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Development of a CAD–FEA Integrated Automation Add-In for DfAM-Aware Topology Optimization: A Case Study on an Additively Manufactured Pusher Duct Support Bracket for a Novel UAV Prototype

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Abstract

The integration of additive manufacturing (AM) and topology optimization (TO) is transforming mechanical design and prototyping practices across multiple engineering sectors, including agricultural and aerospace applications. This study presents the development of TODfAM, a bespoke SOLIDWORKS add-in that automates TO workflows and embeds Design for Additive Manufacturing (DfAM) principles directly within a parametric CAD environment. The tool integrates parametric modelling, finite element analysis (FEA)-based structural evaluation, and TO in a unified platform, enabling automated generation and assessment of design iterations with respect to both mechanical performance and AM-specific manufacturability constraints. A case study on a pusher-duct support bracket for an Unmanned Aerial Vehicle (UAV) was conducted to demonstrate the functionality of the developed workflow. The optimized bracket achieved a 13.77% mass reduction while maintaining structural integrity under representative loading conditions. The CAD-integrated framework reduces toolchain hand-offs and allows early manufacturability evaluation within the design environment, thereby improving workflow continuity and consistency. The principal novelty of this work lies in the establishment of a fully CAD-native, DfAM-aware optimization framework that consolidates the design-to-manufacturing process into a single automated environment. This approach not only streamlines pre- and post-processing tasks but also promotes wider industrial adoption of AM by providing a practical, designer-oriented route to lightweight and manufacturable structures.

Keywords: Unmanned Aerial Vehicle (UAV); bracket design; design analysis; FEA; topology optimization; additive manufacturing; design of agricultural machinery

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1. Introduction

The Agricultural Machinery Design and Manufacturing Industry faces mounting pressure to reconcile structural efficiency with operational robustness, particularly in the context of global food security and the intensifying demand to increase yield from diminishing arable land [1]. In response, the sector is embracing a technological shift towards digitalization, automation, and intelligent systems to enhance productivity, sustainability, and operational precision. A particular focus of this transformation has been the increasing application of Unmanned Aerial Vehicles (UAVs), which have become indispensable tools in advancing precision, efficiency, and adaptability across various agricultural operations. They support a range of applications, such as crop monitoring, precision spraying, mapping, and logistics, that demand highly specialized components [2–4].

From a structural design perspective, these UAV-integrated components must be lightweight, structurally resilient, and adaptable to dynamic multi-task requirements. Such demands mirror a broader shift in advanced manufacturing, characterized by the convergence of digital design, novel materials, and next-generation fabrication technologies. Among these, additive manufacturing (AM) has emerged as a powerful enabler for producing complex, customized parts, most especially in design prototyping. When combined with computational design techniques such as topology optimization (TO), AM can significantly enhance component performance by reducing weight while maintaining mechanical integrity. TO is a mathematical design approach that determines the most efficient material layout within a specified domain based on performance objectives and boundary conditions [5–7]. Its application has been well established in aerospace, automotive, and biomedical engineering, yet it remains underutilized in the agricultural sector despite its promise in addressing harsh, variable operating conditions [8–13]. A key barrier lies in the disconnect between TO-generated geometries and their manufacturability. While TO produces structurally efficient designs, these often require refinement to accommodate AM constraints such as minimum wall thickness, overhang angles, build orientation, and anisotropic mechanical properties [14,15]. To overcome the challenges, the paradigm of Design for Additive Manufacturing (DfAM) provides a suite of principles to ensure optimized parts are both high-performing and printable [14,16–20]. Conceptually, TO focuses primarily on the distribution of material within a given design domain to satisfy structural objectives, typically expressed in terms of stiffness or compliance. DfAM, in contrast, extends beyond this material distribution stage by incorporating process-specific parameters, such as build orientation, support generation, layer thickness, and surface roughness, into the design rationale, thereby coupling structural optimization with manufacturability considerations.

DfAM introduces a transformative design methodology tailored to exploit the geometric freedom, material efficiency, and functional integration enabled by AM technologies. Unlike conventional design paradigms, which often retrofit existing parts for fabrication, DfAM establishes a forward-looking approach wherein components are inherently optimized for layer-wise manufacturing processes. Central to this methodology are DfAM-informed rules, a structured set of design principles that address printability constraints (e.g., minimum wall thickness, overhang angles), material usage strategies (e.g., hollow or lattice structures), and functional requirements such as mechanical strength and thermal stability. These rules also facilitate support minimization, anisotropy reduction, and part consolidation, all essential for high-performance applications, such as UAVs [21,22]. However, implementing these principles early in the design phase remains difficult due to fragmented toolchains and limited CAD software support. The specific research gap addressed in this study is the lack of a fully CAD-native workflow that automates TO while embedding DfAM rules and manufacturability checks within the same environment. Accordingly, the novelty resides in the automation and integration of these functions into a unified commercial CAD software add-in, whereas the UAV bracket serves solely as a validation case to demonstrate applicability rather than as a source of novelty.

Currently, most commercially available CAD platforms provide only limited native support for customized and integrated TO and/or DfAM-aware functionalities. As a result, engineers are often compelled to rely on fragmented software ecosystems that necessitate manual geometry conversions, model reconstruction, and repeated validation processes, leading to elongated development cycles and elevated risks of design errors. These challenges are specifically exacerbated within the agricultural machinery design and manufacturing sector, where constraints on technical infrastructure and a scarcity of specialized digital design expertise further obstruct the adoption of advanced generative and additive design methodologies. Mandolini et al. (2022) highlight that while frameworks integrating TO with DfAM have shown promise, their implementation remains largely confined to research environments and fails to pervade commercial CAD systems [23]. Furthermore, Fernández et al. (2025) demonstrate the difficulty of integrating CAD and FEA in agricultural tool development due to technological fragmentation and skill gaps in small-scale farming contexts [24]. The situation is further complicated by the fact that most CAD systems are not inherently optimized for DfAM, as acknowledged in recent state-of-the-art reviews on Industry 4.0 integration with AM and TO [25–27].

In sectors employing UAV platforms, which are exposed to dynamic loads, thermal gradients, and weight constraints, DfAM rules provide a critical foundation for ensuring component robustness without compromising efficiency. Among these, TO stands out as a particularly impactful DfAM strategy. It enables the automated generation of geometry that minimizes mass while satisfying predefined structural or thermal performance criteria, making it ideally suited for UAV frames, wings, and internal support structures [28,29]. The add-in tool introduced in this study specifically focuses on TO for AM components, examining how they can be applied to design UAV components that are both lightweight and structurally sound, while also being amenable to rapid prototyping and iteration cycles. In practical terms, integrating TO with DfAM expedites prototyping by producing structurally efficient geometries that are inherently manufacturable by AM. As UAV systems increasingly operate in complex and unpredictable environments, the need for agile, robust, and lightweight structures becomes paramount. DfAM-informed design frameworks empower engineers to meet these evolving demands through intelligent material placement, functional consolidation, and streamlined fabrication workflows [18,30]. Ultimately, the DfAM perspective provides the necessary link between design intent and manufacturing capability, unlocking the full potential of AM in next-generation UAV applications.

Recent research efforts have focused on embedding TO and DfAM capabilities directly within the CAD environment to create end-to-end, automation-ready design tools. For example, Asadollahi-Yazdi et al. (2019) introduced a multi-objective fused filament fabrication (FFF)-oriented optimization framework, while Prabhu et al. (2020) demonstrated early-stage manufacturability evaluation for FFF processes. Mandolini et al. (2022) extended this by incorporating real-time simulation feedback, and Sbrugnera Sotomayor et al. (2021) highlighted the benefits of generative design coupled with DfAM. These innovations collectively aim to streamline the transition from concept to fabrication [23,25,31,32]. Additionally, the studies have further advanced DfAM by introducing expert systems, intelligent tooling, and comprehensive methodological frameworks. Aljabali et al. (2025) developed a rule-based DfAM expert system; Uralde et al. (2024) proposed sensorized tooling concepts for aeronautical AM; and Asapu and Ravi Kumar (2025) provided a comprehensive review consolidating current DfAM practices and applications [33–35].

Similarly, recent advances (2023–2025) extend beyond geometry-only formulations towards process-aware and manufacturability-constrained optimization. Physics-informed TO now embeds thermal/process surrogates to curb local overheating and reduce defect risk during Laser Powder Bed Fusion (L-PBF), with experimental validation demonstrating reduced hotspots relative to geometry-based overhang control [36]. Concurrently, support-aware formulations and overhang-constrained schemes have broadened to permit design choices that trade infill- vs. self-supporting strategies while retaining structural efficiency [37]. In parallel, multi-objective DfAM has matured from method proposals to deployable decision-support, integrating rule-based manufacturability compliance with performance targets and early-stage cost proxies [35,38]. Finally, AI-assisted DfAM is accelerating functional integration and closed-loop design-to-print by combining generative/ML models with in situ monitoring and parameter adaptation [39,40]. These developments align with our CAD-native TODfAM emphasis on manufacturability-guided optimization rather than algorithmic novelty. In this context, the proposed TODfAM framework distinguishes itself as a CAD-native, manufacturability-driven workflow that consolidates these recent advancements within a single design environment, rather than introducing a new optimization algorithm. Nevertheless, the practical application of such integrated design tools to UAV systems applicable in agricultural practices remains largely unexplored. The agricultural context presents unique design constraints, related components must withstand vibrations, impacts, humidity fluctuations, and prolonged environmental exposure, while remaining lightweight to preserve aerodynamic efficiency and flight duration. Additionally, UAV systems often require frequent design updates due to evolving field conditions, necessitating rapid and flexible prototyping workflows [41–45].

Despite considerable progress in CAD-integrated TO and DfAM methodologies, there remains a notable absence of a unified design platform specifically tailored to the unique requirements of purpose-built UAV component development. Existing solutions are often constrained by a lack of automation, inadequate incorporation of manufacturability considerations, or the necessity for extensive manual intervention across disparate software systems. This study seeks to address this critical gap by presenting the development and validation of an automated CAD-integrated add-in tool grounded in DfAM-aware TO principles. While the approach does not propose a new optimization algorithm, it contributes through workflow-level integration by embedding TO, DfAM and FEA automation directly into CAD software, thus improving accessibility and design productivity for engineers. In the context of this study, TO is regarded as a geometry generator embedded within a broader DfAM framework, in which manufacturability principles guide post-optimization refinement and validation. The proposed add-in tool is designed to function within a conventional parametric CAD environment, specifically SOLIDWORKS enabling seamless integration of TO algorithms. By embedding these capabilities directly into the CAD interface, the add-in reduces repetitive modelling operations and streamlines the iterative design workflow. As a result, it enhances the manufacturability and structural performance of the designed components, particularly those intended for AM fabrication. To demonstrate the practical utility of the tool, a case study is presented involving the design and prototyping of a pusher duct support bracket for a next-generation UAV applicable for multifunctional logistics applications including precision agriculture. This representative scenario highlights the tool's ability to generate structurally efficient, AM components that are robust under the operational and environmental demands characteristic of modern agricultural systems.

In this context, the present research addresses a critical design challenge: the integration of automated TO workflows within a parametric 3D CAD environment, coupled with manufacturability considerations for AM. The SOLIDWORKS-based implementation exemplifies how such integration can be achieved through a parametric 3D modelling approach, enabling design automation while adhering to DfAM-aware constraints, structural performance criteria, and AM process requirements. By incorporating iterative validation steps, including AM process verification and printability checks, the workflow ensures that optimized designs transition smoothly from digital modelling to reliable physical fabrication.

2. Materials and Methods

2.1. Formulation of the Topology Optimization Problem and Its Integration with DfAM Principles in the SOLIDWORKS Simulation Environment

TO represents a transformative approach in mechanical design, particularly when aligned with the principles of DfAM. This methodology facilitates the creation of lightweight, structurally efficient, and functionally tailored components by optimizing material layout within a predefined design space. Its utility becomes especially pronounced in the context of AM, where geometric freedom enables the realization of complex, non-intuitive forms.

The initial phase of any TO procedure involves clearly specifying the design space, objectives, boundary conditions, and constraints. In structural optimization, a common objective is to minimize material usage while maintaining or enhancing mechanical performance. One of the most prevalent computational strategies employed for this purpose is the Solid Isotropic Material with Penalization (SIMP) method, which allows for a continuous variation in material density throughout the design domain [46,47]. Beyond deterministic density-based strategies such as SIMP, evolutionary and hybrid optimization frameworks have also been investigated. For example, Cardillo et al. (2013) proposed a Genetic Algorithm (GA)-based hybridization of partial solutions to address multi-objective trade-offs between stiffness and mass. Such evolutionary approaches enable broader exploration of the design space but generally incur higher computational costs. In contrast, the present study employs a deterministic SIMP-based formulation directly integrated within the CAD environment, prioritizing workflow automation and manufacturability alignment rather than multi-objective generality [48].

The general topology optimization problem is expressed as shown in Equation (1):

$$
\begin{array}{lll}
\min\limits_{\rho} & f(\rho) = \mathbf{U}^T\mathbf{K}(\rho)\mathbf{U} & (Minimize\ compliance\ /\ Maximize\ stiffness) \\
\text{subject to} & \mathbf{K}(\rho)\mathbf{U} = \mathbf{F} & (Equilibrium\ equations) \\
 & \frac{1}{V_0}\int\limits_{\Omega} \rho(x)dx \le V^* & (Volume\ constraint) \\
 & 0 < \rho_{\min} \le \rho(x) \le 1 & (Densitybounds)
\end{array} \quad (1)
$$

In this formulation, $f(\rho)$: Compliance (reciprocal of stiffness), which is minimized to achieve a stiff structure, $\rho(x)$ denotes the density distribution over the design domain, Ω: design variable, with values ranging between a small positive threshold ρ_{min} and 1. V_0: Original volume, V^*: Maximum allowable volume (Volume constraint) The displacement and force vectors are represented by $\mathbf{U}$ and $\mathbf{F}$, respectively. The global stiffness matrix $\mathbf{K}(\rho)$ is assembled using penalized element stiffness matrices according to Equation (2):

$$
\mathbf{K}(\rho) = \sum_{e=1}^{N} \rho_e^p \mathbf{K}_e \quad (2)
$$

Here, p is a penalization exponent (typically p = 3) intended to drive the optimization towards a near-discrete solution, and $\mathbf{K}_e$ represents the stiffness matrix of the ***eth*** element.

While this formulation is well suited for achieving structurally optimal designs, it does not inherently account for manufacturing feasibility. DfAM principles address this limitation by introducing constraints that ensure the design is suitable for AM processes (Equation (3)) [49–51].

Relevant DfAM constraints may be included:

$$\begin{array}{ll} g_1(\rho) \geq \theta_{\min} & \text{(Overhang angle constraint)} \\ g_2(\rho) \geq l_{\min} & \text{(Minimum feature size constraint)} \\ g_3(\rho) = Symmetryenforcement & \text{(Symmetry or built direction constraint)} \\ g_4(\rho) \leq \varepsilon_{\min} & \text{(Strain energy or local stress constraint)} \end{array} \quad (3)$$

These constraints are essential for ensuring geometric and functional printability. The overhang constraint θ_{min} for instance, prevents unsupported geometries that would require additional support structures. Similarly, l_{min} ensures features do not fall below the resolution of the printing process. Symmetry and orientation constraints help control build direction and load path continuity, while performance-based criteria such as ε_{max} safeguard against localized structural failure. Such constraints may be embedded directly into the optimization process through filtering, projection, or penalization, or they may be handled in a post-processing stage. Although some of advanced platforms may provide explicit DfAM enforcement capabilities, SOLIDWORKS Simulation offers an accessible, albeit limited, framework, a topology study module performs nonparametric TO of parts. The TO module in SOLIDWORKS allows users to define mechanical and geometric constraints in a native CAD environment. These include: (1) Preserved regions, which protect critical zones from material removal; (2) Build direction constraints, which guide the solution toward manufacturable shapes; (3) Symmetry planes, which simplify both the design and manufacturing process. Although constraints such as minimum member size and overhang angle are not natively implemented, the resulting optimized geometries can be exported and refined using external software that supports these features. In this regard, the integration of TO with DfAM principles represents a relatively powerful strategy for the development of efficient, manufacturable designs. SOLIDWORKS Simulation facilitates this process through its intuitive interface and CAD-native workflow, making it particularly suitable for iterative product development cycles in industries where weight, customization, and performance are critical, such as aerospace, medical devices, and unmanned aerial systems.

2.2. Development of the Add-In Tool and Its Operational Workflow

This study presents the development of a custom CAD add-in interface for SOLIDWORKS-Premium 2025 SP.1.0, specifically designed for the target component and integrating parametric modelling, static FEA, and topology optimisation within a unified framework. The framework is structured around a set of predefined key geometric parameters, each constrained by upper and lower bounds. This methodological approach aligns with early-stage design strategies, wherein initial design variables are systematically configured to ensure geometric compatibility with adjacent components, such as the wing and the pusher duct in a UAV platform. By enabling controlled modifications to the geometry, the proposed methodology allows for the generation of multiple component variants with tailored mass–stiffness characteristics, thereby reducing the need for extensive redesign efforts. The automated TO process employed in this context is inherently supported by the parametric design logic, ensuring a streamlined, scalable, and adaptable workflow.

The add-in tool was developed using the Microsoft .NET Framework 4.8 within the Visual Studio integrated development environment (IDE), a widely adopted platform for engineering software development. The application was programmed in C#, an object-oriented programming language well-suited for interacting with external software libraries. To facilitate automated manipulation of both the dimensional attributes of the CAD model and the boundary conditions specified during the TO process, the tool leverages the Application Programming Interfaces (APIs) provided by SOLIDWORKS

CAD and SOLIDWORKS Simulation products. These APIs encompass an extensive suite of callable functions accessible through languages such as Visual Basic for Applications (VBA), VB.NET, Visual C#, Visual C++ 6.0, and Visual C++/CLI. They provide direct programmatic access to key SOLIDWORKS functionalities, including the creation of geometric entities (e.g., lines), the insertion of standard or user-defined components into part or assembly environments, and the interrogation and validation of surface and feature parameters [52,53]. Within this development environment, the dynamic link library (DLL) files SolidWorks.Interop.sldworks.dll, SolidWorks.Interop.swconst.dll, SolidWorks.Interop.swcommands.dll, SolidWorks.Interop.swpublished.dll and SolidWorkstools.dll were added as project references in Visual Studio. These libraries provide access to model parameters and interface elements. Additionally, solidworks.Interop.cosworks.dll was incorporated to enable programmatic definition and manipulation of boundary conditions and simulation-specific functions within the SOLIDWORKS Simulation environment (Supplementary Files "SOLIDWORKS Helper Class" and "TODfAM Form Class" supporting the described methods are provided).

The developed automation tool, named TODfAM (Topology Optimization—Design for Additive Manufacturing), incorporates a custom-designed add-in that facilitates the definition, modification, analysis, and optimization of key design parameters and design volume. Emphasis is placed on parameters affecting the mass–stiffness trade-off within the resulting component geometry. Through this capability, the tool aligns with the overarching principles of DfAM and simulation-driven TO. The TODfAM application is compiled into an executable (.exe) setup file and seamlessly integrated into the SOLIDWORKS during installation. This integration enables native functionality within the SOLIDWORKS environment, allowing for uninterrupted and intuitive user interaction. As part of this study, a tailored algorithm was developed to enable TO of components specifically intended for AM. This algorithm was embedded within the bespoke TODfAM add-in and implemented directly in the SOLIDWORKS environment. To evaluate the tool's functionality and effectiveness, a case study was conducted by methodically applying the procedural steps defined by the integrated algorithm. The structured workflow of the TODfAM add-in tool and following work procedure in SOLIDWORKS' native environment is described in Figure 1.

2.3. CASE STUDY: Topology Optimization of a Pusher Duct Support Bracket for a Novel UAV Prototype

2.3.1. Reference Model

The structural component sampled in the case study—an additively manufactured pusher duct support bracket—was specifically designed for an innovative UAV platform designated as JUPITER. This UAV represents the outcome of a collaborative initiative spearheaded by the Soton UAV team which operates within a multidisciplinary, research-intensive framework, dedicated to the advanced design, prototyping, and operational integration of UAV technologies at the University of Southampton (UK). The bracket forms part of a protected design and serves as a critical subsystem within the JUPITER airframe, which itself is currently subject to an ongoing patent application procedure. Due to intellectual property considerations, the publication of exhaustive technical data and complete visual documentation is currently restricted (see acknowledgement).

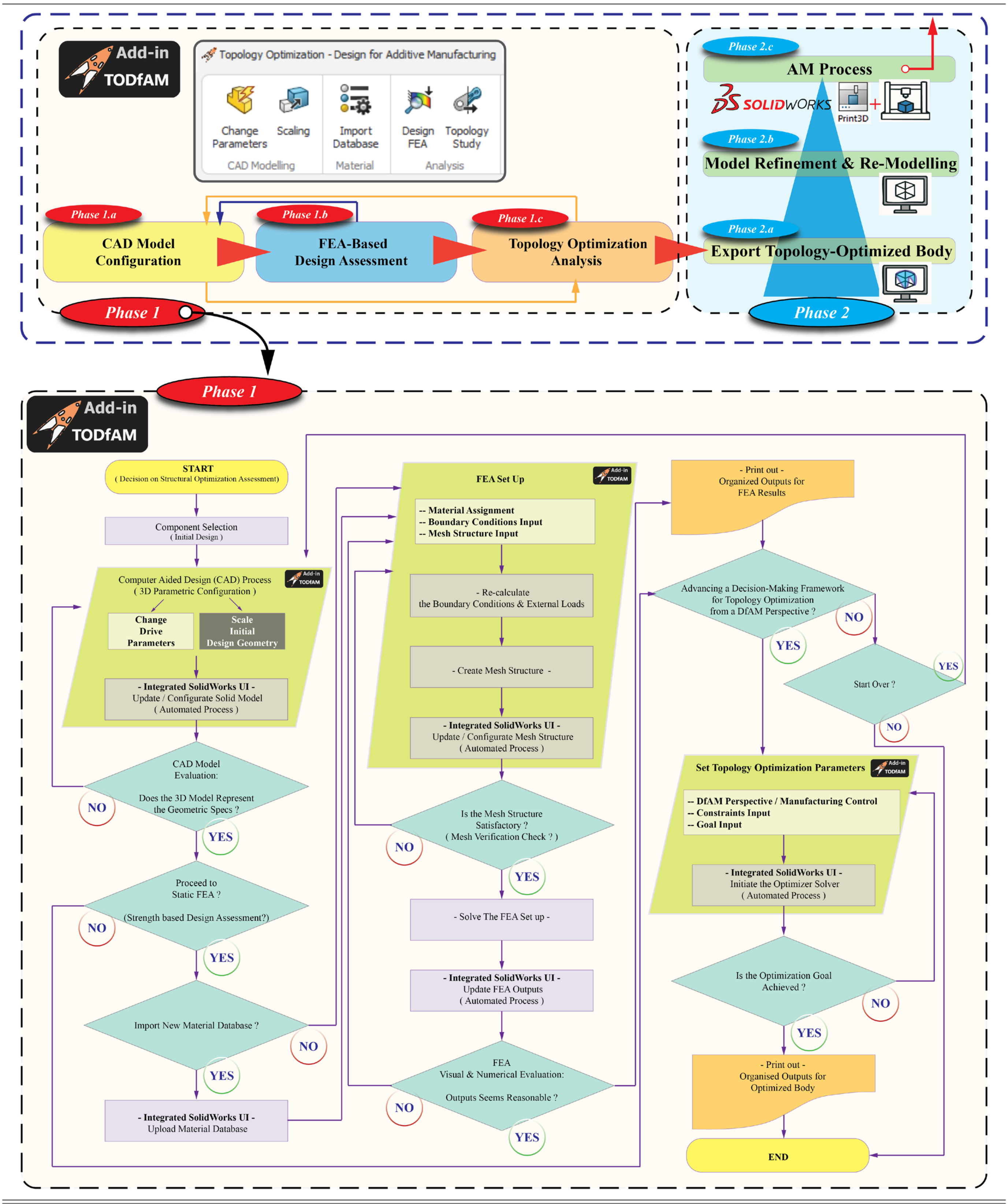

Figure 1. Developed workflow for the TODfAM add-in tool (Phase 1: Automated Phase; Phase 2: Conventional SOLIDWORKS UI).

The JUPITER was engineered to operate within the Civil Aviation Authority's (CAA) A2 Open Category for UAVs weighing under 25 kg, JUPITER being distinguished by its distributed propulsion system. This architecture includes fifteen independently controlled electric motors, offering substantial thrust redundancy and thereby enhancing the platform's operational robustness. In conjunction, a custom-designed powertrain health monitoring system has been implemented to further bolster flight safety and dependability. Aerodynamically, the airframe has been designed to manage turbulent airflow conditions through a streamlined, low-drag configuration and multiple redundant control surfaces, ensuring sustained stability even in unfavourable meteorological environments. The design process has placed a premium on safety, evidenced by fully enclosed propellers and an ergonomically intuitive loading mechanism. In addition to its multi-mission-oriented functionality, encompassing agricultural logistics and precision farming applications, a particularly noteworthy design attribute of the JUPITER UAV is its compatibility with NHS (National Health Service, UK)-standard Small Versapak containers. This feature facilitates seamless integration into established medical logistics workflows, thereby extending the platform's utility beyond the agricultural sector. Moreover, scalability has been strategically incorporated into the system's architectural framework. A higher-capacity variant is currently under development, engineered to transport payloads of up to 15 kg over distances nearing 100 km, thus broadening the operational scope of the platform to meet diverse logistical demands [54–56]. The bracket has been specifically focused to ensure the secure attachment of both the pusher duct and the yaw thruster, while also enhancing the overall aerodynamic performance of the UAV. The geometry of the bracket has been configured to sustain structural integrity under varying dynamic loads.

The initial bracket design was fabricated using additive manufacturing techniques on a Bambu Lab X1E system (Bambu Lab, TX, USA—www. bambulab.com) housed in the Southampton UAV Team's design laboratory at the University of Southampton. Production employed a carbon fibre-reinforced polylactic acid (PLA-CF) filament, a proprietary material developed by Bambu Lab that incorporates carbon fibres into an enhanced PLA matrix. The parts were produced via FFF, resulting in components with a uniform matte surface and minimal layer delineation, characteristics advantageous for prototyping contexts that demand a non-glossy, esthetically refined finish [57]. Printing parameters included the use of a 1.75 mm diameter filament extruded through a 0.4 mm nozzle, with individual layer heights maintained at 0.24 mm. The extrusion temperature was set to a constant 220 °C, and the fabrication speed was uniformly held at 50 mm s^{-1}. To maximize mechanical integrity, the bracket was manufactured with full infill and dense outer shells, a strategy aimed at enhancing load-bearing capacity and ensuring overall structural cohesion. The inclusion of carbon fibres within the PLA matrix imparted notable improvements in stiffness and surface hardness, while retaining the processability and dimensional stability associated with standard PLA materials. Although SOLIDWORKS Simulation supports the use of linear orthotropic material models, in this study the material behaviour was intentionally idealized as homogeneous, isotropic, and linearly elastic, in order to reduce computational overhead and facilitate faster convergence during topology optimization iterations. A technical schematic illustrating the material properties alongside critical geometric and dimensional specifications, is provided in Figure 2.

2.3.2. Setup of the TODfAM Add-In Tool

The TODfAM add-in application has been compiled into an executable (.exe) setup file, allowing for straightforward installation within a Windows operating environment. It is specifically designed to be compatible with SOLIDWORKS versions from 2025 onwards. Upon successful installation, the add-in can be accessed via the SOLIDWORKS user interface, appearing under the 'Tools menu' and 'Command Manager' tabs in the part design window. Additionally, the add-in can be activated or deactivated via the 'Tools—Add-Ins' menu (Figure 3). Currently in its pilot phase, the tool has been developed with future scalability in mind, aiming to support a wide range of parametric design applications. Its initial implementation is particularly tailored to the design evaluation and structural optimization of the pusher duct support bracket. Upon initial launch, the add-in defaults to the 'CAD Modelling, Change Parameters' tab, which functions as the primary gateway for initiating the design and TO workflow. This interface is preconfigured with a material database tailored specifically for AM materials, thereby streamlining the setup process and ensuring compatibility with DfAM-aware design strategies.

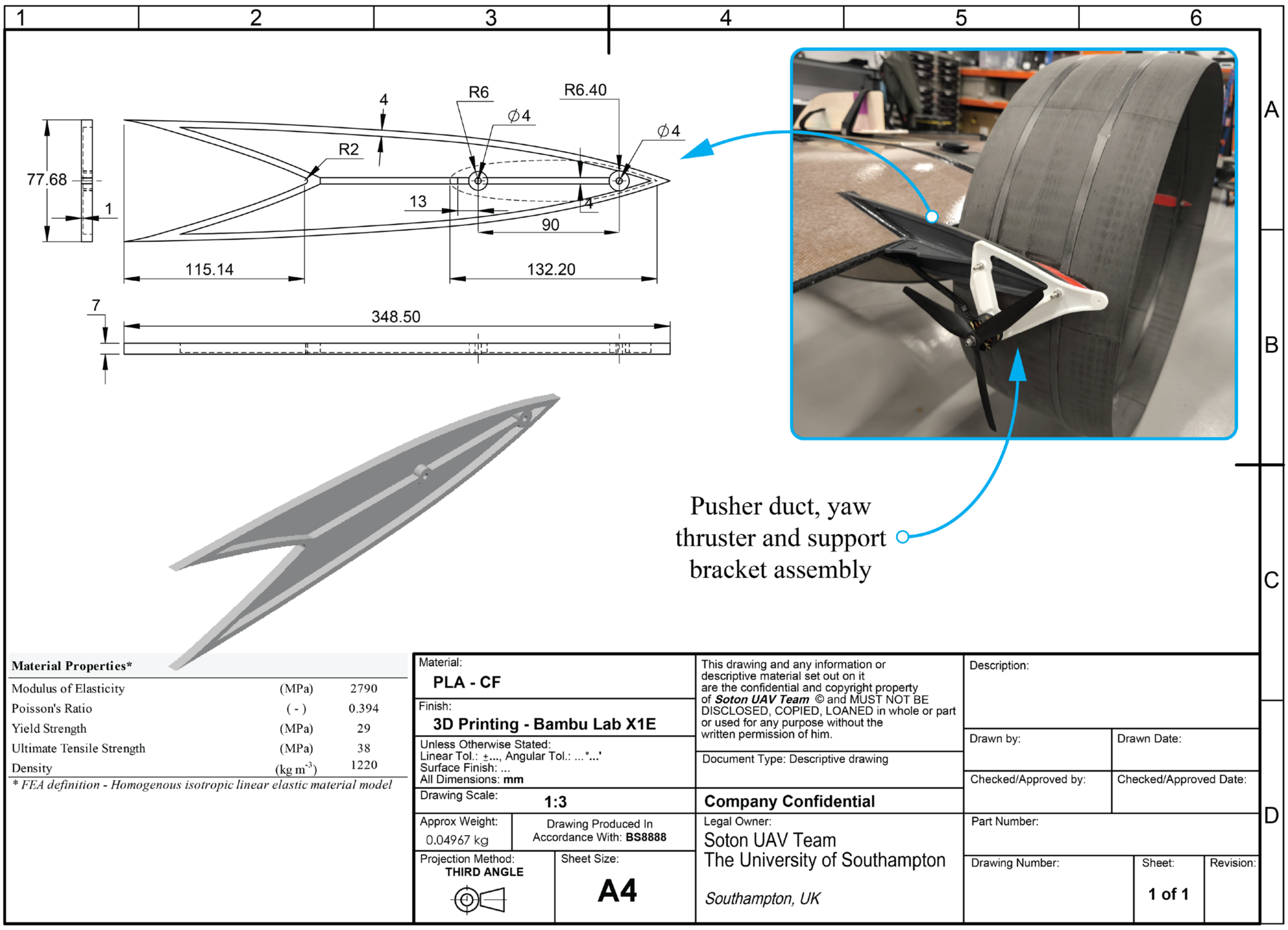

Figure 2. Technical illustration of the material properties, along with key geometric and dimensional specifications of the Pusher Duct Support Bracket.

2.3.3. Phase 1.a: Configuration of the Parametric Model

The initial phase of the TODfAM workflow is dedicated to configuring the parametric model geometry through the 'CAD Modelling' interface in the add-in, which is subdivided into Parameters and Scaling tabs. As illustrated in Figure 4, this phase enables users to define and manipulate key dimensional attributes of the component, in this case, a pusher duct support bracket, within a SOLIDWORKS-native environment. The Parameters tab presents a technical schematic annotated with critical geometric features, including Frame Support Thickness (FST), Base Form Thickness (BFT), Frame Support Depth (FSD), Bracket Tip Height (BTH), and Fastener Hole Diameter (FHD). Each of these parameters is input via a control panel on the right-hand side of the interface, where users can assign values within pre-defined bounds to ensure design feasibility and assembly compatibility. Upon specifying these parameters, the user may invoke the "Configure 3D Model with Parameters" function, which dynamically regenerates the bracket geometry in SOLIDWORKS and provides real-time updates on model mass. This parametric configuration process facilitates efficient exploration of design alternatives without requiring manual redrawing or re-modelling and supports structural refinement at the conceptual stage. The visual outputs shown in Figure 4a demonstrate how changes in parameter values translate into distinct model variants within the CAD workspace, ensuring rapid feedback and iteration. Complementing this, the Scaling tab offers a global transformation feature whereby a uniform scale factor is applied to the entire model (Figure 4b). This capability is particularly useful for early-stage trade-off studies and mass-scaling assessments. Once a scale value is defined, the model is proportionally resized while preserving parametric relationships and design intent. The integration of these two sub-functions—dimension-specific parameterization and holistic scaling—forms the foundational layer for the subsequent TO process by ensuring that the model geometry is both structurally relevant and manufacturable.

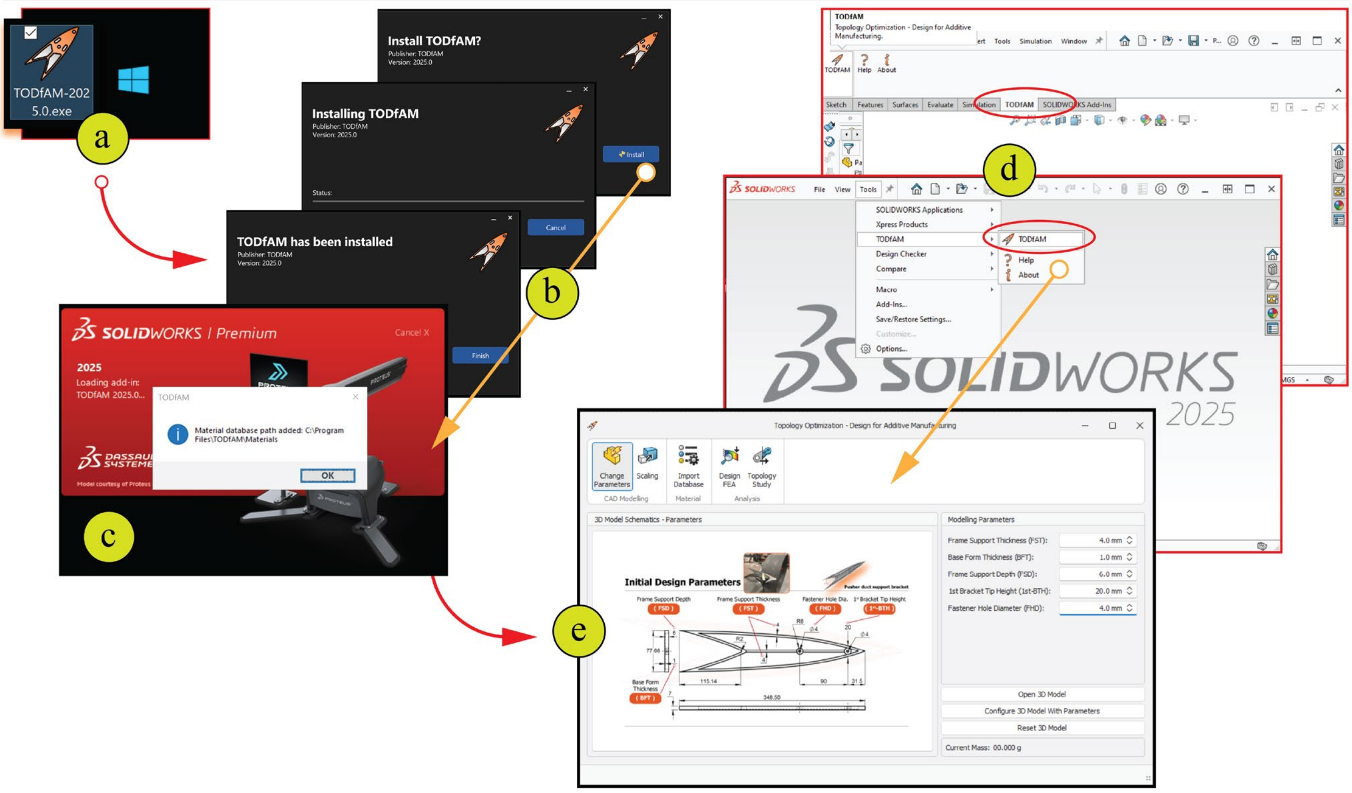

Figure 3. Initial setup procedure and launch interface of the TODfAM add-in: (**a**) Executable (.exe) setup file located on the Windows desktop; (**b**) Installation process screens; (**c**) SOLIDWORKS initialization screen; (**d**) TODfAM launch; (**e**) TODfAM user interface.

In the present case study, the model configuration was retained using the initial design parameters illustrated in Figure 2. This baseline configuration defines the principal geometric features as follows: FST of 4 mm, BFT of 1 mm, FSD of 6 mm, BTH of 20 mm, and FHD of 4 mm. These dimensional specifications provided a consistent foundation for evaluating subsequent design modifications within the study framework.

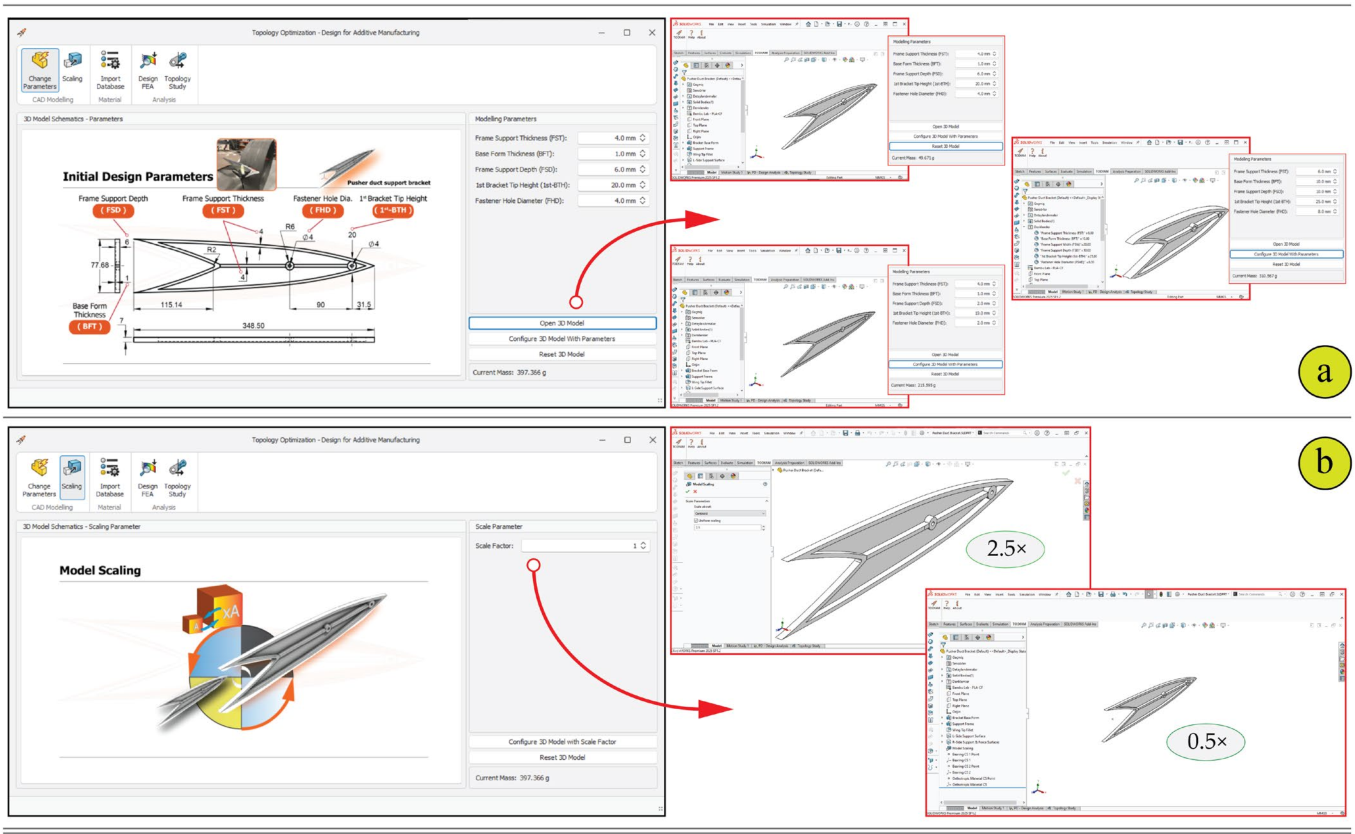

Figure 4. CAD modelling interface of the TODfAM add-in tool: (**a**) Initial design parameter input and CAD model regeneration; (**b**) uniform model scaling for conceptual studies.

2.3.4. Material Database

In the developed add-in interface, a dedicated Material Database Import tab has been incorporated to enhance the material selection workflow for subsequent analyses. This feature enables users to load customized material databases tailored to specific project requirements. Through this interface, users can import external SOLIDWORKS material database files (.sldmat) by integrating them into the designated SOLIDWORKS file locations. The imported database may be manually configured or sourced from reputable online platforms such as MatWeb: Online Materials Information Resource (www.matweb.com) or ANSYS Granta Selector (https://www.ansys.com/products/materials/granta-selector) (accessed on 18 November 2025), which offer comprehensive material datasets. By default, the TODfAM tool comes preloaded with a bespoke, project-specific material library, alongside SOLIDWORKS' comprehensive default material database. Within this database, both isotropic and orthotropic material properties of the PLA-CF are embedded. These properties are critical for ensuring the fidelity of structural and topological simulations. For the case study presented herein, the isotropic material properties detailed in Figure 2 have been employed. For the concept-stage TO, a linear-elastic isotropic material model was adopted to maintain solver stability and consistent SIMP-based compliance evaluation. Raster-aligned orthotropic modelling and a fully calibrated directional property set were not implemented at this stage. Consequently, the mapping between manufacturing parameters and FE material axes is deferred to the post-optimization phase, once the geometry and build orientation are finalized. Figure 5 provides a visual representation of the user interface, highlighting the file loading process within the SOLIDWORKS environment.

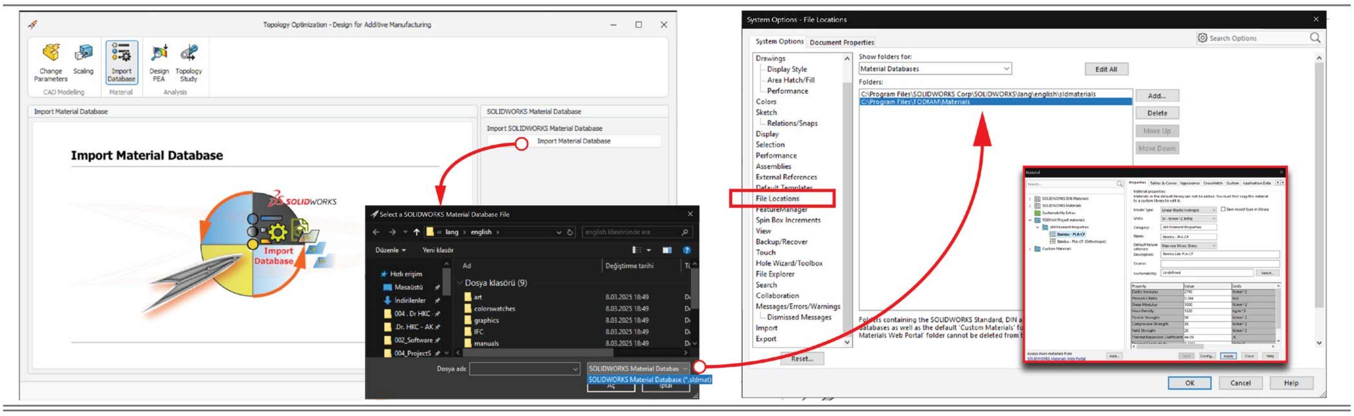

Figure 5. Add-in user interface for importing the material database.

2.3.5. Phase 1.b: FEA Based Design Assessment

Following the geometric configuration of the parametric model (Phase 1.a), Phase 1.b of the TODfAM workflow introduces a built-in FEA environment to assess the structural performance of the initial design under anticipated loading conditions. This phase is integral to pre-optimization validation, ensuring that the baseline configuration is structurally sound and that critical stress, displacement, and safety factors are understood prior to initiating TO.

As illustrated in Figure 6, the 'Design FEA' tab of the TODfAM interface guides the user through a systematic setup of boundary conditions and loading scenarios. The interface includes five primary input domains: material definition, fixtures, external loads, mesh parameters, and output diagnostics. The core of this setup is built around a UAV-relevant loading configuration, where multiple forces and supports are applied to simulate real-world aerodynamic and mechanical demands during take-off. The loading scheme, visualized in the schematic (left), comprises standard gravitational acceleration, two bearing loads acting on the inner wings and duct interface (representing the mass of the pusher duct and associated subsystems), and an externally applied yaw thruster force. The primary load path proceeds from the hub interface through the upper rib members to the outer mounting lugs and into the UAV frame. The bracket is anchored through a fixed support at the wing root and constrained elastically at both lateral faces to replicate semi-flexible mounting conditions commonly encountered in UAV platform assemblies. The elastic restraint conditions are numerically defined by specifying both normal and tangential stiffness values for the right and left support interfaces (e.g., other support brackets or duct joints). To assist users in obtaining accurate stiffness values, the TODfAM tool includes a dedicated Elastic Support Stiffness Calculation window (Figure 6, right). This utility enables the calculation of distributed and total stiffness parameters based on the structural material's mechanical properties, namely Young's modulus (E), Poisson's ratio (ν), and shear modulus (G), as well as geometrical attributes such as support area (A) and wall thickness (t) [58,59]. Stiffness values can be defined analytically as $k_n = EA/t$ and $k_t = GA/t$, and can be verified through compliance runs using $k_i = F_i/\delta_i$ based on the same material and geometric inputs. The derived stiffnesses are then automatically fed into the fixture definition to model contact behaviour under both axial and tangential loading regimes. Here, the left interface was assigned a tangential stiffness of 0 $N{\cdot}m^{-1}$ to simulate its slotted connection allowing minor sliding during assembly, whereas the right interface was constrained to represent the fixed joint.

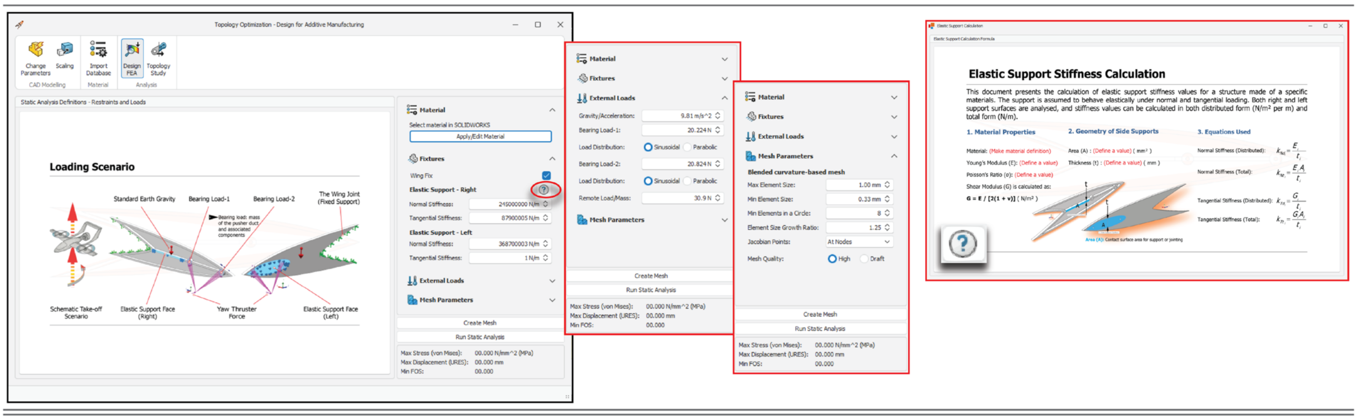

Figure 6. Integrated FEA setup interface within the TODfAM add-in tool (Left: UAV-specific loading scenario and restraint definitions; Centre: GUI for assigning materials, fixtures, external loads, and mesh parameters; Right: elastic support stiffness calculation formula window).

In terms of meshing, the add-in incorporates a curvature-based meshing system, allowing the user to define maximum and minimum element sizes, element distribution in radial patterns, and the mesh growth ratio. This ensures adequate resolution in regions of high geometric or stress complexity. Mesh quality options include both High and Draft, giving the designer control over simulation precision and computational time. Once the simulation inputs are fully defined, the user can generate the mesh and execute a linear static analysis directly within the interface. All analyses were performed in a global cartesian reference frame; no local material axes were assigned during TO process. Resulting outputs, including maximum equivalent stress (von Mises), maximum displacement, and minimum factor of safety (FOS), are presented numerically in the diagnostics section. These values serve as critical indicators for evaluating whether the current geometry meets performance requirements or whether preliminary modifications are necessary before proceeding to TO. Through this integrated FEA capability, TODfAM enables early-stage structural validation without leaving the SOLIDWORKS environment. This accelerates the design-verification loop and allows users to anchor the TO process in a structurally meaningful baseline, thereby reducing the likelihood of impractical or unsafe solutions in later stages.

In this case study, the loading scenario was described according to the maximum structural loading condition which is expected during take-off in the JUPITER UAV platform. Under this configuration, the yaw thruster applies a maximum thrust force of 30.900 N, acting laterally towards the pusher duct. The combined mass of the duct and associated subsystems was defined as 0.650 kg, fully borne by the bracket arms. A design flight load factor of +6.5 g (g-force) was applied to simulate vertical acceleration during ascent, while aerodynamic effects were intentionally neglected under the assumption that they offer limited contribution to worst-case loading. This omission is justified, as aerodynamic forces would in practice act to partially offset the imposed inertial loads. This static case was treated as a representative bounding condition for concept-stage screening, as it corresponds to the wort-case load state of the UAV; extended envelopes including aerodynamic effects will be considered during configuration-specific validation. The bracket–wing interface was modelled as a fixed support, while the bracket–duct connections were treated as elastic restraints. To simulate these elastic interactions accurately, both normal and tangential stiffness values were assigned based on the elastic and shear moduli of the joint materials, as well as contact geometry. The following support stiffnesses were defined: Right elastic face: Normal: 245×10^6 N·m^{-1}, Tangential: 87.6×10^6 N·m^{-1}, Left elastic face: Normal: 368.7×10^6 N·m^{-1}, Tangential: 0 N·m^{-1}.

2.3.6. Phase 1.c: Topology Optimization Study

Phase 1.c of the TODfAM workflow initiates the TO stage, representing the culmination of the pre-optimization setup that includes geometric parameterization and structural validation. The objective of this sub-phase is to generate an optimized structural layout that achieves the desired mechanical performance while reducing unnecessary material usage. The Topology Study tab of the TODfAM interface offers an integrated graphical environment within SOLIDWORKS for configuring and executing this process (Figure 7). This module leverages SOLIDWORKS Simulation's native TO solver, enhanced with DfAM-aware control parameters embedded through the TODfAM add-in. As with the previous FEA phase, the interface allows users to configure material properties, fixtures, external loads, and mesh parameters. These inputs are carried over to maintain continuity and accuracy, ensuring that the TO is grounded in the same physical assumptions used for the initial structural assessment. Additional functional domains within this tab include Goals and Constraints and Manufacturing Controls. The Goals and Constraints section allows the user to define the mass reduction target and factor of safety constraint. In the case study presented here, a mass reduction goal of 30% was applied, with a minimum factor of safety constraint set to $\geq$1.1. This balance was selected to ensure both structural efficiency and manufacturability, particularly in the context of UAV component integration where weight savings are critical but cannot compromise operational safety. For concept-stage screening, a pragmatic lower bound of FOS $\geq$ 1.1 was applied to prevent brittle solutions; programme-level safety factors for flight hardware will be assigned during qualification.

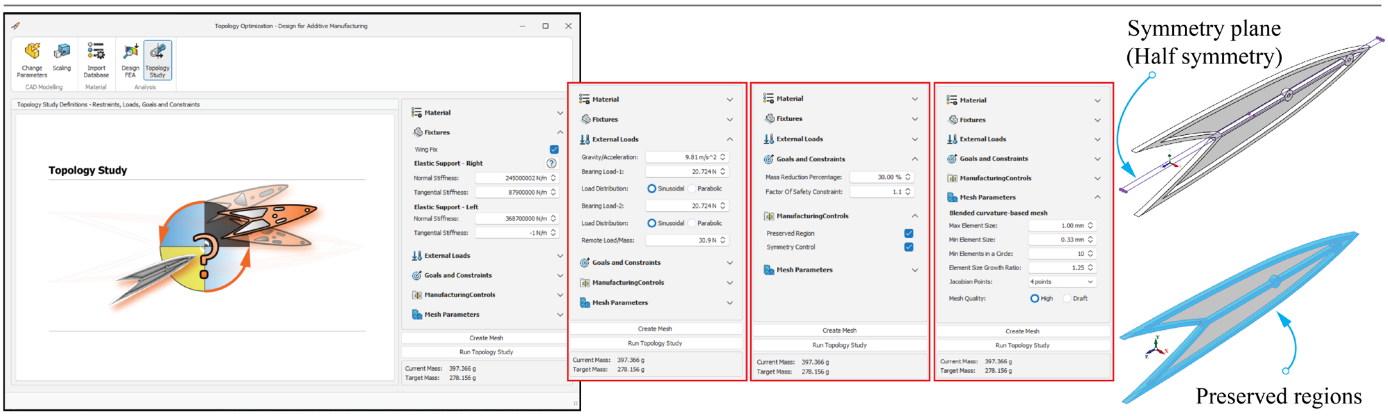

Figure 7. TO interface in the TODfAM add-in tool, showing integrated control panels for DfAM-aware manufacturing constraints (preserved regions, symmetry), optimization targets (mass reduction, factor of safety), and solver convergence monitoring.

The Manufacturing Controls section introduces DfAM-aligned constraints to guide the optimization towards geometries suitable for AM. Two controls were activated in this study:

- *Preserved Region*: To protect functionally critical areas (e.g., bolt holes or interfaces) from material removal (These preserved regions correspond to the as-designed bolt holes and mounting pads shown in Figure 2 and were retained unchanged throughout optimization).
- *Symmetry Control*: To enforce symmetric solutions, thereby improving structural balance and manufacturability while potentially reducing post-processing efforts.

It should be noted that, at the current stage, the manufacturability constraints in TODfAM are limited to geometry-level controls. Advanced DfAM parameters such as minimum feature size, overhang angle, and build direction are currently managed externally during the parametric re-modelling phase, since the SOLIDWORKS TO kernel does not yet provide in-solver enforcement for these parameters.

In practice, these DfAM criteria were applied quantitatively during the post-optimization parametric re-modelling and verified at each hand-off using SOLIDWORKS Print3D and the slicer. Specifically, thin members below ~1 mm were thickened and unsupported overhangs > 45° were corrected; build orientation was set flat on the bracket base, consistent with the fabrication plan, prior to final slicing. This hybrid approach reflects current SOLIDWORKS TO capabilities, verification and correction occur outside the solver, while ensuring that the manufactured geometry satisfies printability constraints.

Mesh generation for the topology study employs the same curvature-based strategy implemented in the FEA phase. Parameters such as element size (min. 0.001 mm, max. 4 mm), growth ratio (1.1), and Jacobian control points can be defined to achieve adequate fidelity. The minimum element size represents the solver's refinement threshold for curvature continuity rather than a physical element length. The effective element dimensions governing accuracy were approximately 0.4–1.6 mm, with a growth ratio of 1.1, while the minimum Jacobian threshold of 0.001 was applied solely as a refinement control. The mesh ensures that material distribution across the design space is optimized with sufficient resolution, particularly around preserved regions and high-load paths. Once configured, the TO is executed by selecting "Run Topology Study." The solver evaluates the material layout that minimizes structural compliance (i.e., maximizes stiffness) within the defined volume and safety constraints. Throughout the process, TODfAM continuously displays the current and target mass values, providing real-time insight into optimization progress and convergence. By embedding this stage within the SOLIDWORKS environment, the TODfAM tool eliminates the need for external mesh translation, manual result interpretation, or iterative geometry adjustments in third-party tools. The result is a functionally optimized, additively manufacturable design aligned with DfAM principles and validated through prior structural simulation. This capability marks a critical milestone in transitioning from conceptual geometry to a fabrication-ready topology driven by performance, manufacturability, and automation. Typical numerical parameters were $p = 3$, a density-filter radius of 1.2 mm, and an element size of 0.4–1.6 mm with a growth ratio of 1.1; finer meshes primarily smoothed local members without significantly affecting the global mass–stiffness response. A formal displacement/stress convergence curve lies outside the current workflow-integration scope and is flagged for future validation. Although most procedures are automated within the developed add-in, certain DfAM checks—such as support accessibility and build orientation—remain manually verified, representing a hybrid automated–manual integration.

2.3.7. Phase 2.a: Exporting the Optimized Body

Upon completion of the TO process within the TODfAM interface, the next step involves the export of the optimized bracket geometry for subsequent post-processing. In this phase, the resulting optimized body—typically a non-parametric mesh representation—is extracted directly from the SOLIDWORKS Simulation environment using the native result export functionality. The model is saved in STL (stereolithography) format, which is the standard file type used in AM workflows due to its compatibility with slicing software and AM hardware. The STL export preserves the integrity of the optimized geometry, including topology-specific features such as internal voids and stress-adaptive load paths. It is crucial at this stage to ensure that the mesh resolution and tolerance settings are sufficiently refined to avoid tessellation artefacts that may compromise manufacturability or structural fidelity. This exported STL model then serves as the baseline geometry for further refinement, correction of non-printable features, or direct preparation for AM, depending on the specific production requirements.

2.3.8. Phase 2.b: Model Refinement and FEA Validation of the Re-Model

Although the exported topology-optimized body provides a structurally efficient configuration, it exists as a mesh-based, non-parametric geometry that limits design adaptability and compatibility with standard engineering workflows. To overcome this, the optimized model is reverse-engineered and reconstructed in SOLIDWORKS as a fully parametric solid model. This re-modelling process reinstates feature-based design flexibility, enabling dimension-driven modifications, precise definition of functional features, and integration with technical drawings and tolerance specifications. It also allows for the inclusion of essential manufacturability enhancements, such as ensuring minimum wall thicknesses, smoothing sharp edges, and correcting mesh irregularities that may impede AM processes.

Following re-modelling, a secondary FEA is performed to validate the mechanical integrity of the refined geometry under the same loading conditions defined during the initial assessment phase. This verification step is essential to confirm that the reconstructed model preserves the structural performance characteristics of the original optimized shape. The same boundary conditions, elastic supports, and load magnitudes are reapplied, and the simulation results are compared against the original performance targets, including stress distribution, displacement fields, and factor of safety. Any deviations that compromise performance can be addressed through iterative adjustments within the parametric model. This dual approach, reconstructing a DfAM-aware parametric model and verifying its structural fidelity, ensures the final design is both manufacturable and mechanically validated prior to AM fabrication.

2.3.9. Phase 2.c: Additive Manufacturing Process

The final phase of the TODfAM integrated workflow involved preparing the optimized bracket for fabrication via FFF. A two-stage AM preparation approach was implemented, combining the use of SOLIDWORKS Print3D and Bambu Studio. First, the SOLIDWORKS Print3D module was used to perform integrated DfAM verification within the CAD environment. This included checks for build volume compliance, overhang angles, and wall thickness, ensuring that the optimized design was suitable for FFF without extensive manual modification. As the Bambu Lab X1E printer model is not directly supported in SOLIDWORKS, custom machine parameters, including build volume, nozzle diameter, layer height, and extrusion temperature, were configured to reflect the X1E's specifications. Following this verification, the bracket model was exported in STL format and processed in Bambu Studio for final slicing and machine-specific parameterization. For this study, the bracket was fabricated on the Bambu Lab X1E FFF system, which offers high-precision fabrication capabilities suitable for functional prototyping. The selected material was PLA-CF. The refined parametric model, verified for AM compliance, was used for final fabrication, resulting in a support-free, dimensionally accurate component. This combined workflow, leveraging both integrated CAD-based DfAM checks and advanced slicing software, ensured that the optimized UAV bracket transitioned effectively from design to reliable physical realization.

3. Results and Discussion

3.1. Interpretation of TODfAM Add-In Workflow, Its User Interface and SOLIDWORKS Integration

The TODfAM add-in developed in this study enhances the integration of TO within the SOLIDWORKS environment by establishing a continuous workflow from parametric modelling to FEA and optimization execution. This integration streamlines the design process by minimizing data translation between software modules. By leveraging SOLIDWORKS' native TO capabilities, TODfAM organizes the design process to allow for rapid iterations and adjustments within a single platform. This approach aligns with the research of Liu et al. (2018), who emphasized the benefits of integrating TO within CAD systems to improve design efficiency and accuracy [60]. The add-in's user interface simplifies the setup of design parameters and constraints, enabling designers to focus on optimizing structural performance without the overhead of managing multiple software windows. TODfAM supports DfAM by incorporating constraints such as preserved regions and symmetry directly into the TO process. This ensures that the optimized designs are not only structurally efficient but also manufacturable using AM techniques. The importance of integrating manufacturing constraints into the TO process is highlighted by Guo et al. (2017), who demonstrated that considering such constraints during optimization leads to designs that are more suitable for AM [61]. Despite its advantages, TODfAM has limitations, particularly in translating optimized geometries into parametric CAD models suitable for further editing and manufacturing. The output from TO is often a mesh-based representation that requires additional processing to convert into usable CAD geometry. Yin et al. (2019) discuss the challenges associated with this translation and the need for automated methods to bridge the gap between TO results and parametric CAD models [62]. Furthermore, while TODfAM facilitates the integration of TO within the CAD environment, there is still a need for enhanced user interfaces that provide intuitive control over optimization settings and better visualization of results.

3.2. Evaluation of the Case Study Outputs

3.2.1. Evaluation of the Baseline Parametric Design (Phase 1.a)

The baseline parametric design established in Phase 1.a served as a critical foundation for the integration of TO and AM strategies. By leveraging parametric design principles and FEA, the study achieved a flexible and efficient design process that supports the development of optimized, manufacturable components. The parametric model was constructed with adjustable parameters, allowing for rapid exploration of design alternatives. This approach aligns with the findings of Holzer et al. (2007), who emphasized the importance of parametric design in enabling early-stage design exploration and facilitating communication between architectural and structural disciplines [63]. By incorporating parametric variables, the design process becomes more flexible, allowing for efficient modifications and iterations. FEA was conducted on the baseline model to assess its structural performance under predefined loading conditions. The integration of FEA within the parametric design workflow ensures that structural considerations are addressed early in the design process, reducing the likelihood of costly revisions at a later point. This integrated approach is supported by the work of García-Dominguez et al. (2020), who demonstrated the benefits of combining parametric design with structural analysis in the context of AM [64]. The evaluation of the baseline design revealed areas for improvement, particularly in terms of material distribution and structural efficiency. These insights informed the subsequent TO phase, where material was redistributed to enhance performance while adhering to manufacturing constraints. The iterative nature of this process underscores the value of parametric design in facilitating continuous refinement and optimization [65].

3.2.2. Structural Assessment of Initial Geometry (Phase 1.b)

In Phase 1.b, a structural evaluation of the baseline geometry was conducted using FEA within the TODfAM interface, prior to initiating TO. Figure 8 summarizes the key output domains of this assessment, including mesh quality diagnostics (a), equivalent stress (von Mises) and resultant displacements (b), and factor of safety (FOS) distribution (c). The mesh quality was validated through a Jacobian Ratio diagnostic, a metric used in SOLIDWORKS Simulation to ensure numerical stability in linear and nonlinear analyses. The model exhibited 29 Jacobian points across all mesh elements, with no elements exceeding the failure threshold of 10, confirming mesh adequacy according to SOLIDWORKS FEA best practices (Figure 8a) [53]. The absence of any poor-quality elements establishes a robust computational foundation for subsequent simulations. The use of a curvature-based meshing strategy also ensured higher resolution in stress-critical regions, particularly near the filleted interfaces and bolted connections. The equivalent stress distribution in Figure 8b reveals that maximum stress concentrations occurred around the bolt hole regions, with a peak stress of approximately 13.30 MPa, which remains well below the PLA-CF yield strength of 26 MPa. Corresponding displacement magnitudes reached a maximum of 0.375 mm under the pre-defined loading scenario. These results confirm that the baseline geometry withstands anticipated operational loads without exceeding material limits. The FOS plot in Figure 8c further supports the structural viability of the design, with minimum safety factors approximately 2 across all evaluated regions. However, these safety margins are accompanied by material redundancy, particularly in the outer bracket arms, which contributes to unnecessary mass and reduced structural efficiency. This observation highlights the importance of TO as a method to redistribute material away from low-stress regions while maintaining mechanical integrity [62]. From an engineering decision-making perspective, the combined outcomes of mesh validation, stress, displacement, and FOS analyses justify the application of TO. The current geometry, while structurally sound, lacks material efficiency, which is a primary criterion for optimization in UAV applications where mass savings translate directly into flight performance gains. Hence, proceeding to Phase 1.c for TO is both technically substantiated and aligned with the project's DfAM strategy.

3.2.3. Evaluation of the Topology Optimization Procedure in TODfAM and the Outputs

The performance of the TO procedure implemented within the TODfAM platform was evaluated with reference to both its convergence behaviour and the quality of the resulting optimized bracket geometry. This assessment provides critical insight into the effectiveness of the optimization strategy and its suitability for generating DfAM-aware lightweight designs.

The convergence data, presented in Figure 9a, demonstrates a stable and well-conditioned optimization process. The Compliance (Best Stiffness) curve shows a smooth monotonic trend towards convergence, with the solver reaching a plateau after approximately 35 iterations. This indicates that the algorithm effectively established the optimal material distribution required to meet the stiffness-driven performance objective. The absence of oscillatory behaviour further confirms the numerical stability of the procedure, a key requirement for reliable TO [66]. Simultaneously, the Mass Target convergence plot illustrates that the optimizer successfully achieved the predefined design goal of a 30% mass reduction. The final converged value of 69.975% retained mass aligns precisely with the target of 70%, confirming the procedure's ability to balance mass efficiency with structural integrity. The synchronization between compliance and mass convergence underscores the effectiveness of the optimization setup in controlling trade-offs between weight and stiffness, which is particularly critical in UAV component design [49]. The evolution of the FOS provides an additional perspective on the robustness of the solution. The optimizer rapidly achieved a FOS well above the required minimum of 1.1, ultimately converging to a final value of 5.409. This outcome demonstrates that the mass reduction was achieved without compromising mechanical safety margins, and confirms that the optimized topology is structurally sound for UAV operational conditions. The resulting optimized geometry, shown in Figure 9b, reflects these convergence outcomes. The bracket exhibits a coherent and efficient material layout, with dense material retained along primary load paths and extensive void formation in low-stress regions. The cross-sectional visualization confirms that material removal is not superficial, but distributed through the component thickness, maximizing the lightweighting potential. Furthermore, the geometry maintains clear load path continuity and structural connectivity, which are essential for both mechanical performance and downstream manufacturability [67]. Despite these strengths, the evaluation also identified DfAM-relevant limitations in the raw optimized output. In particular, thin structural members and unsupported overhangs persist in certain distal regions of the bracket arms. Such features are inherent to conventional density-based TO and highlight the need for subsequent parametric refinement to achieve full compliance with FFF-based AM process constraints [49].

In this phase, the results presented in Figure 9 confirm that the TODfAM optimization procedure effectively met its design objectives, producing a mass-reduced, structurally efficient geometry with excellent convergence behaviour. The outputs provide a robust foundation for the following Phase 2.a re-modelling and validation stages, enabling the transition from optimal topology to DfAM-aware final design.

3.2.4. Phase 2.a: Post-Optimization: Exporting the Mass-Reduced Body and Re-Modelling

Following the completion of the TO process within the TODfAM framework, the optimized mass-reduced bracket geometry was exported in STL format from SOLIDWORKS environment for further refinement (Figure 10). As illustrated in Figure 10b, the exported mesh achieved a 26.83% mass reduction relative to the original baseline design. This mesh represents the direct output of the TO solver and exhibits material concentration along key load-bearing paths, particularly around the bracket root and bolted interfaces, while removing material from structurally non-critical regions. However, due to the inherent characteristics of density-based TO, partial material reduction also occurred within preserved surface regions. This resulted in a mesh that, while highly mass-efficient, exhibited geometries unsuitable for AM processes and demonstrated geometrical fragility in critical zones.

Closer examination of the STL model highlighted DfAM-related limitations that would preclude direct manufacturing using FFF-based AM. Notably, thin members with wall thicknesses below the practical minimum threshold of ~1 mm were observed, along with unsupported overhangs exceeding the 45° process limit. Moreover, the raw mesh surface exhibited non-manifold geometry and irregular wall transitions, which could impair both printability and mechanical performance. To overcome these limitations and ensure DfAM compliance, a parametric re-modelling phase was conducted in SOLIDWORKS, resulting in the geometry shown in Figure 10d. During this process, the optimized load paths identified in the TO mesh were preserved, while key features were refined and thickened to meet FFF constraints. The re-modelling explicitly adopted a full-fill solid body approach to restore robustness in preserved regions and ensure consistent manufacturability. The re-modelled geometry achieved a final 13.77% mass reduction relative to the baseline, representing a deliberate trade-off: some theoretical mass savings were sacrificed in order to eliminate sub-critical features and ensure structural reliability. This transition from algorithmically generated mesh to a production-ready CAD model is aligned with current best practice in UAV component design workflows. While TO provides substantial opportunities for lightweighting, DfAM-guided re-modelling remains essential to bridge the gap between optimization outputs and the practical requirements of AM production [68]. The final model prepared in this phase is both structurally efficient and manufacturable, providing a validated foundation for subsequent FEA assessment and AM fabrication.

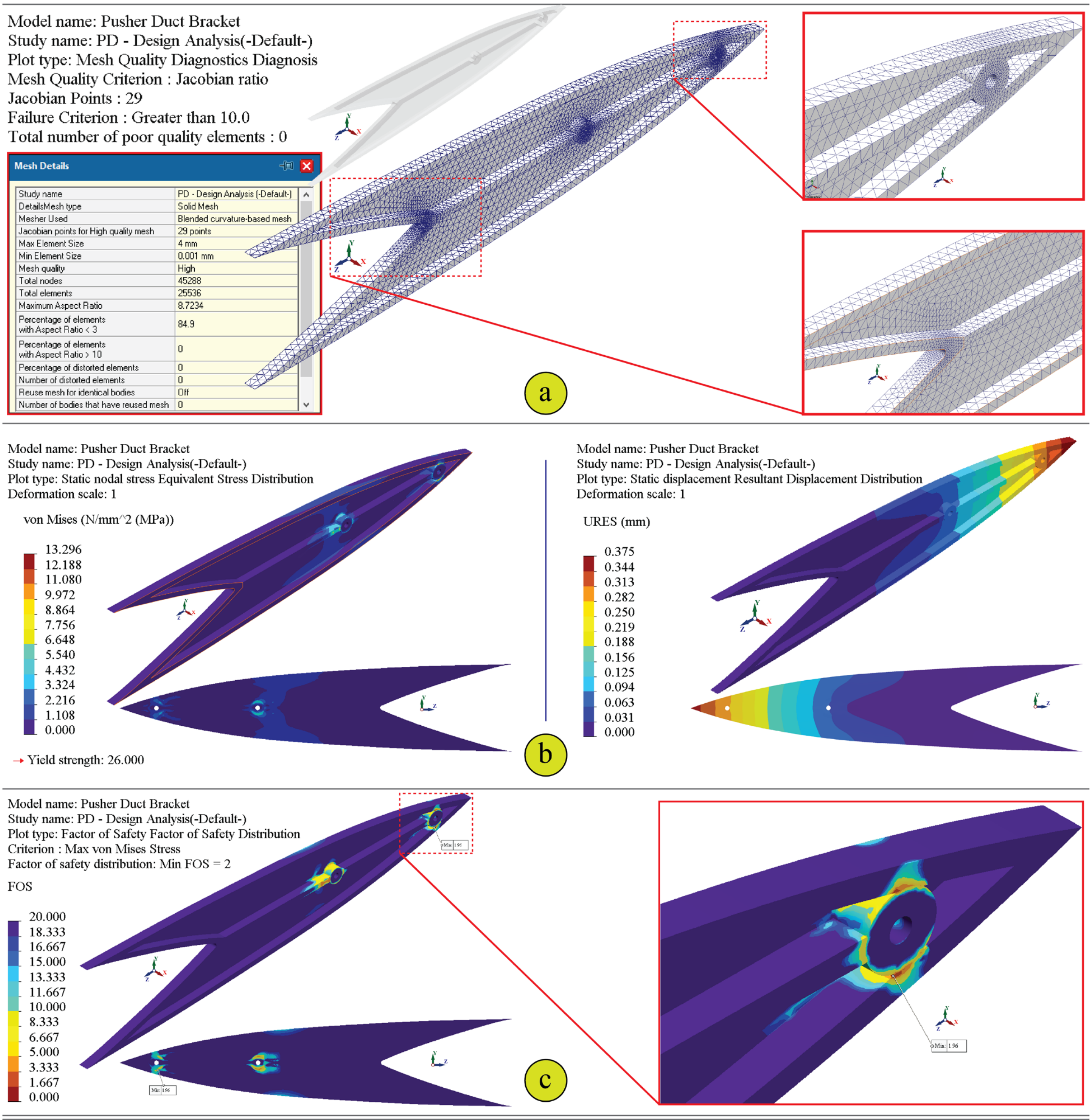

Figure 8. FEA Output and structural assessment of the initial geometry: (**a**) Mesh structure and internal verification; (**b**) Equivalent (von Mises) stress and resultant deformation outputs; (**c**) Factor of safety distribution (baseline FEA).

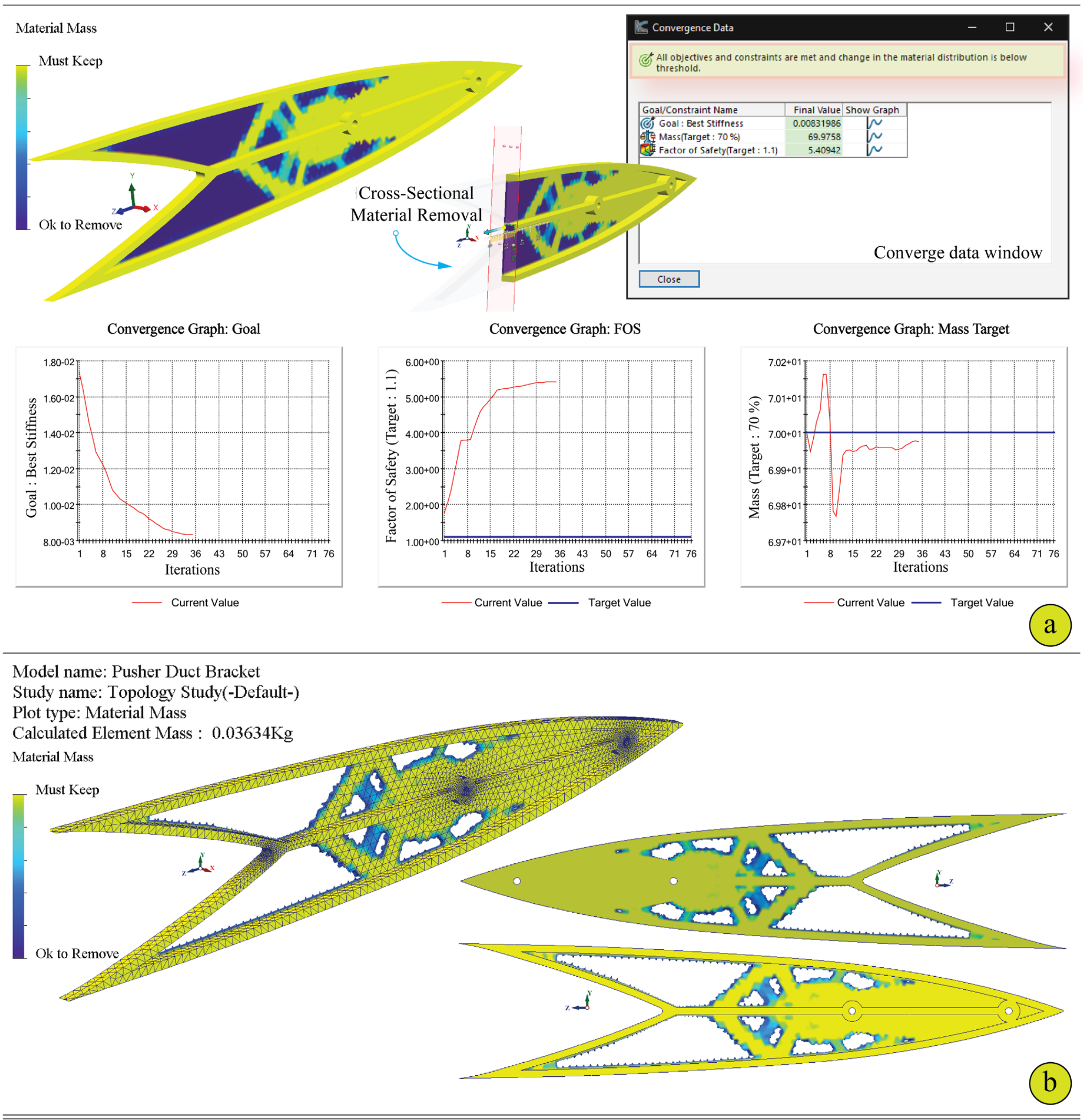

Figure 9. Topology optimization outputs: (**a**) Mass removal and convergence data plots (**b**) Mass reduced mesh body.

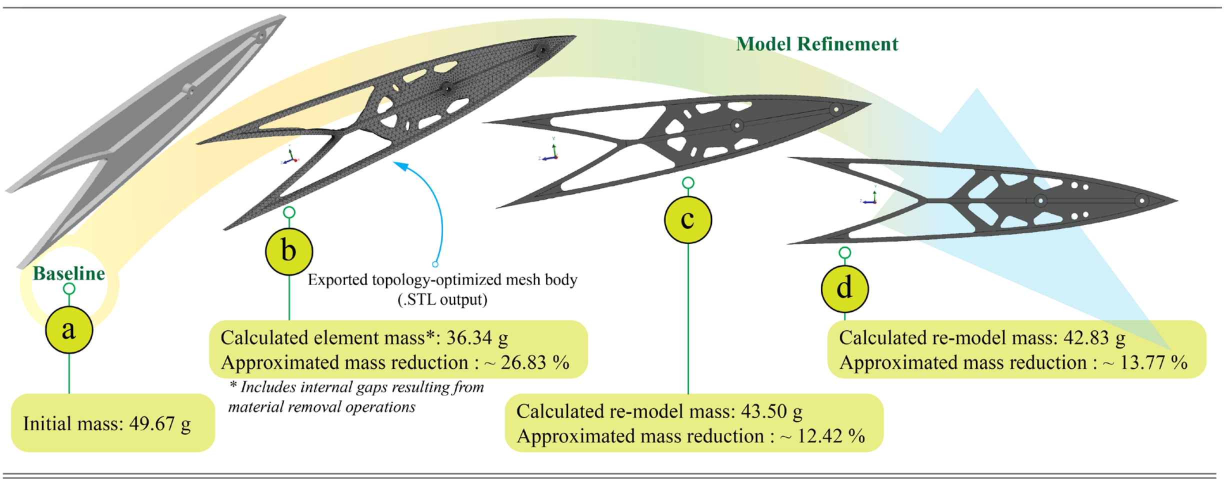

Figure 10. Model refinement process (baseline, topology-optimized, and refined).

3.2.5. Phase 2b.: FEA Validation of the Refined Geometry: Final Evaluation of the Case Study Based on Topology Optimization Results and Performance from a DfAM Perspective

Following the parametric re-modelling of the topology-optimized bracket (Phase 2.a), a FEA validation was conducted to assess whether the refined geometry maintained the desired balance between structural performance and DfAM-compliant manufacturability. This validation was performed under the same boundary conditions and loading scenarios established during the baseline assessment, thereby ensuring a direct comparison of structural evolution across the design stages. As illustrated in Figure 11 and detailed in Table 1, the refined bracket exhibited a maximum equivalent von Mises stress of 13.353 MPa, virtually unchanged (+0.43%) from the initial model (13.296 MPa). The stress concentrations remained appropriately located around the bolted interfaces and filleted internal regions, consistent with the critical load paths identified during the TO phase. This result confirms that the structural integrity of the optimized design was successfully preserved through the re-modelling process. The maximum resultant displacement of the refined model was measured as 0.550 mm at the sharp front tip of the bracket, representing a 46.67% increase relative to the baseline configuration (0.375 mm). While this increase reflects the impact of the substantial 13.77% mass reduction achieved through optimization and re-modelling, it was interpreted that magnitude remains within the acceptable tolerance envelope for this UAV application, given that the absolute difference is only 0.175 mm. Given the bracket's local structural function and the sub-millimetre absolute deflection levels observed, the stiffness reduction is not expected to affect the UAV's global vibration behaviour or control margins. Dynamic evaluation will be included in future validation. Critically, it was also interpreted that this level of low deflection would not adversely affect the operational flight conditions of the UAV (JUPITER). Such outcomes are consistent with trends reported in the literature, where DfAM-aware lightweighting is often accompanied by moderate increases in compliance, which must be judiciously balanced against functional requirements [67].

The FOS remained effectively stable, with the refined model achieving 1.947, a negligible reduction of 0.43% from the baseline (1.955). This result comfortably exceeds the minimum required FOS ($\geq$1.1) established for this UAV bracket, affirming the design's suitability for structural integration and AM fabrication. The reported threshold is appropriate for concept-stage verification, while the final programme-level safety factors for flight hardware will be defined during qualification testing. From a DfAM perspective, the re-modelling phase demonstrably succeeded in addressing the manufacturability constraints identified in the initial topology-optimized mesh. Critical corrections included the elimination of thin members below 1 mm and the adjustment of unsupported overhangs exceeding 45°, both of which are essential for reliable FFF-based AM. The parametric reconstruction enabled precise control over these features while preserving the key performance attributes of the topology-optimized layout. Nonetheless, the analysis also highlights opportunities for further refinement. The observed increase in displacement suggests that targeted parametric thickening in distal bracket regions could enhance global stiffness without significantly impacting mass efficiency. Moreover, advanced DfAM strategies such as anisotropy-aware optimization and the selective incorporation of graded lattice structures, could further improve the mass-to-performance ratio of the design [8].

In this phase, the FEA validation confirms that the refined bracket geometry achieves a robust balance between structural performance, mass efficiency, and manufacturability using AM techniques. The iterative workflow adopted, combining TO, parametric refinement, and validation, exemplifies state-of-the-art DfAM practice for UAV component development. The bracket is thus ready for final AM and experimental evaluation in operational UAV systems.

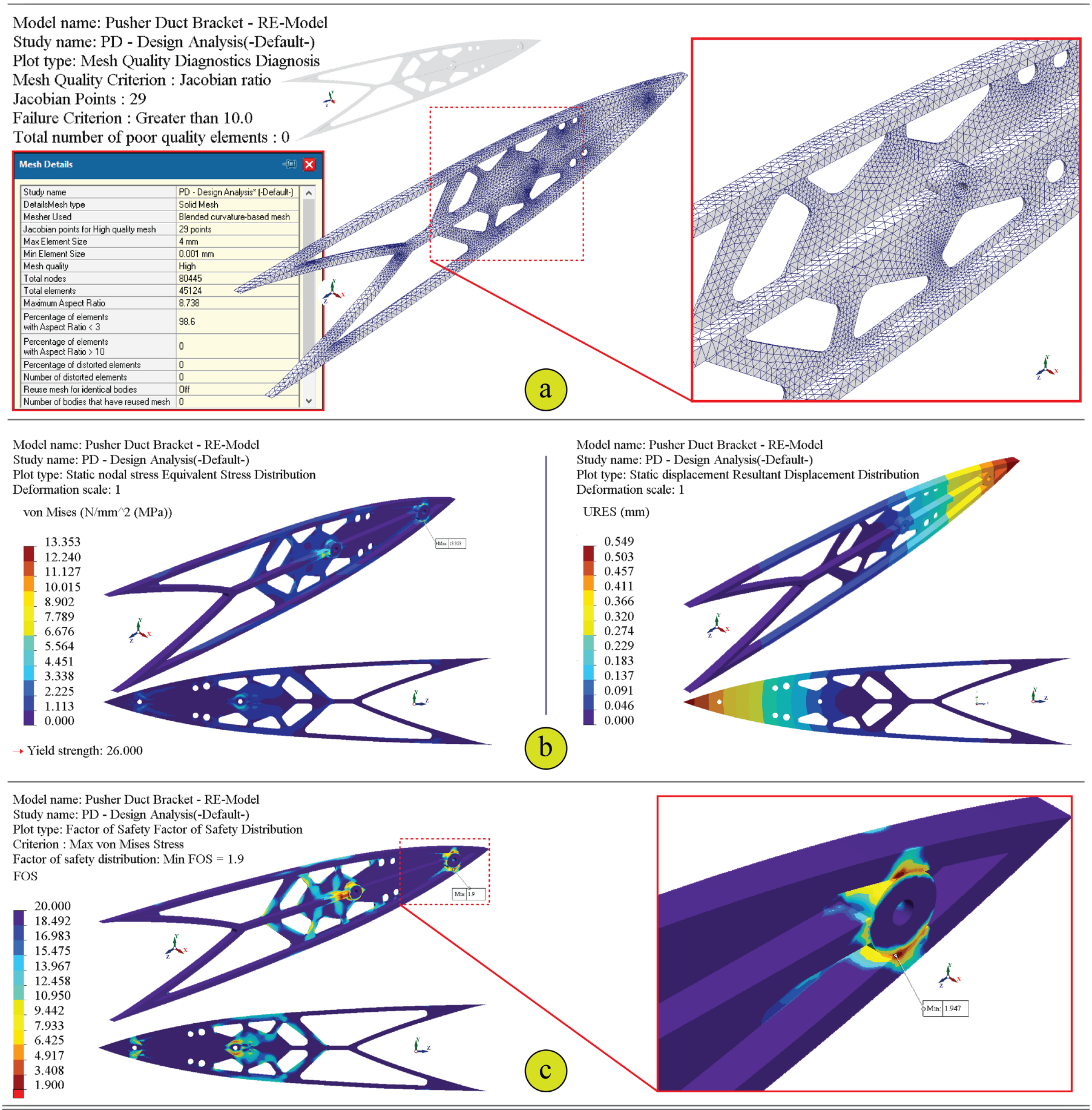

Figure 11. FEA validation of the refined geometry (FEA Output: (**a**) Mesh structure details (**b**) Equivalent (von Mises) stress and resultant deformation outputs; (**c**) Factor of safety distribution).

Table 1. Comparison for initial design assessment and topology study outputs.

Analysis Output	Initial Model	Refined Model	Absolute Difference	Relative Difference
Max. Eq. Stress	13.296 MPa	13.353 MPa	**0.057 MPa**	**0.43%**
Max. Resultant Displacement	0.375 mm	0.550 mm	**0.175 mm**	**46.67%**
Min. Factor of Safety (FOS)	1.955	1.947	**−0.008**	**−0.43%**
Model Mass	49.670 g	42.830 g	**−6.840 g**	**−13.77%**

3.2.6. Additive Manufacturing Process Assessment (Phase 2.c)

Following the completion of the TO and DfAM-aware parametric re-modelling phases, an AM process assessment was conducted to ensure that the refined UAV bracket geometry was fully manufacturable and suitable for FFF-based fabrication without leaving the CAD design environment. This assessment, constituting Phase 2.c, was critical to validate the manufacturability of the final design and to complete the TODfAM workflow loop from optimization to physical prototype. The SOLIDWORKS Print3D module was employed as a DfAM verification tool prior to STL export (Figure 12a). While the STL file could theoretically be processed directly in Bambu Studio, incorporating Print3D at this stage provided an essential early-stage manufacturability check within the native CAD environment. The module allowed for build volume validation, overhang detection, and wall thickness assessment, ensuring that the exported geometry was fully aligned with FFF process requirements before slicing. Mainly, this approach minimizes the risk of downstream iteration, enabling a more robust and agile CAD-to-AM workflow, a critical objective of the TODfAM platform. By integrating DfAM verification upstream, the process maintains design intent fidelity through to final fabrication [8,67].

Upon completion of the Print3D check and approval, subsequently, the slicing process was prepared using Bambu Studio software (v1.10.2) (Figure 12b), targeting fabrication on the Bambu Lab X1E FFF machine. Process parameters were tailored for UAV component requirements, with a focus on dimensional accuracy, surface finish, and structural integrity. Adaptive layer height, optimized wall configurations, and minimal support generation strategies were applied in accordance with current DfAM best practices. Both the Optimized Mesh Model and the Refined Parametric Model were prepared for fabrication to enable comparative evaluation. The fabricated bracket prototypes (Figure 12c) demonstrate the practical outcomes of the TODfAM workflow. The Refined Model exhibits superior manufacturability and structural clarity compared to the raw mesh export, which presented artefacts such as internal voiding in preserved regions and uneven surfaces. The Refined Model also showed significant improvement in print quality, with clean transitions and consistent wall profiles, thereby validating the efficacy of the DfAM-guided re-modelling phase.

The key AM process metrics were extracted from slicing analysis in Bambu Studio software (Table 2). The optimized Refined Model reduced material usage from 49.250 g (CAD Model output: 49.670 g) in the Baseline Model to 42.470 g (Simulation output: 42.830 g), representing a 13.77% material saving at full size (AM-CAD validation). Similarly, filament length was reduced from 16.79 m to 14.48 m. Although the fabrication time increased modestly by approximately 3 min (from 1 h 15 min 30 s to 1 h 18 min 29 s), this was largely due to the more refined geometry introducing additional perimeter and detail passes, despite a reduction in total material used. Importantly, both models remained fully support-free, a direct result of the DfAM-aware re-modelling phase, which optimized overhangs and wall profiles to ensure clean fabrication. The estimated print cost was reduced from $1.81 USD for the Baseline Model to $1.56 USD for the Refined Model, illustrating enhanced material efficiency and cost-effectiveness. The AM process assessment thus confirms that the TODfAM platform can reliably contribute to move a topology-optimized design to a fully manufacturable and structurally validated UAV component. Moreover, the integration of SOLIDWORKS Print3D within the workflow enables rapid manufacturability verification, facilitating agile UAV design cycles where iteration speed and process robustness are critical.

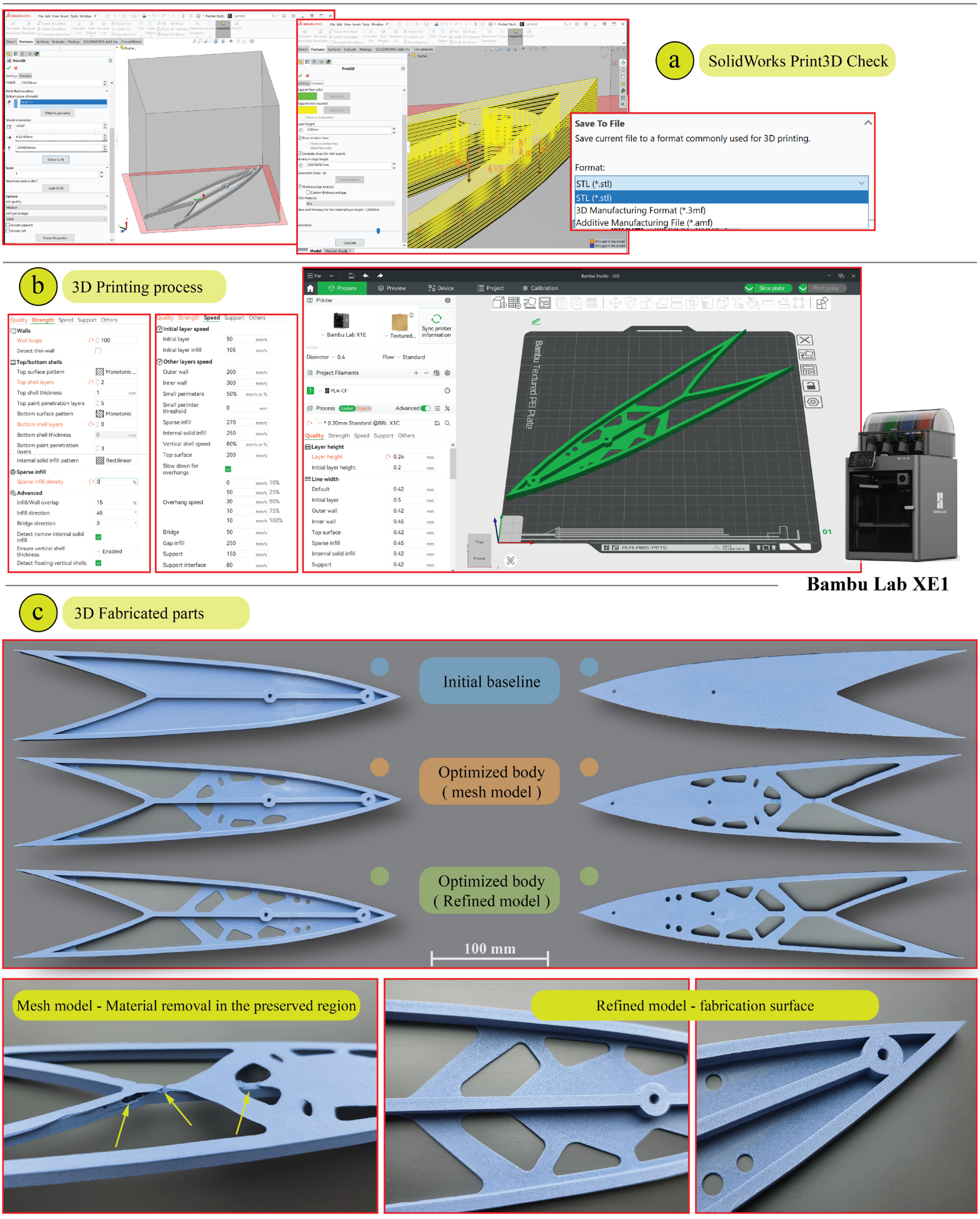

Figure 12. Final TODfAM workflow results: (**a**) Print3D verification; (**b**) slicing setup for FFF; (**c**) fabricated brackets—initial, optimized mesh model, and refined model.

Table 2. The key AM process metrics.

AM Process Parameter	Baseline Model (Full Scale)	Refined Model (Full Scale)	Relative Difference
Material	Bambu PLA-CF	Bambu PLA-CF	-
Estimated print time	1 h 15 min 30 s	1 h 18 min 29 s	+3.95%
Material usage (filament length)	16.79 m	14.48 m	−13.76%
Material mass used (estimated)	49.25 g	42.47 g	−13.30%
Estimated support material volume	0.00 g (support-free)	0.00 g (support-free)	-
Layer height	0.24 mm	0.24 mm	-
Nozzle diameter	0.40 mm	0.40 mm	-
Build orientation	Flat on bracket base	Flat on bracket base	-
Infill density	100% (solid)	100% (solid)	-
Shell/perimeter layers	3 outer walls	3 outer walls	-
Estimated print cost (GBP) *	£1.428	£1.232	−13.74%
Estimated print cost (USD) *	$1.814	$1.564	−13.74%

** 1 kg filament: $ 39.3 (£ 29)/Build time, mass and cost are slicer-calculated estimates for the stated machine/material; they are indicative only and not a formal cost model.*

The re-modelling phase improved DfAM compliance. Overhang violations (>45°) were mitigated through local smoothing and optimized build orientation. Slender members below the practical FFF limit (~1 mm) were thickened, and fillet continuity was standardized. The build orientation was set flat on the bracket base to stabilize deposition. As a result, all three configurations—baseline, topology-optimized, and DfAM-refined—were successfully fabricated support-free, in agreement with the slicer assessment. The consolidated manufacturability outcomes are presented in Table 2, and the printed parts in Figure 12.

3.3. Overall Discussion

The present study introduced the development and evaluation of a novel CAD-integrated add-in tool, the TODfAM, designed to streamline and automate the process of generating lightweight, structurally validated, and manufacturable components for the sectors related to product design including agricultural machinery design and manufacturing industry, with an initial focus on UAV prototyping applications. A key contribution of this work is the creation of an interactive tool within the SOLIDWORKS environment, offering an intuitive user interface for managing the complete workflow: from TO parameter setup, through automated optimization runs, to DfAM-aware parametric refinement and AM process verification. The ability to perform all steps within a single CAD platform addresses a critical need in industrial settings, where seamless CAD-CAE-DfAM integration is often lacking [14,21,69]. By embedding TO and DfAM functionality directly into the familiar SOLIDWORKS interface, the TODfAM tool lowers barriers to adoption for design engineers in the related industrial sectors. The novelty of this study lies primarily in the seamless CAD-native workflow that bridges TO and manufacturability evaluation within a single environment, rather than in the optimization algorithm itself.

The case study for the UAV pusher duct support bracket served to demonstrate the practical capabilities of the TODfAM add-in tool. The target mass reduction of 30% was used to guide the TO phase (Section 3.2.3), with the solver achieving stable convergence and generating an efficient load path-driven geometry. However, as expected, the raw optimized output exhibited geometric features incompatible with FFF-based AM, necessitating DfAM-based refinement in Phase 2.a. Following this refinement, the final validated design achieved a mass reduction of approximately 13.77%, while maintaining a FOS of 1.947 and acceptable displacement performance (Section 3.2.5). These results are consistent with the established observation that DfAM constraints (e.g., minimum wall thickness, overhang limits) typically result in some trade-off against the maximum theoretical mass reduction predicted by TO alone [70]. The use of SOLIDWORKS Print3D within the TODfAM supported workflow further enhanced its industrial applicability, enabling early-stage DfAM verification and minimizing the need for downstream iteration during AM preparation. The successful fabrication of physical prototypes on an FFF platform (Section 3.2.6, Figure 12) confirmed the efficacy of the workflow and highlighted the practical importance of combining algorithm-driven optimization with designer-guided DfAM practices.

Specific to the case study, it should be acknowledged that this study is currently limited to simulation-based validation of the optimized UAV bracket design. Although the fabricated prototypes demonstrate geometric fidelity and printability, experimental mechanical testing (such as static load testing, fatigue analysis, or dynamic vibration tests) was not performed within the present scope due to resource constraints. Likewise, the isotropic linear-elastic assumption may slightly influence local stress or strain distributions, but previous studies have shown that such simplifications have only minor impact on global mechanical behaviour in FFF PLA-CF structures [71–73]. The isotropic assumption is therefore confined to concept-stage studies and may be replaced with calibrated orthotropic models in future testing; cited sources have been selected to evidence the small global-response bias of isotropic surrogates.

The study validated the structural performance primarily through FEA, while DfAM-related constraints were verified via rule-based geometric assessment without physical/experimental testing. The FEA results demonstrated stable convergence, physically consistent deformation behaviour, and adequate reliability for concept-stage design verification. Nevertheless, experimental testing will serve as a complementary step to further substantiate the numerical predictions, particularly with respect to local anisotropy, interlayer bonding, and process-induced deviations inherent to FFF-based additive manufacturing. Such testing will form a subsequent phase of validation to reinforce the robustness of the TODfAM-supported workflow rather than to replace the current findings. Therefore, the FEA-based simulations presented herein serve as the principal indicators of structural performance at the concept-design stage. Future work will include comprehensive experimental validation of printed components to further substantiate the numerical findings and enhance the industrial relevance of the proposed TODfAM-supported workflow. In parallel, ongoing development will focus on refining DfAM integration, extending manufacturability filters for automatic overhang control, incorporating AM process simulations for thermal distortion effects, and validating the outcomes with physical builds.

When compared to existing commercial and academic solutions, the proposed TODfAM add-in offers a pragmatic and accessible alternative for DfAM-aware TO within industry-standard CAD environments. Unlike commercial generative design platforms such as Autodesk Fusion 360 or nTopology, which require proprietary environments and often impose additional licencing costs, TODfAM leverages the widely adopted SOLIDWORKS ecosystem to integrate parametric modelling, FEA, and TO functions. Compared to recent academic frameworks [23,74], which often focus on specific AM processes or rely on fragmented toolchains, the present tool delivers a streamlined, CAD-native workflow with a reduced learning curve and enhanced accessibility for design engineers. While some degree of manual intervention remains (e.g., STL export, parametric re-modelling), TODfAM provides an effective balance between workflow integration, usability, and DfAM compliance, making it well suited for agile prototyping in UAV and agricultural machinery sectors. This hybrid automated–manual integration constitutes the current basis of DfAM-awareness in TODfAM, where manufacturability refinement is performed primarily during the post-optimization parametric stage rather than within the optimization algorithm itself. Additionally, the current SOLIDWORKS TO engine offers more limited DfAM constraint capabilities (e.g., no native control over minimum member size or overhang angles) compared to advanced TO platforms such as nTopology. Nevertheless, the TODfAM add-in compensates for this through designer-guided parametric re-modelling and integrated DfAM verification steps, as demonstrated in this study.

The TODfAM platform offers a scalable and adaptable solution for accelerating the adoption of TO and DfAM principles in related industries. Its application to UAV component design represents an important first step, demonstrating that with proper CAD-integrated tooling, even complex bespoke components can be successfully optimized, validated, and fabricated within a tightly integrated workflow. Future work will focus on several important enhancements to the TODfAM add-in tool. First, improving the tool's ability to support the import and integration of external parametric models, including models created in different CAD environments, would enable greater flexibility for industrial users working with multi-CAD design workflows. This could be achieved by supporting feature-based model transfer (e.g., via advanced parametric interchange formats or API-based connectors) to preserve design intent and enable effective DfAM refinement. Additionally, enhancing the user interface to provide more intuitive visual feedback on optimization progress, constraint management, and DfAM compliance would further improve usability and facilitate broader adoption. Functionally, future extensions could include support for batch optimization of multiple design variants, automated design documentation and reporting, and tighter integration with AM process simulation tools for distortion prediction and build optimization. These enhancements would significantly expand TODfAM's capabilities, supporting its application across a wider range of agricultural machinery and UAV component design challenges.

4. Conclusions

This study developed and validated TODfAM, a SOLIDWORKS-integrated add-in tool that embeds a hybrid, DfAM-aware topology optimization workflow directly within a parametric CAD environment. The tool automates early design stages, including parametric modelling, integrated FEA validation, and DfAM-oriented topology optimization, thereby streamlining iterative design and manufacturability assessment. Its effectiveness was demonstrated through a UAV pusher-duct bracket case study, achieving a 13.77% mass reduction while maintaining structural integrity and manufacturability under FFF-based additive manufacturing constraints.

The principal contribution of this research lies in establishing a CAD-native, automated workflow that unifies topology optimization, DfAM evaluation, and AM preparation within a single design environment. This integration addresses a long-standing gap in engineering practice by mitigating toolchain fragmentation and promoting the practical adoption of DfAM methodologies for UAVs and similar lightweight structures.

Future developments will extend TODfAM by automating parametric re-modelling, supporting multi-objective optimization, enabling multi-CAD interoperability, and incorporating AM process simulations for thermal distortion and residual stress analysis. Experimental mechanical validation, including static and fatigue testing, will also be conducted to correlate numerical and physical performance, further enhancing the robustness and industrial relevance of the proposed framework.

Overall, TODfAM demonstrates that reliable, concept-stage structural verification and manufacturability assessment can be achieved entirely within a CAD-native platform, offering a practical bridge between digital design automation and additive manufacturing.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/app152212341/s1: Supplementary File S1—SOLIDWORKS Helper Class; Supplementary File S2—TODfAM Form Class.

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Conflicts of Interest: Author Recep CINAR is the owner/founder of Elixtek Engineering Software Solutions Ltd. (Elixtek Mühendislik Yazılım Çözümleri San. Tic. Ltd. Şti). The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AM	Additive Manufacturing
CAA	Civil Aviation Authority
CAD	Computer-Aided Design
DfAM	Design for Additive Manufacturing
DLL	Dynamic Link Library
FEA	Finite Element Analysis
FFF	Fused Filament Fabrication
GA	Genetic Algorithm
PLA-CF	Carbon Fibre-Reinforced Polylactic Acid
TO	Topology Optimization
TODfAM	Topology Optimization—Design for Additive Manufacturing
UAV	Unmanned Aerial Vehicles

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