

Industrial Vat-Photopolymerisation Architectures: SLA, DLP, LCD/MSLA and Continuous Printing

Exposure Geometry, Throughput, Supports and Qualification

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Statement of Significance

Vat-photopolymerisation machines are often compared by nominal pixel pitch, laser spot, layer height or headline vertical speed. None of those descriptors identifies the complete optical field, cured feature, interface load or delivered polymer network. A laser scans vectors; a DLP projector images a micromirror field; an LCD/MSLA system masks a backlight; and a continuous route maintains an inhibition or low-adhesion liquid interface while the component is extracted. All still depend on resin identity, spectrum, irradiance, temperature, oxygen, rheology, separation or replenishment, supports, washing, post-cure, conditioning and acceptance. ER-142 provides a state-resolved comparison of these architectures. It treats working curves as measured system states, not portable resin constants; separates green, washed and post-cured parts; and evaluates throughput only after the complete cell has produced accepted components. The resulting qualification framework is particularly important for highly specialised photopolymers, where a nominal material function is inseparable from the printer and post-processing route that creates it.

Keywords: vat photopolymerisation; stereolithography; SLA; digital light processing; DLP; masked stereolithography; MSLA; LCD; continuous liquid interface; working curve; light-engine metrology; separation force; supports; post-cure; process qualification

Abstract

Industrial vat photopolymerisation includes multiple exposure and interface architectures that must not be collapsed into a single `SLA` parameter space. Laser-scanned stereolithography delivers a moving optical spot; digital light processing projects a micromirror image; LCD/MSLA masks a light-engine field; and continuous routes maintain an inhibition or mobile liquid interface to reduce discrete separation and recoating pauses. This qualitative engineering review follows each route from released resin to accepted component. It examines resin conditioning, spectral and spatial light delivery, working curves, voxel and feature formation, separation, resin renewal, heat and mass transport, supports, drainage, washing, post-cure, shrinkage, surface state, safety, full-cell throughput and change control. Primary and interlaboratory studies demonstrate that nominal wavelength, pixel pitch, exposure time or scalar radiant exposure cannot independently determine cured geometry or network state. Continuous extraction can remove one class of mechanical pause while introducing interface-stability, flow, viscosity and thermal constraints. Post-cure can strengthen one resin while worsening dimensional fidelity, and whole-layer exposure does not eliminate geometry-dependent separation or downstream labour. The proposed selection gate requires architecture-specific metrology, state-labelled evidence and acceptance after the qualified post-process. Volumetric/tomographic printing, two-photon polymerisation, material jetting, ceramic/metal green-body conversion and construction-scale applications are outside scope.

1. Purpose and scope

ER-142 applies the state-resolved framework of ER-139 to vat photopolymerisation (VPP). ISO/ASTM 52900:2021 supplies the common process vocabulary [1]. ISO/ASTM 52910:2018 structures design requirements [3], while ISO/ASTM 52920:2023 places process and production-site controls around the machine [2]. ISO/ASTM 52924:2023 and 52927:2024 provide property-classification and characteristic/test-method structures [4,5], and ISO/ASTM 52901:2017 structures requirements for purchased AM parts [6]. These documents help define evidence; they do not establish that a nominal printer resolution, resin label or exposure recipe qualifies a component.

The review compares four industrial architecture groups: laser-scanned SLA, DLP, LCD/MSLA and continuous-interface printing. `SLA` is retained for the laser-scanned route and for literature that explicitly uses that name. It is not used as a precise synonym for every VPP process. NIST similarly distinguishes laser, projected and masked implementations within VPP research [7].

The delivered object in ER-142 is a photopolymer component. Highly specialised rigid, tough, flexible, elastomeric, high-temperature, flame-resistant, optical, dielectric, conductive, barrier, castable, sacrificial, dental and other application-specific resin families are within the selection framework, but no family name establishes final performance. The 3Dresyns platform page documents the declared breadth of SLA/DLP/LCD resin routes [28]; as a manufacturer source, it is not independent proof of accuracy, safety, regulatory status or property retention.

Filled slurries that leave the printer as ceramic or metal green bodies belong to ER-153 and ER-154 because debinding and sintering create their delivered material state. Material jetting belongs to ER-143. Volumetric/tomographic systems belong principally to ER-004 and ER-075, and two-photon polymerisation to ER-029. Construction, concrete, geopolymer, regolith and macroscopic high-volume deposition are excluded.

2. Four exposure and interface architectures

All four routes selectively photopolymerise material held in or supplied from a vat. Their spatial delivery and interface mechanics differ.

Laser-scanned SLA steers a focused beam along vectors. Cure at one location occurs at a different time from cure at another location. Delivered state depends on beam power, profile, focus, wavelength or spectrum, scan speed, hatch or contour strategy, overlap, path ordering and optical position. A spot diameter is not a voxel dimension, and a commanded power is not the absorbed local history. Pulsed-laser modelling by Ajami and Moniri reinforces the need to validate the specific temporal and spatial cure field [22].

DLP projects a two-dimensional pattern from a digital micromirror device through optics. Sun et al. demonstrated this dynamic-mask principle in projection micro-stereolithography [8]. A layer can be exposed in parallel, but projection magnification, focus, field distortion, pixel mapping, irradiance, spectrum, flare and resin response determine the realised field. Projector pixels do not become exact rectangular solid voxels in the component.

LCD/MSLA places a liquid-crystal mask between the light engine and resin. Mask transmission, pixel aperture, backlight optics, spectral distribution, divergence, thermal state and ageing affect delivery. Caplins et al. mapped one nominally 405 nm LCD light engine and observed position-dependent irradiance, spectrum and divergence that changed polymerisation and texture [9]. The study establishes a measurement problem, not a universal ranking of LCD against DLP.

Continuous-interface systems maintain a liquid zone or moving low-adhesion interface while the part is extracted. Oxygen-inhibited CLIP, dual-colour inhibition and mobile liquid interfaces implement this opportunity differently [13-16]. Continuous does not mean unconstrained: resin must flow, heat must be removed, inhibition or interface conditions must remain stable, and the geometry/support system must tolerate extraction.

Table 1. Architecture-specific opportunities and control burdens

Axis	Laser-scanned SLA	DLP	LCD/MSLA	Continuous-interface routes
Spatial delivery	Moving focused beam and vector path	Projected micromirror image	LCD-masked backlight field	Projected field coupled to a maintained liquid interface
Temporal state	Location depends on scan order, speed and overlap	Field exposure followed by separation/renewal	Field exposure followed by separation/renewal	Exposure, resin renewal and extraction may overlap
Conditional opportunity	Vector control without a fixed projector pixel grid	Parallel field exposure with optical projection	Large masked field with comparatively simple optical train	Reduced or removed discrete peel/recoat pauses in a validated system
Characteristic limit	Vector time, beam/focus drift, path heat and optical-position error	Field distortion, focus, projection uniformity and peel loads	Backlight/mask non-uniformity, divergence, ageing and peel loads	Inhibition/interface stability, heat, viscosity, flow and geometry-dependent extraction
Minimum metrology	Beam profile, position, power/spectrum and scan validation	Pixel mapping, focus/distortion and spectral irradiance map	Mask transmission plus spatial/spectral/divergence thermal map	Projected field plus interface thickness/stability, temperature, flow and draw state

Architecture labels do not rank accepted throughput. A projected layer may take less selective-exposure time than a long laser vector path while requiring the same number of bottom layers, separation cycles, wash transfers or support-removal operations. A continuous route may reduce those cycles but become limited by resin replenishment, exotherm, feature cross-section or post-cure.

3. State-resolved production chain

The process starts when a resin lot is released for use, not at the first exposure. Identity, storage, age and mixing are verified; the resin is homogenised, conditioned, degassed or filtered when the validated route requires it; and a controlled quantity is loaded. The build is exposed by scan, projection or mask. A layerwise system separates or recoats and replenishes resin; a continuous system maintains its liquid interface and transport window. The green component is drained, removed, washed, dried, separated from supports, post-cured, conditioned, inspected and accepted. Recovered resin is tested, segregated, returned or rejected under a declared rule.

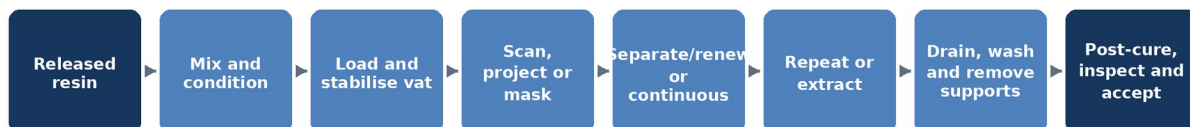


Figure 1. State-resolved vat-photopolymerisation production chain

Each datum must identify the state it represents. A liquid-resin certificate does not describe the green polymer network. A feature measured after washing does not establish its post-cure dimension. A tensile specimen post-cured on all sides does not automatically represent a shaded internal rib. A clean external surface does not establish the absence of resin in a blind channel.

The chain also prevents an accounting error. Resin in the vat is work-in-process and can acquire exposure, heat, moisture, contamination or settling history. Solvent and wash capacity, drying, supports, cure fixtures and inspection are production

resources. A route that produces many green parts quickly may still have lower accepted output if those downstream states are slow or unstable.

4. Resin identity, conditioning and vat state

Resin identity includes oligomers or polymers, reactive diluents, photoinitiators, absorbers, inhibitors, pigments, fillers, stabilisers and any functional additive. Lot release should control composition or justified surrogates, viscosity or rheology at a defined temperature, optical absorption or working response, storage, age, container history and homogeneity. Highly specialised performance increases rather than relaxes this burden because the functional additive can also alter scattering, sedimentation, cure depth, heat, oxygen sensitivity, washability or network conversion.

Mixing must restore the validated state without introducing bubbles, contamination or an uncontrolled temperature. Low-viscosity resins may level quickly yet drain into cavities or move under separation. High-viscosity, filled or thixotropic systems may resist sedimentation but replenish slowly and trap gas. A bulk viscosity value at one shear rate cannot by itself predict squeeze flow, recoating or continuous-interface replenishment.

The vat is part of the material genealogy. Resin can remain after a build, receive stray or scattered exposure, accumulate cured fragments, lose volatile components, absorb moisture or collect support debris. Filled systems can segregate vertically or laterally. Top-up with fresh resin does not erase the prior history. A return-to-use rule should define permitted age, temperature and light exposure, mixing, filtration, sampling, compatibility of lots, maximum hold, contamination checks and disposition.

Temperature affects viscosity, reaction kinetics, oxygen transport, separation and dimensional response. A room setpoint is not a resin-temperature measurement. The qualification record should identify conditioning time, vat and chamber temperature locations, permitted gradients and recovery after a pause or refill. If heating is used, the material safety and reaction boundaries must also be reassessed.

Specialty claims require separate proof. ‘High temperature’ may refer to one test after one post-cure. ‘Biocompatible’ or ‘dental’ depends on the final composition, washing, post-cure, cleanliness and intended use, not the bottle label alone. ‘Water washable’ describes a process compatibility and does not prove low hazard or permit uncontrolled disposal. ‘Monomer free’, optical, flame-resistant, conductive or chemical-resistant claims require defined methods and a qualified final state.

ER-142 owns architecture-level comparison and selection. ER-032 owns storage, reuse and open-vat state, including resin genealogy and return-to-use rules; ER-036 owns rheology, recoating and dispersion control for highly filled VPP suspensions. Those mechanisms are used here only as architecture-specific qualification inputs.

5. Exposure metrology and working curves

The command file contains intended exposure; qualification requires delivered exposure. Radiant exposure at a position is the time integral of spectral irradiance over the relevant wavelength range. A single time value omits irradiance. A scalar dose omits spectrum, spatial distribution, divergence, temporal modulation, optical losses and resin absorption. The same nominal wavelength can contain different bandwidths and tails that interact differently with initiator and absorber spectra.

For a bounded resin and optical system, the classical working-curve form derived by Jacobs is commonly written [29]:

$$\text{Cure depth} = D_p \times \ln(H / H_c)$$

where ‘H’ is measured radiant exposure, ‘H_c’ is a fitted critical exposure and ‘D_p’ is an effective penetration-depth parameter. This relation is useful only within its assumptions, measurement method and fitted range. Kolibaba et al. found enormous interlaboratory scatter when 24 laboratories measured aliquots from one resin batch: fitted ‘D_p’ varied by as much as sevenfold and ‘H_c’ by as much as seventyfold [10]. Caplins et al. further showed that broadband spectra and resin absorption gradients can produce deviations from the monochromatic model [11]. Working-curve parameters are therefore not detached resin constants.

Laser qualification should map power at the relevant plane, beam profile and focus, position accuracy, scan-speed delivery, overlap and field dependence. Projection qualification should map spectral irradiance, focus, geometric distortion, pixel registration and field uniformity. LCD/MSLA additionally requires mask transmission, defective-pixel policy, backlight divergence and ageing. Calibration equipment requires traceability, aperture and spectral suitability, uncertainty and alignment.

A process recipe should retain both commanded and measured states. ‘405 nm, 2 seconds’ does not identify a transferable dose. ‘10 mJ/cm²’ still omits spectrum, field map, exposure sequence, temperature, resin state, layer mechanics and measurement uncertainty. Compensation maps or grayscale corrections can improve delivery only if their input measurement, software version, interpolation and residual error remain controlled.

ER-142 owns architecture-level comparison and selection; ER-002 owns cross-platform exposure equivalence in depth. The exposure states above are therefore comparison inputs, not a substitute for the equivalence analysis in ER-002.

6. Voxel, feature and dimensional formation

The cured feature is an interaction volume, not a copy of a pixel or spot. Light propagates, scatters, reflects and is absorbed; radicals initiate and propagate; oxygen inhibits near exposed surfaces; conversion continues or terminates; and adjacent exposures overlap. The result can extend laterally or vertically beyond the nominal image, undercure a boundary, bridge a gap or leave a conversion gradient.

Nominal laser spot, projected pixel pitch and LCD pixel pitch are sampling or delivery descriptors. Final feature width also depends on focus, point- or line-spread function, threshold, overlap, resin absorption, scattering, layer thickness, orientation and

post-cure. Layer height does not equal vertical accuracy. Cure must extend enough to attach to the previous state, while excess depth can close channels, grow pins, thicken walls or bond to a window.

Edges and isolated features experience different neighbourhoods from large solid fields. Optical flare or scattering can expose nominally dark resin. In DLP and LCD/MSLA, antialiasing or grayscale modifies the commanded field but does not guarantee a geometrically linear material response. In laser SLA, path acceleration, corners, vector starts/stops and overlap can create local differences. A single central calibration coupon cannot qualify the whole build field.

Feature validation should include positive and negative geometry, walls, holes, channels, gaps, pins, edges, slopes and the relevant orientation. Measurements need the final conditioned state and an uncertainty compatible with the acceptance decision. ISO/ASTM 52927:2024 helps organise characteristics and methods [5], but the organisation must still choose geometry and sampling that expose its failure modes.

Shrinkage adds a material-history term. Karalekas et al. investigated shrinkage-induced stresses in photo-curable stereolithography resins [20]. Sarkar et al. showed that changing the curing protocol can alter conversion, stress, temperature, shrinkage and inferred network state from the same initial resin [19]. Software scaling may compensate a repeatable dimensional bias; it cannot make an unstable network or spatially varying cure state equivalent.

ER-010 owns VPP metrology in depth, and ER-030 owns oxygen inhibition and free-surface/interfacial cure. ER-142 invokes those mechanisms only to delimit architecture-level comparison and selection.

7. Separation, replenishment and interface mechanics

In a bottom-up layerwise process, each newly exposed cross-section must detach from a transparent interface before fresh resin fills the gap. The part, supports and build platform form a load path. Separation force depends on exposed area and shape, interface material and age, resin rheology and temperature, gap, motion profile, drainage, prior layers and machine compliance. He et al. demonstrated reduction of separation force using a defined constrained-surface texture in one projection-SLA apparatus [12]. The transferable conclusion is that the interface can be engineered and measured, not that one texture or force limit applies universally.

Large cross-sections, enclosed cups and poor drainage can increase pressure or suction and destabilise supports. A nominally stiff support can protect lift while marking the surface or concentrating stress. A very compliant support can reduce damage at removal but allow lateral movement. Orientation, hollowing and venting are therefore mechanical process decisions, not only material-saving choices.

Films and windows age. Clouding, swelling, scratches, contamination, mechanical relaxation and changes in surface condition can alter light transmission and separation. Replacement by calendar time alone may miss damage; replacement by build count alone may miss material-specific attack. A qualified maintenance rule should link observable state to optical and mechanical consequences.

Resin renewal can be the rate-limiting operation. After separation, resin must refill the gap without bubbles or persistent gradients. Viscosity, temperature, layer area, lift distance, motion profile and filler content affect the required time. A short fixed wait that works for an open low-viscosity resin may fail for a filled or highly viscous specialty formulation. Top-down systems exchange peel mechanics for recoating, free-surface and support/buoyancy constraints; they still need a validated layer state.

Separation telemetry, motor current, force, position, imaging or acoustic signals can support control only after causal validation. A stable average force does not exclude a local support failure, and a force alarm does not identify the cause without resin, geometry, interface and motion records.

ER-034 owns separation and peel mechanics in depth, while ER-036 owns filled-suspension rheology and recoating. ER-142 uses both only as architecture-selection and qualification constraints.

8. Continuous routes and their boundaries

Tumbleston et al. used an oxygen-permeable window to maintain an inhibition ‘dead zone’ beneath the growing component [13]. Janusziewicz et al. reported layerless surface and mechanical evidence for a particular CLIP resin and apparatus [14]. De Beer et al. created an inhibition volume with a second light colour [16]. Walker et al. used a mobile fluorinated-oil interface to reduce adhesion and remove heat [15]. These are distinct continuous-interface mechanisms, not interchangeable trade names or parameter sets; oxygen inhibition and free-surface/interfacial cure are treated in depth in ER-030.

Continuity can remove the discrete expose-separate-recoat cycle when the interface, resin and geometry support simultaneous exposure, replenishment and extraction. The process then becomes constrained by photokinetics, inhibitor or oxygen transport, resin flow, viscosity, pressure, conversion, green strength and heat. A wide solid section can demand more replenishment and heat removal than an open lattice. The maximum sustainable draw state can vary within one component.

Claims of ‘layerless’, ‘isotropic’ or constant speed must retain their experimental boundary. Janusziewicz et al. tested a defined TMPTA-based formulation, geometry and process state [14]. That result does not prove orientation-independent behaviour for every chemistry or post-cure. A continuous trajectory can still receive temporally sampled images and can retain optical, thermal, flow and support directionality.

Volumetric/tomographic AM is adjacent but different. Kelly et al. and Shusteff et al. formed three-dimensional dose distributions within a resin volume [17,18]. Those systems are not another name for continuous extraction through a vat interface. ER-142 excludes detailed comparison because spatial selectivity and material operating windows in volumetric/tomographic AM belong to ER-004 and ER-075; two-photon process photophysics belongs to ER-029.

The industrial opportunity of continuous processing should therefore be stated conditionally: it can reduce interface-cycle overhead for validated material, geometry, thermal and flow states. It does not remove washing, support handling, post-cure, inspection or application qualification.

9. Orientation, supports, drainage and surface state

Orientation determines projected area per layer, separation direction, support contact, drain paths, trapped volumes, layer intersections, optical exposure neighbourhood, build height and post-processing access. The orientation with the shortest machine time may have the largest peel area or worst supported surface. The orientation with the least support may trap resin or shade a critical face during post-cure.

Supports have at least five roles: transmit separation or recoating loads; anchor against motion and distortion; manage thermal or conversion stress; preserve drain and wash access; and define removable contact points. They are part of the process specification. Tip, shaft, spacing, bracing, contact position and removal state must match geometry, green strength and surface acceptance.

Hollow features require openings that work during printing, draining and washing. A hole that admits liquid does not necessarily allow effective solvent exchange or drying. Blind channels can retain resin/solvent mixtures and later leak, swell, crack or interfere with function. For safety- or function-critical cavities, evidence can include mass change, borescope, computed tomography, pressure/flow, extractables or a validated destructive study. If a cavity cannot be cleaned and verified, it is not qualified.

Surface state is location-specific. Up-facing, down-facing, supported, window-adjacent, free and internal surfaces have different exposure, drainage and mechanical histories. Support removal, sanding, blasting, polishing, coating or machining changes dimension and surface chemistry. A quoted 'as printed' roughness is ambiguous unless it identifies orientation, location, wash, post-cure and measurement filtering.

10. Washing, post-cure and polymer-network evolution

The object leaving the vat is a green component containing an incompletely developed polymer network and surface liquid resin. Drain time and orientation affect carryover. Washing removes surface and accessible uncured material but can also extract soluble components, swell the network, soften thin features or redistribute contamination. Solvent identity, concentration, temperature, agitation, time, bath loading, sequence and drying are controlled variables.

A visually clean component can retain resin in crevices or solvent inside the network. Reusing a wash bath changes its dissolved-resin content and cleaning capability. A two-stage wash is not automatically qualified; bath replacement or recovery needs an objective criterion linked to cleanliness and component response. Water-washable formulations still create contaminated wash water that requires an appropriate disposal route.

Post-cure changes conversion, crosslink density, residual monomer, stress, colour, dimension, stiffness, strength and sometimes ductility. It is not a cosmetic afterthought. Sarkar et al. show that curing protocol can create different network states [19]. Cheadle et al. report bounded effects of orientation and post-cure conditions on conversion, colour and tensile response [21]. Menargues et al. found resin-dependent dimensional-mechanical trade-offs across five commercial formulations [23]. Together these sources prohibit a universal 'fully cured' time or the assumption that more UV always improves the part.

Post-cure specification should control spectrum, irradiance or justified dose surrogate, temperature, time, chamber loading, fixture, rotation or shadow management, delay after washing and final conditioning. Thick, pigmented, filled or optically absorbing components may develop a different internal state from thin clear coupons. A surface response does not establish core conversion.

Regulated or biological use needs separate evidence for the final article, including validated cleaning, residuals, cure, ageing, sterilisation if relevant and intended contact. A supplier classification cannot be transferred across printer, wash or cure changes. Similarly, high-temperature, flame-resistant, optical, dielectric, conductive, barrier or chemical-resistant performance must be tested after the qualified process and relevant environmental conditioning.

ER-033 owns washing- and drying-induced extraction, property change and dimensional response in depth. ER-142 uses those downstream states only to compare architectures and define the selection and qualification boundary.

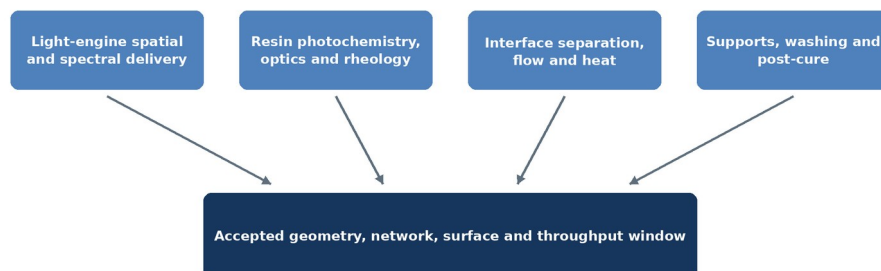


Figure 2. Coupled VPP production window
Table 2. Mechanism-to-defect and evidence matrix

Process stage	Controlling variables	Representative unacceptable state	Minimum discriminating evidence
Resin release and conditioning	Lot, composition, age, viscosity/rheology, optical response, temperature, mixing and contamination	Segregated, aged, contaminated or bubble-laden resin enters production	Lot genealogy, storage/age, conditioning record and validated material tests
Optical delivery	Spectrum, irradiance, spatial map, focus/divergence, mask or beam state, exposure sequence	Under/over-cure, field variation, closed gaps or weak interfaces	Traceable optical map plus feature response across the usable field
Interface and renewal	Window/film state, area, geometry, lift/draw, force, viscosity, temperature and refill	Delamination, support failure, cavitation, bubbles or incomplete layer	Interface history, motion/force evidence and geometry-representative challenge build
Supports and orientation	Cross-section, cups, drainage, contact, green strength, build height and shadowing	Distortion, trapped resin, damaged surface or unsupported motion	Approved build plan, support/load rationale and post-removal inspection
Washing and drying	Fluid, concentration, bath loading, time, agitation, access and drying	Residual resin, swelling, solvent retention or cross-contamination	Bath control, cleanliness/end-point evidence and geometry-specific validation
Post-cure and conditioning	Spectrum, dose/irradiance, temperature, time, fixture, shading and environment	Unequal conversion, shrinkage, colour/property drift or distortion	Chamber mapping, load traceability and final-state dimensional/property tests
Final acceptance	Geometry, surface, network/property, cleanliness, function and uncertainty	Green or convenient coupons substitute for delivered-component evidence	State-labelled measurements tied to critical features and intended use

11. Throughput, automation and factory economics

The relevant denominator is:

$$\text{Effective cell throughput} = \text{accepted components} / \text{elapsed time from released resin to final acceptance.}$$

Elapsed time includes resin release and mixing, vat preparation, file and build-plan checks, base layers, exposure, separation or draw, replenishment, pauses, draining, platform handling, washing, drying, support removal, post-cure, conditioning, inspection, equipment cleaning, deviations, rework and queue time. Yield includes build loss, support damage, trapped-resin rejection, dimensional nonconformance, cosmetic downgrade and destructive sampling.

In laser SLA, exposure time can grow with vector length and scan strategy. In DLP or LCD/MSLA, selective exposure can be closer to field-wise, but layer count, bottom-layer strategy, separation, replenishment and thermal constraints remain. Part count can change the total projected area, peel load, support network, wash density and post-cure loading. Whole-layer exposure therefore does not make accepted throughput independent of nesting.

Continuous extraction may reduce discrete cycle overhead but can require a slower draw through large cross-sections or viscous materials. Thermal management, resin replenishment and interface stability can set the rate. A headline vertical speed measured on one geometry is not a factory capacity. The same applies to marketing claims based on green-part completion rather than final acceptance.

Automation should be evaluated at transfers. Automatic resin dosing does not verify cleanliness. Automated support generation does not establish removal damage. A robotic wash does not prove fluid exchange in a blind channel. A cure chamber timer does not prove spatial dose or part temperature. Lights-out production requires detection and disposition for optical drift, low resin, failed separation, support loss, refill failure, temperature excursion, wash saturation, cure deviation and inspection failure.

Economic comparison must freeze annual mix, accepted geometry and property state, resin loss and recovery, supports, solvent and waste, labour, ventilation, wash and cure capacity, maintenance, calibration, yield, rework, inspection, equipment availability and inventory. The comparator must deliver the same final state. Machine purchase price, bottle price or nominal build speed alone cannot determine component cost.

12. Occupational safety and containment

NIOSH identifies uncured liquid resin and acrylates as potential asthma and dermatitis concerns in desktop VPP and highlights exposures during pouring, printing, resin recovery, isopropyl-alcohol cleaning, UV/heat curing and sanding [24]. The guide also identifies particles and gases that may be emitted during printing or curing. These are task-control topics, not proof that every formulation has the same hazard or that one control is adequate for all production cells.

The preferred hierarchy begins with material and task information, substitution where practicable, closed dispensing and recovery, enclosure and local exhaust at emission points, controlled washing/curing, suitable gloves and eye protection, spill response, hygiene and waste procedures. Glove material and change frequency must match the resin and solvent. Respiratory protection, where necessary, supplements engineering controls and requires an appropriate programme.

Isopropyl alcohol introduces flammability and inhalation/dermal concerns. Alternative cleaning fluids require their own hazard and process assessment. 'Low odour', 'bio-based', 'water washable' or 'monomer free' does not mean harmless. UV and visible-light sources, heated cure chambers, moving platforms and sharp support-removal tools add physical hazards.

Sanding, machining or blasting a cured component can generate dust whose composition includes the polymer and any pigment, flame retardant, ceramic, metal, conductive or nano/micron additive. Highly specialised resins therefore need composition- and task-specific exposure assessment. The current NIOSH AM topic page supports technology-, material- and environment-specific hazard routing [25], not a universal exposure limit.

Production records should include safety-data revision, resin and solvent lot, ventilation/interlock status, wash and cure equipment state, spill or abnormal event, waste stream, training and the basis of task controls. A printer enclosure does not control pouring, platform removal, washing, support removal or maintenance unless those transfers are also designed.

13. Qualification architecture and change control

ISO/ASTM 52920:2023 requires control of the process and production site as a system [2]. For VPP, the boundary includes resin genealogy, conditioning, vat/interface, optical delivery, build plan, separation or continuous transport, supports, drainage, washing, drying, support removal, post-cure, conditioning, measurement and disposition.

The process specification should separate commands from measured states. It should identify material and lot, allowed vat and recovery history, mixer/conditioning method, temperature, machine and optical configuration, calibration, exposure file, layer or draw strategy, build orientation and supports, interface or film identity, separation/replenishment, pauses, wash fluid and bath state, drying, cure chamber and load, conditioning, sampling, inspection and acceptance.

Change control must include resin supplier, formulation, colour, filler or additive; container/lot blending; storage; mixing and filtration; vat, film/window and coating; laser, projector, LCD mask, LED, optics or compensation map; sensor; firmware, slicer and antialiasing; layer thickness; exposure sequence; motion; support algorithm; geometry orientation; wash chemistry/equipment; cure spectrum, temperature and fixture; conditioning and measurement. A change may be called equivalent only when causal characteristics and accepted-component evidence remain inside the validated boundary.

NIST's 2025 Photopolymer Additive Manufacturing Workshop report identifies continuing needs in metrology, materials, data, safety, standards and regulatory readiness [26]. It is a current gap map, not a source of universal process performance. ASTM WK78224 is likewise only a work item [27]; until a standard is published, it must not be presented as a completed tensile-testing standard.

Table 3. Minimum industrial qualification record

Record block	Minimum controlled content	Release question
Resin genealogy	Supplier/lot, formulation, storage, age, opened/vat/recovery history, tests, mixing and contamination disposition	Was the exposure system supplied with resin in the validated material state?
Optical delivery	Architecture, spectrum, irradiance, field/beam map, focus/divergence, mask or optics state, calibration and uncertainty	Was light delivered in the validated spatial, spectral and temporal state?
Interface and build plan	Vat/film/window, orientation, supports, hollowing/vents, layer/draw sequence, separation/refill and monitored deviations	Did geometry and interface remain inside the validated mechanical and transport window?
Post-process	Drain, wash fluid/bath state, access, drying, support removal, cure chamber/load and conditioning	Is the measured object the declared final state and adequately clean?
Measurement	Field/location coupons, positive/negative features, dimensions, surface, network/property, cleanliness, function and uncertainty	Do the tests expose the component-critical failure modes?
Safety and containment	Enclosure and local capture where justified, resin/wash/cure inventory, exposure controls, spill/waste route, PPE and maintenance controls	Were chemical, optical and handling hazards controlled for the actual cell and task?
Acceptance and change	Part/build traceability, software/configuration, deviations, rework, rejects, maintenance and equivalence decisions	Can every accepted component be linked to an unchanged qualified route?

14. Selection gate, limitations and conclusions

Selection starts with the conditioned delivered component. The gate is:

1. Define geometry, surface, dimensional, mechanical, optical, thermal, chemical, electrical, cleanliness, regulatory, functional and environmental acceptance.
2. Eliminate resins and architectures whose spectrum, optical delivery, rheology, interface or post-process cannot create that state.
3. Characterise the usable field or beam and fit working/feature response with traceable methods and uncertainty; do not transfer exposure settings by label.
4. Validate orientation, supports, largest cross-sections, cups, vents, separation or continuous draw, refill and thermal extremes.
5. Demonstrate draining, washing, drying, support removal and internal cleanliness for representative geometry.
6. Qualify post-cure and conditioning for conversion, dimension, property, colour and any application-specific endpoint.
7. Compare accepted-component throughput, yield, labour, solvent/waste, maintenance, calibration and full factory cost against a declared alternative, or issue a no-go decision.

The evidence base contains many defined research resins and commercial systems. It does not provide universal exposure settings, feature sizes, support angles, wash times, post-cure doses, isotropy statements, build-speed factors or cost multipliers. Continuous-route results remain architecture-, resin- and geometry-specific. The NIOSH desktop guide routes hazards but does not qualify an industrial site. Manufacturer pages define portfolio or architecture only.

The following conclusions control industrial use:

1. Laser SLA, DLP and LCD/MSLA use different spatial and temporal light-delivery architectures; their recipes are not interchangeable.
2. Pixel pitch, laser spot and layer height are input descriptors, not final resolution or accuracy.

3. A working curve is a method-, light-engine-, resin- and temperature-dependent measurement state, not a portable material constant; cross-platform exposure equivalence is treated in depth in ER-002.
4. Bottom-up separation and refill couple geometry, supports, interface condition, rheology and motion.
5. Continuous interfaces can remove discrete peel delays while introducing inhibition, flow, heat and draw constraints.
6. Green, washed, post-cured and conditioned components are different material and dimensional states.
7. Supports, drainage, washing and post-cure are production operations inside the qualification boundary.
8. Specialty resin functions require final-state evidence after the qualified printer and post-process; a family label is insufficient.
9. Effective throughput is accepted components per complete cell cycle, not layer exposure or vertical build speed.
10. Qualification must connect resin genealogy, measured optical delivery, interface mechanics, build plan, post-process, measurement, acceptance and change control.

The correct result may be laser SLA, DLP, LCD/MSLA, a continuous-interface route, another manufacturing process or no additive route. The engineering output is the traceable accepted component, not an exposed image or a green part on a platform.

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