

Life-Cycle Assessment of Vat Photopolymerisation: Functional Units, System Boundaries, Inventory Quality and Uncertainty

Juan Seguro

3Dresyns by Resyner Technologies S.L.

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

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Statement of Significance

Environmental claims for vat photopolymerisation (VPP) are unusually sensitive to study design. A resin can contain renewable feedstock yet perform poorly in a cradle-to-gate comparison if its synthesis, cure, washing or waste treatment is burdensome; a water-cleanable workflow can reduce organic-solvent demand while increasing water, drying or wastewater burdens; a recoverable resin can create a circularity option without delivering a net life-cycle benefit if recovery requires high energy, loses material or shortens service life. Consequently, labels such as bio-based, water-washable, recyclable or low-energy are inventory descriptors or design hypotheses, not life-cycle conclusions. This perspective translates ISO 14040/14044 logic into a VPP-specific reporting architecture and identifies the minimum evidence needed before comparative environmental claims are defensible [1,2].

Keywords: vat photopolymerisation; life-cycle assessment; LCA; life-cycle inventory; functional unit; system boundary; stereolithography; DLP; resin; post-processing; uncertainty; sensitivity analysis; circularity; environmental claims

Abstract

Vat photopolymerisation couples liquid photopolymer feedstocks, light-driven conversion, support generation, washing, drying, post-curing and material-management steps that are often omitted or represented inconsistently in environmental assessments. This makes VPP particularly vulnerable to apparently precise but structurally incomparable carbon-footprint results. The present engineering perspective develops a methodology for life-cycle assessment of VPP systems rather than claiming that VPP, bio-based resins or any particular post-processing route is intrinsically sustainable. The framework begins with ISO 14040 and ISO 14044 and incorporates VPP-specific evidence from energy models, reusable unit-process inventories and stereolithography case studies [1-8]. It treats the functional unit, reference flow and delivered performance as the first design decision; defines cradle-to-gate, gate-to-gate and cradle-to-grave boundaries; separates resin production, printing, machine utilisation, failed builds, washing, post-curing, consumables and end-of-life; and requires explicit treatment of recovered resin and reusable materials. Particular attention is given to proxy data for proprietary photopolymer chemistry, allocation of machine and solvent burdens, uncertainty in emerging material systems, and sensitivity to service life and grid electricity. A minimum VPP inventory and reporting template is proposed. Commercial 3Dresyns products are included only as implementation examples that create different inventory questions; they are not used as evidence of lower environmental impact. The central conclusion is that environmental superiority in VPP is a result of a defined comparison, not an intrinsic material attribute.

1. Introduction

The environmental narrative surrounding additive manufacturing frequently begins with plausible advantages: material is placed only where needed, tooling can be avoided, production can be localised, and complex geometries can enable lighter or more efficient products. Those possibilities are real, but life-cycle assessment (LCA) asks a narrower and more demanding question: for a defined function, reference flow, system boundary and set of assumptions, what environmental exchanges are associated with the compared product systems? ISO 14040 defines the LCA framework around goal and scope, inventory, impact assessment and interpretation, while ISO 14044 specifies requirements for conducting and reporting the study [1,2]. Neither standard permits the manufacturing label itself to substitute for the analysis.

This distinction is especially important for VPP. The process does not end when light exposure stops. A printed part may carry uncured resin, require one or more washing steps, need compressed air or drying, undergo post-curing, use disposable gloves, wipes or filters, and generate supports or failed builds. Liquid resin may be recovered to the vat, discarded, aged over multiple jobs or contaminated by cleaning media. The printer can spend significant time in preparation, idle or standby states. The same CAD geometry may demand different support mass and print time when reoriented. Published SLA work has therefore modelled energy at subsystem level, treated polymerised resin and process time as key unit-process variables, and linked build orientation to both support volume and environmental indicators [3-6].

The purpose of this paper is not to publish a new 3Dresyns carbon footprint. No product-level life-cycle inventory suitable for that purpose is reported here. Instead, the review defines the evidence architecture needed to produce such a result responsibly: which choices can change the sign or magnitude of a VPP comparison, what must be measured, where proxies may be acceptable, and how uncertainty should be reported.

2. Why “sustainable” is not an LCA result

A life-cycle result is relational. It compares environmental exchanges associated with a function, under an explicitly defined model. A statement that a resin is bio-based describes origin of part of the feedstock; it does not quantify cultivation, processing, land-use effects, chemical conversion, additives, yield, transport or end-of-life. A statement that a resin is water-cleanable describes a processing option; it does not quantify water consumption, wastewater treatment, drying energy, rejected wash water, cleaning efficiency or displaced solvent. A statement that a network is depolymerisable or reprocessible describes a technical pathway; it does not establish collection rate, recovery yield, recovered-material quality, number of loops, energy demand or substitution of virgin production.

The AM literature reinforces this caution. Kellens et al. reviewed environmental analyses across additive processes and found that the available quantitative evidence was incomplete and heavily concentrated on energy consumption [11]. Faludi et al. demonstrated in a broader AM comparison that utilisation and idle electricity could reverse relative conclusions between manufacturing routes [9]. SLA-specific studies likewise show strong sensitivity to machine configuration, process time, layer settings, support generation and post-processing [3-8]. The engineering consequence is that an environmental adjective should be translated into a measurable inventory hypothesis before it becomes a comparative claim.

3. Goal, functional unit and reference flow

The functional unit is the anchor of the comparison. “One kilogram of resin”, “one printed part” and “one year of delivered service” are not interchangeable denominators. A material-level cradle-to-gate study can legitimately use a mass-based functional unit when the function under study is production of photopolymer feedstock. A manufacturing comparison should normally describe the delivered part function, geometry, quality and conditioning state. A service-level comparison should include lifetime, maintenance, replacement and any use-phase effects that differ between alternatives.

For VPP, the reference flow should include the actual amount of resin and auxiliary materials needed to deliver the functional unit, not merely the CAD part mass. If 100 g of final part requires 125 g of polymerised part plus supports and a further liquid inventory that is lost or discarded, the reference flow is not 100 g of resin. Conversely, resin returned to the vat should not automatically be treated as consumed. The study must state whether returned liquid is reused in the same system, downgraded, treated as inventory carry-over or eventually discarded.

Decision	Defensible VPP choice	Common failure mode
Functional unit	A defined delivered function, geometry, quality state and, when relevant, service duration.	Comparing 1 kg of two resins even when different masses, supports, cure states or lifetimes are required.
Reference flow	All material and energy flows required to deliver the functional unit, including supports and process losses.	Using final CAD part mass as resin consumption.
Comparator	A technically credible alternative that delivers the same function and quality.	Comparing VPP with an incumbent that does not meet the same precision, throughput or service requirement.
Geography	Electricity, transport and waste scenarios matched to the actual or stated location.	Using one grid mix or disposal route as if globally representative.
Temporal basis	Technology state, resin formulation state and process settings identified by date/version.	Combining inventory data from unrelated generations of printers or generic polymers.
Use phase	Included when durability, mass, fluid flow, thermal performance or replacement interval differs.	Ending the assessment at the factory gate while claiming whole-life superiority.

Table 1. Study-design choices that can reverse a VPP environmental comparison.

4. System boundaries for VPP

4.1 Feedstock production and formulation

Photopolymer formulations create a recurring LCI problem because commercial chemistry may be proprietary and background databases rarely contain the exact oligomer, reactive diluent, additive and photoactive package. Replacing an unknown resin with a generic “plastic” dataset can be useful for screening, but it creates model uncertainty that must be visible in the interpretation. A single proxy should not be reported with more numerical precision than the underlying chemistry supports. Where formulation-specific primary data are unavailable, the analyst should use a transparent hierarchy of measured supplier data, chemically relevant datasets, bounded scenarios and sensitivity analysis.

Bio-based content should therefore enter the inventory as composition information, not as an avoided-impact credit. The relevant question is which feedstock and conversion processes are displaced and what burdens replace them. At early technology maturity, ex-ante LCA literature recommends scenario construction rather than pretending that laboratory or pilot information already represents mature industrial production [12,13].

4.2 Printing and machine utilisation

Printing inventory should be measured at the job level wherever practical. Yang et al. decomposed MIP-SLA energy into curing, platform movement and cooling contributions and showed that layer thickness, curing time and orientation can influence total electricity [3]. Simon et al. developed a reusable stereolithography unit-process inventory, while Mele et al. proposed process time and polymerised resin as practical variables for integration into part-level LCA [4,5]. These approaches support parametric inventory models, but they do not justify a universal kWh/kg factor for all VPP machines.

Machine utilisation is a separate modelling choice. Embodied machine impacts, standby electricity and warm-up or preparation burdens can become large on a per-part basis at low utilisation. Faludi et al. showed this effect for other polymer AM platforms, illustrating why comparative LCA should define production volume and utilisation rather than assume full-capacity operation [9], and earlier rapid-prototyping energy studies had already shown that machine choice and part placement change energy demand [10]. For desktop VPP, laboratory idling may be negligible in one study and dominant in another depending on accounting conventions. The convention must be stated.

4.3 Washing, drying and post-curing

Post-processing is part of the VPP process chain, not an optional footnote. A wash fluid has upstream production impacts, may be reused across many jobs, may evaporate, may carry dissolved resin, and eventually requires treatment. The relevant inventory is therefore not the nominal bath volume but the make-up fluid consumed per functional unit plus treatment of the spent stream. Panagiotopoulou et al. found the IPA bath to be a major contributor in their specific SLA case study [7]. That result is valuable as a warning that post-processing can be important, but it should not be transferred as a universal percentage because bath management, solvent recovery, resin chemistry and electricity mix differ across workflows.

Post-cure similarly requires time, power, loading and equipment assumptions. If a chamber cures one small specimen alone, its allocated electricity differs from a fully loaded batch. If additional cure improves lifetime or reduces replacement, the extra gate-to-gate burden may be offset in a service-based functional unit. LCA therefore cannot optimise cure energy independently of delivered material performance.

4.4 Failed builds, supports and consumables

Yield is often underreported. A technically demanding VPP workflow may consume modest energy per successful build but still perform poorly per accepted part if print failures are frequent. Failed parts, supports, purge or calibration structures, filters, wipes and disposable handling materials should be recorded when material. Build orientation also changes support volume and print height; Mele et al. explicitly incorporated these variables into environmental optimisation of stereolithography [6]. A fair comparison should therefore use the validated production recipe, not an idealised zero-failure process unless that assumption is labelled as a best-case scenario.

4.5 Use and end-of-life

End-of-life modelling should begin with realistic collection and treatment routes, not with the most desirable technical possibility. Landfill, energy recovery, hazardous-waste treatment, mechanical reuse, chemical recovery and depolymerisation can all be represented as scenarios when relevant, but the analyst must distinguish technical capability from realised pathway. Recycling credits depend on allocation method, recovered quality and displacement of virgin material. The choice should be tested rather than hidden inside one deterministic result.

5. A minimum VPP life-cycle inventory

A useful VPP inventory separates gross material present in the workflow from material actually consumed. The vat charge is not automatically an emission or waste flow. Likewise, a litre of washing bath is not consumed every time a part is washed. The inventory should track make-up and disposal over a defined number of jobs. The same logic applies to resin returned from the build platform, recovered support material, reusable containers and shared post-curing equipment.

Inventory category	Minimum measured or declared variables	Why it matters
Photopolymer	Fresh resin added; polymerised part mass; support/calibration mass; recovered liquid; discarded liquid; failed-build mass.	Separates delivered material from losses and circulating inventory.
Printer electricity	Job kWh; build time; standby/preparation included or excluded; machine loading; number of accepted parts.	Energy per part depends on machine state and utilisation.
Process settings	Layer thickness; exposure/cure time; orientation; support strategy; temperature if controlled.	Links inventory to the actual validated manufacturing state.
Washing	Cleaning medium; make-up mass/volume; bath lifetime or jobs served; energy; rinse stages; spent-fluid treatment.	Nominal bath capacity is not equivalent to consumption.
Drying and post-cure	Equipment power; time; loading; atmosphere/temperature; number of parts per batch.	Allocation can dominate small-batch laboratory results.
Consumables	Filters, wipes, gloves, liners, containers and other routinely consumed items where material.	Prevents shifting burdens outside the process model.
Waste and emissions	Waste resin; spent cleaner; contaminated water; supports; failed parts; direct emissions if measured.	Defines treatment routes and prevents untracked disposal assumptions.
Transport	Resin, cleaner, consumables and parts where relevant to goal and scope.	Can matter in distributed-production claims.
Service performance	Lifetime, replacements, maintenance and functional performance when alternatives differ.	A more durable part can change the required reference flow over time.

Table 2. Minimum foreground inventory for a VPP manufacturing study.

6. Allocation, recovery and circularity

Allocation choices become unavoidable when one process serves multiple jobs or recovered material crosses system boundaries. Shared printer manufacture, a reusable cleaning bath, a post-cure chamber, reclaimed resin and recycled feedstock can all be distributed by mass, time, economic value, number of jobs or system expansion. ISO 14044 places allocation within the methodological choices that must be handled consistently and transparently [2]. For VPP, time-based allocation can be appropriate for machine electricity or equipment use, whereas mass or causal relationships may be more meaningful for consumables. No single rule fits every flow.

Circularity claims need a mass balance. A recovered liquid that can be printed again is a promising process state, but environmental benefit depends on recovery yield, additional processing energy, quality retention, make-up material, number of cycles and the extent to which virgin resin production is actually displaced. A closed-loop laboratory demonstration should therefore be reported as technical recoverability unless those broader variables are quantified. Similar care is required when assigning credits for solvent recycling or energy recovery.

7. Data quality, proxies and uncertainty

VPP is an emerging and rapidly changing technology family, so uncertainty is structural rather than incidental. Printer architectures, light engines, resin chemistry, cure dose, automation and post-processing can change faster than background databases. Bergerson et al. emphasise that early-stage LCA faces limited data, scale-up uncertainty and uncertain deployment context [12]. Cucurachi et al. similarly describe the need for ex-ante scenarios when laboratory or pilot data are projected to future mature systems [13]. These concepts apply directly to novel VPP chemistries and recovery routes.

Uncertainty should be separated into at least three classes: parameter uncertainty in quantities such as kWh or resin loss; model uncertainty in choices such as allocation and end-of-life credit; and scenario/context uncertainty in future grid mix, production scale or collection rate. Igos et al. recommend explicit identification, propagation, sensitivity analysis and communication of uncertainty rather than a single deterministic result [15]. For engineering decisions, a range that preserves the ranking across realistic scenarios is more informative than an apparently precise point estimate built on weak proxies.

Evidence level	Preferred use	Interpretation rule
A. Direct foreground measurement	Mass and energy measured on the actual printer, resin and post-process route.	Primary basis for the studied manufacturing state; report repeatability and sampling.
B. Supplier-specific verified inventory	Specific material or utility data with defined geography, technology and period.	Use when scope and formulation match; document representativeness.
C. Chemically or technologically relevant proxy	Closest available oligomer, monomer, polymer, cleaner or machine dataset.	Run sensitivity bounds; do not imply formulation-specific precision.
D. Generic proxy	Generic plastic, organic chemical or manufacturing dataset.	Suitable for screening only when influence on conclusions is tested.
E. Assumption without source	Estimated yield, collection rate, lifetime, recycling credit or emission factor.	Make explicit and scenario-bound; never present as measured evidence.

Table 3. Data-quality hierarchy for VPP LCA.

8. Comparative claims, sensitivity and critical review

Comparative environmental claims require more than calculating two totals. The analyst should identify the assumptions most capable of changing the ranking and test them systematically. For VPP these commonly include resin proxy, build yield, support ratio, machine utilisation, electricity mix, wash-medium consumption, bath lifetime, post-cure loading, service life and end-of-life allocation. A tornado analysis, scenario matrix or Monte Carlo analysis can reveal whether the conclusion is robust or conditional.

Results should also be reported across more than one impact category where the goal supports it. Carbon footprint is important but can obscure burden shifting to water use, toxicity-related categories, resource use or other impacts. ISO 14040/14044 provide the core framework, and ISO 14071:2024 provides additional requirements and guidance for critical review processes and reviewer competence [1,2,14,16]. Public comparative assertions therefore require an evidence and review level appropriate to their intended use, not simply a polished carbon number.

3Dresyns implementation examples

Current 3Dresyns products illustrate how material design changes the questions an LCA must ask. They are not presented here as evidence that one route has lower GWP or lower total environmental impact. A valid comparison would require product-specific foreground inventory and appropriate background datasets.

3Dresyn Bio Soya1. Manufacturer documentation reports approximately 82% total bio-based content. In LCA this creates a feedstock-origin variable that requires upstream inventory for the renewable and fossil-derived fractions. The bio-based percentage alone does not establish lower climate impact, lower land-use burden or better end-of-life performance [M1].

3Dresyn WC1 MF Clear. Current documentation describes WC1 MF Clear as a water-cleanable, monomer-free photopolymer. For LCA this changes the post-processing inventory that must be measured, including water use, cleaning efficiency, bath replacement, wastewater treatment, drying and any displaced organic cleaner. Water-cleanability by itself is not evidence of lower environmental impact. [M2]

3Dresyn Circular RePrint Bio. Current documentation describes a depolymerisable resin platform with thermally triggered DP80 and DP150 variants. This creates a recoverability scenario that should quantify recovery yield, thermal energy, filtration or purification, quality retention, make-up resin, cycle count, losses and avoided virgin production. Technical depolymerisability is therefore an LCA input condition, not a circularity result. [M3]

Source basis: current 3Dresyns product and Technical Data Sheet documentation, August 2026. These commercial examples connect the methodological framework to implementation. They are not substitutes for a product-specific ISO-aligned life-cycle inventory, impact assessment or comparative critical review.

9. Minimum reporting framework for VPP LCA

A reproducible VPP LCA should allow another analyst to understand why the model gives its result and to rebuild the foreground inventory. This requires reporting the process state with enough engineering detail to connect environmental flows to print quality and delivered function. A generic statement such as “SLA, 405 nm” is insufficient when layer thickness, exposure, orientation, support design and post-cure differ materially.

Reporting block	Minimum disclosure
Goal and audience	Decision question; intended audience; whether comparative assertions are public.
Functional unit	Delivered function, geometry, quality state, quantity and service period if relevant.
System boundary	Included life-cycle stages, infrastructure treatment and explicit exclusions.
Foreground process	Printer architecture/model class; resin state; layer/exposure/orientation; accepted yield; supports; washing; drying; post-cure.
Inventory accounting	Fresh and recovered resin, waste, cleaner make-up/disposal, electricity by process step or justified aggregate, consumables and transport.
Background data	Database/version or primary sources; geography; year; chemical proxies and their rationale.
Allocation and recycling	Allocation rule; recovered-material treatment; substitution ratio; end-of-life scenarios and credits.
Uncertainty	Parameter ranges; scenario choices; sensitivity analysis; data-quality limitations.
Impact assessment	LCIA method/version and reported categories; avoid carbon-only interpretation unless goal is explicitly carbon footprint.
Interpretation and review	Hotspots, limitations, conditions under which ranking changes, and critical-review status where applicable.

Table 4. Minimum reporting checklist for a VPP environmental assessment.

10. Research gaps

The largest VPP LCA gaps are not a lack of sustainability adjectives but a lack of representative inventories. First, photopolymer feedstock production needs better chemical resolution. Generic polymer proxies can dominate a model while hiding the effects of oligomer synthesis, renewable feedstocks and additive packages. Second, post-processing needs longitudinal measurement: cleaner make-up, bath ageing, resin carry-over, wastewater and solvent recovery should be measured over many jobs rather than inferred from one nominal wash. Third, industrial utilisation and quality yield need to be connected. Laboratory energy per part is not representative of production if printer loading, automation, failure rates or post-cure batching differ. Fourth, circular and depolymerisable photopolymers require repeated-loop inventories that track mass and performance after each cycle. Fifth, environmental comparisons should link process changes to mechanical, dimensional, optical or biological performance so that burden reductions are not obtained by silently lowering product function.

Finally, prospective LCA should accompany new VPP chemistries earlier in development. Scenario-based screening can identify whether a proposed bio-based precursor, lower-temperature cure, alternative cleaner or recovery route is likely to matter before formulation is locked. The purpose of such early assessment is design guidance, not premature marketing claims [12-15].

11. Conclusions

- Environmental performance in VPP is system- and function-dependent. “Bio-based”, “water-cleanable”, “recyclable” and similar descriptors are not LCA conclusions.
- The functional unit and reference flow must capture the delivered part function and the actual material required, including supports, failures and process losses.
- VPP system boundaries should explicitly address resin production, machine electricity and utilisation, washing, drying, post-curing, consumables, waste and any use-phase differences relevant to the comparison.
- SLA literature demonstrates that energy, process time, orientation, support generation and post-processing can materially alter results; no universal environmental factor should be transferred between machines or workflows without validation.
- Proprietary resin chemistry creates unavoidable data-quality challenges. Transparent proxies, scenario bounds and sensitivity analysis are preferable to false formulation-specific precision.
- Circularity requires a mass and energy balance across recovery cycles. Technical recoverability does not by itself demonstrate environmental benefit.
- 3Dresyns products can be used as implementation examples that change inventory questions, but product positioning cannot replace an ISO-aligned product-specific LCA.
- The defensible output of a VPP LCA is a conditional, reviewable comparison with stated uncertainty, not an intrinsic sustainability score attached to a resin or printing technology.

Limitations

This review is a methodological engineering perspective rather than a product-specific life-cycle assessment or a preregistered systematic review. No new foreground inventory or comparative environmental dataset is reported, and conclusions are limited to study design, inventory quality, uncertainty and reporting requirements for VPP LCA.

Author contributions

J.S.: conceptualisation, methodology, literature synthesis, engineering interpretation, writing, review and editing.

Competing interests

The author is affiliated with 3Dresyns by Resyner Technologies S.L. Commercial 3Dresyns products are discussed only in the implementation-examples section and are not used as independent scientific evidence of environmental superiority.

Data availability

No new experimental or comparative life-cycle dataset is reported in this Engineering Review. The manuscript is based on published standards, peer-reviewed literature and controlled 3Dresyns product documentation. A product-specific environmental comparison would require a separate foreground inventory and defined LCA model.

Company information

Legal company name: 3Dresyns by Resyner Technologies S.L. Registered tax address: General Etxague 15B, 20003 Donostia / San Sebastián, Gipuzkoa, Spain VAT number: ESB24827511 Contact email: info@3Dresyns.com Company website: www.3Dresyns.com

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