

From Printer Capability to Qualified Factory Route: A Comparative Decision Matrix Across Additive-Manufacturing Technologies

Juan Seguro

3Dresyns by Resyner Technologies S.L.

Registered tax address: General Etxague 15B, 20003 Donostia / San Sebastián, Gipuzkoa, Spain

VAT number: ESB24827511

Correspondence: info@3Dresyns.com · Website: www.3Dresyns.com

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Abstract

Additive-manufacturing (AM) technology selection is often reduced to a comparison of printer categories, nominal resolution, material labels or deposition rate. That shortcut fails when a factory must deliver accepted components rather than merely produce an as-built object. The relevant decision unit is a complete route: feedstock receipt and conditioning, shaping, support or powder recovery, washing or depowdering, curing, debinding, sintering, infiltration, heat treatment, machining, inspection and release. This review converts that principle into a state-resolved factory decision matrix. It compares vat photopolymerisation, material extrusion, powder-bed fusion, material jetting, direct ink writing, binder jetting, bound-powder routes, lithography-based metal or ceramic manufacturing, directed-energy deposition and indirect tooling routes. The matrix does not rank technologies universally. It applies non-compensatory feasibility gates before any weighted comparison, identifies evidence gaps and factory constraints, and records the comparator required for each claimed advantage. A worked screening example shows how the same complex ceramic component can eliminate apparently attractive routes before expensive trials. The output is a documented decision with an uncertainty record, not a universal score.

1. Objective and decision boundary

ER-162 inherits the general state-resolved selection architecture, invalidation-gate logic and factory-qualification record from ER-139 [20]. It does not redefine that corpus-level framework. ER-162 owns the cross-technology comparative matrix, the four-field level record that separates ISO category, machine architecture, material-state route and direct/indirect role, the evidence-maturity overlay, and the worked method for comparing surviving routes under a common factory boundary.

Within the ER-139 architecture, the objective is to provide a repeatable comparative matrix for screening AM routes under industrial constraints. The output for each candidate route is:

1. delivered state required;
2. candidate process chain;
3. mandatory transformations and operations;
4. invalidation gates;
5. factory constraints and safety controls;
6. evidence gaps and qualification tests;
7. surviving routes; and
8. a no-go rationale for rejected routes.

ISO/ASTM 52900:2021 provides the common seven-category vocabulary, while ISO/ASTM 52920:2023 frames industrial qualification and production-site requirements [1,2]. These standards are necessary anchors but do not select a route for a particular material, geometry or factory. The matrix therefore adds state, direct-versus-indirect production, material function and complete-cell overlays.

2. Why printer capability is an inadequate comparator

Printer specifications describe a machine boundary, not a qualified component. A 25 μm layer height does not establish 25 μm verified feature accuracy after washing, shrinkage or thermal conversion. A high deposition rate does not establish throughput if debinding, machining, inspection or failed-build recovery dominate cycle time. A high filler fraction does not establish the identity or performance of the final material. A powder-bed route may obtain geometric support from surrounding powder, but still incur thermal-history, powder-reuse and surface-state constraints. An indirect printed mould may have lower apparent geometric efficiency than direct printing while delivering better production density or material qualification.

The decision unit is therefore:

accepted components per complete cell cycle, with the state of the component and the evidence supporting acceptance explicitly recorded.

The chain must distinguish at least: received feedstock, conditioned feedstock, green or as-built object, washed or depowdered object, cured object, brown body, sintered or infiltrated component, machined component and released component. A property measured in one

state must not be presented as a property of another state without evidence of state continuity. This distinction is especially important in photopolymerisation, where conversion, washing and post-cure can alter the polymer state [6,7], and in ceramic routes, where colloidal processing and later densification govern different stages of the chain [8].

2.1 Category, architecture and production route are different levels

ISO/ASTM 52900 classifies AM processes into seven categories [1]. NIST provides a complementary public map of the principal technology families and their operating mechanisms [9]. A factory comparison must preserve that vocabulary while recognising that commercial architectures and complete production routes sit at different levels. SLA, DLP and LCD/MSLA are architectures within vat photopolymerisation. Direct ink writing and bound-filament deposition are material-extrusion implementations with different feedstock and downstream states. Lithography-based ceramic or metal manufacturing couples vat photopolymerisation to debinding and sintering. Printed sacrificial tooling is an indirect production route in which the final component may be cast or injection moulded rather than additively shaped.

These levels must not be placed in a flat list and treated as mutually exclusive alternatives. The decision record therefore carries four fields: ISO process category, machine or exposure architecture, material-state route, and direct or indirect role. Sheet lamination is retained in the category map even though ER-140–ER-161 do not assign it a dedicated specialist paper.

The direct-versus-indirect axis is inherited from ER-049 [21], which owns evidence-based route selection for advanced ceramics and metals. The 3Dresyns direct-versus-indirect guidance [10] is retained only as a manufacturer implementation source: it illustrates one practical expression of the axis, not independent proof of density, scalability or universal superiority.

3. Comparative process matrix

Route family	Primary shaping mechanism	Typical state leaving machine	Mandatory downstream operations	Conditional strengths	Frequent invalidation gates
Vat photopolymerisation	Selective optical polymerisation of a liquid resin	Green or partially cured polymer	Washing, post-cure, support removal, dimensional verification	Fine features, enclosed geometry, rapid iteration, broad formulation design space	Inhibited cure, unsupported cavities, residual resin, post-cure distortion, limited service temperature
Material extrusion	Melt, reactive or bound feedstock deposition	Thermoplastic, reactive green body or bound green body	Support removal, cooling/annealing, or debinding and sintering	Accessible equipment, filament/pellet scale, repairability	Bead anisotropy, poor interlayer fusion, rheology window, distortion, green fragility
Polymer powder bed fusion	Selective thermal fusion or chemical activation in powder bed	Fused polymer part in a powder cake	Depowdering, brushing/blasting, conditioning and inspection	No dedicated supports, nesting, batch production	Thermal history, powder refresh/reuse, porosity, surface roughness, powder recovery
Material jetting	Droplet placement followed by UV or phase-change solidification	Cured or solidified multimaterial object	Support removal, cleaning and post-cure where applicable	Multimaterial placement, smooth surfaces, small features	Nozzle reliability, droplet coalescence, support contamination, limited feedstock window
Direct ink writing / paste extrusion	Pressure-driven deposition of viscoelastic ink	Wet, gelled or green filament	Drying, curing, solvent removal, debinding or sintering	Highly filled ceramics, hydrogels, silicone-like systems, embedded structures	Yield-stress mismatch, collapse, drying gradients, nozzle clogging, anisotropy
Binder jetting	Binder placement into a powder bed	Fragile green body	Depowdering, curing, debinding, sintering or infiltration	Large beds, no thermal melt pool, complex packing	Green strength, binder distribution, shrinkage, powder loss, edge chipping
Bound-powder extrusion [22]	Extrusion of polymer-bound metal or ceramic filament or pellet feedstock	Bound green body	Support removal where applicable, debinding, sintering, shrinkage compensation, inspection	Familiar extrusion hardware and filament/pellet feed architectures; mould-free geometry	Filament or feed brittleness, feed traction, road/interface contact density, orifice-to-particle filtration, debinding cracks
Lithography-based metal/ceramic manufacturing [23]	Patterned photopolymerisation of metal- or ceramic-filled photoactive feedstock	Photo-cured bound green body	Cleaning/recovery, debinding, sintering, shrinkage compensation, inspection	Fine patterned green geometry without a melt pool; lithographic tooling of filled feedstocks	Optical attenuation, rheology/viscosity, sedimentation, green cleaning, debinding cracks, density gradients
DED / WAAM	Melt pool formed by powder or wire energy input	Near-net metal deposition on substrate	Heat treatment, support removal, machining, NDE	Repair, large components, high deposition rate	Heat input, residual stress, dilution, surface finish, machining envelope
Sheet lamination	Bonding and selective cutting of sheets or foils	Laminated preform or near-net component	Trimming, machining, consolidation or finishing, depending on material	High build rate for suitable planar feedstock; embedded components in selected routes	Interlaminar bonding, inaccessible excess material, staircase geometry, limited material combinations
Indirect printed tooling	Printed pattern, mould or core used by another process	Pattern, mould or core	Casting or injection, tool removal, final consolidation and inspection	Separates tool geometry from final feedstock densification; scalable in suitable cells	Tool compatibility, release, dimensional compensation, added integration stages

This table is a screening map, not a performance ranking. Some rows are ISO categories and others are state-resolved route overlays; their relationship must be recorded as defined in Section 2.1. The terms “fine”, “large” and “high” require a geometry-specific and factory-specific test plan.

4. State-resolved decision gates

The general decision-gate architecture is inherited from ER-139 [20]. The six gates below are the matrix-specific operationalisation used to compare heterogeneous technology routes on a common delivered-state and factory basis; they should not be read as a replacement for ER-139.

Gate 1: material identity and feedstock state

The purchaser must define whether the required deliverable is a polymer network, a filled composite, a dense ceramic, a dense metal, a porous scaffold or a functional device. 3Dresyns distinguishes nano and micron raw materials, functional additives and modifiers, reactive composites, processing auxiliaries and ready-to-print specialised resins [3,4]. These are not interchangeable categories. A ceramic powder in a photopolymer creates a composite feedstock; it does not make the printed green body a dense ceramic part. A conductive filler does not establish device conductivity until dispersion, connectivity, contacts, geometry and measurement state are controlled.

Gate 2: geometry and recoverability

Supports, uncured liquid, loose powder, sacrificial material and trapped gas must have a defined recovery path. Critical features may be verified by direct inspection, process monitoring, witness structures or another validated qualification strategy. If the route cannot recover or verify a critical internal feature, it is rejected regardless of nominal resolution.

Gate 3: transformation risk

Every mandatory transformation is a possible yield limiter. Washing can leave extractables; post-cure can alter modulus and dimensions; debinding can generate pressure, residue or cracks; sintering can produce shrinkage and distortion; machining can remove the functional surface or expose porosity. A candidate survives only when the transformation window, measurement method and acceptance limits are defined.

Gate 4: factory integration

The cell must provide operators, ventilation, powder or solvent handling, thermal equipment, calibration, inspection and waste controls. The relevant capacity is not the printer queue alone. A route with a one-hour build and a two-day furnace bottleneck is a furnace-limited route. A route with rapid exposure but extensive manual washing may be labour-limited.

Gate 5: evidence and qualification

Manufacturer pages can identify candidate families and implementation options, but they do not establish universal performance, safety or superiority. The 3Dresyns Curing Rate Control system illustrates the correct boundary: exposure, wavelength, irradiance, layer thickness and measured cured thickness are calibrated for a material-machine-workflow combination, not transferred as universal settings [5]. Qualification must link material lot, machine state, process parameters, post-processing, inspection method and change history.

ISO/ASTM 52901 adds purchaser-supplier requirements for bought AM parts, while ISO/ASTM 52920 addresses industrial processes and production sites [2,11]. ISO/ASTM TS 52930 provides an IQ/OQ/PQ framework specifically for laser powder-bed-fusion equipment and must not be presented as a universal qualification procedure for all AM categories [12]. Likewise, ISO/ASTM 52928 addresses the metal-powder life cycle, not polymer powder reuse or liquid-resin control [13]. The scope of each standard is part of the evidence record.

Gate 6: safety, environment and recoverability

A technically printable route is rejected if the facility cannot control its credible hazards or recover its process materials. The record must identify combustible or respirable powder, sensitising or volatile chemistry, inert-gas or vacuum hazards, laser or electron-beam controls, hot surfaces, reactive metals, solvent and wash streams, furnace off-gases and contaminated waste. Recycling claims require a mass balance and a retained-property criterion. Recovery of powder, resin, solvent, support material or sacrificial tooling is not automatically reuse, and reuse is not automatically equivalence.

4.1 Hard gates precede weighted selection

The selection sequence is deliberately non-compensatory:

1. define the delivered component and acceptance criteria;
2. enumerate technically plausible complete routes;
3. reject routes that fail a mandatory material, geometry, transformation, safety, inspection or regulatory gate;
4. identify the evidence required to close every unresolved mandatory gate;
5. compare only the surviving routes using declared weights; and
6. perform a sensitivity test to determine whether reasonable changes in weights alter the decision.

A low cost score cannot compensate for an inaccessible critical channel. High nominal resolution cannot compensate for an unqualified final material state. A weighted score is therefore permitted only after hard-gate screening. Published decision-support frameworks similarly combine process, machine, material, property and cost attributes, but their generic rankings remain inputs rather than factory qualification [18].

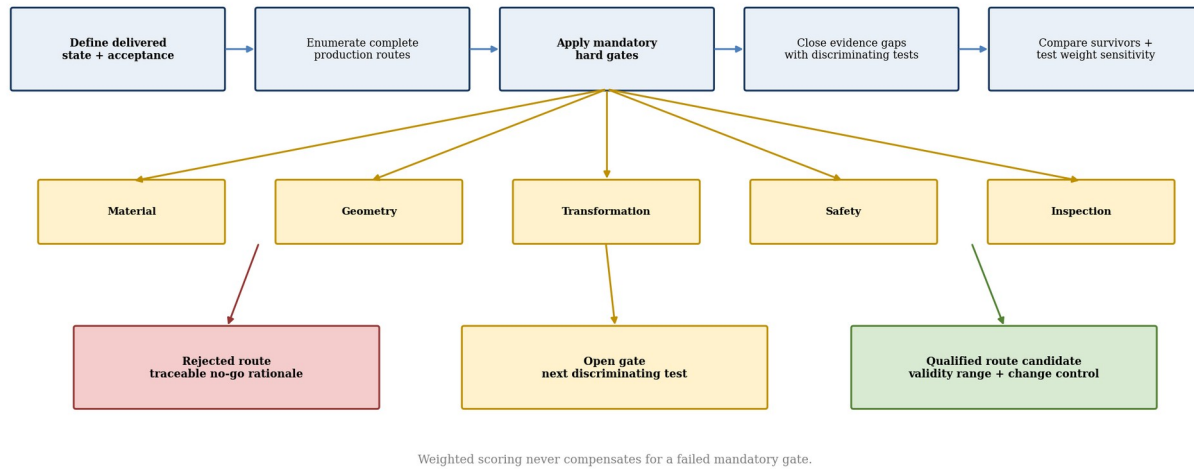


Figure 1. Non-compensatory route-selection sequence.

4.2 Evidence maturity and uncertainty

Each decision cell should carry both a result and an evidence grade:

Grade	Evidence available	Permitted interpretation
A	Qualified production data from the same material-machine-route and acceptance method	Direct decision evidence within the controlled validity range
B	Representative trials or peer-reviewed data with bounded differences	Transfer hypothesis with listed bridging tests
C	Manufacturer data, related-material literature or engineering model	Candidate-screening evidence only
D	Assumption, analogy or missing measurement	Open gate; no positive qualification claim

Uncertainty must not be hidden inside an average score. For every critical criterion, the record states the evidence grade, direction of uncertainty, consequence of error and next discriminating test. NIST identifies complex internal geometry, surface topography, defects, anisotropy and post-process changes as continuing measurement challenges for AM part qualification [14].

5. Factory economics and throughput

The matrix should record at least six time components: preparation, machine occupancy, unloading and recovery, transformation, inspection and rework or scrap. For nested powder-bed routes, powder recovery and refresh are part of the cycle. For vat routes, resin conditioning, cleaning fluid use and post-cure capacity are part of the cycle. For metal and ceramic bound-powder routes, furnace loading, debinding and shrinkage compensation can dominate. For DED and WAAM, machining and non-destructive examination can determine whether the deposition rate has practical value. Metal-powder history requires explicit lot, blend, contamination and reuse control rather than an undefined “recycled powder” label [13].

Two denominators should be reported separately:

Accepted throughput = *accepted components* / *elapsed complete-cell time*

Route yield = *accepted components* / *components entering the defined route boundary*

Neither denominator can be replaced by machine deposition rate. Batch equipment also requires queue and capacity analysis: a furnace, wash unit, depowdering station, post-cure chamber, inspection system or machining centre may set the cell bottleneck even when its own processing time is not the longest operation.

The economic comparator must be declared. “Cheaper than machining” is incomplete unless material utilisation, labour, tooling, energy, inspection, scrap and capital allocation are included. “Faster than injection moulding” may be true for a short pilot run and false for a stable high-volume cell. The matrix records the production horizon: prototype, qualification lot, bridge production, low-volume production or sustained series production.

Design freedom also has a route boundary. Design-for-AM literature distinguishes opportunities created by additive shaping from constraints imposed by process physics, support access, material behaviour and downstream operations [15]. A geometry that can be generated in CAD but cannot be cleaned, depowdered, debound, inspected or repaired is outside the qualified design space.

6. Worked screening example

Consider a ceramic manifold with enclosed channels, a chemically aggressive service environment and a requirement for reproducible internal geometry. Candidate routes are ceramic-filled vat photopolymerisation, direct ink writing, ceramic binder jetting and an indirect printed injection mould.

The direct vat route offers the best initial feature access, but it survives only if the suspension cures through the required thickness, the green body can be washed without channel blockage, and debinding and sintering preserve the channel dimensions. Direct ink writing is eliminated if the required span collapses before drying or if drying gradients crack the manifold. Binder jetting survives the geometry gate only if depowdering is demonstrated with a representative channel network; the powder bed is not proof that powder can be recovered from every channel. The indirect mould route adds injection and tool-removal operations, but may survive because it separates mould accessibility from ceramic feedstock consolidation and can use an established densification cycle.

The provisional decision is not “vat photopolymerisation wins”. It is: test the vat route and indirect mould route against the same channel-recovery, shrinkage, density, chemical-exposure and inspection requirements; retain direct ink writing and binder jetting only if their specific gates are passed. Ceramic AM literature confirms that feedstock preparation and sintering are route-defining constraints rather than incidental finishing steps [17]. This is the type of documented no-go rationale the matrix is designed to produce.

The next experiment should maximise decision value. A channel-recovery witness that simultaneously tests access, wash or depowdering, distortion and inspection may eliminate two routes more efficiently than a large mechanical coupon campaign. Conversely, if final density is the dominant mandatory requirement, a small coupled debinding-sintering trial should precede detailed dimensional optimisation.

7. Advantages, limitations and comparators

Every claimed advantage should be written in three layers:

1. **mechanistic advantage:** what the process physically enables;
2. **demonstrated advantage:** what a cited study or controlled test actually shows; and
3. **factory advantage:** whether the result improves the defined production cell.

For example, surrounding powder may mechanically support complex polymer geometry. A study may demonstrate successful nesting and acceptable parts under its process conditions. A factory advantage exists only if depowdering, powder recovery, surface preparation and inspection fit the cell and the accepted-parts yield improves against the declared comparator. The same discipline applies to high filler loading, multimaterial jetting, high deposition rate, soluble supports and specialised resin functions.

Metal AM provides a particularly clear warning against single-variable comparisons: process conditions govern thermal history, defects, microstructure, residual stress and properties, while heat treatment and other downstream operations can change the state again [16]. The matrix must therefore reject claims that transfer a machine-level metric directly to released-part performance.

8. Qualification record and change control

ER-139 [20] owns the general state-resolved qualification record. ER-162 uses that record as the common backbone and adds the matrix-specific fields needed for cross-technology comparison, including evidence grade, accepted throughput, route yield, bottleneck identity and the bridging tests required before a route can advance.

The minimum route record should bind nine elements:

1. material identity, lot and storage history;
2. machine, firmware, optics or energy source and calibration;
3. geometry, orientation, supports and nesting;
4. process parameters and monitoring data;
5. post-processing and transformation conditions;
6. inspection method, sampling and acceptance limits;
7. deviations, rework, failed builds and change rationale;
8. evidence grade, unresolved uncertainty and bridging tests; and
9. accepted throughput, route yield and identified bottleneck.

Changing a resin, powder refresh fraction, nozzle, vat film, exposure profile, furnace atmosphere, support strategy or inspection method is not automatically equivalent to the qualified route. The change must be screened against the affected state and risk. ISO/ASTM 52920 provides the industrial qualification anchor, but the acceptance record remains application-specific [2].

The record should also distinguish qualification path. Statistical qualification, equivalence or similarity-based qualification, and model-supported qualification impose different evidence burdens. NIST describes these as separate routes and emphasises that minor process changes can trigger substantial requalification when equivalence is not established [19]. A model can prioritise experiments and explain sensitivity, but it does not remove the need to validate the variables and acceptance outputs on which the decision depends.

9. Limitations of this review

This paper is a comparative framework and decision matrix, not a universal database of machine performance. It does not prescribe exposure times, powder fractions, sintering schedules, medical claims, fire classifications or production costs. Commercial pages are used to map candidate material families and process options, while scientific literature and standards define the evidence and measurement boundaries. Detailed specialist mechanisms remain owned by ER-140–ER-161. The framework has not been validated as a predictive scoring model across industries; its intended use is transparent screening, test planning and traceable engineering judgement.

10. Conclusions

1. The correct comparison unit is an accepted component from a complete factory cell, not a printer specification.
2. Feedstock identity, process mechanism, as-built state and final conditioned state must remain separate.
3. Every route should be screened through geometry recovery, transformation, factory integration and evidence gates before trials are scaled.
4. Throughput is governed by the slowest coupled operation and by accepted-part yield.
5. Direct and indirect routes can both be optimal, depending on densification, inspection, tooling and production horizon.
6. Nano/micron raw materials, functional additives, loaded feedstocks and ready-to-print specialised resins must not be conflated.
7. A useful selection outcome is a surviving-route set plus a traceable no-go rationale, not a universal ranking.
8. Hard feasibility gates must be closed before weighted scoring, and sensitivity to weights must be reported.
9. Evidence maturity and uncertainty belong in every critical decision cell.
10. Accepted throughput and route yield must be measured over the complete production boundary.

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