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ADDITIVE TECHNOLOGIES IN THE POLYMER COMPONENTS MANUFACTURING FOR AEROSPACE STRUCTURES: DESIGN AND OPTIMIZATION METHODS

*The **subject matter** of the article is additive manufacturing technologies used in the fabrication of polymer components for aerospace structures. The **goal** is to develop a comprehensive methodology focused on optimizing the design of polymer components manufactured by 3D printing, with a particular emphasis on material extrusion technologies. The **tasks** addressed include: reviewing state-of-the-art approaches to the design and optimization of polymer components for aerospace structures produced using additive manufacturing technologies; and examining polymer additive manufacturing methods, including FDM, SLS, SLA, and MJF, which enable the fabrication of components with complex geometries, reduced mass, and improved functional performance. The **methodology** is based on an integrated and iterative framework that combines parametric design, process-aware modeling, numerical simulation, and data-driven optimization techniques. The following **results** were obtained. The importance of design-stage optimization is emphasized due to the increasing requirements for the mechanical properties, service life, and cost efficiency of aerospace structures. Attention is focused on the challenges associated with polymer additive manufacturing, such as material anisotropy, process-induced defects, and the variability of mechanical properties. Approaches to addressing these challenges are discussed, including design for additive manufacturing, process parameter optimization, numerical simulation, and the application of artificial intelligence methods. The relevance of integrating digital modeling, experimental validation, and intelligent optimization techniques into a unified design methodology is highlighted. Recent studies in the aerospace sector are summarized, key challenges are identified, and promising directions for the further development of additive manufacturing technologies are outlined. **Conclusions.** The scientific novelty of the obtained results lies in the following: a methodology for optimizing the design of polymer aerospace components manufactured using additive technologies is proposed, with an emphasis on material extrusion–based methods. This methodology integrates parametric CAD modeling, process-aware design constraints, numerical stress analysis, and data-driven optimization techniques into a unified framework, in contrast to traditional design-for-additive-manufacturing (DfAM) approaches, which mainly address geometric feasibility.*

***Keywords:** additive manufacturing; polymer aerospace components; design optimization; process parameters; artificial intelligence; finite element analysis.*

1. Introduction

Technologies of additive manufacturing (AM) became an integral part of modern aerospace engineering, significantly influencing approaches to designing, manufacturing, and maintenance of aircraft structures. Reduced lead time, cost efficiency, and the ability to manufacture geometrically complex components that enable lightweighting, part consolidation, and performance enhancement have positioned additive manufacturing as a key enabler in aerospace applications [1]. Constant additive methods development supports the transition from conventional manufacturing to more flexible and digitally driven production paradigms, particularly under strict requirements for reliability and economic efficiency [2].

The role of additive manufacturing in aerospace has become crucial to enable progress in efficiency, fuel economy, and performance improvements [3]. Meanwhile, polymer AM for aerospace faces challenges such as certification and standardization (lack of clear pathways), material limitations (high-temperature performance, moisture, consistency), process control (warping, delamination, accuracy), scalability and size constraints, and ensuring structure-property-performance consistency for critical, reliable parts, all while managing high initial costs and workforce training [4].

1.1. Motivation

Polymer materials occupy a distinct and steadily expanding niche in aerospace applications. They are quite often used for fast prototyping, interior components, system housings, brackets, ducts, and various auxiliary structural elements [5]. Among polymer-based AM technologies, fused deposition modeling (FDM) received particular attention due to its technological simplicity [6], material availability [7], and relatively low production costs [8]. The application of FDM was further expanded by the use of engineering and high-performance thermoplastics, from conceptual prototype to the creation of functional components utilized in testing and operating settings [9].

Among the core benefits of AM, and FDM in particular, there is effectiveness within the product life cycle' early stages [10]. The direct transformation of digital models into physical components enables rapid iterative design, experimental validation, and design refinement, significantly reducing time of development and accompanying costs [11]. Moreover, additive manufacturing eliminates the need for dedicated tooling, allowing design modifications to be implemented with minimal delay, that is especially critical during experimental testing and design optimization phases [12].

Meanwhile, the aerospace industry faces continuously increasing requirements related to weight reduction, mechanical performance, service life, and overall cost efficiency of aircraft structures [13]. These constraints make design optimization a critical task, particularly for polymer components produced using additive technologies. In the case of FDM, the mechanical behavior and structural performance of printed parts are under strong influence by both geometric parameters and variables of process, including layer thickness, raster orientation, infill strategy, and thermal conditions [14]. Consequently, achieving reliable and repeatable performance requires a systematic and scientifically grounded approach to design and process optimization [15].

1.2. State of the art

According to Shen et al. [16], composite additive manufacturing (CAM) is revolutionizing aircraft design by allowing for unprecedented lightweighting and functional integration. However, industrial adoption remains low due to a lack of understanding of the intricate interplay between materials, processes, designs, and performance. However, as the authors correctly point out, previous evaluations lack an integrated analytical approach.

AM technologies also find broadening use in aircraft maintenance, repair, and overhaul (MRO). In operational conditions, there is often a demand for rapid replacement of auxiliary or non-critical components, and for design adaptation to modified functional or installation requirements [17]. FDM-based manufacturing enables on-demand production of polymer parts with customized geometry or alternative materials, reducing lead times and enhancing operational flexibility while maintaining acceptable performance characteristics [18].

Despite FDM technology wide adoption, the design of polymer aerospace components is still frequently based on conventional design principles that do not fully account for the specific characteristics of AM processes. An overview of current developments in this area is given by Li and Chang [19], who concentrate on choosing important printing parameters (such layer thickness, print speed, infill density, and printing temperature) and optimizing material compatibility to improve print quality and tribological performance. The tribological characteristics of the printed polymer composites were examined in relation to different tribo-fillers, including fibers and nanoparticles. When the nanoparticle concentration is less than 5 vol.%, the wear rate can often be decreased by three to five times. However, wear resistance may degrade when the concentration of nanoparticles surpasses 10 vol.% because agglomerates form, disrupting the uniform dispersion of reinforcements and weakening the composite structure.

Often, this contributes to inefficient usage of materials, suboptimal mechanical performance, and limited exploitation of the technological potential of FDM. Therefore, the development of a dedicated methodology for optimizing the design of polymer components manufactured using FDM - integrating parametric modeling, process parameter consideration, numerical analysis, and intelligent optimization techniques - represents a relevant and timely scientific problem [20]. Addressing this problem is essential for improving the efficiency, reliability, and broader industrial adoption of polymer additive manufacturing in aerospace engineering. The overall workflow of design optimization for polymer aerospace components manufactured using FDM, as well as the relationship between design space definition, topology optimization, and AM constraints, is schematically illustrated in Figure 1.

AM acquired increasing relevance for aerospace engineering, enabling rapid iteration, functional integration, and cost-efficient production of polymer components under strict industrial constraints [21]. In polymer AM, the selection of process class and material system is a primary factor that determines achievable mechanical performance, dimensional stability, and long-term applicability in aerospace environments [22].

Classification of AM Technologies for Polymer Aerospace Components. According to international standard terminology, polymer additive manufacturing includes multiple process classes, among which material extrusion (commonly implemented as FDM), powder bed fusion (e.g., polymer SLS), and vat photopolymerization (e.g., SLA) represent the most disseminated techniques [23]. FDM remains the most accessible and broadly implemented polymer AM technology due to its process simplicity, relatively low equipment and operating costs, and availability of engineering thermoplastics [24]. The technology is active used for prototyping, tooling, and auxiliary components production.

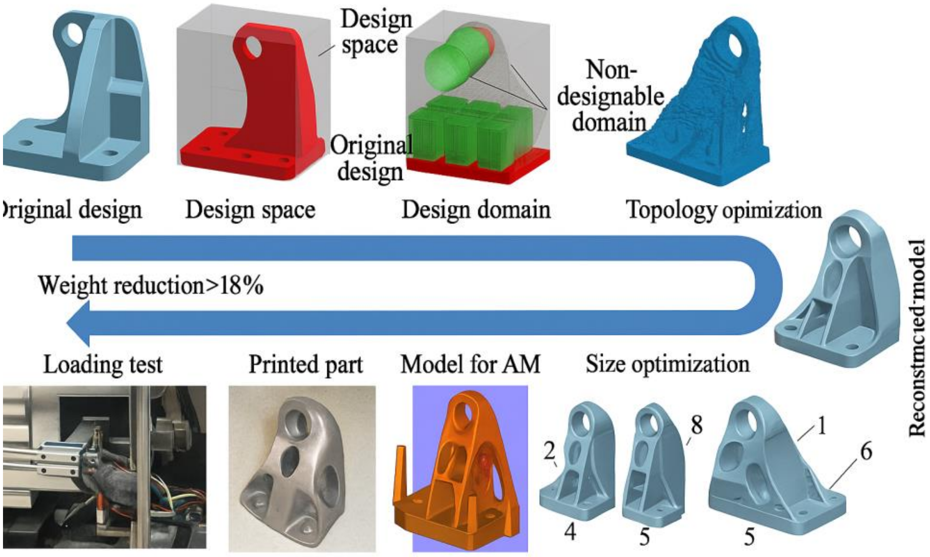

Fig. 1. Design and process optimization workflow for FDM-based polymer components

Powder-based processes such as SLS provide the capability to manufacture complex shapes without support structures and can deliver more uniform mechanical performance compared with extrusion-based processes in many practical cases, which makes them attractive for functional polymer parts [25]. Vat photopolymerization (SLA) offers high quality of surface and dimensional accuracy; meanwhile, aerospace adoption is constrained by material limitations and the long-term stability of photopolymer resins under operational loads and environmental exposure [26]. Overall, technology selection for aerospace polymer components must be based on the required performance envelope, certification considerations, and manufacturability constraints [27].

The classification of polymer additive manufacturing technologies used in aerospace applications, together with typical materials, key limitations, and representative use cases, is presented in Fig. 2.

Polymer Materials and Composites for Aerospace Applications. The portfolio of polymers applied in aerospace additive manufacturing spans from common engineering thermoplastics (e.g., ABS, PETG, polyamides) used for prototypes and non-critical parts to high-performance polymers such as PEEK, PEKK, and PEI, which offer improved thermal stability and mechanical performance for functional applications [28]. High-performance polymer systems often are in the discourse of discussions as enabling materials for advanced aerospace components due to their qualities such as strength-to-weight potential and resistance to aggressive environments [29]. In parallel, polymer composites for additive manufacturing have received growing interest as a pathway to increased stiffness and strength at reduced mass [19]. Nevertheless, composite AM introduces additional challenges related to reinforcement distribution and orientation, interfacial bonding, and repeatability of properties, which must be explicitly considered within the design and process planning workflow [20].

Design Approaches for Polymer Additive Manufacturing. DfAM developed into a distinct paradigm that emphasizes the exploitation of geometric freedom while incorporating process-induced constraints at the earliest design stages [3]. Contemporary strategies of DfAM imply the use of topology-informed geometries, part consolidation, and functional integration to improve mass efficiency and performance [1]. Parametric modeling and iterative digital workflows support rapid evaluation of multiple design variants and provide a basis for optimization-driven development, in particular in combination with numerical analysis and experimental feedback [2].

For polymer AM, and especially for FDM, the design stage must explicitly account for manufacturing constraints that influence interlayer bonding and local stiffness distribution, as these factors can dominate structural response and failure behavior [5]. Consequently, design approaches increasingly couple geometry definition with process parameter considerations rather than treating manufacturing as a downstream step [12].

Challenges and Limitations of Polymer Additive Manufacturing in Aerospace. Despite the demonstrated advantages, polymer AM faces limitations that are especially critical for aerospace applications. A major issue for FDM is mechanical anisotropy arising from the layer-wise deposition mechanism and the sensitivity of interlayer bonding to thermal history and process conditions [5]. This effect can reduce strength and stiffness in the build direction and complicate design allowables.

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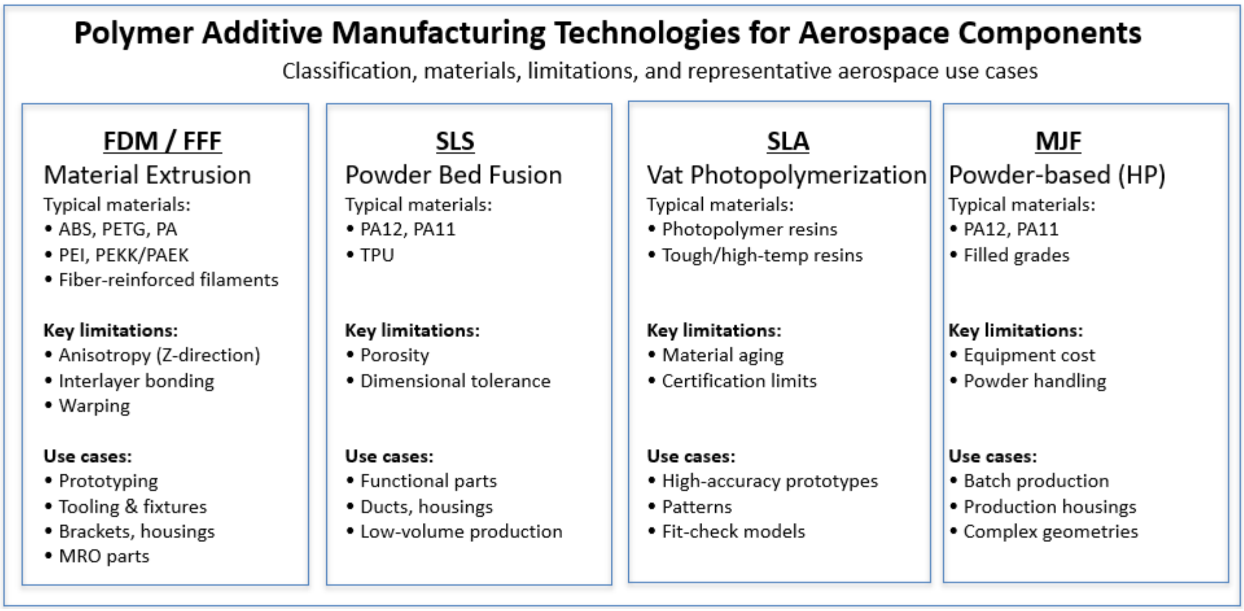

Fig. 2. Polymer AM technologies for aerospace components: materials, limitations, and applications

Process-induced defects, including voids, incomplete fusion, surface irregularities, and dimensional deviations, are also reported quite often and can contribute to uncertainty in structural performance and service life [10]. Additionally, thermal effects during printing and cooling may lead to residual stresses and distortion, affecting both geometric accuracy and repeatability, which are important for aerospace qualification and dependable operation [16]. The range of these challenges represents drivers of robust optimization and validation strategies development, that integrate design, process control, and performance assessment [15].

Existing Methods for Design Optimization of Polymer Components. Existing optimization approaches for polymer AM can be broadly categorized into experiment-driven and model-driven methods. Design of experiments (DOE), including Taguchi-based frameworks and statistical analysis, is, as a rule, used to quantify the geometric and process parameters influence on manufacturability and mechanical performance [6–9]. Such approaches are especially relevant for FDM, where layer thickness, raster orientation, and infill strategy significantly affect tensile behavior and cost-related outcomes [9].

Model-driven optimization commonly relies on numerical simulation, in particular finite element analysis, to evaluate stress distributions, deformation, and sensitivity to core design variables [12]. More recently, data-driven approaches are broadly adopted to accelerate parameter selection and multi-objective optimization. ML methods are employed with the aim to predict part properties from process signatures, support automated parameter tuning, and reduce the experimental burden due to high-dimensional design spaces [23]. Nonetheless, the literature still frequently addresses design, process optimization, and validation as partially separated tasks, emphasizing the need for methodologies of integrated nature, that combine parametric modeling, DOE, numerical analysis, and intelligent optimization within a unified workflow [21].

1.3. Objectives and tasks

Within the landscape of the rapid development and increasing industrial adoption of polymer AM technologies in the aerospace sector, the design of polymer components produced by 3D printing remains largely constrained by traditional engineering approaches not adapted to full extent to the specific features of additive processes. In particular, material extrusion–based technologies such as fused deposition modeling (FDM/FFF) exhibit strong dependencies between geometric design parameters, conditions of process, and resulting mechanical performance, which significantly complicates the achievement of optimal mass, strength, and durability characteristics required for aerospace applications [1]. The research problem' structural scheme, the main objective, and the research tasks are schematically illustrated in Fig. 3.

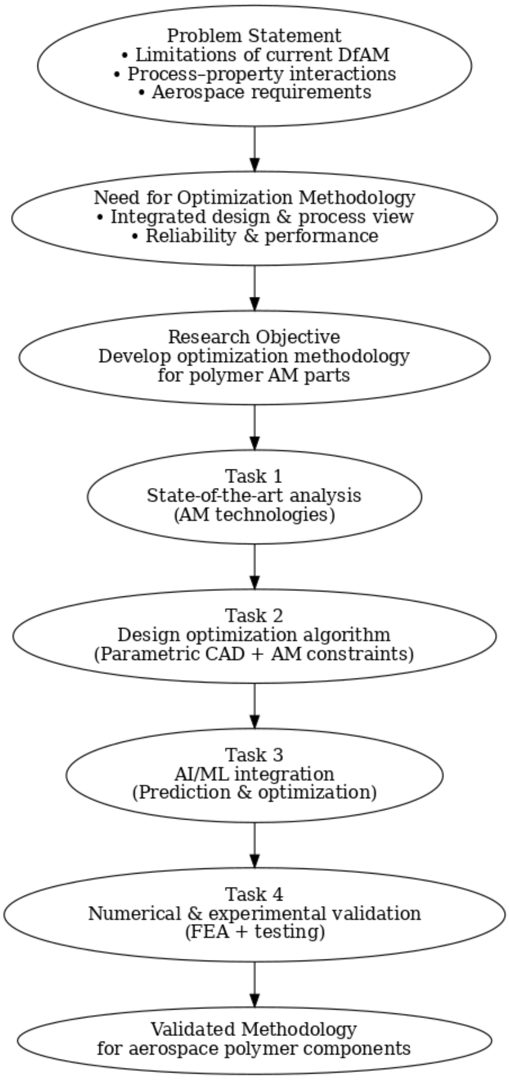

Fig. 3. Research problem and objectives: conceptual framework

Existing design-for-additive-manufacturing (DfAM) approaches primarily focus on geometric feasibility and manufacturability; however, they often neglect the complex interaction existing between printing parameters, material anisotropy, and process-induced defects, especially for polymer components subjected to operational loads [3]. As reported in recent studies, inadequate consideration of layer orientation, raster strategy, infill configuration, and thermal history may lead to pronounced anisotropy, reduced interlayer strength, and significant variability of mechanical properties, thus restricting the reliability and certification potential of additively manufactured polymer parts for aviation use [13]. Thus, a clear need exists for systematic methodologies that integrate geometric design, process modeling, and performance evaluation into a unified optimization framework.

Moreover, current optimization practices in polymer additive manufacturing are frequently limited to isolated parameter studies or statistical approaches, i.a. design of experiments (DOE). These techniques are seen as effective ones for the local optimization tasks, but still they are insufficient for addressing the high-dimensional and nonlinear design spaces characteristic of complex aerospace polymer components [12]. Recent achievements in AI and ML demonstrated sound potential for capturing complex nonlinear relationships between design variables, process parameters, and resulting performance indicators in additive manufacturing processes [23]. Nevertheless, the integration of these techniques into a comprehensive and validated design optimization methodology for polymer aerospace components remains fragmented and iunderdeveloped.

In this vein, a scientific and engineering problem arises related to the designing of a structured optimization methodology that would provide the possibility of simultaneous consideration of geometric design variables, additive manufacturing process parameters, and aerospace-specific performance requirements. Lacking of such holistic approach leads to excessive design iterations, increased experimental effort, and suboptimal design solutions, particularly for polymer components manufactured by FDM technology.

Research Objective. The primary objective of this study is the development of a comprehensive methodology aimed at optimization of the design of polymer components manufactured by 3D printing, with a particular focus on material extrusion technologies. The described methodology aims to account for geometric parameters, technological process variables, and performance requirements relevant to aerospace applications, including mass efficiency, mechanical strength, and structural reliability.

Research Tasks. The following research tasks are defined:

- ‘state-of-the-art’ analysis within the field of polymer AM technologies in aerospace applications, with emphasis on design limitations, material behavior, and process-induced defects [24];

- development of a structured algorithm for optimizing the design of polymer components, incorporating parametric CAD modeling and additive manufacturing constraints [12];

- integration of AI and ML methods into the design optimization process to enable efficient exploration of complex design spaces and prediction of mechanical performance [22];

- conducting numerical simulations and experimental investigations to validate the described methodology and assess its applicability to aerospace polymer components produced by additive manufacturing [9].

2. Materials and methods of research

The proposed methodology is based on an integrated and iterative framework that combines parametric design, process-aware modeling, numerical simulation, and data-driven optimization techniques. Unlike conventional design approaches, where geometric definition and manufacturing considerations are treated as separate stages, the presented methodology explicitly accounts for the interdependence between part geometry, additive manufacturing process parameters, and resulting mechanical performance from the early stages of designing [3].

The methodology' general structure implies the formation of a parametric CAD model, incorporation of technological constraints associated with polymer additive manufacturing, systematic analysis of design variables using DOE, ML techniques application for efficient exploration of the design space, and validation through finite element analysis (FEA) and digital testing. This integrated-nature approach enables finding optimal design solutions under competing requirements related to mass, strength, manufacturability, and cost efficiency [24].

Parametric CAD Model Development. At the first stage of the methodology, a parametric CAD model is developed for the polymer component. Key geometric features are defined using design parameters that can be systematically varied via the optimization process. This approach allows for rapid generation of multiple design variants while maintaining consistency with functional and assembly requirements. Parametric modeling is particularly well suited for additive manufacturing, as it facilitates automated modification of geometric characteristics such as wall thickness, rib configuration, fillet radii, and internal structures [1].

The parametric CAD models application provides a direct link between geometric design variables and downstream analysis tools, including numerical simulations and optimization algorithms. This capability has sound importance for enabling iterative design refinement and supporting the exploration of complex design spaces typical of aerospace polymer components [3].

Incorporation of Additive Manufacturing Process Parameters. A specific feature of the methodology is the explicit consideration of AM process parameters accross the design stage. For polymer components produced by material extrusion technologies such as FDM, process parameters including layer thickness, raster orientation, infill pattern, printing speed, and thermal conditions significantly influence mechanical behavior and structural integrity [8].

These technological parameters are incorporated into the design model as controllable variables or constraints, enabling the assessment of their interaction with geometric features. By integrating process-related factors into the design workflow, the methodology addresses key challenges such as mechanical anisotropy, interlayer bonding quality, and dimensional stability - frequently reported limiting factors for aerospace applications of polymer additive manufacturing [4].

DOE Application. For systematic investigation of the influence of geometric and technological parameters on component performance, the methodology employs DOE techniques. DOE enables efficient sampling of the design space and provides quantitative insight into the relative significance of specific parameters and their interactions [7].

Critical parameters that impact the mechanical characteristics, mass efficiency, and manufacturability of polymer components made by additive manufacturing are identified using Taguchi-based experimental designs and statistical analysis techniques [9]. The DOE stage results are used to lower the dimensionality of the optimization problem and select the most crucial variables for additional data-driven optimization.

Application of ML Methods for Design Optimization. Given the nonlinear and high-dimensional nature of the design space in polymer additive manufacturing, machine learning techniques are integrated into the optimization framework to enhance efficiency and predictive capability. Machine learning models are trained using datasets generated from DOE results and numerical simulations, enabling the prediction of mechanical performance and other core indicators as functions of design and process parameters [21].

Such data-driven models facilitate rapid evaluation of candidate design solutions and support multi-objective optimization under competing constraints. In contrast to conventional optimization approaches, ML-based methods can capture complex parameter interactions and reducing the computational and experimental effort required to identify optimal design configurations [21].

Integration of FEA and Digital Testing into the Optimization Loop. FEA and digital testing are employed as integral components of the proposed optimization methodology. Numerical simulations are used to evaluate stress distribution, deformation behavior, and failure mechanisms of candidate design variants under representative loading conditions [12]. Where appropriate, anisotropic material models and process-informed material properties are applied to account for the layer-wise nature of polymer additive manufacturing. The overall structure and key stages of the described optimization methodology are given in Table 1.

The results of FEA simulations are used both for validation of machine learning predictions and for refining the process of optimization.

Table 1

Methodology for optimization of polymer part design: structure

Stage	Methodological step	Description	Tools/ Methods
1	Definition of design problem	Formulation of functional, structural, and manufacturing requirements for polymer aerospace components	Requirement analysis, DfAM principles
2	Parametric CAD model development	Creation of a parametric CAD model with variable geometric features	Parametric CAD modeling
3	Incorporation of AM process parameters	Integration of additive manufacturing parameters into the design model	Process-aware design, AM constraints
4	Design of Experiments (DOE)	Systematic analysis of geometric and technological parameters	Taguchi DOE, statistical analysis
5	Data generation and preprocessing	Preparation of datasets for data-driven modeling	Data preprocessing, feature selection
6	Machine learning–based optimization	Prediction of performance indicators and optimization support	Machine learning models
7	Numerical validation	Evaluation of stress, deformation, and failure behavior	Finite element analysis (FEA)
8	Digital testing and iteration	Iterative refinement of design and process parameters	Digital testing, iterative workflow
9	Final design selection	Selection of optimal design solutions for aerospace use	Multi-criteria decision analysis

This closed-loop integration of parametric design, data-driven optimization, and numerical validation enables iterative improvement of design solutions and provides a robust basis for subsequent experimental testing and aerospace qualification [24].

3. Results and Discussion

3.1. Design and configuration

Baseline Design and Reference Configuration. The 210 g total mass of the baseline polymer component taken into consideration in this investigation is typical of auxiliary aerospace brackets made via FDM [24,30]. The part geometry corresponds to a load-bearing mounting bracket with rib-stiffened regions, fastening holes, and cantilevered arms, typical for polymer structural components used in secondary aircraft systems [13]. The baseline bracket' geometry and its reference configuration adopted for numerical analysis are given in Fig. 4.

Fig. 4. Baseline polymer bracket geometry and reference configuration for numerical analysis

The baseline configuration was assumed to be manufactured from PETG thermoplastic using standard FDM process parameters without any prior optimization. The printing setup included a layer height of 0.2 mm, a 0.4 mm nozzle, and a rectilinear or gyroid infill pattern, representing commonly applied industrial printing practices [4,5,12]. The build orientation was selected such that the deposited layers were oriented perpendicular to the primary load direction, which is known to be an unfavorable configuration from a mechanical standpoint but remains realistic due to constraints of geometric and manufacturing nature [4,8].

Numerical evaluation of the baseline design was conducted using finite element analysis (FEA) under combined loading conditions, accounting for bending, shear, and tensile effects representative of in-service operational loads [12]. Material properties corresponding to additively manufactured PETG were adopted, considering reduced interlayer strength due to the selected build orientation, as reported in previous studies on polymer

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FDM components [4,8,9]. Analysis provides the evidence that the areas closest to the fastening holes and fillet transitions between the load-bearing arms and the bracket's main body had the highest von Mises stress, which is in line with common stress distribution patterns seen in structures made of polymer additively [11].

Under the loading conditions applied, the total safety factor exceeded 1.5 since the peak equivalent stress was predicted to stay below the PETG's effective yield strength in the build direction [13]. Although the non-optimized rib pattern and uniform wall thickness resulted in rather high compliance, the maximum displacement at the free end of the cantilevered arm was found to be within permissible limits for auxiliary aerospace components [12].

Despite satisfying basic strength requirements, the baseline design exhibited conservative structural behavior, indicating inefficient material utilization. The combination of moderate stress levels, acceptable deformation, and a relatively high safety margin indicates sound potential for mass reduction and stiffness improvement through targeted optimization of both geometric features and AM process parameters [21]. Consequently, the baseline configuration provides a suitable reference for quantifying the performance improvements achieved by the proposed optimization methodology.

Numerical Evaluation of the Baseline Design. It was carried out to quantify its mass-related characteristics, stress–strain response, and stiffness under representative service loading conditions. The total mass of the baseline design is m=0.210kg. Assuming a nominal density of PETG equal to $\rho = 1270$ kg/m³, the corresponding material volume of the component can be estimated as:

$$V = m / \rho. \quad (1)$$

This estimation enables verification of consistency between the CAD-derived geometry and the numerical model and provides a reference for subsequent mass reduction analysis.

The bracket's stress state under combined loading conditions can be understood as a superposition of shear, bending, and axial stress components. The normal stress is expressed as:

$$\sigma = F / A + M \cdot c / I, \quad (2)$$

where F is the applied force, A is the effective load-bearing area, M is the bending moment, c is the distance from the neutral axis to the outer fiber, and I is the second moment of area. The shear stress component is approximated as:

$$\tau = V \cdot Q / (I \cdot t), \quad (3)$$

where V is the shear force, Q is the first moment of area, and t is the local wall thickness.

To evaluate the equivalent stress state and enable comparison with material strength limits, the von Mises criterion is applied. The calculation of equivalent stress is conducted as follows:

$$\sigma_{eq} = \sqrt{\sigma^2 + 3\tau^2}. \quad (4)$$

Based on finite element analysis, the maximum equivalent stress in the baseline configuration was estimated as:

$$\sigma_{eq,max} \approx 22 \text{ MPa}.$$

Considering the reduced interlayer bonding strength characteristic of additively manufactured PETG when the deposited layers are oriented perpendicular to the primary load direction, the effective yield strength is assumed as:

$$\sigma_{y,eff} \approx 35 \text{ MPa}.$$

The following relation is then used to evaluate structural safety factor of the baseline design:

$$n = \sigma_{y,eff} / \sigma_{eq,max}, \quad (5)$$

which results in a safety factor of approximately:

$$n \approx 1.6.$$

The load-displacement relationship was used to evaluate the baseline bracket's stiffness performance. The cantilevered arm's free end's maximum displacement, as determined by numerical simulation, was calculated as:

$$\delta_{max} \approx 1.8 \text{ mm}.$$

For the representative service load F = 800 N, the effective structural stiffness is determined as:

$$k = F / \delta_{max}.$$

resulting in an approximate stiffness value of:

$$k \approx 444 \text{ N/mm}.$$

In overall, the obtained numerical results demonstrate that the baseline design satisfies the basic strength requirements for auxiliary aerospace components. However, the combination of moderate stress levels, relatively high compliance, and a conservative safety factor suggests inefficient material utilization. This confirms the presence of sound potential for mass reduction and stiffness improvement through systematic optimization of geometry and AM process parameters.

Optimized Design and Numerical Results. Following the numerical assessment of the baseline configuration, which revealed conservative stress levels and inefficient material utilization, an optimized design of the polymer bracket was developed using the described methodology. The process of optimization was guided by numerical stress analysis and aimed at redistributing material along the primary load paths while preserving manufacturability constraints associated with fused deposition modeling (FDM) [29]. A generative design–based geometry of the same bracket, obtained under identical loading conditions, is shown in Fig. 5 and shows the principal load paths applied to guide the proposed optimization.

Fig. 5. Generative design–derived geometry of the polymer bracket illustrating material redistribution along principal load paths

The optimized geometry was established on the base of replacing solid load-bearing regions with a truss-like Y-shaped structure connecting the upper mounting lug to the lower fastening points. Low-stress regions identified in the baseline design were removed through the introduction of smooth, topology-inspired cut-outs, whereas local reinforcement was retained in highly loaded zones, particularly around fastening holes and joint transitions. All geometric modifications were constrained by minimum wall thickness and fillet radius requirements to ensure printability and structural integrity of PETG components manufactured via FDM [30].

Due to the procedure of optimization, the total mass of the bracket was reduced from 210 g to approximately 165 g, corresponding to a mass reduction of about 21%. The material volume of the optimized component was estimated using the mass–density relationship:

$$V\_opt = m\_opt / \rho, \tag{6}$$

where m_opt = 0.165 kg and ρ = 1270 kg/m³.

This mass reduction was achieved without increasing printing complexity or introducing unsupported features, which is essential for industrial adoption in aerospace applications [31].

The optimized design was evaluated under the same representative loading circumstances as the baseline configuration with an applied load of F = 800 N. The stress state was assessed using finite element analysis, and the appropriate von Mises stress was calculated as follows:

$$\sigma\_eq = \sqrt{(\sigma^2 + 3\tau^2)}, \tag{7}$$

where the normal and shear stress components are defined as:

$$\sigma = F / A + M \cdot c / I, \quad \tau = V \cdot Q / (I \cdot t). \tag{8}$$

The numerical results indicated that the maximum equivalent stress in the optimized configuration was reduced to approximately:

$$\sigma\_eq,max,opt \approx 18 \text{ MPa}$$

compared to 22 MPa observed in the baseline design. Considering the effective yield strength of additively manufactured PETG in the unfavorable build orientation:

$$\sigma\_y,eff \approx 35 \text{ MPa}$$

the safety factor of the optimized bracket was evaluated as:

$$n\_opt = \sigma\_y,eff / \sigma\_eq,max,opt \tag{9}$$

yielding a value of:

$$n\_opt \approx 1.9.$$

This demonstrates enhancement in structural efficiency, as a higher safety margin was achieved despite a substantial reduction in mass [32].

The load-displacement relationship was used to evaluate the improved bracket's stiffness performance:

$$k = F / \delta\_max. \tag{10}$$

The numerical simulation demonstrated that the maximum displacement at the free end of the cantilevered region was reduced to:

$$\delta\_max,opt \approx 1.3 \text{ mm}$$

resulting in an effective stiffness of:

$$k\_opt = 800 / 1.3 \approx 615 \text{ N/mm}.$$

Compared to the baseline stiffness of approximately 444 N/mm, the optimized design exhibits a notable increase in rigidity. This improvement is attributed to the alignment of material distribution with the principal stress trajectories and the elimination of structurally inefficient regions. A quantitative comparison of the numerical results obtained for the baseline and optimized configurations is summarized in Table 2.

Table 2

Comparative numerical results for baseline and optimized polymer bracket designs

Parameter	Baseline design	Optimized design	Change
Mass, g	210	165	−21%
Maximum von Mises stress, MPa	22	18	−18%
Maximum displacement, mm	1.8	1.3	−28%
Safety factor	1.6	1.9	+19%
Structural stiffness, N/mm	444	615	+38%

Overall, the optimized design demonstrates a favorable combination of reduced mass, lower stress levels, increased stiffness, and an enhanced safety factor. These results testify to the effectiveness of the proposed optimization methodology and highlight its suitability for improving the performance of polymer aerospace components manufactured using additive technologies, particularly material extrusion–based processes [23].

3.2. Scientific Novelty and Practical Significance

Designing and validation of a thorough methodology for optimizing the design of polymer aerospace components produced by additive technologies, with an emphasis on material extrusion-based techniques, constitutes the study's scientific uniqueness. Unlike conventional design-for-additive-manufacturing (DfAM) approaches that primarily address geometric feasibility, the proposed methodology integrates parametric CAD modeling, process-aware design constraints, numerical stress analysis, and data-driven optimization techniques into a unified framework [21].

A core innovativeness of the presented approach is the topology-inspired redistribution of material along principal load paths while explicitly accounting for the anisotropic mechanical behavior and interlayer bonding characteristics inherent to FDM-manufactured polymers. The numerical results obtained for the optimized bracket demonstrate that a significant mass reduction of approximately 20% can be achieved simultaneously with a decrease in maximum equivalent stress and an increase in structural stiffness and safety factor. These results speak in favor of the fact that performance improvements are not limited to weight savings alone but also extend to enhanced component' mechanical efficiency [8].

Furthermore, the methodology establishes a systematic link between numerical evaluation, geometric modification, and performance assessment, providing a scalable foundation for incorporating advanced optimization techniques, including machine learning–based surrogate models, in future research [21].

Practical Significance. Within practical perspective, the proposed optimization methodology is directly applicable to the design of auxiliary and secondary load-bearing polymer components in aerospace engineering. The demonstrated reduction in component mass, combined with improved stiffness and safety margins, contributes to lowering overall system weight while maintaining compliance with structural performance requirements.

The methodology can be effectively implemented in aerospace design offices using standard CAD/CAE tools and does not require specialized or proprietary optimization software, which facilitates its adoption in industrial practice. Moreover, the consideration of manufacturability constraints specific to fused deposition modeling ensures that the optimized designs remain suitable for rapid prototyping, small-batch production, and MRO applications [30].

By reducing design iteration cycles and enabling informed material redistribution at early stages of development, the proposed approach supports shorter development timelines, reduced production costs, and improved reliability of additively manufactured polymer components for aerospace applications.

4. Conclusions

This study presented a comprehensive methodology for optimizing the design of polymer components manufactured by additive technologies for aerospace applications. The proposed approach integrates parametric CAD modeling, process-aware design constraints, and numerical stress analysis, addressing key limitations of conventional DfAM methods when applied to polymer components produced using FDM. By explicitly accounting for the anisotropic mechanical behavior and interlayer bonding sensitivity inherent to material extrusion processes, the methodology provides a more reliable basis for structural design compared to purely geometry-driven approaches.

The described methodology' effectiveness was demonstrated using a representative PETG polymer bracket subjected to combined loading conditions. Numerical evaluation of the baseline configuration revealed conservative stress levels, moderate stiffness, and inefficient material utilization, which are consistent with observations reported in recent studies on FDM-manufactured polymer components. Based on these findings, a topology-inspired optimized geometry was developed through systematic material redistribution along principal load paths. The optimized design increased structural stiffness and safety factor, decreased maximum equivalent stress, and reduced mass by around 20%. These findings demonstrate that shape tuning can yield notable performance gains without sacrificing structural integrity or manufacturability.

Beyond the specific case study, the described methodology represents a scalable and transferable framework applicable to a wide range of auxiliary and secondary aerospace components fabricated from thermoplastic polymers. The use of standard CAD/CAE tools and established numerical techniques enables straightforward implementation in aerospace design environments, supporting reduced development time and improved design efficiency. Furthermore, the integration of numerical evaluation with process-aware design considerations contributes to improved reliability and predictability of additively manufactured polymer parts, which remains a critical challenge for broader aerospace adoption.

Future studies should concentrate on extending the methodology to high-performance thermoplastics and polymer composites utilized in aerospace constructions, as well as experimentally validating the optimized designs by mechanical testing of printed specimens and full-scale components.. Moreover, the incorporation of ML–based surrogate models is expected to further enhance the efficiency of the optimization process by enabling rapid exploration of complex design spaces and real-time performance prediction, as suggested in recent studies on data-driven AM optimization. These advancements will help additive manufacturing become a more established and dependable technique for use in aircraft engineering.

Conflict of Interest

The author declares that they have no conflict of interest in relation to this research, whether financial, personal, author ship or otherwise, that could affect the research and its results presented in this paper.

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Use of Artificial Intelligence

The author confirm that they did not use artificial intelligence technologies when creating the current work.

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АДИТИВНІ ТЕХНОЛОГІЇ У ВИГОТОВЛЕННІ ПОЛІМЕРНИХ ДЕТАЛЕЙ АВІАЦІЙНИХ КОНСТРУКЦІЙ: МЕТОДИ ПРОЄКТУВАННЯ ТА ОПТИМІЗАЦІЇ

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Предметом вивчення в статті є адитивні технології, що використовуються при виготовленні полімерних деталей авіаційних конструкцій. **Метою** дослідження є розробка комплексної методології, спрямованої на оптимізацію проєктування полімерних компонентів, виготовлених за допомогою 3D-друку, з особливим акцентом на технології екструзії матеріалу. **Завдання:** зробити огляд сучасних підходів до проєктування та оптимізації полімерних компонентів для аерокосмічних конструкцій, виготовлених за допомогою адитивних технологій; розглянути методи адитивного виробництва полімерів, включаючи FDM, SLS, SLA та MJF, які дозволяють виготовляти компоненти зі складною геометрією, зменшеною масою та поліпшеними функціональними характеристиками. **Методологія** базується на інтегрованій ітераційній структурі, що поєднує параметричне проєктування, моделювання з урахуванням технологічного процесу, чисельне моделювання та методи оптимізації, засновані на аналізі даних. Отримано такі **результати**. Підкреслено важливість оптимізації на етапі проєктування через зростаючі вимоги до механічних властивостей, терміну служби та економічної ефективності аерокосмічних конструкцій. Акцентовано увагу на проблемах, пов'язаних з адитивним виробництвом полімерів (анізотропія матеріалу, дефекти, спричинені процесом, мінливість механічних властивостей). Розглянуто підходи до вирішення цих проблем, включаючи проєктування для адитивного виробництва, оптимізацію параметрів процесу, чисельне моделювання та застосування методів штучного інтелекту. Підкреслено актуальність інтеграції цифрового моделювання, експериментальної валідації та інтелектуальних методів оптимізації в єдину методологію проєктування. Узагальнено останні дослідження в аерокосмічної галузі, визначено ключові виклики та окреслено перспективні напрямки подальшого розвитку технологій адитивного виробництва. **Висновки.** Наукова новизна отриманих результатів полягає в наступному: запропоновано методологію оптимізації проєктування полімерних аерокосмічних компонентів, виготовлених за допомогою адитивних технологій, з акцентом на методах, заснованих на екструзії матеріалів. Ця методологія поєднує параметричне CAD-моделювання, обмеження проєктування з урахуванням технологічних процесів, чисельний аналіз напружень та методи оптимізації на основі даних в єдину структуру, на відміну від традиційних підходів до проєктування для адитивного виробництва (DfAM), які в основному стосуються геометричної здійсненності.

Ключові слова: адитивне виробництво; полімерні компоненти для авіакосмічної галузі; оптимізація конструкції; параметри процесу; штучний інтелект; аналіз скінченних елементів.

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