

Support Strategies for Internal Channels and Sacrificial Geometries in Industrial Additive Manufacturing

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Abstract

Internal channels are frequently presented as a geometric advantage of additive manufacturing. In production, however, an enclosed channel is acceptable only when supports, uncured liquid, loose powder, sacrificial material, gas and cleaning residues can be recovered and when the resulting feature can be verified. This review compares self-supporting orientation, removable solid supports, soluble sacrificial supports, powder-bed self-support, support-bath or embedded printing, and indirect tooling routes. It separates the printed state from the washed, cured, debound, sintered and conditioned states; identifies non-compensatory access and safety gates; and proposes measurable recovery endpoints, worst-case witness geometries and state-specific acceptance records. The central conclusion is that channel design is a recovery and qualification problem as much as a geometric one. A route that prints a channel but cannot prove its cleanliness, continuity, dimensional state or service compatibility has not demonstrated a manufacturable channel.

1. Objective and scope

The objective is to provide a factory-facing framework for selecting and qualifying support strategies for channels, undercuts, lattices, voids, overhangs and sacrificial geometries. The paper covers polymer, ceramic, metal and nano/micron-filled routes, including vat photopolymerisation, material extrusion, material jetting, direct ink writing, powder-bed processes, bound-powder routes and indirect printed moulds or cores. Concrete, geopolymer and other construction-scale deposition are outside scope. The review does not prescribe a universal minimum channel diameter, a universal cleaning recipe or a universal residue limit. Those quantities depend on geometry, material, machine, post-processing, measurement capability and service risk.

The required output is not a minimum printable diameter. It is a route record containing channel geometry, support or powder state, recovery operation, post-processing, inspection method, measurement uncertainty and acceptance rationale. ISO/ASTM 52900 supplies the process vocabulary, ISO/ASTM 52920 frames industrial production-site qualification, and ISO/ASTM 52902 addresses geometric-capability test artefacts [4,5,9]. NIST similarly describes qualification as the collection of sufficient evidence that a defined feedstock, machine or process will perform as expected, with statistical, equivalence-based and model-supported routes carrying different burdens [19]. None of those sources converts a generic process label into evidence that a particular enclosed channel is recoverable or clean.

Corpus ownership is inherited rather than re-derived. ER-009 owns water-removable sacrificial photopolymer chemistry and its process coupling for indirect additive manufacturing [20]. ER-033 owns washing- and drying-induced extraction, property change and dimensional response in vat-printed photopolymers [21]. ER-044 owns photoabsorber-driven optical response and cure-depth control [22]. ER-037 owns debinding-defect formation in photopolymer-derived ceramic and metal green bodies [23]. ER-010 owns dimensional metrology, trueness, precision and geometric-fidelity measurement in vat photopolymerisation [24]. ER-139 owns the corpus-level non-compensatory selection and decision-gate architecture [25], and ER-049 owns the direct-versus-indirect route-selection axis for advanced ceramics and metals [26]. ER-163 inherits those controls and owns only the cross-strategy channel-recovery and verification architecture: whether a formed internal feature can be emptied, cleaned, transformed, inspected and accepted across soluble-support, powder-bed, support-bath, direct and indirect routes.

2. The channel state chain

An internal feature can pass through several materially different states:

1. CAD void and intended flow path;
2. machine-accessible cavity during shaping;
3. cavity containing liquid resin, support, powder, paste or binder;
4. cavity after removal or recovery;
5. cavity after curing, debinding, sintering, infiltration or machining; and
6. conditioned channel under the intended fluid, thermal, electrical or biological service.

The final state is not inferred from the CAD file or from visual opening of an external port. Residual liquid can polymerise or migrate during post-cure. Powder can remain trapped at bends. A soluble support can leave residue or change surface chemistry. A debinding pathway can close through shrinkage or generate internal cracks. The qualification plan must name the state in which each measurement is made.

Three boundaries should be recorded at every transition:

1. **geometric boundary:** minimum local hydraulic dimension, length-to-diameter ratio, bends, junctions, blind ends, surface texture and port geometry;
2. **material boundary:** viscosity, yield stress, particle size and morphology, solubility or dispersibility, swelling, cure state and adhesion to the channel wall; and
3. **process boundary:** orientation, gravity vector, pressure differential, agitation, temperature, time, exchange volume, drying, thermal conversion and inspection capability.

Changing one boundary can invalidate evidence generated under another. For example, increasing the channel diameter without preserving a representative blind branch may make a cleaning coupon easier than the product. Likewise, showing flow after washing does not establish residue absence if the accepted failure mode is extractable monomer, loose particles or biological contamination.

3. Support strategy matrix

Strategy	Mechanism	Typical benefit	Principal risk	Required proof
Self-supporting orientation	Geometry and orientation avoid internal support	No support-removal chemistry	Stair-stepping, anisotropy, longer build or impossible spans	Sectioned coupons or non-destructive dimensional verification
Printed solid support	Same or compatible material is printed and mechanically removed	Predictable deposition in accessible regions	Tool access, scars, trapped fragments	Removal access, surface and cleanliness evidence
Water- or solvent-removable sacrificial support	Support dissolves or disperses after printing	Complex enclosed networks and low mechanical access	Diffusion, swelling, residue, incompatibility with part or downstream material	Dissolution endpoint, residue test, dimensional retention and effluent control
Powder-bed self-support	Loose powder surrounds the part	No designed supports for many overhangs	Powder entrapment, cake formation, thermal history	Depowdering access, particle count and internal continuity
Support bath or embedded printing	Bath or matrix supports deposited filament	Soft, ceramic and hydrogel geometries	Bath exchange, contamination and drying gradients	Bath compatibility, recovery and final-state test
Indirect mould or core	Printed sacrificial pattern, mould or core transfers geometry	Separates access from final consolidation	Extra process stages and release failure	Tool release, dimensional transfer and final component inspection

No row is universally superior. A soluble support may be the best route for a blind polymeric channel and a poor route for a water-sensitive ceramic green body. Powder-bed support may be efficient for a dry polymer but unsuitable when powder cannot be extracted from a narrow, tortuous passage.

4. Non-compensatory gates before optimisation

A route should be rejected before weighted comparison when any mandatory gate fails. A low cost or fine nominal resolution cannot compensate for an enclosed mass that cannot be removed, an inspection method that cannot see the relevant failure, or a cleaning operation that damages the part. The gate logic is inherited from ER-139 [25]; ER-163 applies it specifically to channel formation, recovery access, compatibility, endpoint, final-state verification and recovery safety.

Gate	Question	Minimum evidence	No-go condition
G1 — formation	Can the channel be formed without unacceptable closure, sag, fusion or wall breach?	State-specific geometry on a representative artefact	Required clearance or continuity is not achieved
G2 — access	Is there a physically credible path for drain, dissolution, depowdering, tool entry or core removal?	Port, vent and path analysis plus demonstrated operation	Blind volume or trapped phase has no removal path
G3 — compatibility	Does the recovery medium preserve the part and downstream interfaces?	Mass, dimension, surface or functional comparison before and after recovery	Swelling, cracking, extraction, corrosion or contamination exceeds the limit
G4 — endpoint	Can completion of removal be measured rather than assumed from elapsed time?	Defined endpoint with calibrated or bounded method	No observable linked to the retained material or residue
G5 — final-state verification	Can the critical attribute be measured after every irreversible transformation?	Qualified direct measurement or validated worst-case witness	Verification is limited to CAD or an earlier process state
G6 — safety and waste	Can pressure, solvent, powder, uncured resin, thermal and effluent hazards be controlled?	Approved work instruction, containment and waste route	Recovery creates an uncontrolled exposure, ignition, pressure or discharge risk

Only routes that pass all applicable gates should be compared for cycle time, cost, surface quality or design freedom. A conditional pass must identify the experiment required to close the uncertainty; it is not equivalent to qualification.

5. Vat photopolymerisation

Vat processes can define fine channel walls, but the liquid state creates a specific recovery obligation. Orientation must permit draining, washing and access to every cavity. Dead legs, menisci and capillary retention can leave resin that later cures during post-cure. Support placement must preserve channel openings without creating a trapped interface. These constraints sit within the wider coupling between photopolymer chemistry, exposure and AM process behaviour reviewed by Ligon et al. [6].

3Dresyns describes a broad SLA, DLP and LCD resin platform and separate soluble and sacrificial material families [1,2]. These pages identify candidate chemistry families; they do not establish a universal channel limit or residue-free result. The Curing Rate Control workflow relates irradiance, wavelength, layer thickness, exposure and measured cured thickness for a defined material-machine combination [3]. The optical mechanisms by which cure depth and lateral spread can narrow a channel are inherited from ER-044 [22]; ER-163 uses that inherited control only to establish whether the as-formed channel still presents a recoverable opening. Published microfluidic work likewise shows that residual resin and light penetration can obstruct small channels, while specialised transfer or

support strategies can alter that limit [10,11]. Those demonstrations are process-specific and should not be converted into generic minimum-feature claims.

For a critical channel, the record should include exposure calibration, orientation, vent and drain design, wash fluid identity, fluid temperature, agitation or pressure method, exchanged volume, wash endpoint, drying method, post-cure conditions and a verification method. General extraction, washing-induced property change and dimensional-response mechanisms are inherited from ER-033 [21]. ER-163 adds the enclosed-channel condition: exchange must be demonstrated through the complete network, including blind branches, dead legs, menisci and constrictions, because a nominally open port does not prove that displaced liquid or gas has an exit.

The channel-specific endpoint must demonstrate completion in the least accessible represented region rather than merely elapsed washing time. A suitable observable may combine successive-exchange chemistry, mass stability after a controlled dry, internal imaging where detection capability is adequate, or a functional flow result with a residue test. The selected observable and limit remain application-specific; if the retained phase or support cannot be shown absent to the required detection capability, the channel remains unqualified [21].

6. Material extrusion and direct ink writing

In filament or pellet extrusion, a channel is shaped by bead placement and interlayer bonding. Bridging can sag, and internal support may be mechanically inaccessible. Soluble support can reduce extraction force, but its dissolution rate depends on exposed area, diffusion path, agitation, temperature, support history and chemical compatibility. Dissolution is not the only event: fragments must leave the network, concentrated solution must be exchanged, and the component must survive the liquid exposure and subsequent drying. A support that swells before dissolving can temporarily increase extraction stress or block a constriction.

In direct ink writing, the deposited material may be wet, gelled or solvent-containing. A channel can lose clearance during drying or shrinkage even when the green geometry appears open. Embedded or support-bath printing can enable soft freeform geometries by providing distributed mechanical support, but the bath is a second material whose rheology, exchange and residue become part of the route [12]. Evidence from one bath-ink pair cannot be assumed transferable to another.

Highly filled ceramic or functional inks add rheological constraints. Increasing solids may improve final loading while reducing recoverability and increasing nozzle pressure, yield stress or sedimentation; the underlying dispersion and colloidal-processing controls are material-specific [7]. A support bath can preserve shape but introduces a second material that must be removed without contaminating the surface or changing the functional state.

Qualification should use representative bends, intersections, blind ends and minimum-clearance features. A straight open tube is not a surrogate for a tortuous manifold.

7. Material jetting

Material jetting can place build and support materials with fine spatial control. The critical risks are droplet coalescence, incomplete support removal, multimaterial interfacial residue and nozzle-state drift. A support chemistry that removes from a flat coupon may remain in a deep channel because exchange is diffusion-limited. Research on support-free enclosed PolyJet channels illustrates that changing the build strategy can avoid photocurable support within selected geometries, but it does not remove the need to qualify trapped liquid, wall state and process-specific resolution [11]. The acceptance method must therefore test the complete geometry or a justified worst-case witness structure.

8. Powder-bed, binder and bound-powder routes

Loose powder can act as geometric support, but powder retention is a channel-recovery problem. Depowdering may require reorientation, vibration, pressure, suction, fluidisation, ultrasonic excitation, vacuum-assisted techniques or a designed extraction path. The choice must consider powder size, morphology, packing, partial sintering, electrostatic behaviour and the sensitivity of thin walls to cleaning energy. Controlled studies using challenge geometries show that removal effectiveness can differ materially between laser and electron-beam powder-bed routes because the retained powder state differs; they also show that weighing and XCT have practical detection limits [13].

The outlet is part of the geometry, not an administrative afterthought. Each trapped volume requires a credible inlet-outlet or access sequence, and the sequence of part orientations may matter. A channel that can be depowdered only before a neighbouring port is sealed must carry that dependency in the manufacturing plan. ASTM F3335-20 is limited to assessing manufacturing-material residues in powder-bed-fused medical devices; it is nevertheless useful as a bounded example of extraction-based qualitative and quantitative assessment and explicitly does not set universal acceptance limits [14].

Thermal exposure can change powder cohesion or binder condition. In binder jetting and bound-powder routes, the printed object is a green body. Debinding-defect mechanisms and their transport limits are inherited from ER-037 [23]. ER-163 adds only the channel-specific consequence: debinding and sintering can shrink, distort or close an internal passage, so a clean green channel is not proof of a clean final channel.

The matrix must record powder family, lot and refresh or reuse state, particle-size distribution, packing condition, thermal history, access direction, recovery process and post-conversion inspection. For ceramic and metal routes, dimensional compensation must be tied to a specific feedstock, furnace cycle and geometry family.

9. Indirect sacrificial geometries

Indirect route selection is inherited from ER-049 [26], and the chemistry and process coupling of water-removable sacrificial photopolymers for indirect additive manufacturing are owned by ER-009 [20]. ER-163 does not redefine either domain. Its extension is

channel-specific: an indirect pattern, mould or core is acceptable only when the sacrificial geometry provides a credible recovery path, preserves the intended internal dimension through transfer, and leaves a final feature that can be inspected after the irreversible transformation.

The 3Dresyns support portfolio distinguishes durable mould-making, water-soluble sacrificial, solvent-soluble sacrificial and easy-breakable support families [8]. This is manufacturer implementation scope only. ER-163 uses the distinction to define different channel-recovery obligations; it does not establish universal dissolution, burnout, compatibility or feature limits, which remain material- and process-specific and, for water-removable sacrificial photopolymers, within ER-009 ownership [20].

For an internal channel, the route record must distinguish removal of the sacrificial geometry from any later binder removal and must verify the transferred channel after each irreversible step. Expansion, gas evolution, ash, cracking and transport during debinding are inherited from ER-037 [23]. ER-163 therefore records only the channel-specific evidence: vent or escape path, dimensional transfer, residue detection and final continuity after the declared thermal or chemical conversion.

10. Verification and metrology

The method must match the failure mode. General dimensional metrology, trueness, precision and geometric-fidelity questions are inherited from ER-010 [24]. ER-163 uses those controls only for internal-feature acceptance, where dimensional probes and optical microscopy can verify accessible openings but not necessarily blind internal surfaces. Pressure-drop or flow-through tests can establish continuity yet may miss adherent residue, surface chemistry or a partially occluded parallel branch. Mass balance, controlled extraction and chemical analysis can support cleanliness claims. Micro-computed tomography, sectioning, endoscopy or validated witness structures may be appropriate when direct access is impossible. NIST identifies complex internal geometry, surface topography and internal defects as continuing AM measurement challenges and treats post-process measurement and non-destructive testing as part of qualification evidence [15].

XCT is powerful but not self-validating. Detectability depends on voxel size, focal spot, material attenuation, part diameter, reconstruction settings, contrast between residue and wall, artefacts and the segmentation rule. A scan that resolves the channel envelope may still fail to distinguish a thin organic film or particles whose attenuation approaches that of the component. The measurement report should state the feature or residue size that the method could detect with justified confidence. The general AM XCT literature emphasises these metrological dependencies [16]. ISO/ASTM DIS 52971 is under development in 2026 and therefore must not be presented as a published International Standard [17].

Internal surface finishing is also state-changing, not merely cosmetic. Chemical or electrochemical polishing, abrasive-flow methods, jet polishing and magnetic or hybrid approaches differ in access, material-removal uniformity and compatibility with blind or tortuous channels [18]. A finishing step must therefore be qualified for wall loss, edge rounding, branch imbalance, chemistry and functional performance rather than accepted solely because average roughness decreases.

No single method proves every attribute. A robust strategy often combines:

1. a geometry method for diameter, form and branch continuity;
2. a residue method for loose, dissolved or adherent material;
3. a functional method such as flow, pressure drop, leakage, heat transfer or dielectric response; and
4. a destructive validation method during process development to establish what the non-destructive method can and cannot see.

Acceptance should specify channel diameter or hydraulic dimension, continuity, allowable residue, surface condition, leakage, pressure or flow range, and the state after conditioning. For functional channels, electrical, thermal, optical or biological performance must be measured in the service-relevant state. ISO/ASTM 52902 test artefacts can support geometric-capability assessment, but a general artefact does not replace a product-specific worst-case feature [9].

11. Worst-case witness design and evidence transfer

A witness is valid only when it is at least as difficult to form, recover and inspect as the product feature it represents. Similarity in nominal diameter alone is insufficient. The witness rationale should compare:

- minimum cross-section and maximum unsupported span;
- total path length and length-to-hydraulic-diameter ratio;
- number and severity of bends, junctions and changes in section;
- blind ends, upward traps and venting;
- surface orientation and expected roughness;
- retained-material volume and removal-medium access;
- wall thickness and susceptibility to cleaning damage; and
- final thermal, chemical or mechanical transformations.

The witness should accompany the relevant build location and orientation when machine-field effects can matter. If the witness is destroyed for sectioning or chemical analysis, the sampling plan must define how it represents the released population. A clean witness is not automatically proof that every product channel is clean; that inference requires controlled process equivalence, traceability and evidence that the witness remains the worst case.

Channel evidence is graded by maturity:

Level	Evidence	Permitted use
A	Literature, supplier information or physical rationale	Screening and experiment design only
B	Simple coupon under recorded conditions	Feasibility within the tested window
C	Worst-case witness or representative component across planned variability	Process qualification candidate
D	Repeated production evidence with calibrated inspection and controlled change	Release within the qualified envelope

Movement from one level to the next requires new evidence. A favourable supplier page, a single transparent coupon or one CT image is not Level D evidence.

12. Worked example

Consider a polymer manifold with three blind branches and a 0.2 mm annular gap intended for silicone casting. A direct vat route is screened first. The channel fails if exposure bleed closes the gap, if washing cannot exchange through the blind branches, or if post-cure creates residue. A mechanically supported extrusion route fails if the support cannot be extracted without damaging the annulus. A soluble sacrificial route survives only after dissolution time, agitation, residue and dimensional retention are demonstrated on a tortuous witness. An indirect printed core survives if the core releases from the silicone and the final annulus is verified by flow and microscopy.

The conclusion is conditional: the smallest nominally printable gap is not the decision variable. The surviving route is the one that maintains the required clearance after shaping, recovery, cure and service conditioning. Before release, the manifold should have quantitative limits for geometry, residue, flow or pressure drop and compatibility with the silicone, together with a stated detection capability for each method.

13. Safety and environmental controls

Soluble supports, cleaning fluids and uncured resins require controlled handling, waste segregation and suitable ventilation. “Water-soluble” describes a removal mechanism, not automatic benignity. The safety data sheet and process-specific exposure controls remain necessary. Effluent composition, dissolved polymer, filler and residual monomer should be considered where the support is removed at scale.

Compressed-gas cleaning can eject particles and can pressurise closed or weak geometries. Combustible metal or polymer powders require process-specific ignition, dust and housekeeping controls. Ultrasonic, abrasive, vacuum-assisted and high-pressure methods can damage thin walls even when they improve removal. Solvents can change dimensions, extract constituents or create flammable atmospheres. Thermal removal can generate exotherm, pressure, smoke or decomposition products when a vent path is inadequate. The recovery recipe must therefore include operating limits, containment, personal protection, ventilation, incompatibilities and a stop/quarantine rule for unexpected pressure, heat, cracking, mass change or effluent.

14. Limitations

This review proposes a decision and evidence framework; it does not validate a universal predictive model for channel manufacturability or cleanliness. The cited studies span different machines, materials and geometries. Numerical limits reported in one study should not be transferred without equivalence evidence. Several measurement methods detect geometry or bulk retained material more readily than thin films or chemically significant traces. Regulatory acceptance criteria remain application-specific, especially for medical, food-contact, pressure, aerospace and biological uses.

15. Conclusions

1. Internal channels are qualified process chains, not CAD voids.
2. The support strategy must be selected together with recovery access, post-processing and inspection.
3. Soluble, powder-bed and indirect routes each solve a different access problem and introduce different residue or transformation risks.
4. A representative tortuous witness is more informative than a straight open tube when recovery is the limiting operation.
5. State-resolved measurements are required before a channel is released for fluidic, thermal, electrical, optical or biological service.
6. The correct output is a surviving route and a traceable no-go rationale, not a universal minimum feature claim.
7. Hard access, compatibility, endpoint, inspection and safety gates must be passed before cost or nominal resolution is optimised.
8. Cleaning time alone is not an endpoint; completion must be linked to a measured residue, geometry or functional criterion.
9. XCT, flow testing and mass balance each have blind spots and should be combined or validated against destructive evidence where risk requires it.
10. Evidence transfer from a witness to a product requires a documented worst-case argument and control of the qualified process envelope.

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