



Additive Manufacturing and 3D Printing Applications in Modern Mechanical Engineering

Adonias van der Velde

Department of Marine and Offshore Engineering, Sundarban College of Technology Studies, Bangladesh
adonias.van.der.velde@scts-bd.net

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Abstract

Additive manufacturing (AM), commonly called 3D printing, has evolved from a rapid-prototyping tool into a manufacturing route for functional polymer, composite, metallic, and ceramic components. This methodology paper develops a structured framework for evaluating AM applications in modern mechanical engineering using peer-reviewed literature published up to 2021. The method combines process classification, material-process compatibility analysis, application mapping, and a qualitative multi-criteria evaluation based on geometric freedom, mechanical performance, dimensional capability, build productivity, post-processing burden, and cost. Seven process families—material extrusion, vat photopolymerization, polymer powder-bed fusion, laser powder-bed fusion, electron-beam powder-bed fusion, directed-energy deposition, and binder jetting—are assessed for prototyping, tooling, lightweight structures, repair, thermal-fluid components, and low-volume customized production. The synthesis shows that no single AM route is universally superior: polymer extrusion remains effective for economical prototypes and fixtures, powder-bed fusion offers the strongest balance for complex functional parts, and directed-energy deposition is particularly attractive for repair and large metal features. The study also identifies persistent barriers including anisotropy, porosity, residual stress, surface roughness, repeatability, qualification, and post-processing. The proposed step-by-step methodology can support process selection and research planning where experimental facilities are limited and a transparent literature-based decision framework is required.

Introduction

Additive manufacturing creates physical components directly from digital three-dimensional models by depositing, curing, binding, or melting material in successive layers. The approach differs fundamentally from conventional subtractive machining and formative processes because material is placed only where required and geometrical complexity is generated by toolpath planning rather than by dedicated tooling. Early reviews established AM as a flexible route for rapid prototyping and small-batch production [1], while later work

documented its expansion into load-bearing metallic components and high-value engineering systems [2]. This shift is especially important to mechanical engineering because part performance, weight, heat transfer, manufacturability, repairability, and lifecycle cost can now be considered simultaneously during design.

The engineering value of AM arises from design freedom and digital integration. Internal channels, lattice structures, topology-optimized members, part consolidation, conformal cooling

passages, and customized interfaces can be produced without the access constraints associated with cutting tools or conventional molds. Gao et al. [3] described AM as a technology capable of altering product design, manufacturing, and distribution, but also emphasized challenges in data preparation, materials, process control, quality assurance, and intellectual property. Bikas et al. [4] further showed that process physics and modelling requirements differ considerably among AM categories, making process selection an engineering decision rather than a simple choice of printer.

For mechanical components, geometric feasibility alone is insufficient. Printed parts may contain pores, lack-of-fusion zones, stair-stepping, support scars, residual stress, and build-direction-dependent microstructures. Consequently, surface finishing, heat treatment, stress relief, hot isostatic pressing, machining, and inspection frequently become part of the AM route. Design for additive manufacturing (DfAM) therefore requires engineers to treat process constraints as design variables and to exploit AM-specific opportunities only where they create measurable functional value [5]. This paper presents a concise methodology for comparing the principal AM processes and mapping them to mechanical-engineering applications using literature available through 2021. The objective is not to claim new experimental material properties, but to provide a repeatable literature-based procedure that can guide process selection, research design, and subsequent validation.

Literature Review

The development of metal AM has been strongly driven by aerospace, energy, tooling, and biomedical requirements. Frazier [2] reviewed metal AM as an emerging manufacturing route and highlighted the need to relate feedstock, energy source, processing conditions, microstructure, and properties. Herzog et al. [6] later summarized how laser- and electron-beam-based processes can produce near-fully dense steels, aluminium, titanium, and nickel alloys, while noting that thermal cycling, rapid solidification, and process-specific defects control final performance. Mechanical-property compilations by Lewandowski and Seifi [7] demonstrated that tensile strength alone is an incomplete indicator: fatigue, fracture resistance, orientation effects, defect populations, and post-

processing are equally important for qualification.

The connection between design and manufacturing has also become central. Thompson et al. [5] organized DfAM opportunities around complexity, customization, consolidation, and functional performance, while also identifying constraints associated with support structures, process resolution, surface quality, and design-rule maturity. From an industrial viewpoint, Ford and Despeisse [8] argued that AM can reduce material waste, tooling, inventory, and transport in selected cases, but warned that environmental benefits depend on energy use, process efficiency, product lifetime, and supply-chain context. Thus, a mechanically efficient printed component is not automatically the most economical or sustainable solution.

Materials research expanded the application space beyond metals. Ngo et al. [9] reviewed polymers, metals, ceramics, composites, and emerging materials, emphasizing AM advantages in design freedom, mass customization, and low-waste production alongside limitations in material availability and process-induced properties. DebRoy et al. [10] provided a detailed process-structure-property interpretation for metallic AM and explained how heat flow, solidification, melt-pool behavior, residual stress, and defects influence part quality. For polymer AM, Nath and Nilufar [11] described extrusion, powder-bed, and photopolymer routes together with composite reinforcement approaches, showing that print orientation, interlayer bonding, voids, and processing temperature substantially affect mechanical behavior.

By 2021, literature increasingly focused on reliability and process-specific defect control. Gong et al. [12] reviewed laser additive manufacturing and identified process parameters, energy input, powder characteristics, melt-pool stability, and thermal history as key variables governing density, microstructure, and properties. Bellini et al. [13] specifically examined metal-AM defects and their effect on mechanical strength, reinforcing the need to combine manufacturing selection with inspection and post-processing. Across these studies, a common research gap is evident: engineers require a compact decision method that translates broad AM literature into process choices for mechanical functions rather than treating AM technologies as interchangeable.

Table 1. Literature basis used to construct the methodology

Reference	Primary focus	Mechanical-engineering relevance	Methodology input
[3] Gao et al. (2015)	AM status and challenges	Digital workflow, process limits, qualification	Selection criteria
[5] Thompson et al. (2016)	DfAM	Complexity, consolidation, constraints	Design criteria
[6],[7] Metal reviews (2016)	Metal AM and properties	Strength, fatigue, anisotropy, defects	Performance criteria
[8] Ford & Despeisse (2016)	Sustainability	Waste, tooling, energy, supply chain	Lifecycle criteria
[9] Ngo et al. (2018)	Materials/processes/applications	Cross-process comparison	Process/material map
[10] DebRoy et al. (2018)	Process-structure-property	Thermal history and defects	Quality criteria
[11] Nath & Nilufar (2020)	Polymers/composites	Interlayer and composite behavior	Polymer criteria
[12],[13] 2021 reviews	Laser AM and defects	Parameter sensitivity and reliability	Risk criteria

Methodology

The study adopts a structured literature-synthesis methodology rather than a laboratory experiment. Its unit of analysis is the AM process family and its suitability for a defined mechanical-engineering function. The procedure contains five stages: scope definition, literature

screening, process/material classification, multi-criteria evaluation, and application mapping. Only peer-reviewed sources published no later than 2021 are used in the reference set. Foundational studies are retained when they establish widely used process categories or property relationships.

**Figure 1.** Step-by-step literature-based methodology for evaluating AM in mechanical engineering.

Step 1 – Define engineering scope. Mechanical applications are grouped into rapid prototyping, jigs and fixtures, functional polymer parts, lightweight metal structures, thermal-fluid components, tooling, component repair, and customized low-volume production. The desired outcome is a process recommendation based on engineering requirements rather than printer availability.

Step 2 – Screen and classify literature. The selected studies are coded by process family, feedstock/material, energy or bonding mechanism, typical mechanical issues, application domain, and reported advantages or limitations. Evidence is separated into polymer/composite and metallic AM because their governing failure mechanisms and post-

processing requirements differ substantially [7,10,11].

Step 3 – Establish evaluation criteria. Six criteria are used: (C1) geometric freedom, (C2) attainable functional/mechanical performance, (C3) dimensional accuracy and surface capability, (C4) build productivity, (C5) post-processing burden, and (C6) relative production cost. Criteria are interpreted comparatively on a five-level ordinal scale, where 5 indicates a favorable condition. For C5 and C6, a high score means lower burden or lower cost.

Step 4 – Build a comparative process matrix. Seven process families are assessed: material extrusion (FDM/FFF), vat photopolymerization (SLA/DLP), polymer powder-bed fusion (SLS), laser powder-bed fusion for metals (LPBF/SLM/DMLS),

electron-beam powder-bed fusion (EBM), directed-energy deposition (DED), and binder jetting. Scores are assigned by triangulating the qualitative conclusions of the reviewed sources; they are not presented as universal measured constants.

Step 5 – Map process capability to application. A process is considered suitable only if material compatibility, geometry, required property level, part size, post-processing access, and economics are simultaneously acceptable. For critical metal components, qualification risk is treated as a gating condition because defects, anisotropy, and fatigue sensitivity can dominate nominal static strength [7,13].

Step 6 – Interpret and validate the synthesis. Recommendations are cross-checked against process–structure–property relationships reported in the literature [6,10,12]. Where the evidence indicates strong dependence on machine, alloy, orientation, or thermal treatment, the result is expressed as a conditional recommendation and experimental validation is identified as the next required step.

Results

The comparative synthesis indicates that process selection is application-specific. Material extrusion scores strongly for cost and productivity and is therefore well suited to concept models, ergonomic checks, assembly verification, fixtures, and noncritical polymer components. Its main mechanical limitation is weak and variable interlayer bonding, which can create pronounced anisotropy [11]. Vat photopolymerization provides high detail and surface quality, making it valuable for precise patterns, visual models, and tooling masters, but

common photopolymer systems are less attractive for sustained structural loading.

Powder-bed routes become more attractive as geometric and functional demands increase. Polymer SLS can produce support-free complex components and nested batches with better functional robustness than many low-cost extrusion systems. For metals, LPBF provides the strongest combination of geometric freedom, density potential, detail, and material performance, explaining its relevance to aerospace brackets, lightweight structures, compact heat exchangers, conformal channels, and high-value customized components [6,10,12]. However, the process remains sensitive to energy density, powder quality, scan strategy, residual stress, porosity, and surface condition. EBM reduces some residual-stress concerns through elevated build temperatures and is particularly established for titanium, but surface finish and material range can be more restrictive.

DED occupies a different application niche. Because material is deposited directly into a melt pool, the process is effective for adding features, repairing worn or damaged high-value components, and manufacturing relatively large near-net-shape metal structures. Its deposition rate can exceed powder-bed processes, although dimensional precision and surface finish generally require finish machining. Binder jetting offers high throughput and avoids a high-energy beam during printing, but final properties depend heavily on debinding, sintering, shrinkage control, and infiltration where used. The decision matrix in Table 2 summarizes these trade-offs as a literature-informed engineering comparison rather than as standardized performance data.

Table 2. Literature-based comparison of major AM process families (1 = unfavorable, 5 = favorable)

Process	C1 Geometry	C2 Performance	C3 Accuracy	C4 Productivity	C5 Low post-process	C6 Low cost	Representative mechanical use
FDM/FFF	4	3	3	4	4	5	Prototypes, jigs, fixtures
SLA/DLP	5	2	5	3	3	3	Precision models, patterns
Polymer SLS	5	4	4	4	4	3	Functional polymer parts

Metal LPBF	5	5	4	2	2	1	Lightweight/thermal parts
EBM	4	5	3	3	3	1	Ti structural parts
DED	3	5	2	5	2	2	Repair, cladding, large parts
Binder jetting	4	4	3	5	1	3	Batch metal/ceramic parts

A second result is that the greatest AM benefit appears when geometry changes the function of the component. Simply printing a part that was designed for machining often transfers cost into slower build time and post-processing. In contrast, topology optimization, lattice design, internal channels, part consolidation, and localized material deposition can reduce mass, assembly count, or maintenance effort [5]. This reinforces DfAM as a prerequisite for value creation rather than a downstream formatting step.

The third result concerns reliability. Mechanical qualification remains a central barrier for demanding applications because defect size, orientation, microstructure, and surface condition affect fatigue and fracture behavior [7,13]. Thus, a process-selection method for safety-critical parts must include inspection, heat treatment, machining allowance, and test-coupon strategy from the beginning. Sustainability is similarly conditional: reduced material waste and tooling are genuine advantages, but energy intensity and post-processing can offset them if AM is used for unsuitable geometries or high-volume commodity production [8].

Conclusion and Discussion

This methodology paper shows how AM and 3D printing can be evaluated for modern mechanical engineering without treating the technology as a single manufacturing process. The proposed workflow begins with functional requirements, screens literature through 2021, classifies process and material capabilities, applies explicit decision criteria, and maps results to mechanical applications. The synthesis confirms that polymer extrusion is advantageous for economical iteration and tooling aids; polymer powder-bed fusion supports more robust complex parts; LPBF and EBM are preferred where metallic performance and geometric complexity justify higher cost; DED is particularly valuable for repair and large-scale deposition;

and binder jetting is attractive when throughput and batch production are prioritized. The broader implication is that AM should be selected because it enables a mechanical function or lifecycle advantage that is difficult to achieve conventionally. Lightweighting, internal fluid passages, part consolidation, customized interfaces, and repair are strong examples. Conversely, components with simple geometry, loose customization needs, very high production volume, or severe surface-finish requirements may remain better candidates for casting, forging, machining, molding, or hybrid manufacturing. The literature also makes clear that mechanical properties cannot be separated from process history: build orientation, energy input, thermal cycling, defects, and post-processing influence the final part [6,7,10,12,13]. The principal limitation of the present study is that the comparative scores are ordinal literature syntheses, not standardized measurements from a single controlled experiment. Machine architecture, software, powder or filament quality, parameter sets, and post-processing differ across studies. Therefore, the matrix should be used for screening rather than final certification. Future work should convert the framework into a quantitative multi-criteria decision model using application-specific weights and verified datasets for tensile strength, fatigue life, surface roughness, dimensional tolerance, deposition rate, energy consumption, and total cost. A subsequent experimental phase can then validate the top-ranked process for a selected mechanical component. Within these limits, the framework provides a transparent and reproducible bridge between AM research and practical mechanical-engineering process selection. From an application perspective, the framework is especially relevant to aerospace and automotive lightweighting, where topology optimization and lattice concepts can reduce mass while retaining load paths, provided that fatigue-sensitive surfaces and internal defects are controlled. It is also relevant to thermal

management: AM can integrate curved or conformal fluid passages into heat exchangers, molds, and compact cooling devices that are difficult to drill or mill conventionally. In maintenance engineering, DED and related deposition processes can restore worn regions and add material selectively, potentially extending the service life of expensive components. These applications demonstrate a consistent rule: AM creates the strongest value when geometric complexity, customization, part consolidation, or localized material placement directly improves the engineering function [5,6,10]. Implementation in industry should therefore follow a staged route. First, the component should be screened for a credible AM value proposition; second, the candidate process and material should be selected; third, the design should be redesigned for AM rather than copied from a conventional drawing; fourth, process parameters and build orientation should be established with manufacturability and support removal in mind; and fifth, post-processing and inspection should be treated as part of the manufacturing plan. For structural metal parts, qualification should include density or defect assessment, dimensional verification, surface-condition control, and mechanical testing representative of the actual build orientation. The literature on metal AM repeatedly shows that as-built quality is coupled to thermal history and defect populations [7,10,12,13], so process monitoring and validation are necessary when failure consequences are high. A final discussion point concerns hybrid manufacturing. AM does not need to replace conventional processes to be useful. A practical production chain may combine additive deposition for geometric complexity or repair with CNC machining for datum surfaces, holes, threads, seals, and final tolerance. Such combinations reduce the demand that the additive step simultaneously provide near-net-shape freedom and finished-part accuracy. This hybrid view also improves economic realism: the relevant comparison is total delivered-part performance and lifecycle cost, not printing time alone. It aligns with the sustainability caution raised by Ford and Despeisse [8], because material savings or local production must be evaluated together with energy consumption, support removal, heat treatment, failed builds, and finishing operations. Consequently, the decision framework is most useful as an early engineering filter that identifies where detailed cost modelling and experimental trials are justified.

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