

Evidence Boundaries for On-Demand Additive-Manufactured Spare Parts and Photopolymer Ageing: Digital Definition, Suitability Screening and Transfer Limits

Separating digital-spare-part readiness from material-state evidence and release practice

Juan Seguro

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

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Abstract

On-demand additive manufacturing can reduce physical inventory and shorten spare-part lead times, but the evidence used to justify a digital spare-part strategy is not the same evidence required to establish material suitability or release a particular photopolymer part. This review defines that separation explicitly. It combines three evidence layers: digital-spare-part readiness and supply-chain feasibility, qualification-cost effects on manufacturing-route selection, and qualitative evidence that photopolymer properties can change with ageing and hydrothermal exposure.

The central conclusion is a missing join rather than a universal qualification rule. Current records can support screening questions about digital definition, production location, manufacturability, economic and qualification burden, and material-state sensitivity. They do not establish a general release criterion for photopolymer spare parts, a universal storage interval, or a transferable ageing allowance. “Transfer limits” therefore means the limits on transferring evidence between the digital-spare-part and photopolymer-ageing layers. Technology transfer to a contract manufacturer remains the separate scope of ER-479; longitudinal ageing-database architecture remains ER-481. A synthetic scheduling comparison separates fabrication readiness from qualified availability and connects the evidence burden to the replacement function.

Keywords: digital spare parts; additive manufacturing; suitability screening; photopolymer ageing; qualification cost; digital definition; evidence transfer; spare parts

1. Significance and scope

Digital spare parts replace some physical inventory functions with controlled digital information and on-demand manufacturing capability. Kretschmar et al. evaluate this concept from an industrial perspective and identify both opportunities and technical barriers [2]. Peron et al. add a distinct economic point: qualification requirements and their costs can materially influence the decision between additive and conventional manufacturing for spare parts [1]. Neither source, however, is a photopolymer-specific release standard.

ER-477 therefore does not ask whether a photopolymer spare part is universally “qualified.” It asks what can legitimately be inferred when generic digital-spare-part evidence is combined with a separate photopolymer-ageing record [3]. The answer is bounded: the combination supports a screening architecture and an explicit statement of missing evidence, not a release threshold.

1.1 Corpus boundary

ER-481 owns longitudinal ageing databases, specimen histories, censoring and data reuse. ER-383 and ER-387 retain their established ageing and storage scopes in the wider corpus. ER-479 owns technology transfer to contract manufacturers. In ER-477, “transfer” refers only to transfer of evidence between the digital-spare-part layer and the photopolymer material-state layer; it does not refer to organizational technology transfer.

2. Layer one: digital definition and readiness

Kretschmar et al. describe digital spare parts as a supply-chain concept in which digital object files and associated information can support in-house or distributed additive manufacture [2]. Their study emphasizes that readiness is constrained by process capability, build volume, post-processing, material availability, repeatability, surface quality, information infrastructure and organizational resources. These are readiness variables, not proof that a specific replacement part meets its service requirement.

A usable digital definition therefore needs more than geometry. At minimum it should bind the released design revision to material identity, manufacturing process family, orientation where relevant, required post-processing, critical dimensions and interfaces, inspection requirements, and the evidence state attached to the intended service function. The digital file is a carrier of requirements and configuration state; it is not itself evidence that those requirements were achieved.

3. Layer two: suitability screening

Peron et al. model the manufacturing-route decision for spare parts while explicitly accounting for qualification costs [1]. Their contribution is important because it prevents a low-inventory or low-lead-time argument from being treated as sufficient justification for AM. The appropriate route depends on the combined manufacturing, inventory and qualification burden for the specific part context.

For ER-477 this becomes a screening gate. Before a digital spare part enters detailed material qualification, the organization should ask whether the part is within the build envelope; whether geometry and tolerances are compatible with the process; whether required post-processing and inspection are available; whether qualification cost is proportionate to expected demand and criticality; and whether a controlled conventional route remains preferable. A “no-build” decision is a valid engineering output.

4. Layer three: photopolymer ageing

Nugraha et al. report long-term hydrothermal and physical ageing effects in an additively manufactured bio-based photopolymer resin [3]. The retained evidence available for this review is abstract-level and supports only the qualitative conclusion that exposure history can change measured material characteristics. It does not support transfer of numerical degradation values, service lives or storage limits.

That qualitative result is nevertheless sufficient to invalidate a common assumption: a digital file can remain unchanged while the material state used to reproduce it changes. A spare-part programme using photopolymers must therefore treat resin lot, storage and environmental history, print/post-cure state and the age of any retained qualification evidence as configuration-relevant variables.

5. The missing join

The three anchors do not provide a study in which a photopolymer spare part is digitally defined, manufactured on demand, aged or stored under a controlled history, and then released against a service-specific acceptance criterion. The literature layers therefore touch the same industrial problem without closing the final evidential chain.

This missing join is the main result of ER-477. It means that generic DSP readiness cannot be transferred into material suitability, and ageing evidence from a photopolymer specimen cannot be transferred into spare-part release without a part-specific bridge. The bridge must be built locally from requirements, representative manufacturing state, ageing or storage exposure where relevant, inspection and functional evidence.

6. Transfer limits

Evidence transfer is acceptable only when the receiving claim is no broader than the source. The DSP studies can support statements about supply-chain options, technical barriers, qualification burden and organizational readiness [1,2]. They cannot establish photopolymer property retention. The ageing study can support a qualitative material-state sensitivity [3]. It cannot establish digital-spare-part economics, service suitability or a release rule.

The safe synthesis is therefore asymmetric: generic AM spare-part evidence defines what must be screened; photopolymer-ageing evidence defines why material state cannot be assumed invariant. The actual release decision still requires evidence from the exact part, material, process, post-process and service context.

Evidence layer	Supports	Does not support
Digital-spare-part readiness	Supply-chain scenarios, technical barriers, digital storage and distributed-production considerations.	Photopolymer property retention or part release.
Qualification-cost model	Manufacturing-route screening that includes qualification burden.	Universal AM-vs-CM economic threshold.
Photopolymer ageing	Qualitative statement that exposure history can change material characteristics.	Universal storage limit, service life or release criterion.

Table 1. Evidence-transfer boundaries for ER-477.

7. Minimum local evidence package

For a candidate on-demand photopolymer spare part, the minimum local package should identify the controlled digital definition; intended function and critical interfaces; material and lot; printer/process route; orientation and build state; post-processing; inspection and acceptance methods; relevant storage or ageing exposure; deviations; and release authority. Where service consequence is significant, representative ageing or conditioning must be tied to the actual property or function that could fail.

No universal test count or acceptance interval is proposed. Evidence depth should scale with consequence, process novelty, material-state sensitivity and the cost of an incorrect release.

8. Practical decision sequence

A bounded on-demand spare-part workflow can be expressed as a sequence of gates. Gate 1 asks whether the digital definition is controlled and whether the intended function and interfaces are explicit. Gate 2 screens AM against conventional manufacture using geometry, quantity, lead time, process capability and qualification burden. Gate 3 asks whether the selected material/process state has evidence relevant to the intended environment and service duration. Gate 4 performs local inspection and functional release.

Failure at an early gate should stop the chain rather than be compensated by downstream testing. An uncontrolled digital definition cannot be rescued by a good material test; an economically attractive AM route cannot compensate for an unqualified critical interface; and a well-characterized resin cannot justify a spare-part release when the actual post-processing or inspection state is uncontrolled.

This sequence also clarifies what can be reused. Digital-definition controls can be reused across production events if configuration is unchanged. Generic AM readiness evidence can support recurring screening logic. Material ageing evidence can inform which state variables deserve control. The final release evidence, however, remains attached to the bounded part/process/service combination.

9. Research gaps that would close the join

The most useful missing studies are not additional generic demonstrations of 3D-printed spare parts. They are joined studies that start from a controlled digital spare-part definition, manufacture a polymer or photopolymer replacement under a documented route, expose it to realistic storage or service histories, and then evaluate a service-relevant acceptance endpoint.

Such studies should report the digital revision, material and lot, printer/process family, orientation, post-processing, inspection, exposure history and failure criterion. Without those fields, apparently similar spare-part results cannot be transferred safely. A longitudinal database could then accumulate comparable evidence, but that database architecture belongs to ER-481 rather than this review.

10. A spare-part decision with two separate readiness clocks

A proposed digital-spare-part record should distinguish the time required to make an object from the time required to justify its use. A controlled design file may shorten preparation, while material-state verification, inspection or a necessary qualification still determines when the part can be accepted. Quoting printing time as delivery readiness would omit those activities.

For a hypothetical comparison, route A can manufacture in two days but requires five further days of defined evidence work. Route B can provide an already qualified part in six days. Under those assumptions, route A is not the faster qualified supply route, even though its fabrication is faster. These invented durations illustrate a scheduling boundary; they are not industry lead times. If the qualification can be reused for later identical orders, that reuse should be stated with its configuration and change limits.

The same distinction applies to stored resin and stored finished parts. A digital design has a revision history; the physical material has an exposure and storage history. A programme needs both histories to reconstruct what was reproduced and the evidence supporting its state.

11. Match the evidence burden to the function of the replacement

Consider two hypothetical replacement functions: an identification cover and a load-transmitting linkage. The relevant acceptance evidence is unlikely to be identical because the consequence and mechanism of failure differ. The example does not assign either function a universal risk category. It shows why a part catalogue should preserve intended function, interfaces and the conditions under which its evidence was obtained.

A proposed screening result would have three possible outcomes: proceed within an established configuration, obtain specified additional evidence, or retain another manufacturing route. A decision to obtain evidence should state the unresolved endpoint rather than request an undirected set of material tests. If the question is retention after storage, an initial dimensional scan alone will not answer it. If the question is an interface tolerance, a general resin ageing result will not answer it.

A useful retrospective study would follow these decisions through actual orders, including rejected AM candidates. Reporting only successfully printed spare parts would not reveal the screening burden or the reasons another route was retained. That evidence would strengthen both the technical and economic assessment while keeping release attached to the specific part and manufacturing state.

12. A service-life qualification matrix

For an on-demand spare part, digital availability and manufacturing readiness are necessary but insufficient. The replacement part must be fit for its service envelope, including sustained loading, dimensional stability, repeated assembly, fluid exposure, light and temperature history. The digital-file revision and the qualified material/process state should be treated as independent configuration identifiers. A current drawing paired with an unqualified resin process does not constitute a ready spare part.

Qualification severity should depend on failure consequence and replacement function. A cosmetic cover and a fluid-contact or structural safety component require different levels of evidence even if both are printable. This is a proposed risk-based selection principle, not a universal acceptance standard. The governing engineering file should identify the original performance requirements, alternative manufacturing route, applicable environment, initial test results and the monitoring needed after deployment.

Ageing comparisons must use specimens that share the final manufacturing state: the same orientation, geometry-relevant thickness, wash history, post-cure and storage interval. Accelerated exposures can reveal sensitivities, but cannot automatically establish field life unless the acceleration mechanism remains representative. Photopolymer absorption, network relaxation and environmental attack may change properties differently, so endpoint selection must be functional: fit, stiffness, fracture resistance, sealing or another prespecified attribute.

An evidence bridge from a laboratory coupon to a spare part should explain scale, local stress concentrations, loading mode, and manufacturing variability. Failure to document any of those links warrants a restricted use decision or further qualification rather than a generalized declaration of equivalence to the original component.

A service-life decision is not a printability decision

A production file may be available and a geometry may be printable, yet neither property establishes suitability as a replacement component. Three distinct questions must be answered: whether the digital definition is controlled, whether the material-and-process combination can reproduce the specified state, and whether that state remains fit for the duty cycle. For photopolymers the last question deserves separate attention because storage before use and environmental exposure after installation are not interchangeable. Qualification should explicitly identify the governing failure mode, service environment and maintenance interval. A spare intended for short-term positioning has a fundamentally different evidence threshold from a load-bearing, electrically insulated or safety-relevant part. The cited additive-manufacturing spare-parts literature supplies economic and readiness context; it cannot be treated as a universal service-life dataset for resin parts.

Evidence hierarchy for substitution

A rational qualification sequence starts with requirements and uncertainty rather than a predetermined printer setting. Geometry verification addresses dimensional transfer; chemical and thermal characterisation address the manufactured material state; mechanical testing addresses specified loading; and conditioning studies address credible ageing. The tests should be linked to the required function and to the selected critical features, not collected merely because instruments are available. Supplier claims and nominal resin-family descriptors are weak substitutes for measurements from the production process in question. Where field exposure is unknown, the review should specify an explicit conditional acceptance or restrict use rather than assume equivalence.

What can be learned from a field return

A failed replacement part is informative only when the installed configuration, service duration, environmental history and inspection chain can be reconstructed. An isolated photograph can support description of a crack or distortion, but generally not a unique ageing mechanism. Returns should be linked to build version, batch, post-cure, inspection and service conditions. Failures that occur early and those developing after repeated environmental exposure should be analysed separately. The objective is to update the qualification envelope without retrospectively presenting preliminary observations as proven root causes.

Readiness of a digital spare part versus release of a physical article

Digital readiness addresses the provenance of the design, access rights, revision identification and whether the manufacturing instructions can be reconstructed. It does not demonstrate that a printed spare part will remain dimensionally stable or functional throughout the intended service environment. Release therefore requires an application-based risk classification: installation-fit evidence may be sufficient for a low-consequence fixture, while load-bearing or safety-relevant components require additional material, geometric, aging and service-simulation evidence. Where failure history is unavailable, this is a limitation to record, not a justification for assuming equivalence.

Photopolymer aging is conditional on chemistry, final conversion, exposure to temperature, moisture, chemicals and light, and mechanical stress. Results from accelerated conditioning cannot be equated with service lifetime without an argued acceleration model or a suitable correlation dataset. The cited spare-part-readiness work and photopolymer aging research cover different elements of this release problem. Their combined use provides a rationale for a tiered qualification matrix, not a measured prediction of lifetime.

Linking digital inventory to service-life acceptance

A spare part becomes functionally available only after its digital definition, material state and intended duty have each been qualified. An archived file can remain unchanged while the currently stocked resin, post-cure device or printer optical state changes. Digital inventory management should therefore reference approved material-and-process configurations, not only geometry and a release date.

The acceptance protocol should separate short-term dimensional fit, load-bearing performance and exposure-dependent retention of properties. A one-off substitution that fits the mating assembly may still be unsuitable if the replacement undergoes temperature, solvent or cyclic-load conditions absent from the screening test. Evidence from other AM families may identify plausible failure modes, but cannot establish the durability of a particular cured photopolymer.

A field return can improve a design only if the exposure history and product identity are reconstructible. The review should recommend capturing installation date, lot, manufacturing route, application duty and observed failure without converting anecdotal returns into population-level reliability rates.

13. Limitations

Peron et al. and Kretzschmar et al. are AM-general rather than photopolymer-specific. The Nugraha source is used at publisher-abstract depth for qualitative ageing only. No source in this evidence set establishes a general photopolymer spare-part release criterion, storage limit, qualified service life or universal economic break-even point.

14. Conclusions

On-demand spare-part readiness, qualification economics and photopolymer ageing are related but non-equivalent evidence domains. A digital definition can make production possible; a readiness screen can determine whether AM is plausible; ageing evidence can show that material state may change. None of those steps, alone or together, releases a part. The defensible workflow is to preserve the boundaries, identify the missing join and create the local bridge only for the exact spare part and manufacturing state under consideration.

Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. The company develops and supplies photoresins and related process materials. No proprietary formulation, manufacturing sequence, process window or comparative product recommendation is disclosed.

Data availability

No new experimental datasets were generated for this review.

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