



Additive Manufacturing Techniques for Rapid Prototyping of Mechanical Components

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Peer Review Information	Abstract
<i>Submission: 13 Jan 2020</i> <i>Revision: 27 Feb 2020</i> <i>Acceptance: 14 March 2020</i> Keywords <i>Additive manufacturing, Rapid prototyping, FDM/FFF, Stereolithography, Selective laser sintering</i>	Additive manufacturing (AM) has become a central rapid-prototyping route for mechanical components because it converts a digital model directly into a physical part without dedicated tooling. This methodology paper establishes a structured framework for comparing four widely used AM routes—fused deposition modelling/fused filament fabrication (FDM/FFF), stereolithography (SLA), selective laser sintering (SLS), and metal powder-bed fusion represented by selective laser melting/direct metal laser sintering (SLM/DMLS). The proposed method uses common CAD benchmark components, controlled file preparation, process-specific but comparable build settings, standardized dimensional and surface measurements, and a decision matrix based on accuracy, build time, material capability, post-processing demand, cost, and functional performance. Published research up to 2020 is used to define process behaviour and realistic comparative trends. The synthesis indicates that FDM is the most economical and accessible route for form-and-fit prototypes, SLA provides the highest visual detail and surface quality for polymer models, SLS is advantageous for support-free functional polymer components, and SLM/DMLS is preferred when the prototype must reproduce metallic strength and end-use behaviour. The proposed methodology helps mechanical designers select a prototyping process according to the functional purpose of a component rather than relying on a single performance criterion.

Introduction

Rapid prototyping shortens the product-development cycle by allowing a designer to evaluate geometry, assembly, ergonomics, and in some cases functional performance before committing to conventional tooling. Additive manufacturing builds components layer by layer from digital geometry and therefore removes many geometric restrictions associated with machining, casting, and moulding. It is especially attractive for low-volume mechanical prototypes, customized fixtures, complex internal passages, topology-optimized structures, and components that require repeated design iterations. The broad process family includes material extrusion,

vat photopolymerization, powder-bed fusion, binder-based processes, directed-energy deposition, and several hybrid variants. Reviews of the field emphasize design freedom, reduced tooling dependence, and the ability to manufacture complex geometries, while also noting limitations in productivity, repeatability, surface integrity, and final mechanical-property control [8,11].

The suitability of an AM process for a mechanical prototype is not determined by resolution alone. A visual housing model may prioritize surface finish and dimensional detail, whereas a snap-fit bracket or gear may require stiffness, toughness,

and dimensional stability. Metal prototypes may need thermal resistance, fatigue strength, or realistic mass. FDM/FFF is widely used because of low machine and material cost, but deposited roads create direction-dependent strength; early experimental work on ABS and later studies of open-source printers demonstrated significant effects of build direction, raster architecture, and material selection on mechanical response [1,7]. SLA can produce fine features and smooth surfaces by selectively curing photopolymer resin, and its high fabrication accuracy has long made it useful for detailed models [3]. SLS fuses polymer powder in a powder bed and can build complex geometries without dedicated support structures; polymer selection, powder condition, temperature control, and laser energy strongly influence density and properties [4]. For metallic prototypes, laser/electron-beam powder-bed processes can produce near-net-shape engineering alloys, but they demand stricter thermal-process control and generally more post-processing [5,6,10,12].

Accordingly, this paper develops a step-by-step methodology for comparing AM techniques specifically for rapid prototyping of mechanical components. The objective is to create a repeatable selection procedure in which the same design intent is evaluated across multiple AM routes. The comparison is organized around geometry fidelity, build time, post-processing, cost, material/functional capability, and measured mechanical quality. Design-for-additive-manufacturing guidance is incorporated because build orientation, support strategy, feature size, part consolidation, and process constraints must be considered during selection rather than after a part has already been designed [9,13].

Literature Review

The development of rapid prototyping into modern additive manufacturing has been accompanied by increasing emphasis on the relationship between process parameters and mechanical performance. Ahn et al. [1] characterized anisotropic properties in FDM ABS and showed that raster orientation and air gap are among the parameters that govern tensile behaviour. This is fundamental for mechanical prototyping because a component that appears dimensionally correct can fail prematurely if load paths are aligned with weak interlayer interfaces. Tymrak et al. [7] later reported tensile properties for ABS and PLA parts produced on open-source printers under realistic operating conditions, confirming that desktop material extrusion can

provide useful engineering strength but that results depend on material and process consistency.

Photopolymerization offers a different balance of attributes. Melchels et al. [3] reviewed stereolithography and identified its high accuracy and wide geometric capability as major strengths. Although the review focused on biomedical applications, the process characteristics are directly relevant to precision mechanical mock-ups, fluidic channels, housings, and master patterns. The principal mechanical limitation is that cured photopolymers may not reproduce the toughness, heat resistance, or long-term behaviour of production thermoplastics. Thus, SLA is often strongest when the prototype objective is dimensional verification, visual inspection, or fine-feature evaluation rather than repeated high-load service.

Powder-bed methods extend the functional range of rapid prototyping. Kruth et al. [2] described binding mechanisms in SLS and SLM, distinguishing solid-state sintering, liquid-phase mechanisms, partial melting, and full melting. Goodridge et al. [4] reviewed laser sintering of polyamides and showed that material properties, powder characteristics, thermal history, and processing conditions determine part quality. SLS is valuable for mechanical prototypes because the surrounding powder provides self-support, enabling complex enclosed or interlocking features and batch nesting. However, the powder-bed route can produce a grainier surface than SLA and may require blasting, dyeing, sealing, or machining when tight surface requirements are imposed.

For metallic components, Murr et al. [5] reviewed laser and electron-beam melting technologies and demonstrated their ability to fabricate dense complex alloy components directly from powder. Frazier [6] described metal AM as a rapidly emerging manufacturing technology while identifying process control, qualification, residual stress, and material-property consistency as critical barriers. Herzog et al. [10] further summarized the mechanisms, materials, and process-property relationships of metal AM, while DebRoy et al. [12] provided an extensive treatment of heat transfer, melt-pool behaviour, solidification, defects, microstructure, and residual stress. These studies show why metallic prototypes demand more rigorous process control than polymer concept models: thermal cycling affects not only shape accuracy but also microstructure and structural performance.

At the system level, Bikas et al. [8] classified AM methods and highlighted the difficulty of process optimization when multiple coupled physical phenomena influence quality. Thompson et al. [9] reframed the problem from simple process capability to design for additive manufacturing, emphasizing opportunities such as part consolidation and geometric complexity alongside constraints such as support, orientation, material, and manufacturability. Ngo et al. [11] reviewed materials, methods, applications, and challenges across the AM field and identified rapid prototyping as one of the technology's core benefits. Finally, Alfaify et al. [13] synthesized DfAM research through 2020 and reinforced the importance of integrating process limitations and design opportunities at the design stage. Together, the literature supports a multi-criteria methodology rather than a single-parameter process ranking.

Methodology

Step 1: Define benchmark mechanical components and requirements

Three representative prototype categories are specified: (i) a mounting bracket containing holes, ribs, and fillets for dimensional and stiffness checks; (ii) a small spur gear/coupling feature for tooth and fine-feature resolution; and (iii) a thin-walled housing segment for surface and assembly evaluation. All models are created in the same CAD system and dimensioned from a common master model. Critical-to-quality dimensions include hole diameter, centre distance, wall thickness, gear-tooth thickness, and flatness. The intended prototype function is classified as visual, form-and-fit, functional polymer, or functional metal. This classification prevents an inaccurate comparison in which a low-cost concept model is judged by the same requirements as a load-bearing metal part.

Step 2: Prepare digital geometry

The CAD models are exported to STL using a fine chord-height tolerance so that tessellation error is small relative to printer resolution. Meshes are checked for open edges, inverted normals, self-intersections, non-manifold surfaces, and unintended thin features. The identical nominal geometry is then imported into each process-specific preparation environment. No geometry is altered between processes except supports, orientation, and process-required compensation. This step is important because DfAM studies show that feature size, orientation, support accessibility, and process constraints influence whether a nominal CAD design can be reproduced successfully [9,13].

Step 3: Select processes and materials

Four process routes are compared: FDM/FFF using PLA or ABS for economical prototypes; SLA using an engineering photopolymer resin for high-detail models; SLS using PA12-type polymer powder for functional support-free polymer components; and SLM/DMLS using an engineering metal such as 316L stainless steel or AlSi10Mg for metallic functional prototypes. The selection reflects distinct process physics: filament extrusion and inter-road bonding in FDM [1,7], photopolymer curing in SLA [3], polymer-powder fusion in SLS [2,4], and full melting/solidification in metal powder-bed fusion [5,10,12].

Step 4: Establish comparable build conditions

Each benchmark is produced in at least three replicates per process when experimental resources permit. Build orientation is selected to balance surface quality, support demand, dimensional stability, and load direction. FDM raster direction is documented because anisotropy can strongly affect mechanical response [1]. SLA support contact is kept away from critical mating surfaces. SLS components are nested with adequate thermal spacing, and the powder-refresh condition is recorded. Metal powder-bed fusion uses the supplier-qualified parameter set, controlled atmosphere, and documented preheat/scan strategy. Typical layer thickness is selected within each machine's normal operating range rather than forcing all machines to use the same layer height, because process physics and material form differ substantially [8,11].

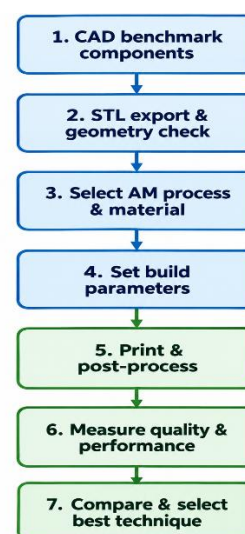


Figure 1. Step-by-step methodology for process comparison and selection.

Step 5: Fabricate and post-process prototypes

All build times are measured from process start to completed machine cycle, while post-processing time is recorded separately. FDM parts undergo support removal and light deburring; SLA parts are washed, support structures are removed, and the prescribed UV post-cure is applied; SLS parts are cooled in the powder bed, excavated, and bead-blasted; metal parts are depowdered, removed from the build plate, and stress-relieved or machined when required. Separating machine time from finishing time is essential because rapid prototyping decisions are driven by total lead time, not printing time alone. Metal AM reviews consistently identify post-processing and qualification as major contributors to final component performance and cost [6,10,12].

Step 6: Measure dimensional, surface, and mechanical performance

Dimensional accuracy is evaluated using a coordinate measuring machine or calibrated digital metrology. For each critical dimension, absolute error is calculated as $|\text{measured} - \text{nominal}|$ and relative error as the absolute error divided by nominal size. Surface roughness R_a is measured on an upward-facing and side-facing surface when suitable equipment is available. Build mass and material usage are recorded from slicer or machine reports. Functional testing includes assembly fit of mating features and, for load-carrying prototypes, tensile or flexural coupons built with the same orientation and parameter set. For FDM, tensile testing is particularly important because apparent part quality does not eliminate interlayer anisotropy [1,7]. For metal powder-bed fusion, density/porosity, hardness, and surface condition should be added when the prototype is intended to represent final service behaviour [10,12].

Step 7: Compare alternatives using a decision matrix

The final process-selection matrix contains six criteria: dimensional accuracy, surface finish,

functional material behaviour, total lead time, post-processing burden, and prototype cost. Each criterion is rated on a five-point scale using measured results and documented process observations. Weighting is assigned according to prototype purpose. For a visual prototype, accuracy and surface quality receive the highest weight; for a functional polymer bracket, strength and lead time dominate; for a metal verification part, material fidelity and dimensional stability are prioritized. This approach follows the broader DfAM principle that process selection should be linked to product requirements and manufacturing constraints rather than to technology novelty [9,13].

1. Experimental/assessment variables

The independent variables are AM technique, material, build orientation, and process-specific layer setting. Controlled variables include the master CAD geometry, inspection locations, nominal dimensions, and acceptance criteria. Dependent variables include dimensional deviation, surface roughness, build/post-processing time, prototype cost, assembly fit, and mechanical response. A process is considered suitable when it satisfies the critical functional thresholds at the lowest practical lead time and cost. Statistical comparison can be performed using mean, standard deviation, and one-way analysis of variance when replicate experimental data are available; otherwise, the framework can be used as a structured engineering screening procedure using literature-supported ranges.

Results

The methodology produces a clear process-application map rather than a universal winner. Table 1 summarizes representative trends reported in the literature and the expected outcome of applying the proposed selection criteria. The ranges are intentionally presented as typical engineering ranges rather than machine-independent specifications because actual values change with machine architecture, material, layer thickness, orientation, and post-processing [4,8,11].

Table 1. Literature-based comparison of major AM techniques for rapid prototyping [2-5,7,10-12].

Technique	Typical layer range	Primary advantage	Main limitation	Best prototype role	Overall RP assessment
FDM/FFF	0.10-0.30 mm	Low cost; rapid iteration; common thermoplastics	Visible layers; anisotropic strength	Concept, fit checks, low-load functional parts	Excellent for economical iteration

SLA	0.025-0.10 mm	High detail and smooth surface	Resin post-cure; material brittleness/aging	Visual models, fine features, master patterns	Best for appearance and precision
SLS	0.06-0.15 mm	Support-free complex geometry; durable PA parts	Higher equipment cost; powdery surface	Functional polymer assemblies and enclosed geometry	Strong balance of function and freedom
SLM/DMLS	0.02-0.06 mm	Near-dense metal; realistic structural/thermal behaviour	High cost; residual stress; machining often needed	Functional metal prototypes and pre-production parts	Best when metal fidelity is essential

For FDM/FFF, the most important result is the trade-off between accessibility and structural directionality. Low material and machine cost make it highly effective for repeated design iterations, jigs, housings, and fit checks. However, Ahn et al. [1] demonstrated anisotropic behaviour in FDM ABS, and Tymrak et al. [7] showed that practical desktop-printed ABS and PLA can achieve useful tensile properties while still displaying process-dependent variability. Consequently, FDM is recommended when rapid learning per design iteration is more important than isotropic strength or premium surface finish.

SLA ranks highest for fine detail and visually smooth prototypes. The photopolymerization mechanism permits smaller layers and precise feature reproduction, which supports dimensional reviews and presentation models [3]. Its limitation for mechanical components is material representativeness: even engineering resins may not reproduce the long-term toughness, fatigue behaviour, or temperature capability of production thermoplastics. Therefore, the methodology selects SLA for appearance-critical and precision prototypes but not automatically for load-bearing qualification.

SLS provides the strongest overall polymer option when geometry complexity and functional handling are required. The powder bed supports overhangs and internal features, while polyamide materials provide practical toughness. Kruth et al. [2] and Goodridge et al. [4] show that fusion mechanism, powder properties, and thermal conditions govern final density and performance. SLS is therefore well suited to clips, ducts, brackets, articulated assemblies, and prototypes with enclosed geometry, provided that its rougher as-built surface is acceptable or can be finished.

Metal powder-bed fusion provides the highest material fidelity for prototypes that must behave

like metallic end-use components. Reviews by Frazier [6], Herzog et al. [10], and DebRoy et al. [12] demonstrate that dense alloy components with complex geometry are feasible, but residual stress, microstructure, porosity, support removal, heat treatment, and machining must be controlled. The selection framework therefore assigns SLM/DMLS to functional metal prototypes only when the value of realistic structural or thermal performance justifies its higher cost and longer finishing route.

Across all four routes, the main result is that rapid prototyping performance is purpose-dependent. Ngo et al. [11] describe the broad AM advantage as the combination of design freedom, customization, and reduced material waste, but the practical benefit appears only when process capability is matched to the prototype objective. The proposed method makes this matching explicit: FDM maximizes low-cost iteration, SLA maximizes detail, SLS maximizes polymer geometric freedom and functional robustness, and SLM/DMLS maximizes metal-property realism. Bikas et al. [8] further support the need for process-aware comparison because multiple coupled physical phenomena prevent simple one-variable optimization.

Conclusion and Discussion

This paper presents a structured methodology for selecting additive manufacturing techniques for rapid prototyping of mechanical components. The procedure begins with a common CAD benchmark and explicit prototype requirements, then controls geometry preparation, process and material selection, build orientation, fabrication, post-processing, inspection, and final decision weighting. The framework is deliberately process-neutral: it does not assume that the most accurate or strongest technology is automatically the best rapid-prototyping option. Instead, suitability is determined by how well the process satisfies the specific purpose of the prototype.

The literature synthesis shows four distinct application zones. FDM/FFF is the preferred starting point for economical design iteration and basic functional validation, provided that build-direction effects are considered [1,7]. SLA is particularly effective for detailed polymer models, surface inspection, and precision geometry because of its photopolymerization accuracy [3]. SLS offers a strong compromise for functional polymer parts and complex support-free geometry, though powder management and surface texture remain important [2,4]. Metal powder-bed fusion is most appropriate when a prototype must reproduce metallic stiffness, temperature capability, or near-end-use behaviour; however, its thermal-process complexity, residual stress, surface condition, qualification requirements, and finishing burden make it less suitable for early low-cost iterations [5,6,10,12]. A major implication is that additive manufacturing should be treated as an integrated design-process system. DfAM research emphasizes that orientation, feature size, support structures, material choice, consolidation opportunities, and manufacturing constraints must influence the design itself [9,13]. In practical product development, a sequential strategy can be efficient: early concepts may be printed in FDM, appearance-critical revisions in SLA, functional polymer verification in SLS, and only the final high-value prototype in metal powder-bed fusion. Such staged use reduces development cost while progressively increasing prototype fidelity.

The methodology also has limitations. Machine-specific parameter windows vary substantially, and the representative comparison in Table 1 cannot replace empirical qualification for a specific printer-material combination. Mechanical properties should be measured using specimens built with the same orientation and thermal history as the target component, and metal prototypes may require microscopy, density measurement, heat treatment verification, and fatigue testing when safety-critical service is involved. Future work may extend the framework with quantitative multi-criteria decision methods, lifecycle cost, energy consumption, in-situ monitoring, and topology-optimization metrics. Nevertheless, the proposed step-by-step procedure provides a practical basis for choosing AM routes for mechanical rapid prototyping using evidence available up to 2020 [8,11].

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