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Toward a holistic approach for design for additive manufacturing: a perspective on challenges, practical insights, and research needs

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Highlights:

- Advocates a holistic, system-level perspective for Design for Additive Manufacturing.
- Additive manufacturing supports sustainable, eco-friendly urban infrastructure.
- Identifies limitations of geometry-focused heuristics in current DfAM practice.
- Emphasizes process-aware design: tolerancing, build orientation, anisotropy.
- Highlights strategic opportunities in part consolidation and mass customization.
- Calls for integrated digital tools, AI feedback, and interdisciplinary collaboration.

Abstract: Additive Manufacturing (AM) has advanced significantly, offering capabilities that extend well beyond those of traditional production methods. However, the integration of these capabilities into design practice remains limited, often constrained by conventional methodologies developed for subtractive manufacturing. This perspective examines the current state of Design for Additive Manufacturing (DfAM) and argues for a comprehensive, system-level approach that aligns design intent with process-specific constraints and opportunities. The paper identifies critical limitations in existing DfAM strategies, including the widespread application of geometry-focused heuristics and the insufficient consideration of material-process interactions, build orientation effects, and lifecycle implications. Through the synthesis of theoretical insights and practical considerations, this work outlines essential design factors—such as tolerancing for functional assemblies, support structure optimization, and the management of anisotropy—that influence manufacturability and performance. Furthermore, it highlights strategic applications of AM, including part consolidation, customization, and the use of functionally graded materials. It concludes by emphasizing the need for integrated digital tools, enhanced educational frameworks, and interdisciplinary collaboration to advance DfAM as a critical enabler of innovation in engineering design and manufacturing.

Keywords: design for additive manufacturing; additive manufacturing workflow; build orientation; mechanical anisotropy; tolerancing strategies; support structure optimization; functional integration; lifecycle considerations; process-aware design; AM-specific design guidelines

1. Introduction

Additive Manufacturing (AM), commonly referred to as 3D printing, has undergone a significant transformation—from a tool primarily used for rapid prototyping to a fully capable production technology [1]. Its ability to create complex geometries, reduce material waste, and enable customized fabrication has disrupted traditional design and manufacturing sectors [2,3]. Yet, the full design potential of AM is often underutilized due to the persistence of design approaches inherited from conventional subtractive methods. As AM continues to mature and gain popularity in critical industrial applications, a comprehensive rethinking of design methodologies becomes essential [4]. This work offers a perspective on how Design for Additive Manufacturing (DfAM) must evolve, not only to align with the technical affordances of AM but to influence broader shifts in design thinking, practice, and education.

1.1. Motivation for the study

Despite technological advances in AM systems and materials, design strategies have not evolved at the same pace. Designers and engineers frequently apply traditional design-for-manufacturing principles to additive processes, resulting in missed opportunities and avoidable inefficiencies. For example, the direct translation of conventionally designed parts into printable models can lead to excessive support requirements, poor surface finish, or mechanical underperformance due to anisotropic material behavior [5,6]. These outcomes are less a reflection of AM limitations and more indicative of a gap in process-aware design knowledge. Thus, a key motivation for this paper is to address the underdeveloped integration between AM capabilities and contemporary design practices, advocating for a transition from substitution-based thinking to AM-native design strategies.

Additionally, as AM is increasingly adopted in high-performance and regulated sectors—such as aerospace [7], biomedical engineering [8], and automotive manufacturing [9]—the consequences of poor design decisions become more significant. Functional integrity, compliance with industry standards, and cost-effectiveness hinge not only on the printing process itself but on informed design decisions made at the earliest stages of product development. This further underscores the need for DfAM approaches that go beyond geometric optimization, and that encompass manufacturability, material-process interactions, and lifecycle considerations from the outset [10].

1.2. Scope and perspective approach

This work takes a perspective-based approach to exploring the current state and emerging needs of DfAM. Rather than introducing a new design algorithm or presenting empirical data, the work reflects on established practices, identifies knowledge gaps, and proposes directions for improvement based on interdisciplinary expertise in CAD, AM processes, and design engineering. The scope encompasses core DfAM concerns such as build orientation [11], dimensional tolerancing [12], surface quality [13], part consolidation [14], support strategies [15], and post-processing implications [16]. By integrating insights from both research and practical implementation, the paper aims to bridge theory and application in a way that is accessible to both academic and industrial audiences.

Importantly, this perspective recognizes that DfAM is not a monolithic set of rules, but a context-sensitive framework that must adapt to the specific AM technique being used—be it polymer FDM [17], resin-based

SLA [18], powder-bed fusion [19], or directed energy deposition (DED) [20]. This perspective article emphasizes the need for a system-level view that connects design intent with fabrication realities, and that accounts for downstream operations such as inspection, assembly, and lifecycle sustainability. The intention is to contribute to a more holistic understanding of DfAM as a discipline that intersects design, manufacturing, and systems engineering.

1.3. Outline of the paper's contributions

While a number of studies have explored specific DfAM techniques and case studies, this paper distinguishes itself through a holistic and integrative perspective that combines theoretical design frameworks with practical manufacturing constraints across multiple material categories. Unlike traditional reviews that focus narrowly on optimization algorithms or process-specific adaptations, this work emphasizes critical design considerations that are often treated in isolation. Furthermore, it highlights the broader organizational and supply-chain disruptions enabled by DfAM, extending the discussion beyond the part level to encompass enterprise-wide transformations. By synthesizing existing knowledge and identifying key challenges alongside future research directions, this perspective aims to provide a comprehensive contribution that can potentially guide both academic inquiry and industrial practice in advancing the field of additive manufacturing design.

The contributions of this paper are threefold. First, it articulates a set of practical design considerations that often emerge when transitioning from conventional CAD workflows to additive manufacturing contexts. These include assembly tolerance planning, fit and clearance optimization, orientation-dependent accuracy, and mechanical property variation. The section aims to offer practitioners and educators a structured overview of the kinds of design decisions that must be re-evaluated in AM contexts.

Second, the paper identifies and analyzes prevalent misconceptions and challenges that hinder the broader adoption of effective DfAM strategies. This includes the tendency to "retrofit" designs for printing rather than design with AM in mind, as well as the overuse of generative design tools without understanding their limitations or process dependencies. By examining these challenges, the paper encourages a shift toward more process-integrated and purpose-driven design methodologies.

Third, the paper outlines future directions for the field, including the development of integrated CAD-AM platforms, the use of AI for manufacturability feedback, and the expansion of DfAM education in engineering and design curricula. It advocates for a more explicit alignment between design goals, manufacturing constraints, and digital tools—positioning DfAM as a foundational pillar in next-generation product development pipelines. To synthesize the intellectual framework presented throughout this perspective paper, Figure 1 offers a concise, actionable flowchart that distills the transition from conventional CAD-based design to a fully realized AM-native DfAM workflow. Specifically, it integrates the three core contributions outlined in Section 1.3: (1) the re-evaluation of entrenched design assumptions, (2) the identification and mitigation of persistent misconceptions in AM implementation, and (3) the forward-looking integration of simulation, optimization, and process-aware decision-making.

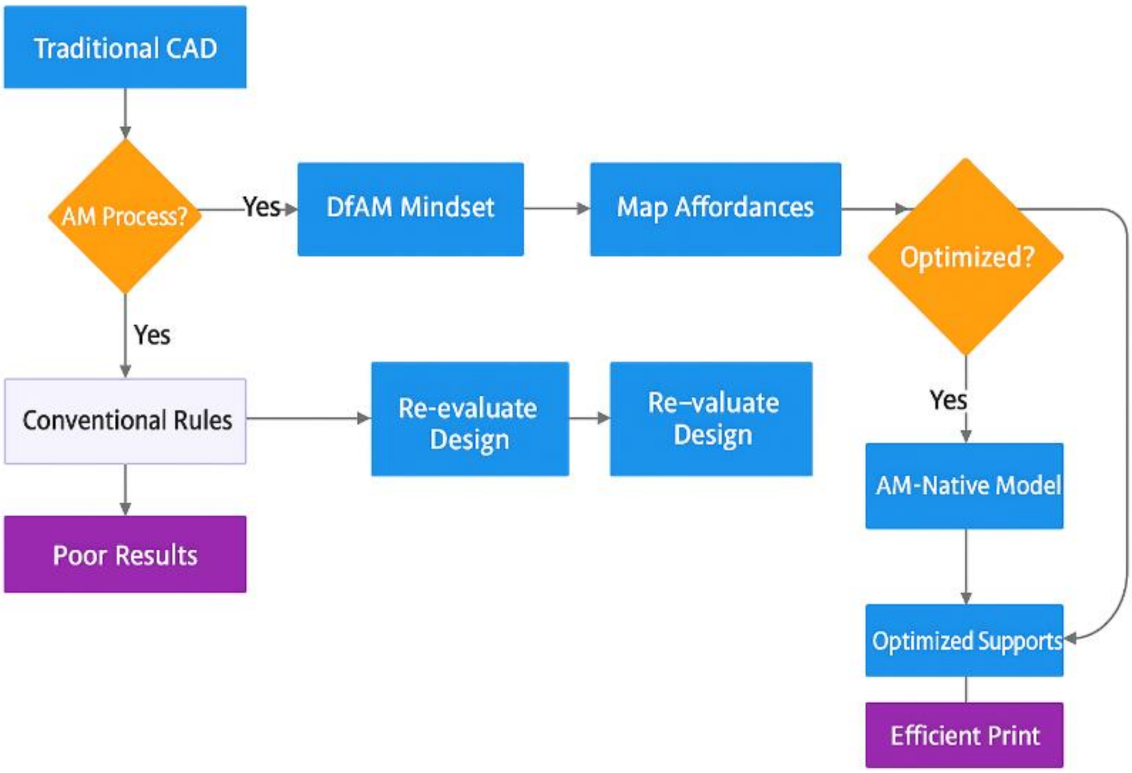


Figure 1. Traditional *vs.* AM-native DfAM workflow.

2. Expanding the conceptual framework of design for additive manufacturing

One of the most important aspects of Additive Manufacturing (AM) is its capacity for geometrical freedom—allowing designers to create complex, organic, and highly customized shapes that would be impractical or impossible to fabricate through conventional methods [20–22]. However, while this capability draws attention on Design for Additive Manufacturing (DfAM) concept, it does not explore the full potential of AM. Limiting the design discourse to geometrical novelty risks obscuring the broader, systemic shift that AM demands from product conception to end-use realization. In this section, the evolution of Design for Additive Manufacturing (DfAM) is examined, with an emphasis on moving beyond geometry-centric thinking to encompass strategic, functional, and system-level opportunities afforded by Additive Manufacturing (AM). An initial contrast is drawn between traditional part substitution approaches and holistic design redefinition. Subsequently, limitations inherent in current interpretations of DfAM are analyzed, and unexplored capabilities offered by advanced AM technologies are highlighted.

2.1. From part substitution to design redefinition

A common entry point into additive manufacturing for many designers and engineers is the substitution of conventionally manufactured parts with 3D-printed equivalents [23]. This approach, while often practical during early adoption phases, tends to treat AM as merely an alternative production method rather than a transformative design enabler. In such cases, parts are often reverse-engineered or slightly modified to be printable, retaining legacy features optimized for subtractive or formative manufacturing. This mindset fails to exploit the intrinsic advantages of AM, such as integrated functionalities, part consolidation, and internal structuring [24]. As a result, the end product may be successfully printed but is suboptimal in terms of performance, cost, or sustainability.

Redefining design for AM involves a more fundamental reconsideration of form, function, and structure. It requires designers to think about products not as assemblies of discrete parts defined by manufacturing constraints, but as cohesive systems that can be reimagined under a new prism. A classic example is the redesign of aerospace components into single monolithic parts with built-in features such as ducts, joints, or lattice reinforcements [25]. These redesigns eliminate fasteners, reduce mass, and enhance mechanical performance—all by exploiting the abilities of AM. The resulting objects are not just printed versions of old ideas; they are new ideas made possible by AM [26].

Furthermore, design redefinition opens the door to incorporating previously unfeasible innovations such as conformal cooling channels, bio-inspired internal structures, and functional grading of materials [27]. These opportunities can dramatically enhance product performance but are invisible to a substitution-oriented mindset. Thus, moving from substitution to redefinition is not merely a technical pivot—it represents a complete re-evaluation of how products are conceived, and it is central to unlocking the full potential of DfAM.

Although this work emphasizes conceptual insights and strategic directions for DfAM, there is also concrete industrial evidence that the approaches discussed are practical and scalable. For example, industry-scale deployment in aerospace has demonstrated how design-led AM (including lattice and topology-optimized geometries together with careful support strategies) produces both performance and manufacturing benefits: GE Aviation's transition to mass production of complex fuel-nozzle components—now produced in tens of thousands of units—illustrates how design optimization and AM process integration enable economies of scale and functional consolidation that are difficult to achieve with conventional manufacturing [28]. Academic studies mirror this industrial experience: targeted lattice and support-aware design strategies have been validated in case studies that report reduced support volume, easier post-processing, and improved part performance when compared against naïve support/layout choices [29]. Finally, recent reviews of DfAM tools and workflows show that ready-to-use computational toolchains (for topology optimization, lattice generation and support minimization) are maturing and being applied in industrial contexts, reinforcing the argument that the conceptual DfAM strategies advanced here can be implemented with existing software and production practices [30].

2.2. Limitations of current interpretations of DfAM

While the academic and industrial communities have worked towards formalizing DfAM principles, many existing frameworks remain narrowly focused. A large proportion of available guidelines concentrate on geometric design rules—such as overhang angles, wall thicknesses, and support strategies—offering deterministic rules to ensure printability. These are necessary considerations, but they reduce DfAM to a checklist of constraints rather than a creative design methodology. Such oversimplified interpretations can be counterproductive, as they frame AM as a delicate and error-prone process, rather than an opportunity space for innovation and performance optimization.

Another limitation lies in the generic application of DfAM across different AM technologies without due regard to process-specific characteristics. A design optimized for fused deposition modeling (FDM) may fail in selective laser sintering (SLS) or stereolithography (SLA) due to differences in layer resolution, material properties, thermal behavior, and post-processing requirements. Yet, many DfAM guides are platform-agnostic, leading to misconceptions or failed prints. This lack of granularity prevents designers from making informed decisions about material-process interactions, leading to suboptimal outcomes in both function and manufacturability.

Additionally, current DfAM practices often neglect broader lifecycle considerations. Issues such as recyclability, serviceability, inspection, and repair are frequently overlooked in the early design phase [30]. Without addressing these downstream factors, the promise of sustainable and efficient production through AM remains incomplete. True DfAM should not only ensure that a part is printable but that it performs well across its entire lifecycle—from raw material sourcing to end-of-life reuse or recycling. Addressing this gap requires interdisciplinary collaboration between design engineers, materials scientists, and systems operators—an area still in nascent development.

2.3. Strategic opportunities enabled by AM technologies

Additive Manufacturing presents a vast number of strategic opportunities that go well beyond geometric complexity. One such opportunity is part consolidation, which allows multiple components—often requiring separate production, assembly, and quality assurance steps—to be unified into a single printed structure [31]. This reduces not only weight and space but also the complexity of supply chains, inventory management, and maintenance logistics. By designing with consolidation in mind, engineers can create systems that are both simpler and more robust, while simultaneously reducing failure points and overall costs.

Another strategic domain is mass customization. AM enables individualized product design at scale, a capability that is redefining industries such as medical implants, orthodontics, and consumer goods [32]. Traditional manufacturing methods treat variation as a cost driver; AM treats it as a default mode of operation. Designers can embed customer-specific parameters directly into CAD models, creating personalized products without interrupting the production flow. This example unlocks new business models and shifts design thinking from "design for the average" to "design for the individual," enabling more inclusive and user-centered innovations [33].

Finally, AM technologies empower functionally graded and multi-material designs, where a single object can exhibit spatially varying mechanical, thermal, or optical properties [34]. While still limited by current hardware and software integration, this approach holds promise for applications in aerospace, defense, energy, and biomedical engineering [35]. Designing for these capabilities demands a new level of digital control and material understanding—broadening the current limitations of both CAD tools and engineering curricula [36]. The integration of these advanced capabilities repositions DfAM not merely as a means to ensure manufacturability, but as an enabling technlogy for cross-disciplinary innovation in next-generation product development. To synthesize the insights presented in this section, Table 1 provides a structured overview of the evolving dimensions of Design for Additive Manufacturing (DfAM). It highlights the contrast between traditional design paradigms and advanced, AM-enabled approaches, categorizing them under three key thematic areas: design philosophy, technical limitations, and strategic opportunities.

Table 1. Comparative overview of conventional and advanced approaches in Design for Additive Manufacturing (DfAM).

Aspect	Traditional Approach	Advanced DfAM Perspective	Strategic Impact
Design Focus	Geometry optimization for printability	System-level design redefinition	Unlocks functional integration and performance enhancement
Design Approach	Part substitution (1:1 replacement)	Holistic product redesign	Enables weight reduction, part consolidation, new functionalities
DfAM Guidelines	Checklist of geometric constraints (e.g., wall thickness, overhangs)	Process-specific, lifecycle-aware methodologies	Enhances manufacturability, sustainability, and reliability
Technology Assumptions	Platform-agnostic rules	Process- and material-specific design strategies	Reduces print failures, improves quality and performance
Lifecycle Considerations	Often neglected (focus on printability only)	Includes serviceability, repair, recyclability	Supports sustainable AM adoption
Customization	Design for average user	Mass customization and personalization	Enhances user experience and broadens market reach
Material Use	Homogeneous single-material parts	Multi-material and functionally graded structures	Enables tailored mechanical, thermal, and optical properties
Role of DfAM	Tool for manufacturability	Driver of cross-disciplinary innovation	Positions AM as transformative rather than alternative

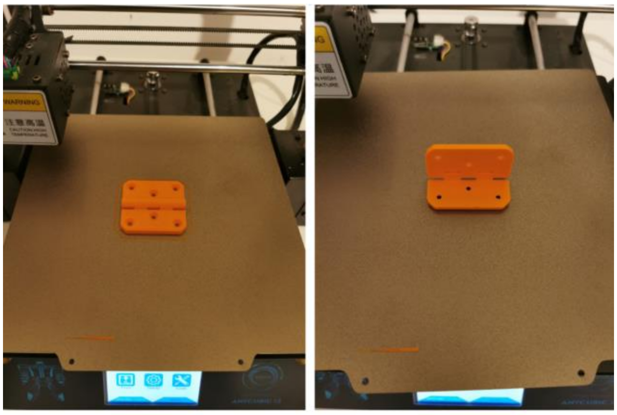
3. Critical design considerations in additive manufacturing workflows

The effective implementation of additive manufacturing extends beyond conceptual design innovation and critically depends on the meticulous integration of practical considerations throughout the entire production workflow. This section addresses key design factors that influence not only the manufacturability of individual parts but also their functional integration within assemblies and broader systems. Unlike traditional manufacturing, where established standards and predictable behaviors guide design decisions, AM introduces unique challenges related to process variability, material behavior, and machine-specific constraints. By systematically examining topics such as tolerancing, build orientation, support structures, feature resolution, and material-specific nuances, this section aims to provide a comprehensive framework for optimizing part design to align with the operational realities of AM technologies. These considerations are essential for eliminating the gap between theoretical design potential and reproducible, high-quality outcomes in additive manufacturing practice.

3.1. Tolerancing strategies for functional assemblies

Achieving precise dimensional control and functional fit in additive manufacturing (AM) remains a significant challenge due to the inherent variability of AM processes and materials. Central to this challenge is the appropriate specification of fit types in assemblies—how parts are intended to interact dimensionally to achieve desired mechanical behavior [37]. Traditional manufacturing relies on standardized fit classes such as clearance, interference, and transition fits, each prescribing precise tolerances to ensure reliable mating of components. In AM, these classifications must be reconsidered in light of layer-by-layer fabrication and the resulting surface roughness and dimensional inaccuracies [38]. Designers must carefully select and adjust fit types based on the functional requirements of the assembly, taking into account the specific AM process capabilities and anticipated deviations. For example, press fits may require looser tolerances than conventionally machined parts to accommodate surface irregularities, while clearance fits might need intentional oversizing to compensate for expected material expansion or warping during printing and cooling [39].

Dimensional changes due to material shrinkage represent another critical factor that must be integrated into AM tolerancing strategies. Unlike subtractive manufacturing, where material removal is predictable and stable, many AM processes involve thermal cycles and phase changes that induce anisotropic shrinkage and distortion [40]. These phenomena vary widely with material type, build volume, geometry, and process parameters such as laser power or extrusion temperature [41]. To ensure functional assemblies meet design intent, designers and engineers employ compensation techniques at the CAD and slicing stages, adjusting nominal dimensions preemptively to counteract shrinkage effects. Such compensation requires thorough empirical characterization or simulation-based modeling of shrinkage behavior, often process- and machine-specific, to derive reliable scaling factors [42,43]. Without adequate compensation, critical mating features may become undersized or oversized, resulting in assembly failures or compromised performance. An illustrative example of tolerance-sensitive design in AM is a 3D-printed hinge mechanism. When designed with appropriate allowances for material shrinkage and thermal distortion, such components can be fabricated as fully functional assemblies in a single print. The figure below (Figure 2) showcases a hinge produced via fused deposition modeling (FDM), where precise gap tolerancing and dimensional compensation were applied during the CAD stage to ensure free rotational movement post-printing, without requiring post-processing or assembly. The item was fabricated using PLA thermoplastic raw material, with nozzle and platform temperatures set to 205 °C and 50 °C respectively. Layer thickness was set to 0,1 mm and printing speed to 60mm/sec. The stl file was sliced using Simplify3D (Ohio, USA) software and the 3D printer used was Anycubic (Shenzhen, Guangdong, People's Republic of China) I3 Mega. This example emphasizes the critical importance of predictive design adjustments in achieving functional outcomes in AM.



(a) (b)

Figure 2. 3D-printed PLA hinge showcasing precise tolerancing for functional rotation without post-processing.

Furthermore, printer-specific adaptations are essential components of tolerancing strategy due to variations in machine resolution, calibration, and material deposition mechanisms across different AM platforms. For instance, the dimensional accuracy achievable with fused filament fabrication (FFF) is generally lower than that of selective laser melting (SLM) or stereolithography (SLA), necessitating distinct tolerance schemes and design modifications [44]. Certain printers may exhibit systematic offsets or directional biases influenced by hardware components like extruder nozzles, galvanometers, or recoaters, requiring tailored corrections [45]. Additionally, factors such as layer thickness, scan patterns, and thermal gradients can influence dimensional fidelity differently depending on the printer model and build orientation. Therefore, tolerancing strategies must be dynamically adapted through iterative prototyping and quality control feedback to ensure repeatability and precision. This machine-centric approach underscores the importance of close collaboration between design engineers and manufacturing specialists to translate theoretical designs into reliably functional AM assemblies.

3.2. Influence of build orientation and layering effects

In additive manufacturing, the build orientation and the inherent layering process significantly affect both the mechanical performance and dimensional accuracy of printed components. Unlike traditional manufacturing methods that produce isotropic material properties, most AM technologies introduce anisotropy due to the layer-by-layer material deposition. This anisotropy manifests in variations in strength, stiffness, and failure modes depending on the direction relative to the build layers [46]. Understanding and strategically managing these orientation-dependent characteristics are fundamental to optimizing part design and ensuring that functional requirements are met. Moreover, build orientation influences surface quality, print time, and the necessity for support structures, further linking it directly to manufacturability and post-processing considerations. This section explores how mechanical anisotropy arises from layering effects and outlines design principles aimed at leveraging or mitigating these phenomena through informed orientation choices.

The layer-wise fabrication intrinsic to most AM processes generates material properties that vary with direction, commonly resulting in mechanical anisotropy [47]. This anisotropy typically presents as reduced strength and toughness along the build direction—perpendicular to the layers—compared to the in-plane directions. The causes include weaker interlayer bonding due to incomplete fusion or adhesion, residual stresses from thermal gradients, and microstructural heterogeneity. For example, in fused deposition modeling (FDM), the polymer filaments melt and resolidify layer by layer, creating interfaces where bonding quality may be inferior to the bulk material [48]. Similarly, in powder bed fusion processes, incomplete melting or powder consolidation at layer boundaries may induce planes of weakness. The degree of anisotropy depends on process parameters such as layer thickness, energy input, and material chemistry [49]. Designers must account for these directional dependencies when specifying load-bearing orientations and safety factors, especially in structural or dynamic applications, to prevent premature failure or degradation of performance.

The performance implications of mechanical anisotropy extend beyond strength to include fatigue resistance, impact toughness, and dimensional stability. Parts loaded parallel to the layers generally exhibit higher durability, while those subjected to stresses perpendicular to the layering are more susceptible to delamination or crack propagation. In some cases, anisotropy can be advantageous if leveraged intentionally, for instance by orienting layers to align with principal stress directions or by designing features that capitalize on directional flexibility [50]. However, failure to consider anisotropy can result in significant functional compromises or necessitate costly redesigns. Consequently, thorough characterization of material behavior under multiaxial loading and environmental conditions becomes essential for reliable AM part qualification [51]. Incorporating anisotropy into finite element analysis and simulation tools is increasingly common, enabling predictive modeling to guide orientation decisions early in the design process [52].

Optimizing build orientation is a critical design decision that balances mechanical performance, surface finish, print efficiency, and post-processing requirements. Design-for-orientation principles advocate for deliberate alignment of parts and features to exploit or mitigate anisotropic effects while minimizing supports and build time [53]. Key guidelines include orienting critical load-bearing surfaces and features parallel to the build platform to maximize interlayer adhesion and mechanical integrity. Additionally, minimizing overhangs and steep angles reduces the need for support structures, which can impair surface quality and increase post-processing labor [54]. However, orientation decisions may involve trade-offs; for example, orienting a part to optimize strength may increase build height and print duration or complicate support removal. To illustrate the impact of build orientation on mechanical properties, Figure 3 presents a schematic of a 3D-printed tensile test specimen fabricated via FDM. The figure depicts the specimen in three distinct orientations: horizontal (X-Y plane), vertical (Z-axis), and diagonal (45-degree angle). Each orientation highlights the direction of layer deposition, which influences mechanical anisotropy and interlayer adhesion. The schematic qualitatively demonstrates how these orientations lead to variations in strength, with the vertical build typically exhibiting weaker interlayer bonding com-pared to the horizontal orientation, which aligns layers along the loading direction. This visual representation underscores the importance of considering build orientation during the design phase to optimize part performance in additive manufacturing.

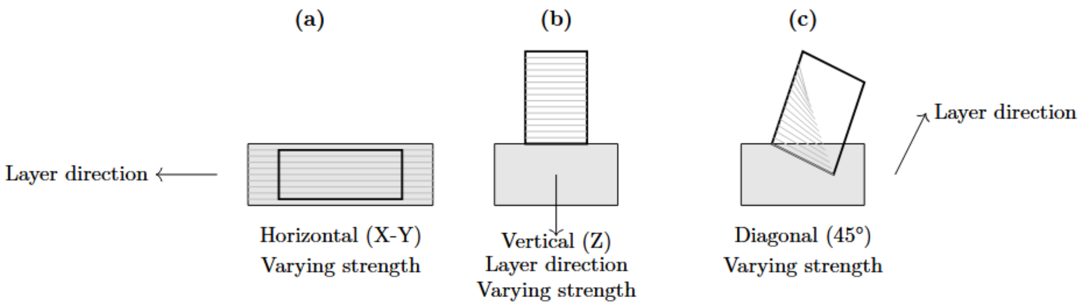


Figure 3. Schematic of build orientation effects on mechanical properties in additive manufacturing. A 3D-printed tensile test specimen (fabricated via FDM with PLA) is shown in three orientations: **(a)** horizontal (X-Y plane); **(b)** vertical (Z-axis); and **(c)** diagonal (45-degree angle). Annotations indicate layer deposition direction, illustrating qualitative variations in strength due to anisotropy.

Advanced design strategies incorporate simulation-based orientation optimization, integrating mechanical property predictions, thermal distortion models, and build time estimations [55]. These approaches enable the identification of orientation configurations that maximize part quality and process efficiency. Designers may also segment complex assemblies to print components in orientations best suited to their functional requirements before post-assembly. Furthermore, emerging multi-axis and robotic AM systems offer increased flexibility in orientation, potentially alleviating some constraints imposed by traditional layer-based builds [56]. Nonetheless, adherence to fundamental orientation principles remains essential for current AM workflows to ensure part reliability and manufacturability. Ultimately, embedding orientation considerations early in the design phase fosters a more holistic, process-aware approach aligned with the unique capabilities and limitations of additive manufacturing.

3.3. Constraints related to support structures and post-processing

Support structures are a fundamental consideration in additive manufacturing, particularly for processes that involve overhangs, complex geometries, and intricate internal features [57]. While these supports enable the successful fabrication of otherwise unprintable designs, they introduce a range of constraints impacting accessibility, removal effort, surface quality, and overall post-processing workload [58]. Addressing these challenges requires a careful balance during the design phase to optimize part geometry and orientation for minimal support usage without compromising structural integrity or functionality. Post-processing itself often constitutes a substantial portion of total production time and cost, underscoring the necessity for design strategies that mitigate labor-intensive finishing steps. This section explores the multifaceted implications of support structures and post-processing constraints on the additive manufacturing workflow.

Regarding access constraints, effective access to support structures is a primary challenge during the design and fabrication of AM parts. Supports must be positioned such that they can physically reach overhanging or bridging features to provide adequate stabilization during printing. However, complex geometries and internal cavities can obstruct access, preventing either the application or subsequent removal of supports. In some cases, insufficient access leads to incomplete support generation, resulting in deformation, warping, or print failure [59]. Designers must therefore anticipate these spatial limitations early in the design process, employing techniques such as modularization, part segmentation, or incorporation of access channels. Computational tools that simulate support placement and accessibility are increasingly used to predict and address these constraints, helping optimize geometry for manufacturability while ensuring necessary support coverage [60].

As far as removal constraints are concerned, the removal of support structures presents a significant post-processing hurdle that can affect part integrity and throughput. Supports are often composed of the same material as the part or, in some cases, soluble materials requiring specialized treatment. Mechanical removal of supports can damage delicate features, especially in thin-walled sections or complex internal channels, potentially compromising dimensional accuracy or functional performance. Furthermore, the time and labor involved in manual support removal can be substantial, influencing production scalability and cost-efficiency [61]. To mitigate these issues, design considerations may include minimizing support volume through optimized orientation, using self-supporting geometries, or adopting breakaway or soluble supports. Advances in automated support removal technologies and design-for-removal principles aim to streamline this phase, but careful planning remains essential to reduce risks and labor intensity associated with support extraction. Figure 4 compares two support structure designs for a 3D-printed T-shaped part with overhangs, highlighting their impact on material usage and post-processing requirements. The schematic contrasts (a) a traditional support structure with dense branching, which demands higher material use and more extensive post-processing, against (b) an optimized lattice-like support structure ("tree" structure), designed to reduce material consumption and simplify removal. An inset in the optimized design illustrates the ease of support detachment, emphasizing practical benefits. This visual comparison underscores the potential of design optimization to enhance efficiency in additive manufacturing by minimizing resource use and post-processing time.

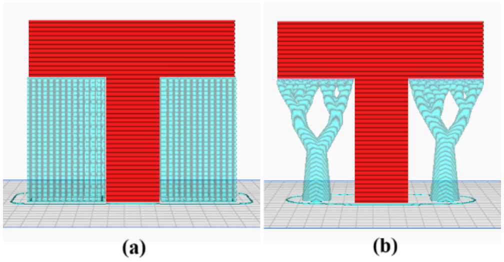


Figure 4. Comparison of support structure designs for a 3D-printed T-shaped part with overhangs. **(a)** Traditional support structure with dense branching, requiring higher material use and more post-processing; **(b)** Optimized lattice-like support structure ("tree" structure), designed for reduced material use and less post-processing, with an inset illustrating easier support removal.

Also, regarding surface finish implications, the presence and removal of support structures have a pronounced impact on the surface finish quality of AM parts. Surfaces in direct contact with supports typically exhibit roughness, residual marks, or geometric inaccuracies that deviate from nominal design intent [62]. These imperfections often necessitate additional finishing processes such as sanding, polishing, or chemical smoothing to achieve functional or aesthetic requirements. The degree of surface degradation depends on the support design, material compatibility, and removal method employed. Moreover, the anisotropic layering inherent to AM further complicates achieving uniform surface quality across supported and unsupported regions [63]. Therefore, design strategies should prioritize minimizing support contact areas on critical surfaces and orienting parts to place supports on less visible or non-functional faces. Integration of surface finish considerations with support planning is crucial to balance manufacturability with end-use requirements, particularly in applications demanding high precision or visual appeal.

Labor and cost trade-offs are another significant factor. Support structures and post-processing contribute significantly to the overall labor and cost profile of additive manufacturing production. While supports enable complex geometries, their generation increases material consumption, print time, and subsequent finishing workload [64]. The labor associated with support removal, surface refinement, and quality inspection can constitute a major bottleneck in production workflows, particularly for high-volume or time-sensitive applications. Designers and manufacturers must therefore evaluate trade-offs between design complexity and manufacturability, seeking to reduce support reliance through geometry optimization and build orientation. Advanced software tools facilitate this evaluation by simulating support requirements and estimating post-processing efforts, enabling more informed decision-making [65]. Balancing these factors is critical to realizing the economic advantages of AM, ensuring that design innovations do not inadvertently lead to prohibitive production costs or delays.

3.4. Managing overhangs, bridging, and feature resolution

The inherent layering process in additive manufacturing presents unique challenges related to overhangs, bridging, and the resolution of fine features. These challenges directly affect the fidelity of the printed part to its digital design and, consequently, its functional and aesthetic qualities. Overhangs and bridging refer to the unsupported geometrical sections that require careful management to avoid defects such as sagging, warping, or incomplete fusion [66,67]. Feature resolution concerns the minimal feature sizes that can be accurately produced, constrained by the specific AM technology and material used. Effective design strategies are essential to anticipate and mitigate these issues during the design phase, thereby enhancing print quality, minimizing failures, and reducing post-processing effort. This section delves into preventive approaches for addressing these critical factors in additive manufacturing workflows.

Managing overhangs through geometric and process optimization is of paramount importance for a successful AM part fabrication. Overhangs pose a significant risk of print defects when their angle exceeds the critical threshold for self-support, typically around 45 degrees (or higher) depending on the AM process and material [68]. Unmanaged overhangs can lead to drooping layers, poor surface finish, and compromised structural integrity. Preventive strategies include reorienting the part to minimize steep overhangs, integrating support structures where unavoidable, and redesigning features to incorporate gradual slopes or chamfers that remain within printable angles [69]. Additionally, emerging process parameters such as controlled cooling rates and adaptive extrusion can improve the printability of challenging geometries [69]. Incorporating these considerations early in the design cycle allows for a reduction in support material usage and enhances overall print reliability, thus contributing to optimized manufacturing efficiency.

Bridging on the other hand, the process of spanning unsupported gaps between two points, is constrained by the material's ability to solidify rapidly enough to support subsequent layers without deformation. Excessive span lengths or inadequate cooling can cause sagging, resulting in dimensional inaccuracies and potential functional impairments [70]. Design interventions include limiting bridge spans to within empirically established maximum lengths specific to the material and technology, subdividing large spans with internal supports or lattice structures, and orienting the build to reduce unsupported horizontal distances [71]. Moreover, fine-tuning process parameters such as extrusion speed, layer height, and cooling fan intensity plays a complementary role in managing bridging quality [72]. These combined geometric and process controls are essential to maintain dimensional fidelity and structural soundness in printed components with complex internal features or cavities.

Also, the resolution of fine features in AM parts is limited by factors including nozzle diameter, layer thickness, and material flow characteristics, which collectively define the smallest printable details [73]. High-resolution features are critical in applications demanding tight tolerances, intricate aesthetics, or precise functional interfaces. Designers must balance the desired feature fidelity with manufacturability by understanding the capabilities and limitations of the target AM technology [74]. Strategies to enhance feature resolution include increasing layer resolution where process time permits, avoiding sharp internal corners that are prone to material accumulation or stringing, and incorporating fillets or chamfers to ease material deposition. Additionally, selecting materials with appropriate rheological properties can improve the accuracy of small features [75]. Coordinated design and material selection decisions thus play a pivotal role in achieving the intended functional and visual outcomes in AM parts.

In conclusion, Table 2 presents a concise, process-specific printability matrix for managing overhangs, bridging, and fine feature resolution across four major AM technologies. This at-a-glance reference enables designers to anticipate geometric constraints early in the DfAM workflow, minimize support structures, and avoid print failures—reinforcing the importance of process-aware design decisions.

Table 2. Printability summary for overhangs (> 45°), bridging (> 10 mm), and fine features (< 0.5 mm) in FDM, SLA, SLS, and DED.

AM Process	Overhang > 45°	Bridging > 10 mm	Min. Feature < 0.5 mm
FDM	⚠ Supports or reorient	✓ ≤ 12 mm (fan + slow)	✓ ≥ 0.4 mm (nozzle limit)
SLA	✓ Self-supporting (~60°)	✗ Resin sags	✓ ≥ 0.1 mm (high-resin)
SLS	✓ No limit (powder bed)	✓ Full support	⚠ ≥ 0.6 mm (grain size)
DED	✗ High risk (gas shield)	⚠ Multi-axis only	✗ ≥ 1.0 mm (bead size)
Legend: ✓ = Feasible	**⚠ = Conditional**	**✗ = High Risk**	

3.5. Material-specific design implications

Additive manufacturing encompasses a diverse range of materials, each exhibiting distinct physical, chemical, and mechanical characteristics that profoundly influence design strategies. Thermoplastics, photopolymers, and metals each present unique opportunities and constraints that must be carefully considered to optimize part performance, manufacturability, and post-processing requirements. Effective design for additive manufacturing thus necessitates a material-specific approach, integrating knowledge of material behavior with process capabilities to fully leverage the benefits of the chosen AM technology. This section examines critical design implications associated with thermoplastic, photopolymer, and metal AM, highlighting tailored strategies to address their respective challenges and potentials.

Firstly, thermoplastic materials, commonly used in fused filament fabrication (FFF) [76] and selective laser sintering (SLS) [77], offer a wide range of mechanical properties and cost-effective processing. Design considerations for thermoplastic AM include accounting for anisotropic mechanical behavior resulting from layer adhesion, which affects tensile strength and fatigue resistance predominantly along the build direction [78]. Additionally, thermoplastics are prone to thermal shrinkage and warping, necessitating compensation strategies in dimensional tolerancing and support structure design [79]. Designers must also consider the relatively lower resolution compared to photopolymers or metals, which impacts the fidelity of fine details and surface finish [80]. Choosing appropriate infill patterns and densities can further tailor mechanical properties, while modular design approaches help mitigate distortion risks during cooling [81]. By aligning design intent with these material-specific behaviors, engineers can optimize thermoplastic AM parts for both functional performance and manufacturability.

On the other hand, photopolymer-based additive manufacturing, including stereolithography (SLA) and digital light processing (DLP), excels in producing high-resolution parts with excellent surface finishes and complex geometries. [82] However, the inherent brittleness and limited mechanical strength of many photopolymers impose constraints on load-bearing applications [83]. Design strategies must therefore emphasize geometrical features that minimize stress concentrations and avoid thin-walled sections prone to cracking. Moreover, the layer-by-layer photopolymerization process requires careful management of support structures to prevent damage during removal, especially on delicate surfaces [84]. Post-processing steps such as UV curing and washing significantly affect final material properties, adding complexity to the design-to-production workflow [84]. Considerations around material shrinkage and isotropy also influence dimensional accuracy and feature fidelity [85,86]. Tailoring design parameters to accommodate these material-specific traits is essential to maximize the functional utility and aesthetic quality of photopolymer AM parts.

In addition, metal additive manufacturing techniques, including selective laser melting (SLM) [87] and electron beam melting (EBM) [88], enable the fabrication of highly complex, load-bearing components with superior mechanical properties. The design freedom offered by metal AM allows for topology optimization, internal lattice structures, and part consolidation previously unattainable with traditional methods [89]. Nonetheless, metal AM processes impose stringent requirements on thermal management, residual stress control, and surface finish quality [90]. Designers must consider support structures not only for geometric stability but also to dissipate heat and minimize distortion during printing. Feature resolution and minimum wall thickness are constrained by powder characteristics and laser spot size, necessitating careful dimensioning to ensure manufacturability without compromising strength [91,92]. Additionally, post-processing requirements such as heat treatment and surface machining must be factored into the design to achieve desired material properties and tolerances [93]. A thorough understanding of metal AM-specific design implications enables the realization of optimized components that fully exploit the potential of advanced manufacturing technologies. The following table (Table 3) summarizes the key critical design considerations that influence the success of additive manufacturing workflows, highlighting their descriptions and practical implications to guide designers in optimizing parts for accuracy, functionality, and printability.

Table 3. Summary of critical design considerations in additive manufacturing workflows.

Design Consideration	Description	Implications for AM Design
Tolerancing	Adjusting dimensional allowances to account for AM-specific inaccuracies such as surface roughness and shrinkage.	Use looser fits, apply compensation during CAD/slicing, validate through iterative prototyping.
Material Shrinkage & Warping	Thermally induced deformation due to phase changes and cooling behavior.	Implement scaling factors, use simulation or empirical data for compensation.
Fit Types in Assemblies	Reassessment of clearance, interference, and transition fits for printed parts.	Redefine tolerances considering layer bonding and process-specific inaccuracies.
Machine-Specific Adjustments	Variations in accuracy, resolution, and thermal gradients depending on printer model.	Tailor designs and tolerances to printer capabilities; apply printer-specific corrections.
Build Orientation	The orientation of the part during printing, affecting strength, accuracy, and surface quality.	Align load-bearing features parallel to the build platform; minimize overhangs and supports.
Mechanical Anisotropy	Directional dependence of mechanical properties due to layering.	Orient parts to exploit or mitigate anisotropy; use FEA tools to simulate mechanical behavior.
Support Structures	Necessity of temporary scaffolding for overhanging features or complex geometries.	Optimize geometry to reduce supports; factor in removal effort and surface finish impact.
Resolution and Feature Size	Minimum achievable feature detail is constrained by printer resolution and process type.	Avoid overly fine details; match feature complexity to process capabilities.
Post-processing Requirements	Needs such as support removal, surface finishing, or thermal treatments after printing.	Design with ease of post-processing in mind; reduce supports and enable access to critical areas.
Simulation & Optimization	Use of software tools to model thermal behavior, mechanical response, and print time.	Employ orientation optimization and predictive simulation for design refinement.

4. Design failures and misinterpretations in additive manufacturing practice

The Despite the growing maturity of additive manufacturing (AM) technologies, design failures continue to arise from persistent misinterpretations and incomplete adoption of process-aware design strategies.

These failures are not solely the result of machine limitations or material inconsistencies; rather, they often stem from fundamental misunderstandings about the nature of AM itself. As organizations transition from conventional manufacturing toward AM-integrated workflows, the success of this transformation depends heavily on rethinking design philosophies and adapting engineering practices accordingly. This section critically examines three recurrent pitfalls observed in AM design practice: the inadequate transition from subtractive to additive thinking, the overreliance on software-driven optimization without contextual understanding, and the disregard of post-print functionality and assembly constraints. Each of these challenges reflects a disconnect between conceptual design intentions and the operational realities of AM production, ultimately impeding the realization of reliable and high-performance outcomes.

4.1. Inadequate transition from subtractive to additive thinking

One of the most prevailing design misinterpretations in AM adoption is the assumption that conventional, subtractive manufacturing geometries and practices can be directly ported to additive workflows with minimal adaptation. This mindset, often driven by legacy engineering cultures and toolchains, overlooks the core premise of AM—that it is not simply a different way to make the same things, but a fundamentally different approach to conceiving products. For example, many early AM applications replicate machined parts layer by layer without questioning whether those parts could be consolidated, internally structured, or reoriented to exploit AM's capabilities [94]. The result is often inefficient, support-heavy designs that underperform in mechanical strength or production efficiency. This conservative design tendency undermines AM's unique value proposition, leading to missed opportunities for part count reduction, embedded functionality, or enhanced performance characteristics that are only accessible through additive-native thinking.

Inadequate transition is further exacerbated by educational and organizational gaps. Engineers trained predominantly in subtractive manufacturing may lack exposure to DfAM principles, including considerations such as anisotropic material behavior, support avoidance, or functional surface alignment [95,96]. As a consequence, companies attempting to implement AM at scale often face friction in integrating design and manufacturing teams around a shared understanding of what AM enables. To address this, a systematic shift in design education, certification frameworks, and interdisciplinary collaboration is required [97]. Design intent must be reframed not only in terms of how a part looks or fits within an assembly but also how it grows within the layer-wise logic of AM processes.

4.2. Overreliance on software-driven optimization without understanding constraints

With the rise of generative design and topology optimization tools, many designers have turned to software-driven approaches to create geometrically complex, lightweight structures optimized for performance. While these tools hold significant promise, their misuse—or rather, their use in isolation from manufacturing constraints—has led to a new class of design failures in AM. A common issue is the generation of forms that, although optimized in simulation, are unprintable or require excessive support structures, complex post-processing, or orientation-specific compromises [98]. When AM-specific constraints such as overhang angles, support access, and build orientation are not encoded into the generative design logic, the resulting parts may be functionally ideal but practically infeasible [99]. The gap between digitally optimized geometry and physical realizability thus remains a central tension in the current DfAM landscape.

Moreover, a reliance on automated design tools without critical human oversight can obscure the process-specific nuances that influence successful fabrication. Different AM technologies—whether fused filament fabrication, stereolithography, or metal powder bed fusion—each introduce specific limitations related to resolution, thermal distortion, material compatibility, and post-processing requirements [100]. Software-driven outputs that ignore these variables often shift the burden of correction to the manufacturing stage, leading to increased iteration cycles, wasted material, and prolonged lead times. To overcome this, DfAM must not be reduced to a digital automation task; instead, it must remain an informed and iterative process that actively incorporates feedback from real-world AM practice. Designers must develop literacy in both the capabilities and the limitations of the manufacturing technologies they aim to use, ensuring that computational design tools serve as enablers—not substitutes—for engineering judgment.

4.3. Disregard of post-print functionality and assembly context

Another recurrent source of failure in AM design is the insufficient consideration of post-print functionality and the operational environment in which the printed component will be deployed. In the rush to exploit AM's geometric freedom, designers may focus on printability and visual aesthetics at the expense of performance, integration, and usability. This is particularly evident in complex assemblies or systems where printed components must interface with other parts, undergo mechanical loading, or be subjected to environmental conditions such as heat, humidity, or abrasion. Failure to account for tolerancing, mating clearances, fastener integration, or ease of assembly can lead to fitment issues, reduced reliability, and increased post-processing demands. In some cases, a printed part may meet all design specifications in isolation but fail when deployed due to lack of compatibility with surrounding systems.

This disconnect is also visible in multi-part systems where additive manufacturing is used for only a subset of the components. In such hybrid assemblies, the functional role of the printed part must be carefully harmonized with traditionally manufactured elements, necessitating consistent surface finishes, mechanical properties, and dimensional tolerances. However, AM-centric design workflows often lack the mechanisms for ensuring this alignment, especially when designers operate in digital silos without upstream or downstream integration. To mitigate this risk, DfAM must adopt a systems-oriented perspective that treats the printed part not as an isolated artifact but as an integrated element within a larger product ecosystem. This requires enhanced communication across design, manufacturing, and assembly domains, supported by process-aware design standards and verification protocols. Only by embedding post-print functionality and real-world usage contexts into the design phase can AM components transition from proof-of-concept prototypes to robust, production-grade solutions. Table 4 summarizes the key design misinterpretations discussed in this chapter, linking each to typical failure modes, underlying causes, and recommended strategies to enhance the reliability and effectiveness of additive manufacturing practices.

Table 4. Prevailing design misinterpretations and failures in additive manufacturing practice.

Prevailing Design Misinterpretation	Observed Design Failure	Underlying Cause	Recommended Strategy
1. Inadequate transition from subtractive to additive thinking	Suboptimal designs that replicate traditional parts without leveraging AM capabilities	Legacy design habits; lack of AM-oriented education	Promote DfAM-specific training; encourage part consolidation, functional integration, and geometry redefinition
2. Overreliance on software-driven optimization	Unprintable or inefficient geometries; excessive post-processing	Use of generative tools without incorporating process constraints	Combine computational tools with AM process knowledge; simulate buildability alongside performance
3. Disregard of post-print functionality and assembly context	Poor fit, mechanical incompatibility, or functional failure in assembled products	Siloed design workflows; neglect of lifecycle integration	Adopt a system-level design approach; coordinate design with assembly and usage environment; validate interfaces early

5. Educational and methodological imperatives for effective DfAM

The full realization of Design for Additive Manufacturing (DfAM) as a mature engineering discipline requires not only technological innovation but also educational and methodological reform. As discussed in earlier sections, many design failures and inefficiencies stem from a lack of comprehensive understanding of AM process constraints, material behaviors, and lifecycle integration. These shortcomings are often reinforced by the limitations of traditional CAD education, fragmented toolchains, and the absence of standardized datasets to guide evidence-based design. In order to embed DfAM as a core competency within the broader engineering and design professions, it is necessary to develop updated pedagogical models, integrate multidisciplinary tool environments, and establish reliable reference data frameworks. This section outlines three key imperatives: integrating AM-aware principles into CAD education, promoting interoperable design-to-manufacturing platforms, and supporting the creation and use of benchmarking resources and open-access design repositories.

5.1. Integrating AM-aware design principles into CAD education

One of the most pressing needs in advancing effective DfAM practice is the integration of AM-specific knowledge into the foundations of design education. Most traditional CAD curricula are built around assumptions and constraints derived from subtractive manufacturing paradigms, emphasizing orthogonal geometries, standard tolerances, and machinability. As a result, engineering graduates are often inadequately prepared to design for the unique affordances and limitations of AM processes. To close this gap, CAD directives must evolve to include layer-based fabrication logic, process-specific design rules (e.g., overhang constraints, support minimization), and strategies for exploiting AM features such as lattice structures, part consolidation, and mass customization [100]. Instructional content should further emphasize the importance of build orientation, material anisotropy, and surface finish implica-tions—elements rarely addressed in conventional design coursework but critical for AM success.

Beyond theoretical instruction, the use of experiential learning and design-to-print workflows is essential to reinforce DfAM competencies [101]. Students should be ex-posed to hands-on projects that integrate digital modeling, slicing, fabrication, and evaluation of printed components. This iterative cycle fosters an intuitive understanding of how design decisions translate into real-world outcomes—positive or negative—within the constraints of AM technology. Institutions should also consider partnerships with industry and equipment manufacturers to provide access to a diverse range of technologies and materials [102]. Moreover, interdisciplinary collaboration between mechanical engineering, materials science, and industrial design departments can enrich the curriculum, offering students a more holistic perspective on how form, function, and process intersect in AM-based design.

5.2. Toward interoperable platforms combining modeling, simulation, and print validation

The current digital ecosystem supporting AM remains fragmented, with discrete software tools used for CAD modeling, structural simulation, process planning, slicing, and print validation. This separation creates inefficiencies in the design workflow and increases the likelihood of print failures due to lack of feedback between stages. Designers often operate in isolation from manufacturing engineers, relying on exported files that may not preserve critical metadata such as tolerances, material properties, or build orientation intent. To address this challenge, there is a growing need for interoperable design platforms that seamlessly integrate geometric modeling with performance simulation and manufacturing process validation.

An effective DfAM environment should support bi-directional data flow between design and analysis, allowing designers to visualize not only how a part will look but also how it will behave under mechanical stress, thermal gradients, or distortion during fabrication [103]. Emerging tools are beginning to incorporate build simulation into the design stage, predicting residual stresses, warping, and support requirements in parallel with geometric modeling [104]. The incorporation of machine-specific parameters and material profiles enables real-time manufacturability checks, reducing the need for costly physical iteration [105]. Furthermore, cloud-based platforms can facilitate collaboration across disciplines and locations, ensuring that design intent is preserved and validated throughout the digital thread. Ultimately, these integrated environments will empower designers to make informed, process-aware decisions earlier in the workflow, thereby improving both print success rates and end-use functionality.

5.3. The need for design repositories and parametric benchmarking datasets

Another methodological imperative for the advancement of DfAM is the development of shared reference resources that support evidence-based design and technology validation. At present, many AM design decisions are made based on heuristic knowledge, vendor-specific recommendations, or anecdotal experience. This lack of standardized data hinders repeatability and makes it difficult to compare performance across materials, machines, or design approaches. To overcome this, there is a pressing need for open-access design repositories that catalog validated geometries, best practices, and failure case studies across a wide range of AM processes and applications [106]. Such repositories would serve not only as educational tools but also as practical design aids for engineers and researchers. Table 5 summarize the educational and methodological imperatives for advancing DfAM practice.

In parallel, the creation of parametric benchmarking datasets is essential for characterizing and comparing the effects of design variables on print outcomes. These datasets should include controlled studies that vary key design parameters—such as wall thickness, overhang angle, feature resolution, and lattice density—across different AM technologies and materials [107]. By capturing quantitative relationships between geometry, process conditions, and part performance, these benchmarks would enable more informed decision-making and support the development of predictive design rules [108]. Furthermore, their integration into simulation tools and design platforms could facilitate automated manufacturability assessments and quality assurance protocols [109]. Collaboration among academia, industry, and standards organizations is essential to create these datasets, significantly enhancing DfAM reliability and scalability [110]. The following table synthesizes the key educational and methodological imperatives discussed and links them to current gaps, desired outcomes, and strategic recommendations.

Table 5. Educational and methodological imperatives for advancing DfAM practice.

Imperative	Current Limitation	Desired Outcome	Strategic Recommendation
Integration of AM-aware principles in CAD education	Traditional CAD curricula based on subtractive manufacturing assumptions	Graduates with process-aware, AM-ready design skills	Revise curricula to include AM-specific design rules, layer logic, anisotropy, support avoidance, and build orientation
Interoperable platforms combining design, simulation, and validation	Fragmented toolchains and lack of real-time manufacturability feedback	Seamless design-to-manufacturing workflows with reduced iteration	Develop integrated platforms with embedded simulation, build validation, and machine/material-specific settings
Open-access design repositories and benchmarking datasets	Reliance on heuristic or vendor-specific guidelines; lack of standardized reference data	Evidence-based, repeatable, and optimized design practices	Establish collaborative databases cataloging validated designs, case studies, and quantitative benchmarks

6. Conclusions

This work has provided a critical analysis of the changing role of Design for Additive Manufacturing (DfAM) as a discipline that needs to move beyond its current applications focused on geometry-centric aspects by creating an optimal convergence of functional, material, and system dimensions inherent in additive manufacture technology. Exploring aspects of design like tolerancing, build orientation, support control, and material-dependent behavior, and knowledge assimilation regarding processes, functional needs, and lifecycle issues, has identified that effective DfAM applications demand more than awareness of printability; instead, a deep convergence of knowledge regarding processes, functional needs, and lifecycle effects is required. In addition, analysis of commonly held design fallacies and corresponding failure modes has identified that innovation enabled by additive manufacture is frequently limited not by technology, but by conventional thinking, poor comprehension of automation of design, and persistent neglect of downstream functionality. These comparative insights provided in this analysis highlight that DfAM cannot be treated as a rigid checklist of prohibitions, but instead as a dynamic philosophy towards design, continuously refined by collaboration between disciplinary fields and empirical validation based on actual use.

To evolve toward a function-oriented, process-informed design state, several imperatives must be prioritized by both academia and industry. First, educational institutions must modernize design curricula to embed AM-specific principles, emphasizing experiential learning and process-aware modeling strategies. Second, tool developers should accelerate the convergence of CAD, simulation, and print validation within unified digital platforms that support intelligent, feedback-driven design workflows. Third, the AM community must support the creation of open, validated design repositories and benchmarking datasets that allow for reproducible experimentation and data-driven optimization. Ultimately, realizing the full potential of AM has to do with a fundamental rethinking of design intent—not merely as the definition of geometry, but as the articulation of function, behavior, and manufacturability within a specific technological and material context. Only by adopting this broader perspective can DfAM evolve from a niche set of constraints into a modus operandi of next-generation engineering design.

Authors' contribution

Conceptualization, A.K., T.G., E.P. and M.P.; methodology, A.K., T.G., E.P. and M.P.; validation, A.K.; formal analysis, A.K. and T.G.; investigation, A.K.; resources, A.K.; writing—original draft preparation, A.K.; writing—review and editing, A.K., T.G., E.P. and M.P.; visualization, A.K.; supervision, T.G., E.P. and M.P.; project administration, A.K., T.G., E.P. and M.P. All authors have read and agreed to the published version of the manuscript.

Conflicts of interests

The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AM	Additive Manufacturing
DfAM	Design for Additive Manufacturing
CAD	Computer-Aided Design
FDM	Fused Deposition Modeling
SLA	Stereolithography
DLP	Digital Light Processing
SLS	Selective Laser Sintering
SLM	Selective Laser Melting
EBM	Electron Beam Melting
AI	Artificial Intelligence
FEA	Finite Element Analysis
FFF	Fused Filament Fabrication
UV	Ultraviolet (in context of post-curing)

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