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*Review*

# Design for Additive Manufacturing: Recent Innovations and Future Directions

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**Abstract:** Design for additive manufacturing (DfAM) provides a necessary framework for using novel additive manufacturing (AM) technologies for engineering innovations. Recent AM advances include shaping nickel-based superalloys for lightweight aerospace applications, reducing environmental impacts with large-scale concrete printing, and personalizing food and medical devices for improved health. Although many new capabilities are enabled by AM, design advances are necessary to ensure the technology reaches its full potential. Here, DfAM research is reviewed in the context of Fabrication, Generation, and Assessment phases that bridge the gap between AM capabilities and design innovations. Materials, processes, and constraints are considered during fabrication steps to understand AM capabilities for building systems with specified properties and functions. Design generation steps include conceptualization, configuration, and optimization to drive the creation of high-performance AM designs. Assessment steps are necessary for validating, testing, and modeling systems for future iterations and improvements. These phases provide context for discussing innovations in aerospace, automotives, construction, food, medicine, and robotics while highlighting future opportunities for design services, bio-inspired design, fabrication robots, and machine learning. Overall, DfAM has positively impacted diverse engineering applications, and further research has great potential for driving new developments in design innovation.

**Keywords:** design; engineering; additive manufacturing; 3D printing; materials; processes; optimization; mechanics; modeling; applications



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## 1. Introduction

As additive manufacturing (AM) technologies continue to advance, there is a need for design methods to guide innovations that benefit from AM's capabilities for fabricating complex structures with novel materials [1]. Unfortunately, recent research suggests that AM technologies remain underutilized [2]. For designers to achieve AM innovations, they must do more than simply possess AM technologies—both the effective use of resources and information management for decision making are crucial. Design for additive manufacturing (DfAM) provides a framework that facilitates decision making with AM technologies. DfAM is a multifaceted field of study in which diverse topics such as creativity [3], bio-inspiration [4], materials [5], optimization [6], and validation [7] are all considered for enhancing AM design with integrated approaches. Advances in DfAM are necessary to keep up with the exponential increase in interest for AM applications [8], especially in fields such as medicine that benefit from on-demand design and manufacturing for personalized solutions [9]. Here, DfAM research is surveyed by considering perspectives from stages across the design process and discussed for diverse application areas that may foster AM design innovations.

An important aspect of DfAM is the establishment of a framework for learning and implementing relevant tools and techniques for a particular design application. A DfAM product development framework subdivided into the stages of process selection, functional redesign, and optimization has been demonstrated as an effective approach for both research and industry case studies [10]. These stages enable designers to reason about the entire life cycle of an AM product and iterate between steps in the design process. Another DfAM framework has focused on assembly by considering architecture minimization that relied on using AM's advantages for part consolidation and assembly-free mechanisms [11]. The framework provides the context of an 'AM-factory', which was illustrated with a gripper case study produced with automated design generation and lattice structures to improve mechanical efficiency. Lattices are common AM structures and have been investigated in a design–build–test framework that used an integrated computational generation and experimental validation strategy to tune lattices for biomedical applications [12]. The process resulted in the experimental validation of a design space where lattices were configured based on the specific physiological needs of patients. These DfAM endeavors provide a context for reviewing recent research in the framework proposed in Figure 1, in which Fabrication, Generation, and Assessment phases are considered during AM research and development.

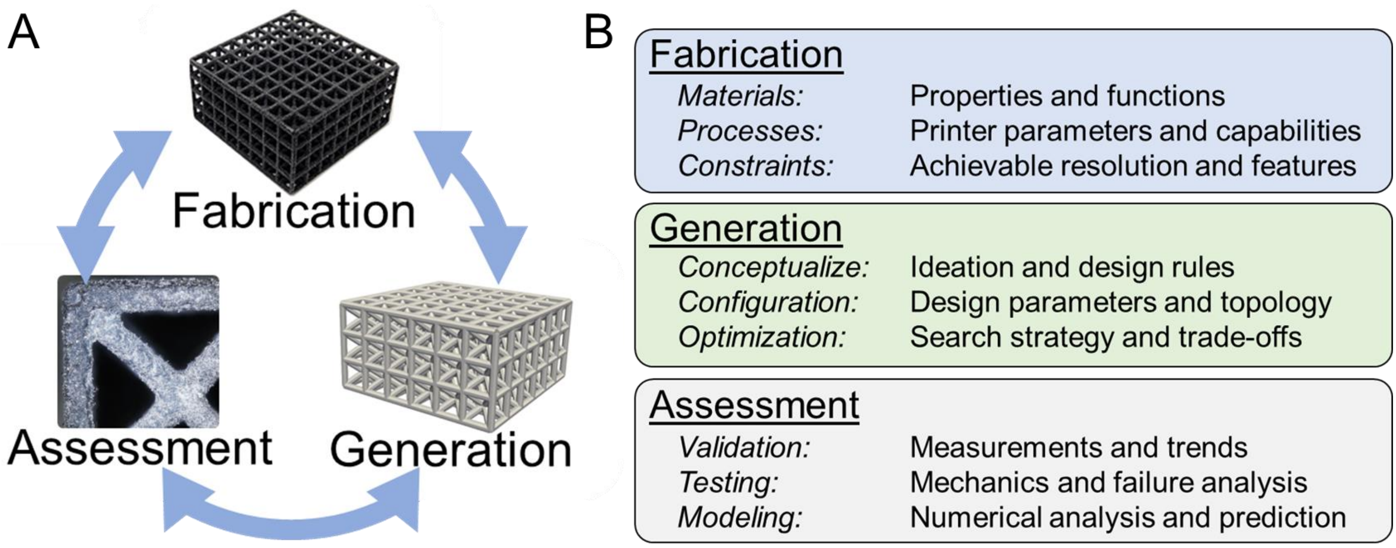


**Figure 1.** Design for additive manufacturing framework (**A**) for Fabrication, Generation, and Validation phases (**B**) with key steps to consider in each phase. Design example provided for porous nylon 11 lattices fabricated with powder bed fusion.

The Figure 1 framework demonstrates a case study with Nylon 11 material printed with powder bed fusion, which is a novel AM process that facilitates printing integrated parts and non-assembly mechanisms [13]. The Fabrication phase is demonstrated with a lattice design, in which minimum manufacturing constraints were measured during the Assessment phase using microscopy and mechanical testing to define a design space for configuring lattice structures in the Generation phase. Steps across phases may be iterated in a non-linear fashion to better understand AM capabilities that result in more efficient approaches for producing new designs, with specific steps highlighted in Figure 1.

Non-linearity for DfAM phases is necessary to consider since the specific sequence of steps and phases is contextually dependent on the current state of the art for an application. Depending on the application, it is potentially best to start by characterizing fabrication processes to develop new materials and manufacturing innovations, such as when novel biomaterials come to fruition and open a new design space for medical applications. In this case, the designer would begin with the Fabrication phase to determine the capabilities of a printing process in terms of materials and fabrication constraints that enable different design configurations using the new material. If the Generation phase were initiated prior to having this knowledge, it is highly likely a designer could explore infeasible solutions of the design space that would not result in manufacturable designs. In other cases, a designer may begin with generation steps that focus on innovations by proposing a novel structural configuration while using well-established AM technologies to fabricate the end product. Here, designers may begin directly with generating solutions according to rules and constraints that have been established as prior best practices and then move directly to the Assessment phase after printing.

Similar DfAM steps have been investigated for nylon powder printing using multijet fusion techniques. For instance, during fabrication, the differences in refresh rates of powder can affect the thermal, morphological, and mechanical characteristics of printed parts [14]. During design generation, parameter alterations for lattices may affect print accuracy and the reaction loads of structures [15]. During assessment, such as testing the mechanics of honeycomb structures, finite element (FE) models have been created that facilitate computational design with accurate predictions of structural performance [16]. Using these techniques can aid in the creation of novel systems using AM, such as multi-helical springs with experimentally validated stiffness predictions [17]. The directed design of AM springs has great potential for applications in multiple areas, including the aerospace and automotive sectors, by providing a higher stiffness for competing alternatives of a similar mass. By carefully considering the technology at hand and previous works across phases, it is possible for designers to recognize which steps and methods may facilitate the greatest opportunities for innovation.

The DfAM framework in Figure 1 has broad generalizability across AM technologies and applications. For instance, in the Fabrication phase for extrusion printing, anisotropic part mechanics are dependent on the base material selected and print orientation [18]. Such tuning extends to further processes for tailored thermoplastics and photopolymers, with a possibility to adjust parts mechanically by adding nanoparticles and fibers [19]. During the Generation phase, a configuration of efficient micro-architected structures has significantly improved heat exchanger effectiveness compared to traditionally manufactured designs [20]. The optimization of mechanical metamaterials has resulted in lightweight helical coils with advantageous structural rigidity and large deformation capabilities compared to equivalent coil springs of identical weight [21]. In the Assessment phase, experiments have measured the dimensional accuracy of metal powder bed fusion processes and found both micro- and millimeter scale deviations from the intended design [22]. Mechanoluminescent particles have also been embedded in prints to provide insights for mechanical failures of AM parts that open the possibility for the real-time evaluation of mechanical responses in designs [23]. These cases highlight a great potential for innovative AM designs to outperform designs from traditional technologies and a need for a careful consideration of DfAM methods and AM limitations to ensure the technology is used to its fullest potential.

In this review, DfAM research for innovations in diverse applications is surveyed in the context of Figure 1 phases. The review critically considers the integrated nature of DfAM steps, particularly across design phases and applications that are often non-obvious and necessitate multiple iterations, thereby contributing to the literature by filling gaps between individual research studies that focus on specifics. For instance, when designing for innovative applications, success requires considering AM materials and processes paired appropriately since not all printing processes use the same materials. These decisions in turn affect fabrication constraints and uncertainties in the manufacturing process that lead to printed parts responding differently than idealized models. Depending on the application area and current state of knowledge in the field, different design problems necessitate emphasis on different DfAM phases and steps to identify the greatest opportunities for innovation, which are difficult to identify when considering DfAM steps in isolation. Considering these phases and steps provides context for discussing innovative AM applications for diverse sectors including aerospace, automotives, construction, food, medicine, and robotics. The review concludes by considering future DfAM directions, highlighting them with challenges and directions for researchers to consider as both DfAM frameworks and AM technologies continue to advance. Reviewing these multifaceted tools and techniques across DfAM perspectives represents a critical advancement for better understanding how DfAM frameworks drive AM innovations.

## 2. Fabrication

Determining the fabrication capabilities of AM processes is an essential step in DfAM because it provides bottom-up knowledge for designers to form decisions. The capabilities of designs from fabrication depend primarily on the materials and deposition processes used to form three-dimensional parts. Each combination of a material and a process has constraints that dictate rules for minimum dimension size and features that further inform design generation.

### 2.1. Materials

Material selection is a crucial step in DfAM that influences the properties, functionality, and printability of AM parts. Common AM materials span from elastomers to polymers to metals. AM processes enable the creation of innovative designs by the directed deposition of novel materials such as superalloy metals [24]. For superalloys, AM reduces manufacturing steps and minimizes waste compared to traditional investment casting while also opening the possibility of fabricating hollow, foam-like, and lattice-based architectures. According to one study, nickel-based superalloys created with binder-jet processing do not introduce residual stress during fabrication due to the sintering process providing more consistent and controlled heating than traditional processes [25]. Fatigue-tested superalloy materials have been produced by comparing as-printed, as-sintered, and mechanically ground samples, as demonstrated in Figure 2A. Mechanically ground samples provided the highest engineering stress per number of cycles to failure (350 MPA at approximately 1 million cycles). The mechanical grinding resulted in fatigue performance that significantly surpassed that of a cast alloy. Further research in superalloys has resulted in a new class of alumina-forming superalloys with advantageous crack resistance and directional structures [26,27]. Such materials demonstrate that AM not only provides new capabilities for material deposition to form complex geometries but also provides enhanced mechanical properties compared to conventional manufacturing processes.

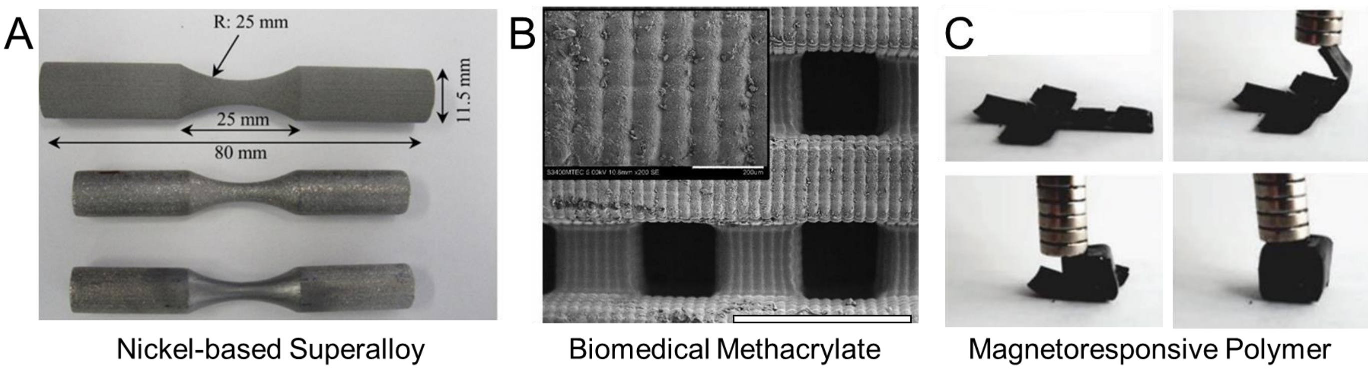


**Figure 2.** Highlighted material innovations for additive manufacturing including (**A**) nickel-based superalloy [25], (**B**) biomedical methacrylate (1 mm scale bar) [28], and (**C**) magnetoresponsive polymers [29]. Images adapted with permission.

AM is also providing new capabilities in medical applications in which DfAM enables personalization for patient-specific needs. Typical printing materials used in medicine include polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polyvinyl alcohol (PVA), thermoplastic polyurethane (TPU), polyether ether ketone (PEEK), biological tissues, carbon fiber, titanium, and nitinol [5]. One emerging application of AM materials in medicine is the tailoring of complex three-dimensional tissue scaffolds in which optimized geometry supports the curvature-driven growth of new tissues [30]. Biocompatible polymers are necessary for such applications, with methacrylates becoming a preferred option due to their advantageous stiffness and toughness, which are necessary to withstand forces of the human body [28]. Biocompatible methacrylates have been recently developed for printing with vat photopolymerization processes that produce complex structures with microscale resolutions [31], as demonstrated in Figure 2B. The methacrylate specimens had compressive moduli in the range of 10 to 19 MPa, with cytotoxicity results suggesting they are not toxic for porcine chondrocytes, thereby demonstrating their suitability for regenerative medicine.

AM is also enabling innovation via the fabrication of functional magnetic materials that are suitable for diverse applications in thermal generation, electronics, and small-scale robotics [32]. An advantage of AM is the creation of parts with intricate internal structures with complex geometries that enable the placement of magnetic materials strategically throughout a design. Such designs are difficult or impossible to replicate with traditional subtractive manufacturing processes. Magnetic photopolymerizable resin has been optimized by creating samples with varied proportions of solid loading for magnetic nanoparticles needed to maximize magnetic actuation forces by weight [33]. A high performance was achieved for samples with 30% solid proportions. Figure 2C demonstrates a printed magnetoresponsive polymer with 2% of its weight composed of magnetite nanoparticles [29]. The mechanical properties of the polymer were demonstrated with tailorable stiffness by varying urethane–acrylate resins and butyl acrylate, which functioned as a reactive diluent. The magnetic response was tailorable by altering the amount of $Fe_3O_4$ nanoparticles for up to 6% weight. Material tuning demonstrated capabilities for controlling movements of objects with magnetic responses, including rolling, translation, stretching, and folding/unfolding. These material examples demonstrate the novel capabilities and functions enabled by AM while also highlighting important considerations for designers when selecting AM processes based on material compatibility and needs.

### 2.2. Processes

There are diverse AM processes for fabricating designs including extrusion, photopolymerization, powder printing, and sheet lamination for polymers [19]. There are further processes to consider beyond polymer manufacturing in areas such as bioprinting, food printing, and metal melting/sintering. Each process has its own unique material libraries and capabilities. A brief description of these highlighted AM technologies will be provided as a necessary context for discussing their role in DfAM.

Fused deposition modeling (FDM) is an inexpensive and popular approach for extruding polymers that relies on melting filaments and depositing them layer by layer to construct a design [34]. FDM has resolution limits based on nozzle sizes that are typically 0.25 to 1.0 mm. The technology is capable of rapidly producing parts with a diverse material library including polymers of ABS, PLA, polyethylene terephthalate (PET), polycarbonate (PC), and nylon. Once a material is selected, process parameters for controlling orientation, infills, rasters, and layering all require consideration due to their influence on final part properties [35]. The Taguchi method is a common technique for designing experiments to systematically alter process parameters and measure their effects, which informs an optimum set of parameters for specified materials and applications [36]. By careful consideration of process parameters, designers may tune tensile strength, impact resistance, damping, and further properties for application-specific needs.

Further extrusion processes include those for bioprinting and food printing that rely on the direct deposition of materials using a nozzle [37,38]. Common biomaterials for bioprinting include polycaprolactone (PCL), tricalcium phosphate (TCP), and alginate [39]. Food printing commonly uses starch, protein, and gel materials [40]. Both bioprinting and food printing processes can use temperature control to improve printability by altering the rheological properties of the printed material. Further improvement in the printability of these soft materials is achievable by combining additives with materials to alter their consistency, such as thickeners for food.

Powder printing is another common AM approach that has several different implementations for fabricating designs. Direct metal laser sintering (DMLS) uses the energy from a laser to heat and join powder particles together layer by layer to produce parts with specified geometries. The process is suitable for metals such as gold, silver, stainless steel, and titanium that can produce jewelry or bone tissue engineering scaffolds with microscale features [41,42]. Selective laser melting (SLM) is another common powder process that melts metal powder that cools to form designed parts [43]. Selective laser sintering (SLS) has been used to process polystyrene parts [44], while mulijet fusion (MJF) can fuse polymer powders to form flexible designs such as nylon springs [45]. An advantage of powder processes is that unused power acts as support material during printing, which can enable the design of complex geometries and mechanisms difficult to fabricate with other AM processes.

AM fabrication from resin materials relies on photopolymerization to fabricate high-resolution parts with microscale resolutions. Stereolithography (SLA) uses a laser for curing resin, while digital light processing (DLP) uses a planar projection of light. In each case, liquid resin with photopolymers is exposed to ultraviolet light that promotes cross-linking to solidify material. Such processes have been used to produce ultralight and strong porous ceramics to form mechanically efficient lattice structures [46]. The printing process parameters of exposure time and printing angle can be altered during resin printing to tune the curing behavior and mechanical strength of printed samples [47]. DLP printing has been demonstrated for tissue scaffold applications in which its capabilities for microscale resolution create a biological niche with a suitable geometry to promote bone growth [48]. Overall, these diverse AM technologies and their respective process parameters present a complex space for designers to navigate and a need to identify the constraints and capabilities of each process to inform design decisions.

### 2.3. Constraints

Characterizing constraints for 3D printing processes is essential to provide a set of rules for designers to follow when selecting appropriate materials and processes for configuring parts [49]. Within a class of 3D printing processes, general capabilities, such as an extrusion printer's ability to produce overhangs, remain similar, which suggests that a set of general guidelines is useful for designers. When considering 3D-printed springs with material extrusion [50], guidelines were developed by printing springs with PLA material and assessing their print quality and capabilities. Determined guidelines suggest that square wire cross-sections, mono-directional in-fills, and thin layers are recommended for printing springs to ensure consistency and functionality.

Researchers have systematically studied printing constraints and created worksheets for designers to follow that promote the use of design decisions that improve printing success [51]. Figure 3 shows a highlighted scoring criteria in the Design for Additive Manufacturing Worksheet, in which designers score parts according to criteria in each column such as complexity, functionality, material removal, and unsupported features. Each criterion has multiple levels of assessment with associated scores in which designers choose one level that their design fits for each category. For instance, in the material removal category, a part with no support material scores the best, while a part with support material that is difficult to remove scores worst. Designers score the sum across rows with features that are more difficult to fabricate providing lower scores. Based on the total design score, designers are recommended that the part 'Needs redesign', should 'Consider redesign', has a 'Moderate likelihood of success', or has a 'Higher likelihood of success'. These guidelines were tested with FDM-printed parts designed by students that demonstrated that the use of the worksheet resulted in an 81% decrease in the rate of poorly designed parts. The study demonstrates the practical benefits of incorporating DfAM practices to train designers to use AM technologies properly and maximize their potential.

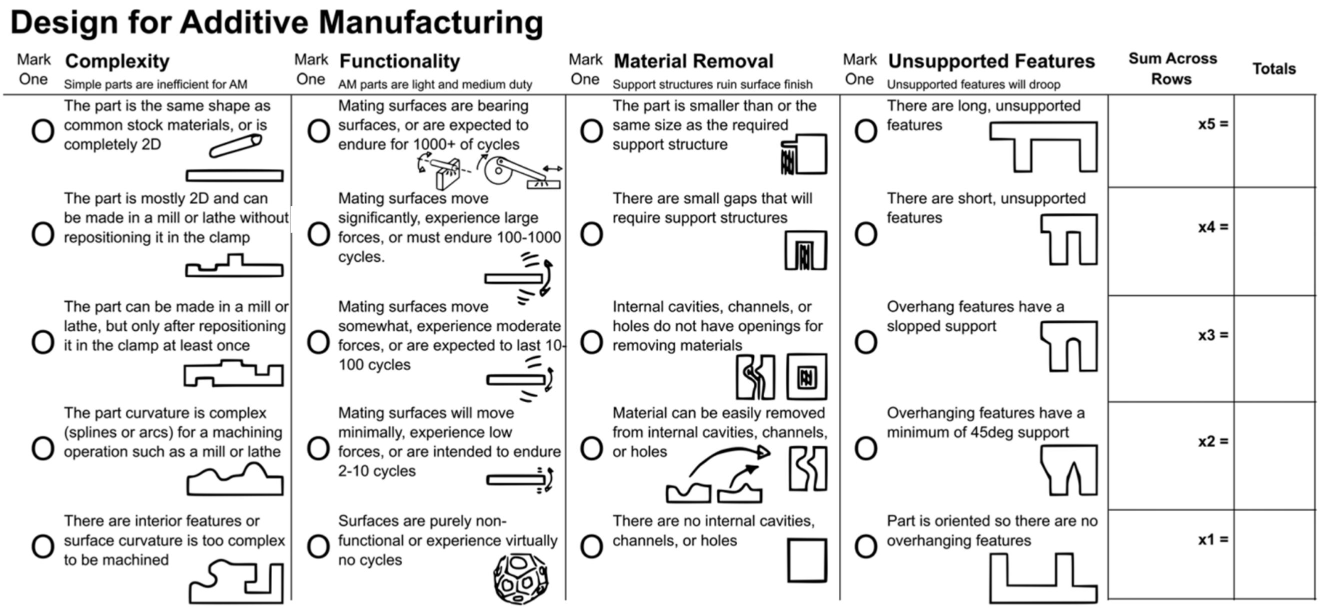


**Figure 3.** Highlighted scoring criteria from the Design for Additive Manufacturing Worksheet [51]. Image adapted with permission.

The sizes of clearances and tolerances are further constraints that designers must consider with AM parts, especially when creating working mechanisms. A study using a layered manufacturing process created revolute non-assembly mechanisms and demonstrated that the designed clearance of a mechanical joint critically affects its dynamic performance [52]. An algorithmic process was created to resize clearances to aid designers in configuring clearances that resulted in feasible designs. Non-assembly mechanisms have also been created with dissolvable support material with FDM processes [53]. In these studies, joint clearances that were too large were found to impair functionality and were a more important consideration than the length of linkage mechanisms. Powder printing processes are particularly useful for non-assembly mechanism creation since unused powder is present in areas between components of joints that, once removed, enables the movement of mechanisms requiring no further assembly. A recent study on nylon-powder-printed prosthetics found that relevant mechanisms operated best within a specified range of gap sizes from about 0.2 to 0.4 mm [13]. Further studies with geometric tolerances of laser powder bed fusion found that 15 mm diameter holes had mean printed diameters of 15.05 and 15.03 mm with standard deviations of 0.04 mm [54]. Based on these ranges, designers can specify suitable tolerances for parts based on empirical observations detailing the expected variation of 3D-printed parts. Such DfAM considerations are important to ensure that design efforts are focused on feasible designs that have a higher likelihood of working once printed.

## 3. Generation

Generation steps help designers use AM processes to create innovative designs based on material capabilities and constraints. Conceptualization is an early step in the design process in which designers use creative processes to form solutions to problems. AM enhances conceptualization by providing new capabilities compared to competing manufacturing technologies; however, AM also creates an exceedingly large and complex design space to navigate. Configuration steps aid designers in selecting a structural embodiment, such as a lattice architecture, that is further tunable via optimization that specifies parameter values within the design space for a specific application. By considering these DfAM steps, designers may leverage the unique facets of AM technologies while forming engineering solutions.

### 3.1. Conceptualization

During design conceptualization, it is important for designers to consider the advantages of AM, such as the generation of complex geometries, compared to its deficits, such as the difficulty in printing overhangs with some processes. Since AM has differing capabilities from traditional manufacturing methods, creativity is essential for designers to think outside the box to use AM to create novel designs that progress beyond the limitations of conventional technologies [55]. A design study comparing classrooms with and without formal DfAM training demonstrated that AM ideas were more elegant in terms of aesthetics but often less feasible [56]. Another study found that re-mixing AM designs, which is a process of adapting or recombining existing design elements into something new, promotes the creation of designs that are more often printed by online community members [57]. Since these designs modify already printable components, it promotes the diversity and quantity of ideas within the confines of DfAM constraints that ensures manufacturability. An experiment with 343 junior-level engineering students investigated effects from teaching three different design approaches: (1) no DfAM, (2) restrictive (considers limitations) DfAM, and (3) opportunistic (considers capabilities) and restrictive DfAM [58]. Each type of DfAM approach was found to improve the technical proficiency of AM designs but not creativity. These studies suggest that curriculum and delivery play an important role for influencing designers' AM capabilities with a need for effective approaches that promote diverse design generation while retaining practicality for printing.

Teaching multi-modal design heuristics has been demonstrated as a viable strategy for improving designer creativity for thinking beyond the traditional manufacturing mindset [59]. Heuristics are general rules that designers may follow to find viable solutions quickly. The multi-modal heuristics taught for AM included categories of part consolidation, customization, convey information, material, material distribution, embed–enclose, lightweight, and reconfiguration. Some specific heuristics included part consolidation to reduce assembly time, customization with geometry to the use case, and material distribution to absorb energy with small interconnected parts. The use of these multi-modal heuristics led to an increased creativity of concepts generated by individuals and teams while also stimulating more diverse design concepts. The timing of design heuristics provided to novices has also been investigated [60], and it was found that providing DfAM lessons improved the manufacturability of designs but did not affect overall quality. The novelty of designs decreased after being provided heuristics, which suggests a decrease in creativity. These studies demonstrate that improving creativity using DfAM is challenging, and further research in these areas could help discover improved means of increasing designer creativity while ensuring quality and viability of designs.

### 3.2. Configuration

Computational approaches are often used to aid human designers in the configuration of AM parts due to their inherent complexity. Parametric design enables the adjustment of definable values related to a design's geometry to rescale parts and mechanisms for specified applications. Scalable AM mechanisms have been created parametrically for revolute, prismatic, and spherical joints with cylindrical spur, spiral bevel, and straight bevel gears [61]. Spiral gear mechanisms have been printed using a stereolithography apparatus machine that demonstrated a successful rescaling and functioning of the mechanism. Parametric design can also benefit from biomimetic approaches, such as approaches for modeling and optimizing L-systems inspired by plant growth algorithms [62]. Since biological systems are typically optimized via evolution for efficiency, mimicking such structures often leads to mechanically efficient systems. Honeycombs inspired by nature are common AM structures due to their high relative mechanical properties per weight. Mechanical testing has demonstrated that increases in material distribution at honeycomb nodes increases both stiffness and absorbed energy but may weaken other aspects of the structure if material volume is further increased [16]. The design of more complex architected structures, such as regular truss lattice cells, is another AM configuration strategy that enables mechanical efficiency [63] (Figure 4). Different configurations of lattices provide trade-offs in performance, such as those among strength, stiffness, and energy absorption, which designers may manipulate to tailor structures with properties for specified applications.

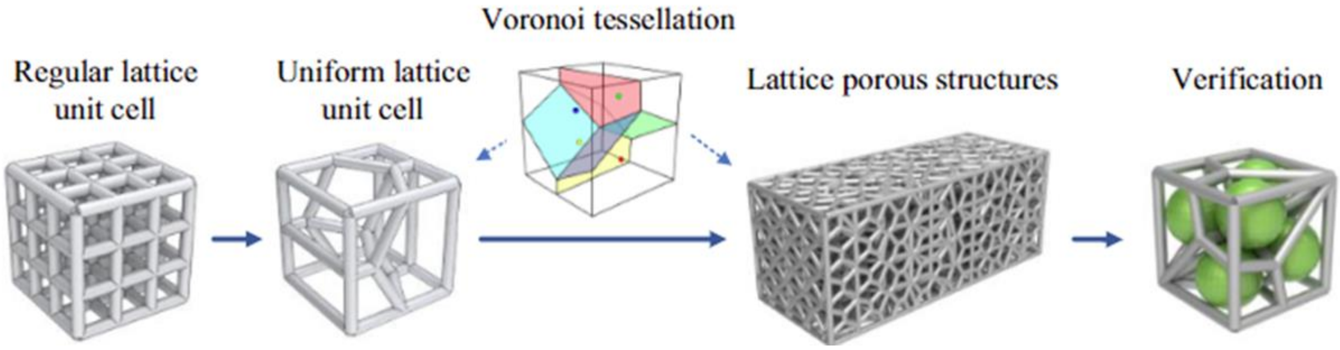


**Figure 4.** Parametric design of porous Voronoi lattice structures [64]. Image adapted with permission.

Voronoi-based lattice structures have been designed parametrically to create porous structures with properties that are globally controllable while locally uniform [64]. In the process, individual unit cells are divided throughout the design space, seed points and beam radii are determined for unit cells, and a Voronoi tessellation is used to distribute seed points uniformly. The seed points are tessellated globally with edges cylindered according to their corresponding beam radius values. Such structures have high stability that ensures that spatial deviations in porosity and surface area are small. Voronoi models are suitable for applications that need mechanical efficiency and have geometry-dependent needs, such as tissue growth based on a scaffold's shape [65]. Further strategies for configuring AM structures include functional gradients that gradually change parametric values spatially through a lattice [66], altering topologies of unit cells for transitioning properties throughout a lattice [67], or using multiple materials placed within a lattice to generate anisotropic properties [68]. Due to the diversity of strategies and decisions at local and global levels during design generation, optimization is often necessary to maximize the potential of configuration strategies.

### *3.3. Optimization*

Optimization is used in DfAM for improving both the manufacturing process and the performance of final parts. One study investigating anisotropic lattice mechanical properties and support material removal employed a snap-fit configuration strategy to enable more efficient printing of structures while resulting in a 100% increase in strength and energy absorption [69]. The approach demonstrated that the overall configuration strategy plays an important role in final achievable properties and performance. Once a configuration strategy is determined, computational approaches are often employed to refine designs according to specified objectives and constraints. For instance, one successful approach paired a lattice unit-cell library with parametric design and topology optimization to obtain lightweight structures [70]. Topology optimization is a process for optimizing the material layout within a given design space with reference to loads, boundary conditions, and constraints. The combined approach led to designs with improved stiffness while enabling the rapid generation of different topologies to find optimized stiffnesses.

Topology optimization has been used for medical AM applications to design tissue scaffolds and customizable shoes, thus demonstrating the adaptability of the approach for varied systems [71]. The core algorithm used was termed as an automatic complex topology lightweight structure generation method. The algorithm uses a mesh generation algorithm to produce a node distribution inside an object representing a boundary surface of a targeted complex structure. Low-weight trusses are generated using the distribution of nodes. Radii are then adjusted based on an FE analysis with an optimization algorithm to produce a lightweight truss structure. The algorithm pseudocode is provided in Figure 5A with shoe design results for the loading of the truss structure without optimization and with optimization provided in Figures 5B and 5C, respectively. The results of the topology optimization demonstrate a more consistent level of loading throughout the shoe and a lower peak load, thus improving the pressure distribution for patients.

A

1 Prepare the boundary edge (for 2D case) or surface (for 3D case) of the target lightweight truss structure; assign the maximum stress $\sigma_c$ that is allowed in the truss structure
2 Assign target node distances inside the boundary object
3 Assign nodes inside the object using the PIMesh
4 Generate a raw lightweight truss structure based on the node distributions. Let $N$ be the number of the bars of the truss structure, and $N_{\text{updated}} = N$
5 While $\sigma_{\max} > \sigma_c$ or $N_{\text{updated}} > 0.05N$ (optimize the lightweight truss structure)
5.1 Run finite element analysis to obtain the von Mises stress distributions $\boldsymbol{\sigma}_v$ of the structure, and let $\sigma_{\max} = \max(\boldsymbol{\sigma}_v)$
5.2 Update the diameter of the bars of the truss structure according to the von Mises stress distributions, and $N_{\text{updated}}$ is the number of the bars with radius changed
6 Generate the 3D models of the optimized lightweight truss structures

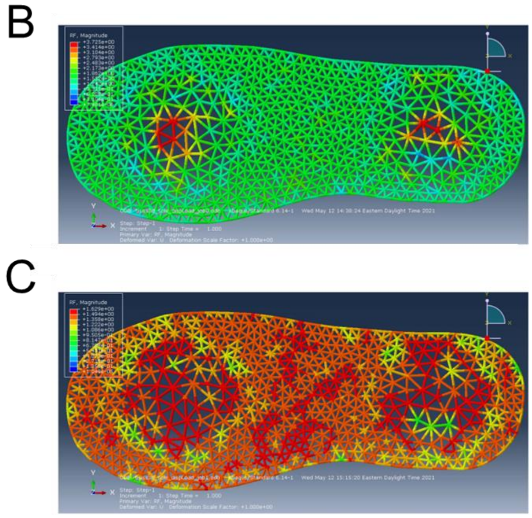


**Figure 5.** Topology optimization. (**A**) Algorithm for 3D-printed shoes with reaction forces of (**B**) a non-optimized shoe (max force = 1.88 N) compared to (**C**) an optimized shoe (max force = 0.94 N) [71]. Image adapted with permission.

It is possible to place constraints on structural features, such as overhang angles, to reduce the amount of support material necessary to fabricate a topology-optimized print. Build orientation and topology have been optimized together to accomplish these goals by using direction gradients to control the overhang angle within the design domain to reduce internal supports. A second density-based global constraint was used to control design domain boundaries for a reduction in external supports [72]. Another study used truss topology optimization with anisotropic struts that demonstrated improved material properties for trusses with anisotropic struts over struts optimized with isotropic materials [73]. The approach simultaneously optimized the struts along with the volume fraction of fibers or holes as reinforcements. Further steps included accommodating material symmetries, penalizing size variables, and improving manufacturability by introducing no-cut constraints to ensure symmetry across planes and faces of unit cells. Design and optimization has also been conducted on hybrid structures with solid and lattice portions [6]. Empirical validation with simulation results demonstrated that hybrid structures achieved higher stiffness, yield strength, and critical buckling compared to pure lattice or solid structures. Important last steps in optimization from these studies are validation and controlled comparisons. Validation with fabrication and experiments is necessary to confirm the accuracy of predictions from optimization, while controlled comparisons to different algorithms and cases enables designers to identify the most favorable design methods for a particular domain.

## 4. Assessment

Once generated designs are fabricated, it is necessary to assess their capabilities to determine if they perform as intended. A first step is the validation of printed designs to determine if features are printed accurately, especially those that may affect engineering performance. Testing, such as mechanical characterization, is then conducted to measure the properties of printed parts. Modeling steps can incorporate validation and testing results to account for differences between theorized performance and actual performance. Depending on the application and best practices, these steps may occur in a non-linear and iterative fashion. For instance, when using well-established FDM processes for macroscale designs with simple geometries, modeling and computational assessment may be considered prior to testing and validation to confirm predictions. However, when considering lattices that are printed near the fabrication limits of AM processes, such as those with microscale struts, designs may not print at all or print with highly different consistencies than predicted by ideal cases in modeling. Therefore, validation is necessary to determine achieved features prior to the creation of accurate modeling techniques that incorporate deviations incurred by printing processes. If validation is not conducted prior to evaluating the mechanics of a design, designers may spend excessive amounts of time modeling and testing designs that are impossible to fabricate or printed with very different structures and performances than expected. In all cases, by considering these steps and iterating appropriately, designers may review their designs and improve them according to the information obtained during each step.

### *4.1. Validation*

Validation is necessary to determine if parts are printed accurately and function as intended. Discrepancies emerge in the fidelity of final parts due to inherent limitations in the printing process. For instance, in FDM printing, globules of material form due to the inconsistent melting of filaments, which, in turn, affects mechanical functioning [74]. Subjective assessments have been conducted for FDM surfaces that had 93 observers rate 107 images of printed surfaces prepared by nine different types of ABS filaments for three different printers [75]. Their approach quantified metrics for monitoring printed parts for use in automated systems to either improve processing parameters during printing or determine early part failures. During the laser sintering of polyamide-12, research has found inconsistencies in printed surfaces from powder properties, processing parameters, and surface orientation. These have been investigated using contact profilometry, focus variation, and micro-CT techniques as a function of applied energy density, XY location, orientation, and percentage porosity [76]. The results demonstrated that the roughness profile for top/bottom surfaces were distinct, with top surfaces having peaks of greater amplitude. Such inconsistencies can inform designers about where cracks may occur that could lead to part failure. Fidelity has also been studied for bioink printed structures in which extrusion can lead to inconsistencies in printed diameters of lattices and the relative placement of material [77]. Additionally, bioprinted structures may become distorted due to the deformation of soft materials used for printing.

The effects of design and processing strategies have been studied for lattices fabricated with DLP printing. Microscopy measurements have determined that structures with higher relative density and more beams per unit cell tended to print with more material than expected compared to other designs [7]. Mechanical testing demonstrated that the added material improved mechanical properties. However, material added by altering process parameters led to more mechanically efficient structures than those with increased relative density from designed topology alterations. Figure 6 demonstrates the microscopy process used to validate each structure's accuracy by measuring beam diameters, which was affected by the processing parameters of print orientation and exposure time. Print orientation affects beams due to layers needing to bridge large gaps or build on top of previously placed materials. Beams were printed with smaller diameters than expected on average, and fusion of pores tended to occur towards the center of the lattice. Such inconsistencies occur in DLP printing due to pixel size, stage motion, optical focus, and resin properties, which has led to new methods proposed as corrective factors. The grayscale manipulation of pixels has been demonstrated for smoothing discontinuities in surfaces with manipulations to improve accuracy informed by a reaction–diffusion simulation to predict final cured shape [78]. Compensation methods have been used to alter beam diameters throughout a lattice design to correct for spatially dependent inconsistencies such as beams printing larger than expected towards the center of a lattice [79]. These methods improve upon the already highly accurate DLP process to provide prints that better match a designer's intentions with more consistent, predictable performance.

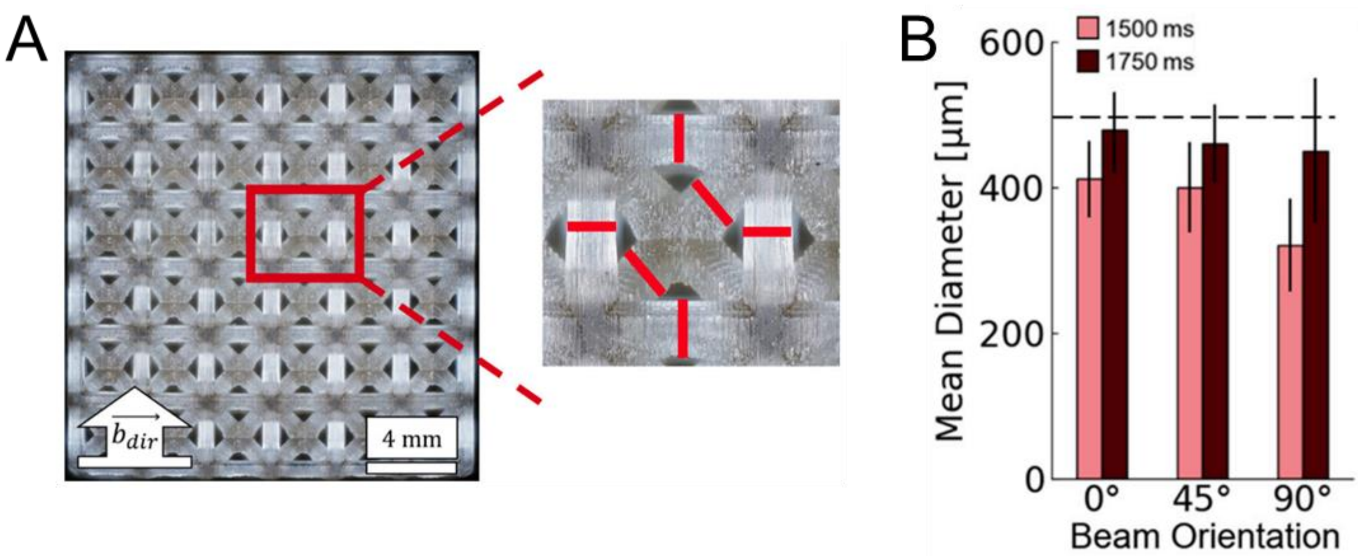


**Figure 6.** Validation of BCC lattice using (**A**) microscopy to (**B**) measure mean diameters based on beam orientation [7]. Images adapted with permission.

Inconsistencies in printing have also been observed for metal lattices produced with SLM [80]. Beams were printed larger than intended with material agglomeration occurring at corners due to overmelting, which resulted in fillet-like features. Octet topologies were more sensitive to inconsistencies than tetrahedron topologies, which demonstrated a dependency of accuracy on the configured design. Due to inherent limitations in metal additive manufacturing, methods have been developed for quantifying the effect of manufacturing defects using the automated analysis of microscope images [81]. The results found that parts were generally printed larger than expected and that increases in the sizes of nodes/beams increased stiffness. When designs were scaled smaller, mechanical properties increased due to the proportional increase in material per volume. Uncertainty quantification is another validation technique used to characterize the inconsistencies in printed lattices that uses data to inform design decisions [82]. Error propagation for metal printing has been determined in tandem with multiphysics simulations to better predict how microscale defects may affect global functioning, which can inform design decisions. Such methods are essential for designers to improve AM outcomes by understanding how differences in ideal models and tested outcomes affect final design performance.

### *4.2. Testing*

Testing is a key assessment step that helps validate findings while also providing empirical measurements of mechanical behavior for creating accurate models to predict performance. Mechanical testing in compression is often used for measuring lattice properties and provides information regarding the effective elastic modulus, yield strength, and ultimate strength. The effective elastic modulus is the slope of the stress–strain curve, which accounts for the relative density of the lattice and its topology that is proportional to the elastic modulus of the base material used to construct the lattice. For SLA printed lattices with a base material elastic modulus of about 1670 MPa, the effective elastic moduli of lattices with four different beam-based topologies ranged from 100 to 260 MPa [83]. Designs tended to have higher effective elastic moduli when more beams were aligned with the loading direction. Mechanics can also fluctuate due to manufacturing inconsistencies for the same design. Studies of DLP-printed lattices that tested 30 prints of the same design demonstrated a distribution of density and mechanical property measurements that occur due to fabrication inconsistencies [84]. The study investigated uncertainty and reliability for lattice mechanics and found that lattice failure due to yielding was highly affected by fluctuations in beam diameter.

Further studies in lattice mechanics have investigated energy absorption for multi-material honeycomb structures printed with ABS and TPU by measuring the area under the force–displacement curve [85]. The study found that adding material bands of TPU to ABS hexagonal honeycombs resulted in a linear decrease in energy absorption from 15.1 to 2.9 kN·mm, which was linearly proportional to the amount of TPU added for out-of-plane testing. Out-of-plane failure responses for the two different designs were similar and demonstrated a deformation of the flexible TPU structure prior to the deformation of the stiff ABS material. Since the TPU deforms first and is highly recoverable, the system is reusable for low displacement cases yet retains high energy absorption for failure scenarios, such as crashing, that benefit from the stiff ABS material with more overall energy absorption. For in-plane testing, failure mechanisms of square and hexagonal honeycombs demonstrated that more consistent failures occurred from hexagon designs, while square designs resulted in discrete collapses of unit cell layers. These results provide quantifications for designers to tailor designs while also highlighting the differences in behavior during failure that inform decisions for selecting one type of design over another.

Studies on titanium SLM lattice structures have conducted extensive measurements of the deformation and failure behavior of diverse lattice topologies [86]. The study sought to understand the influences of lattice cell topology, cell size, and unit cell count. By mechanically testing diverse lattices, it was found that $10^3$ unit cells and higher are necessary for the convergence of mechanical properties. During compression, different states of lattice behavior were identified from initial to elastic preload, to initial failure, to progressed failure, and to gross failure, the results of which are highlighted in Figure 7. The pattern of unit cells failing differed based on the design's topology. BCC structures had a comparatively large compliance followed with deflection that occurred due to strut bending near the lattice joints, with subsequent failure that leads to unit cell collapses. BCC-S3 lattices had a horizontal layer collapse with diagonal shear failure, while BCC-S2 lattices had a combined collapse of diagonal and horizontal layers. FCCZ structures had struts buckling vertically, followed by a fracture that led to unit cell collapse, followed by a diagonal layer collapse in two directions for the specimen's lower half. Trends from the study suggest that the Maxwell number and the alignment of struts along the loading direction affect lattice failure modes. Topologies with high lateral stiffness were observed to have horizontal layer crushing, which suggests they are appropriate for energy absorbing applications.

Further studies have investigated 30 strut-based lattices with cubic structures printed with SLS using polymeric materials [87]. Lattices were constructed by combining unit cells with topologies for cubic, diagonal, octahedron, and V-octet topologies. FE simulations were conducted to help interpret experimental results for effective stiffness, yield strength, and buckling strength for uniaxial, shear, and hydrostatic loadings. General results concluded that the modes of deformation differed for various loading conditions for stretching-dominated, bending-dominated, and mixed types of structures. Stretching-dominated structures with triangulated micro-architectures within unit cells provided greater stiffness and strength per unit weight than bending-dominated structures. The study demonstrated that topology and relative density also played a major role in mechanics, which suggests there are many routes for manipulating designs and conditions to achieve a desirable set of mechanical properties.

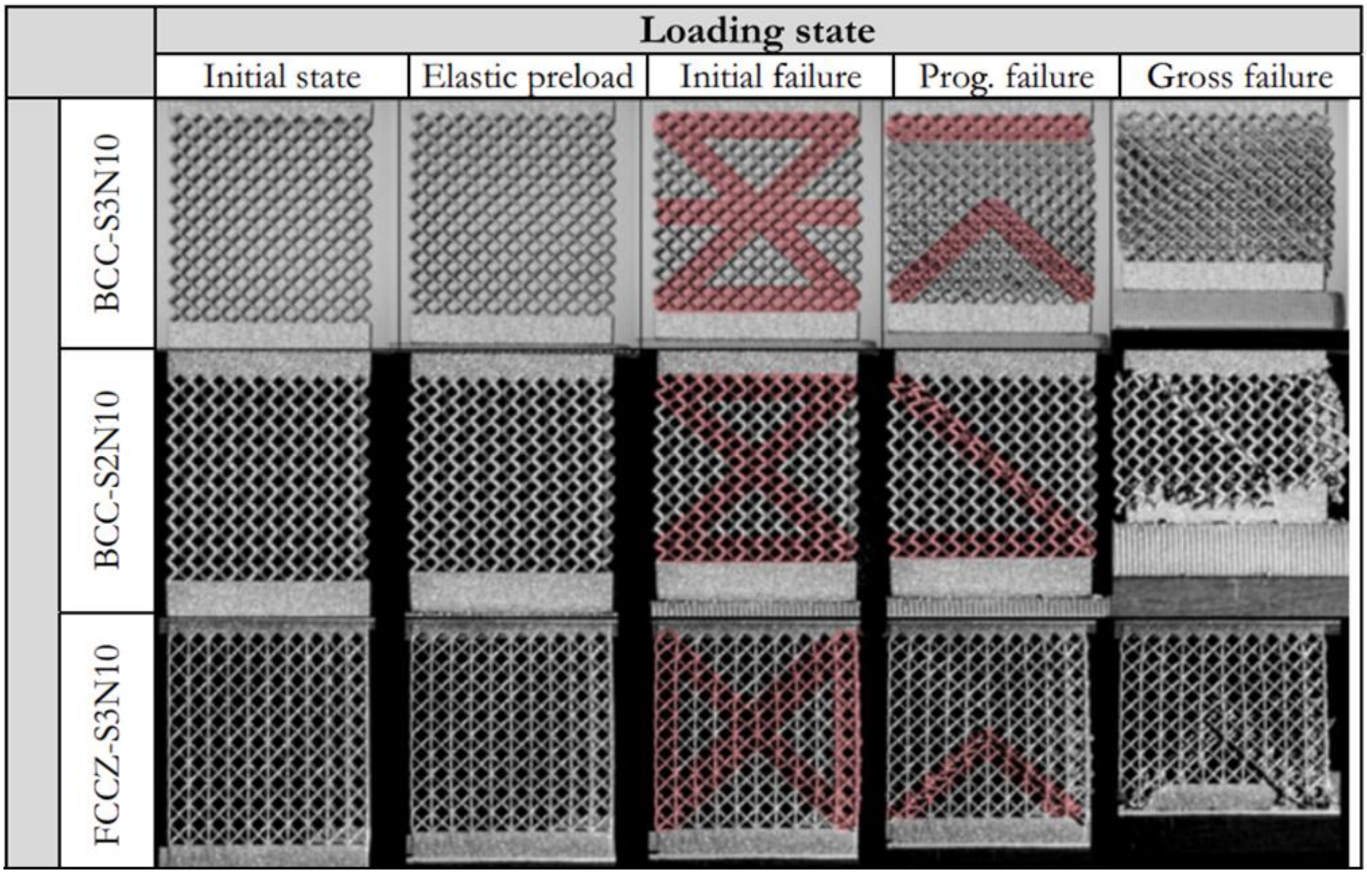


**Figure 7.** Lattices tested in compression with failure modes highlighted [86]. Image adapted with permission.

Diverse topologies for metal structures have also been studied from SLM processes with Inconel, which provides a high resistance to oxidization, creep, and a loss of mechanical properties at high temperatures [88]. The lattices demonstrated stable crushing behavior up to densification with exceptional ductility and high damage tolerance. Several observations were summarized regarding failure modes for the lattices. For all topologies and cell sizes, the behavior was apparently linear for strains of 2%. When strain was increased to 4%, BCC and FCC topologies remained linear while BCCZ and FCCZ topologies demonstrated a local plastic collapse for specific unit cells. The collapse had bands associated with maximum shear stresses aligned 45° to the loading direction. Topologies with Z-struts also had catastrophic failures followed by densification, with cyclic behavior of plateau stresses as local collapses occurred. For the FCC and BCC topologies, further strains resulted in mostly homogenous deformation behavior throughout the lattice. Additionally, the degree of bending and stretching-dominated behavior was possible to control by modifying the local cell structure, with Z-strut addition driving structures to have a greater degree of stretching-dominated behavior that was increased with larger cell sizes. Overall, mechanical testing demonstrates the diverse behaviors exhibited by AM structures that necessitate designers to create and validate models to accurately predict outcomes.

### *4.3. Modeling*

Modeling is the process of creating a design and predicting its performance, which occurs throughout different periods in the design process as information is gained. Although a digital design is necessary to create prior to printing, proper modeling of its mechanics requires validation and testing to create an accurate digital geometry to determine how printing defects play a role in mechanical behavior. The most common approach for modeling mechanics of AM lattices is the finite element method (FEM), which numerically solves differential equations. FEM subdivides a large system into smaller simpler parts via discretization and mesh creation. Titanium structures fabricated with PBF processes have been represented with FEM for 50% to 90% porosity designs that found a high agreement with the Gibson–Ashby model [89]. The Gibson–Ashby model predicts mechanical properties, including elastic modulus and yield strength, from the relative density of a structure using an exponential scaling law and empirically informed constants. Scaling laws have been used to predict the compressive mechanical properties of BCC lattice structures with 117 design variations, first with FEM and then using mathematical equations to reduce computational effort [90]. The study also found that increased strut angles lead to increased relative stresses and elastic moduli for the stretch-dominated behavior of lattices.

FEM approaches have demonstrated the importance of modeling as-manufactured lattice geometries that differ from the idealized design case [91]. Numerical simulations from micro-CT assessments have provided a means for including manufacturing defects in modeling to determine their effect on buckling. The study found that analytical and linear numerical assessments for buckling consistently over-estimated effective buckling performance, which suggests the need for corrective factors to account for reduced performance from ideal cases. The modeling approach considered the boundary conditions, unloaded response, and first buckling mode of struts, while evaluating the ratio of the buckling strength to the slenderness ratio. Struts with a greater slenderness ratio had a higher tendency to buckle and fail. Numerical simulations in which non-linear geometry was considered with a non-linear material model provided higher consistency with experimental results compared to linear numerical methods.

Further modeling methods are necessary to consider as AM capabilities continue to advance and outpace traditional evaluation methods. For instance, researchers have modeled multi-material AM structures with complex geometries that used smooth material transitions with a semi-analytical unit cell decomposition strategy [92]. The strategy splits the complex lattice into units of struts and connectors with further interpolation of discrete material property values using a multiquadric radial basis function network. When uses of the model are compared to functions for traditional material distributions, the approach has advantages for handling an arbitrary number of base materials. Case studies have demonstrated consistency with theoretical material composition values. For lattices in biomedical applications FEM is possible to use in tandem with lattice and biomechanical models to determine lattice behavior for cases such as spine fusion [93]. These models can be combined with tissue growth simulations to determine trade-offs between lattice mechanical and biological performance [94]. Generally, these are opposing trade-offs due to the need for high relative density to improve stiffness, with low relative density to improve tissue growth density and nutrient transport. Due to the complexity in trade-offs, simplified models are useful to characterize trends and identify high-performing candidate designs prior to using more expensive modeling and optimization techniques to finalize designs for specific applications.

## 5. Applications

There are diverse engineering application areas enhanced by AM's capabilities for novel materials, complex optimized geometries, and rapid design iterations. The use of DfAM enables the creation of efficient structures for load-bearing applications relevant for the aerospace, automotive, and construction industries in which minimizing weight is crucial. Application-specific tailoring is particularly beneficial in food and medical applications in which design performance is dependent on each person's individual needs. Novel AM materials, such as the combination of soft and magnetoresponsive polymers, enable the creation of new engineered systems such as mobile tensegrity robots. Here, the state of the art in these application areas (Figure 8) is briefly reviewed while highlighting how DfAM may benefit future design innovations. A table is provided at the end of the section that highlights the relevant materials and processes for each application area considered.

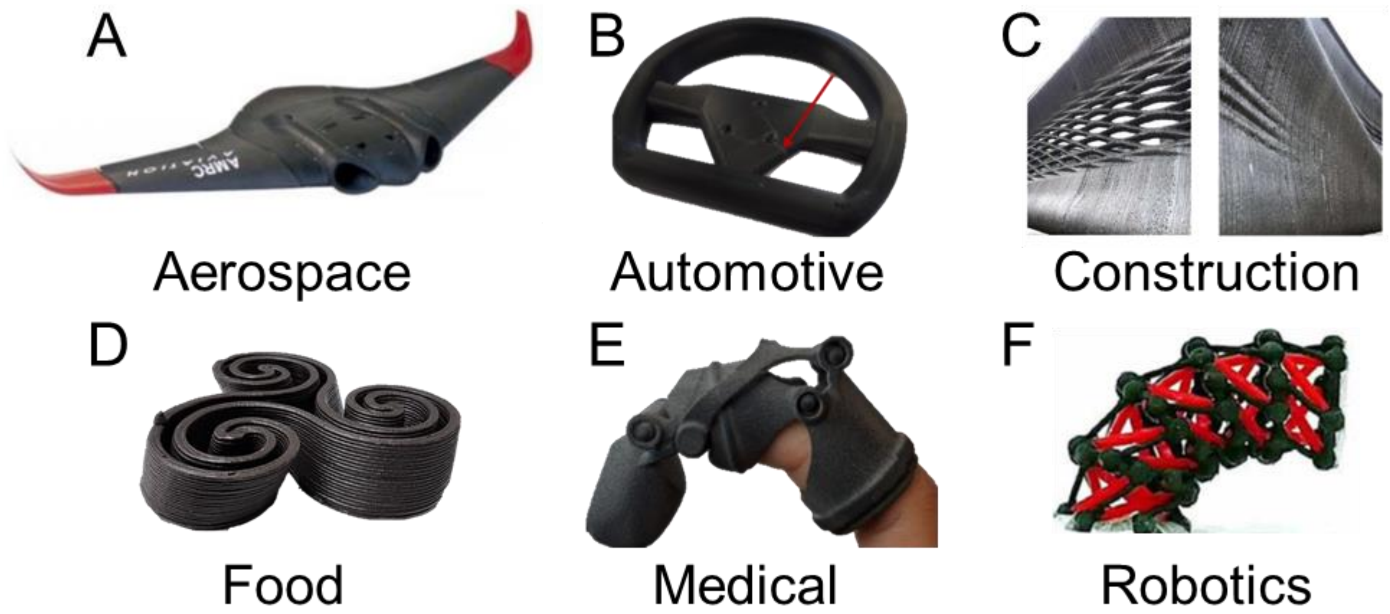


**Figure 8.** Representative innovative AM applications in diverse fields demonstrating (**A**) an unmanned aerial vehicle [95], (**B**) a lightweight steering wheel [96], (**C**) bridge construction [97], (**D**) a chocolate printed geometry [98], (**E**) a finger prosthetic [13], and (**F**) a soft tensegrity robot [99]. Images adapted with permission.

### *5.1. Aerospace*

AM technologies have high relevance in aerospace applications since they provide high mechanical efficiency for high-strength low-weight systems favorable for flight. FDM technology has been applied for printing wings and/or fuselages for small remote control (RC) and unmanned aerial vehicles (UAVs) due to its low machine/material cost and high print speed/quality [100]. Parts for UAVs were assembled with the aid of glue and carbon rods for positioning, while support material was removed with pliers. Printed planes performed well in thermal soaring and high-speed glides but required further work for integrating airbrakes and reducing pitching-up effects. Fixed-wing UAVs have been successfully built from ABS materials that required less than 24 h to print all parts for the airframe (Figure 8A) [101]. Studies on process parameters recommended that layers with long contours aligned with the loading direction provided the greatest mechanical performance [102]. When considering AM in the aircraft industry, fuzzy systematic approaches have identified five critical factors for its success: (1) cost effectiveness, (2) special demand capabilities, (3) part printability, (4) a lack of manufacturing technologies, and (5) the size of the local maintenance market [103]. These considerations highlight that, beyond the design itself, logistics and market demands play an important role in the success of AM technologies.

AM has also been investigated for space applications, including the use of microsatellites. Microsatellites perform functions of earth observation, service, and on-orbit inspection and, due to their low volume production, may benefit from customized AM designs [104]. AM is suitable for creating heat shields for microsatellites using SLM processes, and many companies are fabricating relevant parts in rocket engines, solar panel supports, and valves suitable for use in space. AM may be suitable for Moon or Mars colonization due to its capabilities for using localized resources for construction without the need for space transport [105]. For instance, suitable sulfur concretes for Martian habitats have been created using microwave processes combined with FDM for casting. A comparison of suitable technologies between AM and casting methods for lunar regolith simulants has demonstrated ranges of compressive strengths between 2 to 31 MPa [106]. These trade-offs highlight the need for DfAM considerations for these applications to ensure that the optimal processing approaches are realized to reach the desired design capabilities.

### 5.2. Automotive

The automotive sector is another growing application area of AM, which is contributing via rapid prototyping, tooling creation, and the production of finished components [107]. Using AM, designers can create simple interior elements for a dashboard or fabricate scale models of entire cars. The technology saves time during prototyping by significantly lowering costs for manufacturing, leading to improved agility and reduced prices for the company. FDM printing using PLA materials has demonstrated success for rapid prototyping deep drawing tools for automobile parts manufacturing [108]. Several printers, material compositions, and processing parameters were varied to fabricate the drawing tools. Tool wear was measured using digital image correlation principles, and printing parameters and materials capable of safely producing a minimum batch of 100 parts were found. AM has also been used to improve sustainability in the automotive sector by promoting a circular economy for scrap metal [109]. A sequence of metallurgical operations was proposed to carry out circular economy component manufacturing that included steps for (1) milling, (2) physical–chemical treatment, (3) 3D printing, and (4) mechanical tests for validation. Prior to the establishment of the circular economy, further research is necessary for empirical validation with equipment and an assessment of financial feasibility.

Lattice structures are advantageous for automobiles and have been considered for use in electric vehicles to protect the battery pack against impact loading [110]. Lattices with high energy absorption can improve a vehicle's crashworthiness, which is a measure of a vehicle's ability to absorb energy from a collision. One proposed bio-inspired concept used a multi-layer approach to protect the battery by combining aluminum and steel parts that provide differing structures and functions for crash impacts throughout a hierarchical system. Topology optimization has been applied for AM parts in cars for weight reduction, which was demonstrated by redesigning a suspension arm [111]. A static analysis of suspension arm models before and after optimization demonstrated that topology optimization reduces stress and weight, with results dependent on a lattice's unit cell type. Weight reduction has been conducted by altering the infill of FDM-printed parts for automobiles, which is demonstrated by an optimized steering wheel example in Figure 8B [96]. During optimization, twelve different infill configurations were experimentally tested under tensile and flexural loading, which revealed that their elastic moduli ranged from 0.74 to 1.80 GPa, while their yield strength ranged from 15.3 to 30.7 MPa. These results demonstrate the wide-ranging performance of AM parts and the need for DfAM to consider and evaluate variations in designs to determine optimal configurations for applications.

### 5.3. Construction

AM is growing in prominence in construction applications due to advancements in printable concrete materials that enable automated fabrication for large structures that would otherwise require extensive human labor. Researchers have created complex walls fabricated from two polyurethane foams encased in a third wall of concrete [112]. The concrete consisted of CEM III cement, limestone filler, sand, gravel, water, and a set accelerator. The concrete was directly pumped to flow easily without any need for vibration. A robotic printer was used for construction to produce a finished house with 95 $m^2$ surface area built on-site that housed one family in Nantes, France. Another study using a self-developed printer that constructed structures in Guangzhou, China processed materials of C25 ready-mixed concrete with 5 to 15 mm coarse aggregate [113]. Large-scale construction has also been facilitated for on-site printing in Dresden, Germany using cement materials [114]. The concept of CONPrint3D was proposed, which adapts concrete 3D printing to current trends in architecture and structural design, provides a maximal use of common construction machinery, uses concrete compositions aligned with existing standards, and has printheads for construction with suitable surface quality and precision. The printer has demonstrated successful construction for a variety of materials and designs.

Concrete bridges have been 3D printed with certification for public use in Eindhoven [115], which went through a sequence of testing to determine safe mechanics prior to use. The construction of 3D-printed bridges has also been successfully completed and tested using metal materials with a wire and arc additive manufacturing method (Figure 8C) [97]. The bridge has a 10.5 m span, is suitable for walking and was validated by testing, analysis, and verification steps. Experiments were conducted to first test the handrails, followed by the substructures with handrails, and finally the completed bridge with its deck welded to its serviceability limit. FE simulations were used to provide further insights for the structural response, load-bearing capacity, and long-term health of the printed structure. In further uses of concrete, digital design-to-manufacture processes have been used to create a post-tensioned concrete girder with a novel topology and shape optimization procedure [116]. Experimental methods were used to investigate the girder's load-carrying capacity, which demonstrated that the optimized printed structure had a significant material reduction. Material reduction is favorable in construction applications due to the decrease in cost and environmental impact.

Metal printing is desirable for construction due to its high quality and resource efficiency [117]. Sustainability is particularly important for construction since it is responsible for a large share of the world's carbon footprint. The high strength of metals, combined with DfAM methods such as topology optimization, enable a reduction in material use compared to traditionally manufactured parts while also facilitating rapid construction and customization. Other materials, such as cob and concrete, have also been assessed for their environmental impact. A comparison between the materials found trade-offs: Concrete had a higher overall environmental impact when considering factors such as global warming potential but less impact on land use and resource scarcity [118]. Further studies in DfAM for environmental impact are essential to optimize sustainability in construction, particularly in determining the impact of the materials themselves, the energy used for processing, and further logistical considerations such as transport.

### 5.4. Food

Food printing is an emerging area in AM that enables the directed deposition of foods to create appealing shapes with personalized nutritional profiles. The most common type of printing for food is extrusion, which is suitable for soft materials. A DfAM study on food printing created custom food inks by combining pureed pumpkin with corn starch or guar gum materials to alter the material's rheological properties [119]. The results found that a formulation with 4% guar gum added by weight provided the most accurate print for a three-dimensional squirrel design. Further trade-offs in printability, texture, and sensory properties have been investigated for mashed potatoes fortified with protein or lipid materials to improve nutrition and/or taste [120]. The results found that added butter improved the sensory properties of taste, mouthfeel, smell, and visual appeal, whereas added pea protein reduced sensory appeal while reducing calories and increasing protein. The use of a non-conventional cricket powder improved the protein content of the food while decreasing sensory appeal. 3D food printing is extendible to diverse foods, such as mimicking the mechanical properties of apple tissue with plant-based ingredients to create innovative cereal-based snacks [121]. Genetic algorithms and response surfaces have been used to optimize the printing of a chicken gel [122], which demonstrates the use of DfAM principles to create novel foods.

A key advantage for printing foods over conventional manufacturing processes is the possibility to create complex shapes with geometries that appeal to consumers [98], as demonstrated with the chocolate print in Figure 8D. The study determined fabrication constraints for chocolate and marzipan printing materials and assessed their capabilities for printing complex features, such as overhangs. The study created designs of varied complexity that were rated by participants who preferred the most complex shapes enabled by AM. The fabrication of appealing shapes can promote healthy eating practices, such as creating illusions with foods to look larger while retaining a fixed amount of calories [123]. The improved aesthetics of food can also increase the adoption of healthy foods that consumers are reluctant to eat otherwise [124], especially when combined with further strategies such as serving foods in facilitating environments or social structures. These strategies highlight the need to consider DfAM principles beyond just improving printability since social factors also play a key role in the success of AM designs.

*5.5. Medical*

AM technologies are well suited for medical application due to their customizable geometry that enables the design and fabrication of parts specifically tailored for patients. Prosthetics are a prominent application for AM that could benefit the approximately 3 million people across the globe that have upper-limb amputations [125]. Flexibility for prosthetic hands has been achieved by fabricating soft joints and supporting body-powered movements with non-elastic cables for flexion. Powder bed fusion has been used to create components for integrated prosthetics that include lattices for mechanical efficiency, springs for energy absorption, and non-assembly mechanisms to support movement [13]. An example finger prosthetic is provided in Figure 8E, which was constructed via a series of design, fabrication, and assessment steps to determine printable dimensions and tolerances for constructing functional mechanisms. Orthopedic solutions are another area for AM designs to aid patients, especially by computational engineering processes to configure structures for unique patient needs [126]. Such solutions reduce the labor requirements for creating customized solutions while also improving fit and compliance for patients. There is also a possibility for extending AM designs to orthopedic footwear, which is a prominent issue for patients with diabetes [127]. Medical solutions can benefit from the ubiquity of lattice structures in AM [128], which enable tailorable and anisotropic solutions for functioning in relation to the uneven forces and complex geometries of the human body.

Regenerative medicine applications benefit from AM designs for tissue scaffolds that are mechanically efficient and tailorable. Tissue scaffolds, such as those for bone, have mechanical and biological trade-offs that are often in conflict. Scaffolds have been created using DLP printing processes to produce hierarchical structures using truss-based unit cells for mechanical efficiency while providing large voids to support the biological growth of blood vessels [129]. The structures were tuned using a combination of computational design approaches to generate hierarchies and finite element analysis to evaluate mechanical stiffness. Further computational design approaches for tissue scaffolds have used voxel-based simulations to predict tissue growth in unit cell structures that were validated with in vitro biological experiments [130]. Lattice structures enable the creation of tunable geometries to adjust surface area to provide more places for tissue seeding while providing curvature that is necessary for three-dimensional growth. Open-source libraries of tissue scaffolds have also been created using lattice structures to facilitate multi-scale and multi-material AM designs [131]. The libraries benefit from enabling systematic parameter variations to generate solutions and mapping to compare design trade-offs. Advances in fabrication, such as dual extrusion printing, have enabled the regeneration of tissues with high aesthetics and shape retention [132]. In vitro and in vivo trials were conducted that demonstrated complex bioprinted scaffolds could facilitate nipple–areola reconstruction. These solutions highlight the practicality for AM solutions in medicine, in which continued design research can enable the creation of algorithms for tuning structures for patient-specific needs.

*5.6. Robotics*

AM has become a key technology in the fabrication of robotics, particularly for soft robots, by providing capabilities for printing materials with large deformations and varied functionalities [133]. Soft robots are a new generation of robots that may cooperate with humans or traverse constrained environments, such as steering through narrow environments. The primary materials for soft robots are fluids, gels, and functional polymers that were traditionally created with molds and are now being replaced with faster and more reliable AM technologies. For instance, AM-fabricated hydrogel actuators have been printed for use in jellyfish soft robots [134]. Researchers conducted compression testing to evaluate the gel actuators with normalized trade-offs between length, contraction, pressure, and volume as key design criteria. Tensegrity structures, which are a combination of stiff struts and flexible tendons, have been used to create soft robots that function with the aid of magnetic forces for actuation (Figure 8F) [99]. The robots were created using smart materials with no need for further assembly. Printers with dual print heads created a sacrificial mold for the tendon material fabricated with PVA while struts were printed with PLA. After printing, polymeric smart materials were injected into the sacrificial mold. The robot was able to conduct various transformations in response to torsional, compression, and shearing stresses with designers able to predict outcomes using simulations informed by experiments.

Robotic applications are well suited for medicine, in which tactile sensing has been enabled by AM-printed soft pressure sensors [135]. Several materials including TPU, conductive PLA composites, and graphite ink were used to develop five different variations of sensors fabricated with a modified 3D printer capable of outputting diverse inks, pastes, and polymer materials. The highest performing touch sensor formed with silver paint and soft rubber exhibited a stable response with a sensitivity of 0.00348 $kPa^{-1}$ for pressures less than 10 kPa and a pressure of 0.00134 $kPa^{-1}$ at higher pressures. Surgical robots have been created for patient-specific applications, which is advantageous for operations such as treating lesions of different sizes and shapes for the removal of deep intracranial brain tumors [136]. The customized AM robots can reach a surgical site by avoiding or minimizing damage to critical brain structures. Although the technology for customizable surgical robots is promising, there is a need for further research to improve sterilizability, biocompatibility, and stiffness. Multi-material robots in medicine have also been proposed for on-demand drug delivery that benefits from the design freedom offered by AM [137]. Digital design optimization has been used to create a robot divided into parts that mimicked the movements of an inchworm with modeling supported with multiphysics software to inform design decisions. The robot exhibited linear and turning locomotion powered by magnets, which demonstrated its capabilities for traversing the inside of the human body, such as traveling through the lungs. These works highlight the potential for DfAM to further improve capabilities for robotics, in which new advances could considerably improve robotic functionality in healthcare.

### *5.7. Applications Summary*

Application areas commonly use different additive manufacturing processes and materials according to their specific needs. Table 1 summarizes the materials and processes for each surveyed application that provides designers with starting points to consider when approaching DfAM in these areas. The table includes material used directly during the AM process and, for some cases, such as Martian habitats, materials that are used to form final parts from AM casts. By referring to the table, designers may recognize the current state of the art and gaps in which the consideration of further applications, materials, and processes open opportunities for innovation.

**Table 1.** Highlighted materials and processes considered for each application area.

| Area | Applications | Materials | Processes | References |
|---|---|---|---|---|
| Aerospace | Aircraft, UAVs, air ducts, wings, turbocharger blades, spare parts, prototyping, and rapid tooling | PLA, ABS, PET, nylon, carbon fiber, steel, titanium, and custom resins | FDM, SLS, DMLS, and SLA | [95,100–103] |
| Aerospace | Microsatellites, heat shields, magnetic shields, and spacecrafts | PEEK, PEKK, PEI, polyamide, carbon fiber, $AlSi_{10}Mg$, and molybdenum | FDM, SLM, and DMLS | [104] |
| Aerospace | Lunar and Martian habitats | Sulfur, magnetite aggregate, silica sand, regolith, and geopolymer composites | Extrusion, powder jetting/fusion, and vat polymerization | [105,106] |
| Automotive | Steering wheel, suspension arm, interior elements, drawing tools, and replacement parts | PLA, ABS, metal powders, and composites | FDM and metal powder printing | [96,107–111] |
| Construction | Bridges, walls, houses, girders, joints, and stiffeners | Concrete, cob, polymer-foam, glass fibers, geopolymers, and metals | Large-scale extrusion, robotic printing, and wire and arc | [97,112–118] |
| Food | Health treatment, weight loss, consumer appeal, and sustainable food production | Cereals, fruits, vegetables, chocolate, marzipan, meats, dairy, gels, and insects | Extrusion and powder binding | [98,119–124] |
| Medical | Prosthetics, medical devices, footwear, implants, orthopedics, and prototyping | PLA, TPU, PETG, carbon fiber, nylon, and stainless steel | FDM, SLA, and PBF | [13,125,126,128] |
| Medical | Tissue scaffolds and interbody spinal cages | PLA, PCL, PEEK, TCP, methacrylates, titanium, biomaterials, and living cells | Extrusion, SLA, DLP, and SLS | [129–132] |
| Robotics | Soft robotics and actuators | ABS, silicone, polyurethane, hydrogels, nylon, varied elastomers, smart composites | FDM, SLA, inkjet, SLS, Multi-material processes, light-scanning gel printer | [99,133,134,137] |
| Robotics | Surgical robots and robotic prosthetics | PLA, ABS, PVA, TPU, methacrylates, polymer resins, multi-material, and metal paste | FDM, SLS, SLA, inkjet, and multijet | [135,136] |

## 6. Outlook

As AM continues to provide innovations across diverse industry sectors, there are also many new opportunities in research and development for applying the technology. Figure 9 highlights four areas of interest, including innovation services, bio-inspired design, robotic fabrication, and machine learning, that are relevant to the advancement of AM using DfAM frameworks.

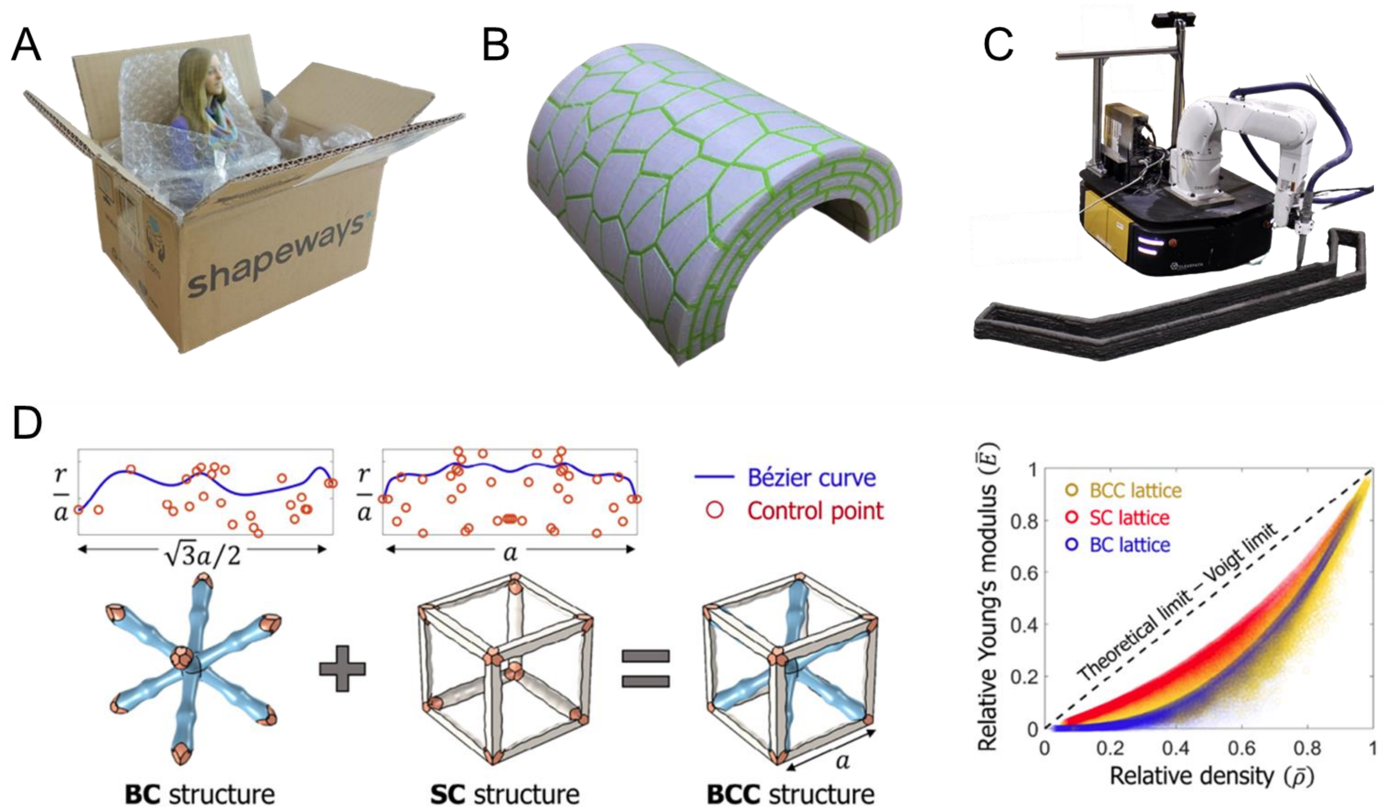


**Figure 9.** Future outlook in highlighted areas for DfAM, including emerging (**A**) innovation services [138], (**B**) bio-inspired design [139], (**C**) robotic fabrication [140], and (**D**) machine learning approaches [141]. Images adapted with permission.

*6.1. Innovation Services*

The emergence of AM technologies is producing new services and maker spaces that encourage widespread innovation by lowering the barrier required to design and fabricate parts. Outsourced 3D printing services are companies that receive digital designs primarily via online orders from consumers and then fabricate and deliver prints, as demonstrated in Figure 9A for a customized figurine [138]. A reason consumers prefer outsourced printing services over at-home fabrication is due to the higher costs associated with printers that fabricate with multiple materials and provide high-quality finishes for personal use. Makerspaces, in contrast, provide designers access to shared equipment and materials at a low cost that encourages more hands-on innovation. Makerspaces provide environments for these designers to create and fabricate who otherwise would not have the resources to do so, thereby democratizing innovation [142]. Makerspaces can combine resources in new ways and, by providing open access, facilitate the creation of designs that may otherwise never be realized. Although a bottom-up approach is often employed in the organization of makerspaces, a more structured approach can improve the commercial viability of designs. One interesting example of AM for commercial products is the creation of nail-art technology to produce diverse patterns with varying aesthetic appeal for consumers [143]. The technology provides precision control with a resolution below 50 microns using various colors that are printable on demand. Such technologies and approaches have viability in other sectors, such as when overlapping with aesthetics for the controlled release of drugs, which could improve the appeal of vitamins for children.

Innovations enabled by AM also have great potential to influence sustainability globally and play a large role in the advancement of Industry 4.0 by interfacing with the Internet of Things. As AM replaces traditional manufacturing processes in obvious metrics such as material efficiency and mechanics, there is a need to consider less obvious metrics such as AM's impact on sustainability [144]. AM is sustainable with less processing steps to reduce energy use, waste, and emissions while also requiring little post-processing. The technology is also sustainable societally by enabling automation in developed countries and lowering the barrier for skills use in under-developed countries. AM's ability to support mobile phone production has been examined to determine its effects on sustainable supply chains by considering the interactions between printer availability, consumer attitudes, and entry to market [145]. The effects of AM technologies for small firms were investigated and suggest that there is an unmet need for social sustainability that could be driven by AM to form new business models. Industry 4.0 is poised to automate manufacturing and data across products, which can help AM technologies become interconnected and respond to customer requirements more efficiently with smart manufacturing [146]. AM can support Industry 4.0 directly with applications or indirectly with processes in which interactive experiences with consumers, such as the use of augmented reality, can result in the tangible construction of high-value designs. Smart materials are also possible to construct with AM for integration, which is expected to gain wider prominence as Industry 4.0 technologies advance [147]. Application areas that could benefit from further AM research include beacon technology for signals with unique identifiers, cyber-physical systems for maximizing product fabrication rates, and big-data-driven manufacturing that informs decision making across a product's entire lifecycle.

### 6.2. Bio-Inspired Design

Bio-inspired design relies on mimicking structures, behaviors, and/or functions of natural systems to improve engineering systems, often by increasing efficiency. Protheses have been improved by bio-inspired workflows that incorporated steps of 3D imaging, modeling, and optimization to design and fabricate a transtibial prosthesis [148]. The designs used a combination of FE analysis with topology optimization to create foot geometries printed with nylon materials. When compared to traditional prosthetics, these designs lowered the average cost by 95%, the weight by 55%, and the production time by 95%. Novel viscoelastic dampers with mechanical interlocks have also been developed using additive manufacturing with bio-inspired principles [149]. The dampers were designed with a jigsaw-like mechanism informed by various natural systems including turtle shells, skull suture joints, and frost crystal fractals. The device had a steel hard phase and a TPU soft phase, which were configured using experimental and computational methods for testing and validation. DfAM principles were used to investigate loading rates and patterns of specimens that found that density greatly affects the design's mechanical response.

A bimaterial structure that mimics nacres' multilayer structure has been developed by observing natural nacreous shells and mapping features, such as their dome-shaped structures (Figure 9B) [139]. The design was generated with Voronoi tessellation and printed using ABS plastic for impact resistance, while softer TPU material was selected for bonding. The design's performance under impulse loads was assessed numerically and demonstrated that cohesive and adhesive bonds within the nacre mitigated energy that reduced damage to the composite. Bio-inspiration has also been used to mimic plant cell morphology, which facilitates water and mineral transport to enable powder removal from printed parts such as lattices [150]. Powder removal is difficult in lattice structures due to their complex network of interconnected pores, which can be improved by adjusting unit cells' centers and the size of ventilation holes that promote material removal. Bio-inspired femoral stems have benefitted from an efficient lattice design [151], which reduced stress shielding by 28%, thereby promoting better long-term outcomes for bone health.

Further cases in bio-inspired design have used honeycomb structures to achieve efficient mechanics that mimic natural structures at micro- and macroscales [152]. Hierarchy was introduced by altering hole positions, orientations, and shapes, which resulted in tunable mechanics. Mechanical testing results demonstrated that hierarchical honeycombs with circular holes performed best compared to those with square or hexagonal holes for stiffness, strength, and energy absorption metrics. Zero Poisson's ratio structures have also been investigated with combined soft and stiff unit cells for controlled deformation patterns during compression [153]. When novel bio-inspired designs were compared to auxetic materials, they possessed an improved ability to remain stable while simultaneously providing high energy absorption. Bio-inspired principles of lattice designs have also been applied towards scooter decks for enhanced performance using honeycombs [154], as well as for water sports boards [155], which demonstrates the versatility for such structures across application areas. Future research has great potential for uncovering useful structures and functions in natural systems, in which rapid testing and creation can occur with AM to further improve the performance of engineered systems.

### 6.3. Robotic Fabrication

Robotic fabricators are systems that aim to move beyond the limitations of current AM processes by incorporating robotic movements and control during fabrication. One effort combined a six-axis robotic arm system with hybrid extrusion–photopolymerization to enable the fabrication of layerless lattices [156]. Octet lattices were printed with processing phases including nozzle approach, pre-extrusion, extrusion, post-curing, nozzle removal, and nozzle travel, which were facilitated by the robotic arm. The failure mechanisms of the hybrid printed lattice compared to lattices produced using DLP resulted in a higher maximum load achieved with a smoother load–displacement response. Parametric programming for robots has been used to produce large-scale steel constructions [157]. Programmed robots have capabilities for printing with steel, concrete, or clay, and the parametric programming approach facilitates automatic calculations of z-coordinates, requires small memory capacities, and enables the efficient scaling of objects. Robotic fabrication has been improved with error modeling and optimization via analytical derivation and experimentation [158]. The process is necessary to minimize the maximum trajectory execution error in a computationally efficient manner to support the six degrees of freedom of motion necessary to print complex objects.

Mobility is essential for fabrication robots so that they may print structures on large scales. One mobile robotic printing system was built using components of a mobile base, a six-degree freedom manipulator, a 1 cm nozzle, and a hose/pump system to enable material flow (Figure 9C) [159]. The robot was able to construct a structure of approximately 200 cm by 45 cm by 10 cm, which was much larger than the 87 cm reach of the robotic arm used to deposit the material. Ten layers of printed material were deposited in about nine minutes using a nozzle speed of 10 cm/s. Large-scale construction is also possible by coordinating the efforts of multiple collaborative robots [160]. The use of multiple robots was coordinated by the optimized scheduling of tasks that begin with a segmentation process to sub-divide a design into smaller pieces assigned to each robot. Since interference between robot paths can lead to collisions, an approach was developed that divides printing areas into safe and interference zones, with only one robot acting in the interference zone at a time. There are many research opportunities and challenges for further improvements in robotic fabrication, with context, requirements, materials, and mechanics identified as key criteria to consider [161]. By further developing robotic fabrication technologies it is possible to repair, renovate, and retrofit constructions with novel AM designs, such as curved walls and intricate structures that enable high aesthetics and function in future applications.

### 6.4. Machine Learning

Machine learning support for AM is gaining prominence for improving processes and design using algorithms and statistical analyses [162]. Recent applications in machine learning for AM have incorporated reinforced, unsupervised, and supervised learning. Supervised learning, which requires training, is suitable for regression and classification tasks that enable closed loop control and defect detection. Unsupervised learning, which identifies patterns within datasets, can provide capabilities for clustering and principal component analysis. Reinforcement learning is suitable for improved AM by sequentially forming decisions based on reward signals. All types of learning have their own inconsistencies and biases that designers must consider.

Machine learning has been applied in areas such as medical diagnoses, the processing of images, and associated learning while also optimizing AM processing parameters [163]. Incorporating machine learning in DfAM is advantageous as there is little upfront work required for establishing equations, and the approach is well suited for managing data of highly complex design problems. Multi-material process parameters have been optimized using artificial neural networks for multi-material FDM printing that were experimentally validated via mechanical testing [164]. The artificial neural network model was trained with data from experimental designs and used in tandem with a genetic algorithm to determine optimized parameters that increased tensile strength. Machine learning has also been used to detect defects in real time using a convolutional neural network [165]. The method was built from image classification with computer vision to check the quality of parts using an integrated camera. The approach represents an initial step for improving the consistency of printed parts using real-time parameter adjustments, which is one of the largest open problems for improving AM outcomes.

Machine learning can improve the design of AM parts, such as architected materials for improved mechanical efficiency [141] (Figure 9D). A process was used to propose unit cells of different topologies, superimpose them, and assess their mechanical properties such as Young's modulus relative to a theoretical limit based on the Gibson–Ashby model. Beam shapes were optimized while retaining a fixed relative density of lattices. Neural networks were trained to understand the relationship among high-dimensional design inputs and mechanical outputs that resulted in modulus and density predictions at a much faster rate than FE analysis. Artificial neural networks have also been used for patient-specific optimization for spinal disc applications [166]. The approach was combined with topology optimization to size lattice components for fast convergence that was facilitated with design space reduction by optimizing unit cell distributions with a predefined grid. Machine learning has also been used to design multi-material AM tissue mimics using neural networks to consider complicated combinations of design parameters [167]. Further AM applications in medicine have used machine learning to produce pharmaceutical products fabricated via hot melt extrusion and FDM techniques that necessitated an integrated computational and experimental approach to generate and understand data [168]. These cases highlight the need to integrate steps across all phases of DfAM to achieve innovations while also demonstrating how new advances in machine learning can greatly enhance AM outcomes.

## 7. Conclusions

This review provided a recent survey of DfAM advances in the context of Fabrication, Generation, and Assessment phases, which are the foundation for engineering design innovation. Each of these phases plays a pivotal role in the design process for maximizing the use of AM technology by implementing novel materials, optimizing designed structures, or providing validated models to support improvement in future iterations. Engineering innovations were highlighted in diverse areas, including the creation of Martian concrete for in situ construction, texture modified foods for personalized nutrition, a sustainable circular model for automotive scrap, and soft tensegrity robots with walking capabilities. The reviewed DfAM phases facilitated a discussion for future research opportunities, such as the creation of innovation services that democratize design, bio-inspired design methods for high-performance structures, robots with AM capabilities to fabricate large-scale designs, and machine learning for design optimization. The culmination of continued research in these areas highlight promising opportunities in DfAM, in which further advancements have great promise for driving wide-spread engineering innovation.

Key implications and considerations for future work are as follows:

- **Fabrication:** There are diverse materials and printing processes currently available, with research innovations leading to new material capabilities such as strong superalloys, biocompatibility, and magnetofunctional materials. Many of these materials are limited by suitable printing processes and fabrication constraints. Future work could consider expanding the available AM design space by improving printing time and accuracy across scales as new printable materials emerge.

- **Generation:** Due to the complex AM design space, it is challenging to configure optimal designs tailored for specific applications. Human designers are necessary to generate innovative solutions but have difficulty overcoming biases and barriers, while computational design requires a well-defined search space that limits innovation. Future work could consider intelligent computational methods that work with, or mimic, humans while incorporating mechanisms to reduce biases during searches.
- **Assessment:** There is often a mismatch between the ideal digital design and the as-fabricated design that can affect dimensional accuracy and mechanical performance, especially near the resolution limits of a printing process in which innovation occurs. Future work is necessary to better characterize how different printing processes affect design accuracy and mechanics, in addition to understanding the complex failure mechanics of AM parts based on their topological configurations.
- **Applications:** AM innovations are prevalent across numerous application areas that benefit from the diversity of materials and processes available, especially regarding polymers and metal printing. Soft material printing, such as that for food and tissue engineering, are emerging areas with a need for applying well-established DfAM principles to characterize new design opportunities. Across all domains, there is a need for advancing DfAM to more efficiently tailor and optimize designs to fully leverage AM's capabilities for customization.
- **Outlook:** Emerging areas in DfAM include considerations of on-demand printing services and using the broad capabilities of DfAM to enable new functionality via bio-inspiration. Robotic printing processes are enabling large-scale design and more efficient printing, while machine learning capabilities provide promise for automated design tailoring and integration across DfAM phases. Further advances in these fields provide great opportunities for researchers to impact AM and drive new innovations.

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