

Machine-Readable Material Passports for Photopolymer Products: Composition Boundaries, Process History and End of Life

Defining the information contract that follows a photopolymer product through manufacture, use, service events and recovery without disclosing unnecessary formulation secrets

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Abstract

Digital product and material passports are moving from conceptual circular-economy tools toward operational lifecycle information systems. For photopolymer products, a useful passport must represent more than product identity: it must preserve formulation boundaries, print and post-cure history, service-relevant state changes, repair or recoating events, and end-of-life constraints. This review proposes a machine-readable passport architecture that separates public, controlled and confidential information while retaining provenance. It emphasises state transitions and uncertainty, because a printed photopolymer component can no longer be described adequately by the identity of the original liquid resin alone.

Keywords: material passport; digital product passport; photopolymer; lifecycle; circular economy; provenance; traceability

1. A passport is a lifecycle interface, not a static datasheet

Recent DPP literature converges on the need for persistent product identity, lifecycle information and interoperable access across stakeholders [1,2]. For photopolymer parts, the passport must capture transformations that occur during printing, washing, post-cure, ageing and service. A resin identifier is therefore the starting node, not the finished passport.

2. Composition can be bounded without full disclosure

Machine readability does not require publication of proprietary formulation. The passport can state declared chemistry family, regulated-substance status, filler class, relevant concentration bands, recyclability constraints and version identifiers while keeping exact composition in a controlled-access layer. The engineering requirement is to know which changes invalidate equivalence, not to expose trade secrets.

Table 1. Passport information layers.

Layer	Typical content	Access
identity	product ID, material family, version, manufacturer	public or customer
process	printer, exposure, wash, post-cure, date	controlled
qualification	claims, evidence IDs, limits, expiry/review state	customer/regulatory
confidential composition	exact constituents or proprietary ranges	restricted
end of life	hazards, separation, recovery/disposal route	public/downstream

3. Process history changes the product identity

Two parts printed from the same liquid batch may have different service states if exposure, post-cure, thermal history or orientation differ. Passport design should therefore include immutable process-event records linked to the resulting state. PROV-O supplies a generic pattern for entities, activities and derivations [3], and RO-Crate demonstrates how machine-readable metadata can travel with a bounded research object [4].

4. Access control must be part of the schema

A useful passport serves operators, customers, recyclers, regulators and internal quality teams. These audiences should not receive identical detail. Each field should have an access class, source authority and update rule. Public safety information should remain available even if commercial ownership changes; confidential formulation information may be resolvable only by authorised parties.

Table 2. Lifecycle events that create a new state.

Event	State change to record	Why it matters
printing	geometry, orientation, exposure history	initial solid state
post-cure	energy/temperature/time history	network development
surface treatment	coating or bonding system	compatibility and recycling
service event	chemical, thermal or radiation exposure	durability state
repair	added material and method	traceability of mixed states

5. End of life depends on the as-used state

End-of-life instructions based only on virgin resin can be wrong after coating, bonding, contamination or radiation/chemical service. The passport should therefore record service events that alter recycling, disposal or recovery routes. Circular-economy passport research emphasises the link between object identity and lifecycle registrations [5]. For photopolymers, this means that end-of-life logic is evaluated from the current product state.

6. Validation requires read-back, not just schema compliance

A JSON object can satisfy a schema yet contain stale or contradictory information. Passport validation should test whether a downstream actor can reconstruct the declared product state, identify unresolved transformations and retrieve the authority for critical fields. FAIR principles support findability and reuse [6], but the qualification question is whether the passport remains decision-usable after transfers between systems.

Table 3. Passport validation tests.

Test	Pass condition
identity resolution	persistent ID resolves to current and historical records
provenance	critical field identifies source authority and version
state reconstruction	ordered events reproduce declared current state
access control	restricted fields are protected without breaking public record
end-of-life decision	downstream actor can select a route from available data

7. Scope boundary and neighbouring reviews

ER-393 owns the machine-readable passport for a product and its declared composition boundary, process history and lifecycle state. ER-392 owns the minimum study-reporting fields that may feed that passport, while ER-394 owns the provenance graph that links passport assertions to versioned evidence. ER-393 does not replace either reporting or provenance governance.

8. Confidentiality-preserving composition boundaries

A useful passport must support engineering decisions without requiring unrestricted disclosure of proprietary formulation chemistry. The solution is not to omit composition entirely, but to separate disclosure layers. A public layer can identify material family, hazard-relevant classifications, regulated substances where required, recycled or bio-based content claims and stable identifiers. A controlled engineering layer can hold bounded constituent ranges, functional additives and compatibility constraints. A confidential manufacturer layer can retain exact formulation and supplier provenance. The passport should state which layer supports each downstream claim. This prevents a common failure in which 'confidential' becomes a blanket reason for losing all composition traceability, while also avoiding the opposite error of treating a product passport as a public recipe.

9. Process history should be event-sourced

For photopolymers, product identity evolves through events: mixing, printing, washing, drying, post-curing, machining, assembly, ageing, repair and recycling. A passport that stores only the latest state cannot explain how that state was reached. Event-sourced representation preserves each transformation with time, actor, input entity, process parameters and resulting entity. PROV-O provides a general model for entities, activities and agents [3], and RO-Crate provides a practical packaging mechanism for contextual metadata [4]. The engineering benefit is that a later failure can be traced to a specific process branch rather than to an undifferentiated material name.

10. Synchronisation, read-back and contradiction handling

Machine readability is not proven by successful export. The receiver must be able to read back the record and recover the intended identity, state and constraints. A validation test should therefore round-trip representative passports through the target exchange format and compare semantic content, not only file syntax. Conflicts must also be resolvable: if a recycled-content field, a formulation revision and a process-history event disagree, the schema needs authority and precedence rules. The passport should retain both the original assertion and the corrective event rather than silently overwriting history. This makes version history auditable and allows downstream users to know which state was valid at the time of a decision.

11. Digital-product-passport regulation is a framework, not a photopolymer qualification

Regulation (EU) 2024/1781 establishes the EU framework for ecodesign requirements and digital product passports, and its implementation is being supported by harmonised standardisation work [7]. That regulatory architecture is relevant to identifiers, data access and lifecycle information, but it does not itself establish which photopolymer composition, cure or performance fields are sufficient for engineering qualification. ER-393 therefore uses DPP concepts as an interoperability and lifecycle-governance framework while retaining application-specific qualification requirements in the technical record.

12. End-of-life decisions require the as-used state

End-of-life routing cannot be inferred from virgin-resin identity alone. Printed parts may contain pigments, fillers, embedded conductors, coatings, adhesives, contamination or absorbed service chemicals. The passport should therefore distinguish nominal formulation from as-used assembly state and should capture events that change disposal or recycling compatibility. A recycling or recovery claim should name the route, required preprocessing and exclusion conditions. Where no validated route exists, the correct passport state is 'not qualified for a defined recovery route', not a generic recyclability label. This keeps circularity claims tied to an auditable material state rather than to marketing categories.

13. Identifier and data-carrier architecture

A passport needs a stable logical identifier that is independent of the physical data carrier. QR code, RFID, embedded tag or database lookup can point to the record, but replacing the carrier should not create a new product identity. Conversely, a formulation or process revision that changes the engineering state may require a new passport version even if the physical identifier remains linked to the same product family. The identifier architecture should therefore distinguish product concept, revision, batch or serial instance and passport version. This separation supports recall, correction and historical reconstruction without requiring one identifier to serve incompatible purposes.

14. Access control is part of interoperability

Different actors need different views: a regulator may need compliance and substance information; a recycler may need disassembly and material-route information; a customer may need performance and care data; the manufacturer may retain confidential formulation details. Access rules must therefore be explicit, testable and independent of the data semantics. A field that exists but is inaccessible should be distinguishable from a field that was never recorded. Audit logs should record access-controlled updates so that a later decision can identify which information was available to the actor at the time. This makes confidentiality compatible with traceability rather than an exception to it.

15. Passport conformance and failure modes

A passport can fail even when its JSON, XML or RDF is syntactically valid. Engineering failure modes include stale formulation revision, missing process events, broken identifier resolution, ambiguous units, contradictory lifecycle states, inaccessible required fields and unsupported end-of-life claims. Conformance testing should therefore combine schema validation, semantic validation, identifier resolution and use-case read-back. Representative receiving systems should demonstrate that they can recover the intended state and constraints. A passport that only the issuing software can interpret is not interoperable.

16. State transition model for the passport lifecycle

The passport should represent lifecycle transitions rather than only snapshots. A useful state machine distinguishes formulated resin, received batch, opened container, processed material, printed green part, washed part, post-cured part, assembled product, serviced product and end-of-life state where relevant. Each transition records the responsible actor, timestamp, process event and evidence object. Not every product needs every state, but transitions should be explicit enough to prevent an as-manufactured property from being attributed to a serviced or aged product without evidence. Event-sourced history also permits reconstruction after a correction: the current passport can be read as the latest state while the immutable event log explains how it was reached. [3,4,7]

17. Contradiction handling and trust

A distributed passport can contain conflicting data from manufacturer, converter, user and recycler. The system should not resolve contradictions by last-write-wins unless the field is explicitly designed that way. Each assertion should retain source identity, time, authority and supersession relation. A measured mass, a declared nominal mass and an estimated mass may all coexist if their semantics differ. Where two authoritative assertions genuinely conflict, the passport should expose the conflict and block uses that require a single value until adjudication. Trust therefore depends on provenance and authority rules, not merely cryptographic integrity. A digitally signed incorrect statement is still incorrect; the signature only proves who asserted it.

18. Qualification use cases and end-of-life decisions

Passport conformance should be demonstrated against real read-back tasks. A qualification engineer should be able to recover the material revision and process history behind a tested product. A service engineer should determine whether a repair changes the qualified state. A recycler should determine whether additives, contamination or assemblies exclude a nominal recycling route. A regulator or customer should retrieve the evidence subset to which they are entitled without gaining confidential formulation details. Passing these use cases is stronger evidence than schema validity alone because it tests whether the passport actually supports lifecycle decisions. [1,2,5,7]

19. Limitations and research priorities

Digital-product-passport frameworks are developing faster than photopolymer-specific qualification evidence. The principal gap is not syntax but validated lifecycle use: whether a receiving actor can recover the state needed for a real decision without disclosing unnecessary proprietary information. Priorities include pilot passports that follow printed products through manufacture, service, repair and end of life; contradiction tests involving multiple actors; durable-identifier studies after software or supplier change; and recycling decisions made from as-used rather than nominal composition. Photopolymer passports also need explicit treatment of cure conversion, residuals, additives, contamination and irreversible process history. ER-393 therefore stops short of claiming that a generic DPP implementation is sufficient for these materials; qualification requires use-case read-back and controlled state transitions. [1-7]

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L.; ER-393 is a methodological engineering review and does not provide a comparative commercial recommendation.

Data availability

ER-393 is a literature-based engineering review; no new experimental dataset was generated.