації та інтелектуальних інструментів оптимізації в єдину методологічну структуру визначена як критичний фактор для підвищення ефективності та надійності полімерних компонентів літаків, виготовлених методом 3D-друку. На основі аналізу останніх досліджень та промислової практики визначено існуючі прогалини та окреслено перспективні напрямки подальших досліджень і розвитку адитивного виробництва полімерів в авіаційній інженерії.

Ключові слова: 3D-друк полімерів; авіаційна техніка; адитивне виробництво; оптимізація конструкції; параметри процесу; штучний інтелект; чисельне моделювання.

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