

A State-Resolved Framework for Industrial Additive-Manufacturing Technology Selection Across Polymers, Metals, Ceramics and Advanced Materials

Process Chains, Invalidation Gates, Factory Constraints and Qualification

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Statement of Significance

Additive-manufacturing technologies are often compared through machine-level descriptors such as nominal resolution, build rate, material label or purchase price. Those descriptors do not identify the state of the object leaving the machine or the operations required before it becomes an accepted component. A photopolymer object may still require washing and post-cure; a metal or ceramic green body may require debinding and sintering; a powder-bed component may remain unusable until it can be recovered and verified; and a deposited metal form may require machining and interface qualification. ER-139 establishes a state-resolved selection framework that links process category, feedstock, geometry, scale, orientation, shaping mechanism, recovery, mandatory transformations, factory resources, economics and intended-use evidence. It also supplies a documented output record and a worked screening example. Its central rule is that an additive route has no unconditional advantage: a benefit is meaningful only against a declared comparator and within a controlled material-process-workflow-factory state.

Keywords: additive manufacturing; process selection; material extrusion; powder bed fusion; vat photopolymerisation; binder jetting; material jetting; directed energy deposition; solid-state deposition; sheet lamination; polymers; metals; ceramics; advanced materials; post-processing; factory qualification

Abbreviations: AM, additive manufacturing; AFSD, additive friction stir deposition; DED, directed energy deposition; DIW, direct ink writing; ESD, electrostatic discharge; LMM, lithography metal manufacturing; PBF, powder bed fusion; UAM, ultrasonic additive manufacturing; VPP, vat photopolymerisation; WAAM, wire-arc additive manufacturing.

Abstract

Industrial additive manufacturing spans seven standard process categories and a growing set of adjacent, non-layerwise, direct, indirect and hybrid implementations. Category names alone do not identify the state of the object leaving the machine, the transformations needed to obtain a usable component or the factory evidence required for repeatable production. This qualitative engineering review develops a state-resolved framework for screening additive-manufacturing routes across polymers, metals, ceramics and advanced materials. It separates feedstock state, shape-creation mechanism, usable scale and orientation, support or depowdering strategy, as-built state, mandatory post-processing, delivered material state and intended-use qualification. The seven categories are mapped together with exposure-architecture, indirect-tooling, functional-material and adjacent solid-state-deposition overlays. The comparison addresses geometry, throughput, material utilisation, labour, safety, surface state, anisotropy, shrinkage, inspection and economics without assigning universal scores. Representative primary studies show why raster direction, powder history, exposure architecture, droplet waveform, melt-pool regime, green-body processing, particle impact, thermomechanical deposition, thermal history and support environment remain route-specific. The decision gate begins with the required delivered state and works backward through the complete process chain. A worked ceramic example shows how the framework records candidate routes, invalidation gates, evidence gaps, provisional survivors and no-go rationale. The framework supports route screening, experimental planning and qualification design; it does not replace application-specific costing, process validation, regulatory assessment or production-site qualification.

1. Purpose, scope and objectives

The selection question addressed here is not "which printer is best?" It is: **which controlled production route can deliver the required geometry, material state and function at an acceptable factory burden, with evidence suitable for the intended use?** ISO/ASTM 52900:2021 supplies a common vocabulary for AM processes, while ISO/ASTM 52920:2023 frames requirements for industrial processes and production sites [1,2]. The National Institute of Standards and Technology (NIST) likewise treats material, machine, process, post-process measurement and part qualification as connected problems [5-7].

ER-139 covers polymers, metals, ceramics, glasses, reinforced systems, nano/micron-filled composites and highly specialised resins at component-relevant scales. Construction, concrete, geopolymer, regolith and other macroscopic high-volume deposition routes are outside scope. Current 3Dresyns portfolio pages distinguish nano/micron raw materials from ready-to-print specialty resins; they define the declared scope of later specialist reviews but are not independent evidence of performance [32,33].

The objectives are to:

1. establish a common state-resolved record for comparing direct, indirect, hybrid and adjacent AM routes;

2. identify material, geometry, scale, recovery, transformation, safety, economic and qualification conditions that can invalidate a route before machine-level optimisation;
3. distinguish mechanistic, demonstrated and factory advantages so that evidence is not transferred beyond its tested boundary; and
4. define a compact selection output that preserves surviving routes, evidence gaps and no-go rationale for later experiments and change control.

The paper does not rank vendors, pool numerical properties across incompatible machines or assign universal values for speed, accuracy, density, cost or sustainability. Green, as-built, washed, post-cured, debound, sintered, heat-treated, machined and conditioned specimens remain distinct evidence states.

2. Why the category name is necessary but insufficient

The seven ISO/ASTM categories identify the primary shaping mechanism, but an industrial route requires more variables. The minimum route description is:

R = {feedstock and lot history; machine state; geometry, scale, orientation and build plan; shaping mechanism; recovery; mandatory transformations; measurement; delivered state; intended use}.

Changing one member can alter the process window or invalidate an earlier comparison. A resin swap can change exposure depth and washing. A powder reuse policy can change flow, packing or thermal history. A new geometry or orientation can change heat accumulation, support demand, recovery and measurement access. A furnace change can alter debinding, atmosphere, dimensional evolution and final microstructure. The category is therefore an entry point, not a selection result.

Table 1. State-resolved map of the seven base process categories

Category	Typical feedstock and shaping mechanism	Typical as-built object	Mandatory or common downstream operations	Primary factory gate
Binder jetting	Powder bed; liquid bonding agent deposited selectively	Powder-supported, binder-bound green object	Cure, depowder, debind, sinter or infiltrate; finish and inspect as required	Powder packing, binder distribution, green handling, furnace capacity and dimensional change
Directed energy deposition	Powder or wire delivered into a focused energy source	Metallurgically consolidated, near-net deposit or repair	Support removal where used, heat treatment, machining and inspection	Atmosphere, heat input, distortion, access, deposition strategy and machining allowance
Material extrusion	Filament, pellet, melt, paste, slurry or reactive material forced through a nozzle	Bead-built polymer, reactive network or green body	Support removal; thermal or chemical cure; drying; debinding and sintering when bound	Flow stability, bead interfaces, anisotropy, thermal history and support access
Material jetting	Discrete droplets placed and solidified or cured	Droplet-built material, often with a separate support phase	Support removal, washing or post-cure; surface finishing	Ink-temperature-waveform coupling, nozzle health, placement and material compatibility
Powder bed fusion	Polymer, metal or ceramic powder selectively fused by thermal energy	Consolidated object retained within loose or partially fused powder	Cooling, depowdering, support removal for many metals, heat treatment, finishing and inspection	Powder life cycle, atmosphere, thermal history, recovery access and defect control
Sheet lamination	Sheets or foils bonded and cut, or ultrasonically welded and machined	Bonded laminate, sometimes containing embedded elements	Excess removal, trimming, machining, heat treatment or interface inspection	Bond integrity, trapped interfaces, tool access and embedded-component survival
Vat photopolymerisation	Liquid photopolymer or particle-filled suspension selectively exposed	Partially cured polymer network or polymer-bound green body	Drain, wash, support removal and post-cure; debind and sinter for indirect ceramic or metal routes	Optical attenuation, separation, cleaning, residual liquid, green strength and thermal conversion

Five overlays complete the route record. First, exposure architecture distinguishes scanned, projected, masked, continuous, tomographic and highly localised routes without promoting every implementation to a separate category. Continuous liquid-interface production changes the exposure-transport boundary but retains formulation, conversion and final-property controls [10]. Second, this review uses three explicit route conventions. In a **direct route**, the printed object supplies the material of the delivered part, although conditioning may remain. In an **indirect route**, the printed object is a green preform, pattern, mould, core or sacrificial tool that is materially transformed, consumed or removed. In an **integrated hybrid route**, additive and non-additive operations alternate inside one controlled chain, for example deposition interleaved with measurement and machining. This differs from an external comparator such as a wholly machined or moulded route. Third, every candidate needs a state-transformation record. Fourth, a functional-material overlay is required for conductive, ESD, dielectric, magnetic, optical, radiation-functional, adaptive and soft systems because shape fidelity does not establish service function. Fifth, adjacent solid-state metal-deposition routes are recorded by their mechanism and delivered state even when an exact placement in the seven-category taxonomy is not asserted.

3. The feedstock-to-delivered-part chain

Figure 1 defines the minimum object-state chain. "As printed" is a final state only when no mandatory transformation remains and acceptance evidence is valid in that state.

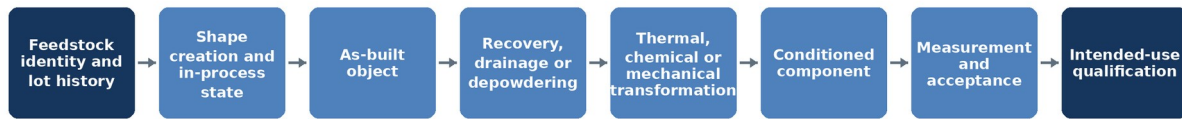


Figure 1. State-resolved production chain

Polymer material extrusion can produce the final polymer chemistry directly, yet bead orientation and interlayer formation remain part of the material state. Ahn et al. demonstrated direction- and process-variable dependence in one acrylonitrile-butadiene-styrene system; that result establishes an anisotropy gate, not a transferable percentage [8]. Polymer PBF may avoid separate supports for many geometries, but powder history and thermal exposure remain consequential. Vendittoli et al. reported changes in reused polyamide 12 powder and parts within their selective-laser-sintering workflow, supporting lot-history and refresh-policy controls without defining a universal reuse limit [9].

Photopolymerisation transfers another set of variables. Cured geometry depends on absorption, scattering, exposure, separation and transport, while the delivered network depends on washing, post-cure and conditioning. Filled photopolymers intensify the coupling: particles alter viscosity, sedimentation, scattering and cure depth, while the binder must either remain as a composite phase or be removed without damaging a green body.

In metal and ceramic sinter-based routes, the printer intentionally creates an intermediate. Bound-metal extrusion, binder jetting and LMM all require a green-to-final transformation, but their green structures arise by different mechanisms. Shima et al. linked deposition and densification to microstructure and tensile behaviour in a specific 17-4PH bound-metal workflow [14]. Chen et al. and Cabo Rios et al. showed that binder-jet printing conditions and sintering can control densification and directional dimensional evolution in 316L systems [15,16]. LMM studies likewise separate suspension preparation and cure from debinding and sintering [17,18]. Final-metal properties therefore cannot be assigned to the printed green state, and nominally identical furnace schedules are not presumed transferable across green-body architectures.

4. Material-class eligibility and invalidation gates

Material class narrows route eligibility, but labels such as polymer, metal or ceramic remain too broad. A thermoplastic melt, a reactive elastomer, a metal powder in a photoactive binder and a free-flowing metal powder have different shaping and consolidation requirements even if the desired part uses the same bulk-material label.

Table 2. Material classes, plausible route families and invalidation evidence

Delivered material or function	Plausible route families	Delivered-state gate	Common invalidation condition
Structural thermoplastic or thermoset polymer	Material extrusion, polymer PBF, VPP, material jetting, reactive or paste deposition	Conversion, morphology, porosity, anisotropy, surface and conditioning match the intended use	Evidence comes from another build direction, thermal history, cure state or specimen geometry
Elastomer, hydrogel or other soft material	VPP, DIW, material jetting, support-bath or embedded printing	Network state, solvent or water content, dimensional recovery, cyclic response and ageing are controlled	Printability or initial softness is substituted for retained function
Metal	Metal PBF, DED or WAAM, solid-state deposition, sheet lamination or UAM, binder jetting, bound extrusion, LMM and selected indirect routes	Composition, density or porosity, interfaces, microstructure, residual stress, dimensions, surface and heat-treatment state are recorded	Green-body data, machine density claims or one alloy's process window are transferred to another route
Oxide or non-oxide ceramic	Ceramic VPP, DIW or robocasting, binder jetting, bound extrusion, selected PBF and indirect routes	Green integrity, debinding, sintering, phase state, defects, shrinkage and final properties are linked	Printed geometry is treated as final ceramic, or furnace history is omitted
Silica or glass	Particle-loaded photopolymerisation with thermal conversion, paste routes and specialised direct processes	Organic removal, viscous flow or sintering, optical loss, bubbles, dimensions and surface are qualified	Transparency or fused-silica identity is inferred from precursor composition alone
Particle- or fibre-reinforced composite	Extrusion, VPP, material jetting, DIW and selected powder-bed routes	Dispersion, orientation, interfaces, retained loading and anisotropy are measured in the part	Feedstock loading is used as a proxy for realised function or uniformity
Electrical, thermal, dielectric, magnetic, optical or radiation-related function	Route depends on carrier rheology, particle interaction, exposure and required field response	Component-level function, contacts, orientation, ageing and environment are tested	A filler datasheet or bulk coupon value is promoted to a device claim
Extreme-service or adaptive specialty resin	VPP, jetting, extrusion or an integrated hybrid route compatible with the network and activation mechanism	Service temperature, chemical exposure, fire-test method, barrier condition, stimulus, recovery and ageing are explicit	A product-family label is treated as qualification

Ceramic evidence illustrates the final-state gate. Wang [19] and Fernández-Abia et al. [20] resolved alumina stereolithography through printing, debinding, sintering and defect evolution rather than through print resolution alone. Mendoza Jimenez et al. linked oxide-powder and sintering behaviour in ceramic binder jetting [21]. For DIW, M'Barki et al. connected rheology, post-deposition deformation and the fired ceramic outcome in one boehmite-derived alumina system [22]. The transferable logic is

causal: the ink must flow through the nozzle, recover sufficient structure, dry without unacceptable damage and survive thermal conversion. The study's numerical criteria remain specific to that ink and test configuration.

Glass-forming routes impose a similar boundary. Kotz et al. demonstrated that a photocurable nanocomposite can be shaped and thermally converted into fused-silica structures [23]. That evidence supports a multistage route, not the claim that any silica-filled resin will become transparent glass. Particle identity, loading, dispersion, organic removal, shrinkage, bubbles and thermal history belong to the delivered optical material.

Reinforced and soft systems show different transition risks. Matsuzaki et al. used in-nozzle impregnation to print continuous-fibre composites, making reinforcement path and interface formation explicit variables [24]. Hinton et al. used a reversible support bath to stabilise complex hydrogel geometries [25]. In each case, the environment surrounding deposition is part of the route; demonstration of shape retention is not long-term mechanical, biological or service qualification.

5. Conditional advantages and process-specific losses

An advantage should be assigned to one of three levels. A **mechanistic advantage** follows from the shaping principle. A **demonstrated advantage** requires matched evidence for the material, machine, geometry and workflow. A **factory advantage** requires accepted-part throughput, labour, yield and cell-cost evidence. Without a comparator and boundary, the statement remains an unresolved claim.

5.1 Polymer-dominant routes

Material extrusion can place material selectively with comparatively simple feedstock handling and can scale from fine filament deposition to high-flow pellet systems. Its mechanistic losses include bead-scale surface texture, direction-dependent interfaces, start/stop defects, thermal gradients and support-access constraints. Larger nozzles may improve volumetric deposition while sacrificing feature access and surface state; smaller nozzles reverse that trade-off.

Polymer PBF uses surrounding powder as geometric support for many features and permits three-dimensional batch nesting. The complete cycle includes bed preparation, heating, building, cooling, excavation, depowdering, powder segregation or refresh and surface finishing. Internal channels can be geometrically printable yet operationally unacceptable if powder cannot be removed or verified.

VPP can localise cure through scanning, projection or masking and can provide fine exposure-defined features. Its losses include support contact, separation forces, residual liquid, washing, post-cure, oxygen or optical effects and conversion gradients. Continuous exposure can alter vertical transport and machine occupancy [10], but speed remains geometry-, resin- and acceptance-dependent. Material jetting offers spatial placement and multimaterial potential, yet the result depends on droplet formation, temperature, rheology, waveform, nozzle condition and support strategy. Chen et al. demonstrated that coupling in one waveform-modelled material-jetting system [11]; its operating window is not a generic printhead or ink specification.

5.2 Fusion, sinter-based and solid-state metal routes

Laser PBF (L-PBF) can create complex metal geometries through local melting, but it combines powder handling, rapid thermal cycling, support design, residual stress, surface roughness and internal-defect control. Ultrafast X-ray work by Cunningham et al. linked pore formation to a keyhole-regime transition in a bounded laser-melting experiment [12]. The transferable lesson is that nominal energy density does not replace control of the melt regime. Electron-beam PBF (EB-PBF) changes the energy source, vacuum environment and preheat strategy; Al-Bermani et al. linked thermal history to microstructural diversity and properties in Ti-6Al-4V [13].

DED and WAAM can add material to existing components, repair local regions and generate large near-net forms. Their conditional benefit is deposition access and material addition where fine powder-bed feature control may not be the objective. Their losses include high heat input, thermal accumulation, residual stress, deformation, coarse surface state and machining allowance. Carroll et al. reported directional tensile behaviour in DED Ti-6Al-4V [26], while Ma et al. treated scanning strategy as a control variable for stress and deformation in one WAAM Al-Si system [27].

Binder jetting, bound-metal extrusion and LMM move much of the consolidation burden from the printer to debinding and sintering. This can reduce melt-related thermal stress during shaping and enable batch furnace processing, but it creates a fragile intermediate, dimensional transformation, furnace loading constraints and risks from binder removal, atmosphere and contamination. Binder jetting adds green-part excavation; bound extrusion adds bead interfaces and green anisotropy; LMM couples metal loading to suspension flow and optical cure. Output must be measured after sintering and final acceptance.

Solid-state metal deposition changes the governing invalidation gates because consolidation proceeds without intentional bulk melting. In cold-spray AM, powder morphology and native particle state interact with particle flight, impact conditions, bonding and deposited properties. Anumandla et al. demonstrated those couplings for commercially pure titanium powders of different manufacture and morphology [34]. A candidate route therefore needs controls for powder identity, particle-size and shape distributions, gas and nozzle conditions, substrate preparation, interparticle and substrate bonding, deposited defects and any finishing required; absence of melting does not itself prove an acceptable interface or property state.

AFSD uses thermomechanical deformation and plastic flow rather than local melting and solidification. Kincaid et al. combined AFSD with structured-light measurement, turning and milling in two manufacturing demonstrations [35]. Their work shows why a near-net deposit that requires measurement and machining is an integrated hybrid chain: coordinate transfer, datum strategy, deposition allowance, tool access and operation sequence contribute directly to the accepted geometry. Cold spray and

AFSD are retained here as adjacent solid-state metal-deposition routes and are not forced into an unverified exact position within the seven-category taxonomy.

Sheet lamination occupies another solid-state boundary. UAM bonds metal foils at relatively low bulk temperature and can embed temperature-sensitive elements. Hehr et al. demonstrated integration of fibre-optic strain sensors within metal using UAM [28]. This establishes an opportunity under the studied conditions, not general production qualification; interface, foil, geometry, machining and sensor-survival evidence remain necessary.

5.3 Advanced and highly specialised materials

Nano/micron feedstocks should be classified by physical form, chemistry, surface state, dispersion route and whether the particulate phase remains in the component. A nanopowder, agglomerate, nanofibre, micronised powder, concentrate and ready-to-print resin are not interchangeable. For a retained composite, particle distribution, interface state, orientation and percolation may control function. For an indirect metal, ceramic or glass route, the carrier must be removed and the particles consolidated; final function belongs to the transformed structure, not the wet formulation.

Highly specialised resins should be selected from service state backward. Electrical or ESD materials require geometry-specific resistance and contact evidence. Thermally conductive systems require direction, interface and boundary-condition control. Dielectric, ferroelectric, piezoelectric and magnetic systems may require alignment, poling or field-history records. Optical, photonic, luminescent and radiation-functional systems require spectral, attenuation, dose or energy definitions. Extreme-service resins require the actual temperature, chemical, flame, barrier or insulation test. Adaptive and soft systems require activation, recovery, fatigue, solvent or humidity state. These topics are assigned to ER-156-ER-161; ER-139 defines their common selection boundary.

6. Factory-cell constraints and occupational safety

The factory cell comprises every resource needed to convert feedstock into an accepted component. A printer cannot be evaluated separately from material storage, atmosphere, recovery, cleaning, curing, furnaces, machining, ventilation, waste handling, metrology, maintenance and operator competence.

Table 3. Minimum factory comparison record

Axis	Required question	Frequent comparison error
Scale and orientation feasibility	Does the part fit the usable build envelope, and in which orientations? Do those orientations remain acceptable for anisotropy, supports, recovery and measurement?	Nominal build volume is treated as usable volume, or any fitting orientation is assumed acceptable
Geometry and recovery	Can supports, loose powder, liquid, paste or sacrificial material be removed and verified?	Printable geometry is assumed to be recoverable geometry
Time and capacity	What are build, cool, recover, transform, inspect and queue times at the target batch mix?	Printer exposure or deposition time is reported as total lead time or steady-state output
Yield	How many started parts survive every transition and meet final acceptance?	Green or as-built count is used as saleable output
Material state and reuse	How are lots, age, moisture, contamination, powder history and reclaimed fractions controlled?	Nominal chemistry is treated as a complete feedstock specification
Labour and automation	Which transfers, cleaning, support, depowdering, furnace and inspection operations are manual?	Low in-printer labour is used to claim a lights-out cell
Utilities and equipment	Which gases, vacuum, thermal, ultraviolet, solvent, water, filtration, furnace and machining resources are required?	Printer footprint or power is used as the cell footprint or energy demand
Safety and containment	What exposure, fire, explosion, oxygen-depletion, chemical, radiation, hot-work and waste controls apply at each transition?	A closed printer is assumed to close the complete exposure route
Metrology and qualification	Which surface, internal, dimensional, chemical, microstructural and functional features must be measured or otherwise verified?	Coupon data are assumed to qualify inaccessible part features

Safety evidence must be bounded by task and facility. In a 2025 National Institute for Occupational Safety and Health (NIOSH) evaluation of one metal-powder AM facility, airborne particles increased during tasks, metals were detected in breathing zones and on surfaces, skin and clothing, and feedstock powder migrated through production and non-production areas; measured breathing-zone values were below the applicable occupational exposure limits in that facility [29]. This facility-specific result shows why powder transfer, depowdering, cleaning, maintenance and transport belong in the process map; it does not establish another site's exposure or compliance.

For desktop VPP, NIOSH identifies uncured resin, acrylates, cleaning solvents, curing emissions and sanding dust as exposure-control topics and recommends appropriate ventilation, handling and personal protection [30]. Nano/micron materials require separate hazard and exposure assessment based on composition and physical form. Current NIOSH nanotechnology guidance directs users to containment, engineering-control, sampling and material-specific resources rather than treating "nano" as one hazard class [31]. Particle size alone neither proves nor excludes risk.

7. Economics without marketing shortcuts

The primary production denominator is accepted output from the complete cell:

Effective cell throughput = accepted components delivered / observation period, measured at steady state for the declared batch mix and utilisation.

Lead time is separate: it is the elapsed time from released feedstock to final acceptance for one batch. In a pipelined cell, steady-state throughput is controlled by the bottleneck stage rather than by the sum of one batch's stage times. Printer output, lead time and cell throughput must therefore be reported independently.

The cost boundary includes equipment occupancy, labour, feedstock loss, reusable fractions, consumables, utilities, atmosphere, supports, cleaning, post-processing, inspection, maintenance, rework, scrap and failed qualification. A route may have low marginal geometry cost but high recovery labour; high printer output but a furnace bottleneck; good material utilisation but costly containment; or rapid green-part output followed by low final yield.

Comparisons should freeze annual volume, part mix, geometry, acceptance criteria, utilisation, queue model and comparator. Machining, moulding, casting and a separately defined integrated hybrid chain are legitimate comparators when they deliver the same accepted state. AM should not receive credit for unused geometric freedom or customisation, and the comparator should not be burdened with tooling or inventory assumptions absent from the actual case.

Environmental claims require the same boundary discipline. "Less waste" may describe near-net placement while omitting supports, unrecoverable powder, solvents, inert gas, furnaces, failed parts or machining. This framework retains energy and material flow as case variables but assigns no universal sustainability rank.

8. Qualification architecture and change control

ISO/ASTM 52920:2023 separates industrial-process and production-site requirements from the claim that a particular part is qualified [2]. ISO/ASTM 52927:2024 maps main AM characteristics to corresponding test methods, while ISO/ASTM 52928:2024 addresses metal-powder life-cycle management [3,4]. These standards help structure controlled records; they do not replace application-specific acceptance criteria.

A minimum qualification architecture contains:

1. **Feedstock record:** identity, supplier or preparation route, lot, storage, age, conditioning, reuse or blending history, and process-controlling properties.
2. **Machine-state record:** configuration, software and parameter set, calibration, maintenance, critical consumables, atmosphere and pre-build checks.
3. **Build record:** geometry revision, scale check, orientation, nesting, supports, exposure or deposition history, interruptions and in-process evidence.
4. **Transition record:** recovery, washing, cure, drying, debinding, sintering, infiltration, heat treatment, machining, polishing and conditioning, including equipment identity and load configuration.
5. **Measurement record:** traceable dimensional, surface, internal-defect, composition, microstructure, mechanical or functional evidence with uncertainty appropriate to the decision.
6. **Acceptance record:** intended use, critical characteristics, direct-inspection or validated indirect-verification strategy, sampling logic, non-conformance disposition and linkage between specimens and production parts.
7. **Change-control record:** rules for reassessing material, machine, geometry, parameters, post-process equipment, site, software or inspection changes.

NIST's part-qualification programme highlights measurement challenges created by complex surfaces and internal geometry, defects, anisotropy, residual stress and post-processing [7]. Those challenges make "same material and printer" an inadequate equivalence argument. Qualification should follow the causal route from feedstock and machine state to the features that control final performance.

9. Selection gate and documented output

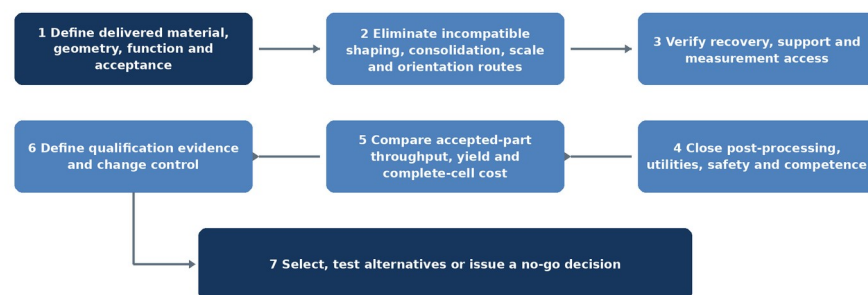


Figure 2. Backward route-selection logic

The gate starts at the right-hand end of Figure 1. If the intended use requires a dense ceramic with inaccessible internal channels, the first questions concern fired-state defects, shrinkage, evacuation and verification, not nominal printer resolution. If it

requires an embedded sensor in metal, sheet lamination may be credible because low-temperature foil bonding can protect some embedded elements, but interface and sensor survival become acceptance criteria [28]. If a functional nanocomposite requires isotropic electrical response, a route that aligns fillers may be rejected even when it reproduces the geometry.

More than one route may survive screening. Those routes enter a matched comparison using the same delivered-state requirements and declared comparator. A route should be rejected when the part cannot fit an available usable envelope in an orientation that also satisfies anisotropy, support, recovery and measurement needs; when mandatory transformations cannot preserve geometry or function; when recovery or verification is inaccessible; when the factory lacks a controllable safety or post-process resource; when accepted-part throughput, yield or complete-cell cost cannot meet the frozen commercial boundary; or when the qualification burden is disproportionate to the application. A documented no-go is an engineering output.

9.1 Worked screening example: dense alumina insert with internal channels

Consider a component specification that requires a dense alumina fluid-distribution insert with curved internal channels, stable external datums after firing, verified channel continuity and cleanliness, and a documented path to final acceptance. No dimensions, tolerances, pressure class, batch volume or target cost are invented here; those values must be supplied by the actual application. The example demonstrates how the framework changes the questions and the output.

Initial candidates are ceramic VPP, ceramic DIW and ceramic binder jetting. All three deliberately create an intermediate and therefore share a fired-state acceptance boundary. They do not share the same shaping, recovery or defect mechanisms. VPP must demonstrate suspension stability, optical cure, drainage and washing of the channels, green strength, debinding and sintering. DIW must demonstrate rheology, unsupported-span or support-medium feasibility, drying and removal of any support phase before firing. Binder jetting must demonstrate green strength and complete extraction of loose internal powder before thermal conversion. A nominally printable channel is a no-go if retained liquid, support or powder cannot be removed to the required state or verified through direct measurement or a validated qualification strategy.

Table 4. Example selection-output record

Output field	Worked-example record
Delivered state required	Dense fired alumina insert; stable external datums; continuous and clean internal channels; application-specific final acceptance evidence
Candidate routes	Ceramic VPP; ceramic DIW; ceramic binder jetting
Mandatory transformations	Route-specific recovery; drying or washing where applicable; debinding; sintering; datum finishing if required; conditioning and verification
Invalidation gates	Usable envelope and acceptable orientation; green handling; channel drainage, support removal or depowdering; predicted and measured shrinkage; cracking or distortion; verification access
Factory constraints	Controlled suspension or powder handling; cleaning and waste controls; furnace atmosphere and load capacity; dimensional and internal-feature verification; trained transfer operations
Evidence gaps	Route-specific channel-clearing trial; green-to-fired dimensional map; internal-defect and continuity evidence; final-state yield; steady-state cell capacity and cost
Provisional survivors	No universal winner. Each route survives only if its route-specific recovery and fired-state gates can be closed with the actual geometry and site resources
No-go rationale	Reject any candidate whose channels cannot be cleared and verified, whose transformation cannot hold the required datums, or whose final yield, capacity, cost or qualification burden misses the declared boundary

The example yields a test plan rather than an unsupported technology ranking. A useful next experiment uses matched channel coupons and external datums, records every green-to-fired transition and compares only final accepted outcomes. If all routes fail an indispensable gate, the correct result is redesign, a different manufacturing chain or no-go.

10. Discussion, limitations and research priorities

The framework changes the comparison unit from a printer or category to a controlled causal chain. That change is consequential in three ways. First, it exposes early route-killers such as unusable orientation, trapped process material or an unavailable furnace before parameter optimisation. Second, it distinguishes missing evidence from poor performance: a candidate can remain provisional because recovery, yield or function has not yet been demonstrated. Third, it preserves why a route was rejected, which supports later redesign and change control instead of repeating an undocumented comparison.

The framework is deliberately qualitative. It does not provide machine prices, universal process windows, pooled property tables, route scores or life-cycle results. The worked example demonstrates the record structure but cannot produce a final selection without application dimensions, tolerances, volume, site resources and acceptance thresholds. The literature anchors demonstrate why state variables matter but do not represent every alloy, ceramic, polymer, printhead, exposure system or factory. Volumetric, high-resolution, aerosol-jet, electrophotographic and electrochemical implementations require specialist treatment when they become plausible candidates for a defined component.

Priority research should connect feedstock history to final properties; report geometry-specific accepted yield; compare complete cells on matched delivered states; quantify dimensional transformations with uncertainty; develop verification strategies for inaccessible features; control reuse and contamination; measure exposure during actual tasks; and publish route records that preserve machine, material, geometry, orientation and post-process state. Specialist papers ER-140-ER-161 apply this architecture to individual process and material families.

11. Conclusions

Industrial AM selection is a route-selection problem, not a printer-selection problem. Seven standard categories provide necessary vocabulary, but they do not determine the delivered material state, factory burden or evidence requirement. The conclusions controlling this series are:

1. The comparison unit is the complete feedstock-to-qualified-component chain.
2. As-built and final are separate states unless the route demonstrates otherwise.
3. Every advantage requires a comparator and a material-process-workflow-factory boundary.
4. Geometry is acceptable only when supports, powder, liquid or sacrificial material can be recovered as required and critical features can be verified through direct inspection or a validated qualification strategy.
5. Printer output, batch lead time and steady-state factory throughput are different metrics; accepted yield after every transformation controls saleable output.
6. Advanced-material function must be measured in the conditioned component, not inferred from filler identity, feedstock loading or a commercial label.
7. Qualification requires linked feedstock, machine, build, transition, measurement, acceptance and change-control records.
8. A valid screening output may be a provisional survivor, a bounded test plan, redesign or a documented no-go; absence of a universal winner is not a framework failure.

This framework does not select one universal technology. It is designed to expose invalid assumptions before they are hidden behind a category name, a headline specification or a property measured in the wrong state.

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