

Techno-Economic Analysis of Photopolymer Additive Manufacturing: Functional Unit, Utilisation and Yield, and Where Metal-Powder-Bed Cost Models Do Not Transfer

Industrial economics and deployment

Juan Seguro

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

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Abstract

Techno-economic evaluation of photopolymer additive manufacturing depends on the functional unit, accepted-output yield, asset utilisation and the complete production boundary. This critical review distinguishes the limited methodological transfer from a metal-oriented manufacturing analysis [1] from direct techno-economic evidence for vat-photopolymerised investment-casting patterns [2]. It compares pre-processing, printing, washing, support removal, capacity constraints, scenario-dependent crossover volumes and uncertainty. A transparent synthetic accepted-output model illustrates utilisation and reject sensitivity without presenting hypothetical values as measured factory costs. The available evidence supports process-specific modelling but does not justify universal machine rankings or cost coefficients across applications.

Keywords: techno-economic analysis · photopolymer additive manufacturing · functional unit · utilisation · yield · scale

1. Scope and transfer boundary

ER-471 owns cost per defined functional unit and the economic consequences of utilisation and yield. ER-459 owns physical material-flow accounting, recovery and inventory reconciliation. The controlled techno-economic anchor is a laser-based additive-manufacturing study [1]; its process-specific cost structure must not be transferred as photopolymer evidence.

2. Functional unit first

A cost number is meaningless without a denominator. A photopolymer study should state whether the functional unit is one accepted part, one build, a unit volume, a validated device, a production campaign or another declared output. Changing the denominator can change the interpretation even when the underlying expenditure is unchanged.

3. Utilisation

Equipment cost allocation depends on productive use, idle time, setup, cleaning, maintenance and scheduling. As an engineering accounting example, a metal powder-bed model could include chamber time, inert-gas use and post-machining; their magnitude would require route-specific data. Those terms are not automatically the major terms in vat photopolymerisation. The transfer-safe principle is to measure the actual state occupancy of the equipment used.

4. Yield and accepted output

Yield affects cost through the ratio of accepted output to input and machine time. ER-471 uses yield only as an economic variable. Physical reconciliation of resin, wash stream, recovered material and waste remains ER-459. The economic model should consume the measured yield rather than recreate the material-flow model inside the cost paper.

5. Photopolymer-specific cost structure

A photopolymer analysis should account explicitly for resin consumption, supports where applicable, cleaning media, post-cure, labour, rejects, maintenance and the time state of printing and post-processing. This list is a reporting architecture, not a universal statement about which term dominates. Dominance must be measured for the actual system.

6. Scale

Scale can change utilisation, labour allocation, purchasing, maintenance and reject consequences. A desktop machine, a production cell and a distributed network need not share one cost structure. Scale claims therefore require the same functional unit and comparable quality state.

7. Where metal-powder-bed models do not transfer

The source provides general decision-making context [1], not numerical coefficients for the present model. Powder procurement, inert-gas supply, chamber occupancy and post-machining are illustrative route-dependent accounting items, not a cost breakdown extracted from that source. A photopolymer model may have analogous categories, but category names are not evidence of equal magnitude or equal economic significance.

8. Minimum reporting set

Report functional unit, accepted-output definition, equipment capital basis, utilisation, build time, setup and changeover, material input, physical yield sourced from ER-459-style accounting, consumables, post-processing, labour, reject/rework treatment, maintenance, facility allocation, scale and uncertainty or scenario assumptions.

9. A cost model with an accepted-output denominator

The proposed model separates annual fixed expenditure F , attempted builds B , variable expenditure per build v , nominal parts per build n and accepted fraction y . Under the simplifying assumptions that each build has the same loading and cost and that rejected output produces no recovery, annual accepted output is Bny and average cost per accepted part is $(F + Bv)/(Bny)$. These assumptions make the

model inspectable; they do not describe an observed factory. Product-specific finishing, inspection and recovery would require additional terms.

For a synthetic example, set F to 30000 monetary units, B to 300 builds, v to 60 units, n to 20 and y to 0.80. Accepted output is 4800 parts and the model gives 10 units per accepted part. Raising y to 0.95 while holding every other input fixed gives 5700 accepted parts and approximately 8.42 units per accepted part. The result is a conditional calculation, not an estimated benefit of a particular quality intervention. If achieving the higher yield costs money, that expenditure must enter the model before any saving is claimed.

Utilisation is a different lever. At 150 builds with the original yield, the same fixed expenditure is distributed over 2400 accepted parts, giving 16.25 units per accepted part. A comparison that reports material price alone would miss this effect. Conversely, a calculation that assumes full utilisation despite insufficient demand would understate the relevant unit cost.

10. Expose the constraints behind the sensitivity

A practical application would first test whether the assumed build count and loading can be achieved. Machine capacity, labour availability, post-processing capacity, inspection and demand can each constrain output. An extra printer does not necessarily increase accepted throughput if a downstream operation remains limiting. The cost boundary should identify shared resources so that the same labour or equipment expenditure is not charged twice.

Sensitivity analysis should vary the inputs that could change the route decision, rather than applying the same arbitrary percentage to every entry. A useful result would identify the yield, utilisation or finishing burden at which the preferred option changes. If the available evidence does not bound an influential input, the decision remains conditional. The next measurement can then be chosen to resolve that input. This connects economic analysis to manufacturing evidence while retaining the distinction between a transparent model and a measured photopolymer business case.

11. Direct evidence from vat photopolymerisation techno-economic assessment

Sartini, Favi and Mandolini [2] provide a directly relevant, open-access techno-economic assessment of vat-photopolymerisation routes for rapid investment casting. Their comparison covers stereolithography and digital light processing alongside material jetting and wax injection. Because material jetting is not a vat process, the comparative technology groups must remain distinct. The study models pre-processing, build and post-processing, and evaluates scenarios with varied production batch, part geometry and printer load factor. Unlike a metal-powder-bed extrapolation, it explicitly treats resin-model manufacturing, washing and support removal. However, its functional unit is an investment-casting pattern, not a qualified medical device or a finished functional photopolymer component. Its numerical crossover points therefore cannot be ported to those other outputs without re-estimation.

The authors report that relative route economics depend on component size, batch quantity and loading, with different cost-based and time-based crossover points [2]. These are comparative outcomes within their tested scenarios, not universal evidence that digital light processing is cheapest for every photopolymer application. Their published evaluation includes assumed and measured parameters. Specifically, the estimated parameters are stress-tested, and the paper reports a worst-case DLP model-error bound for a low-load scenario. Uncertainty derived from that accounting framework should not be confused with repeated-production yield statistics or an independent validation of commercial cost forecasts.

12. Cost-accounting boundaries and measurement hierarchy

To avoid double counting, the model boundary should separate capital recovery, machine occupation, direct operator time, shared operator availability, consumables, finishing and inspection. Printing hours are not necessarily equivalent to paid labour hours: unattended exposure and operator intervention require separate time clocks. Washing, drying, post-curing, support removal and inspection may be serial for one part yet overlap across parallel batches. A throughput model therefore needs a process-flow representation with resource capacities, not merely a sum of machine cycle times.

An auditable data hierarchy distinguishes (i) transactional costs verified by invoices, (ii) observed machine-state and worker-state time, (iii) measured scrap and accepted-output counts, (iv) estimated consumable depletion and capital allocation, and (v) hypothetical scenario inputs. Comparisons become fragile when a measured competitor quote is compared with a theoretical internal cost that excludes overhead, quality control or rejected output. Results should provide both an explicit scope of cost and a reconciliation between total-period expenditures and allocated unit costs.

13. Part nesting, geometry and capacity constraints

For a layerwise vat process, the number of parts per plate, orientation, support design and maximum projected area can change build duration and support burden. DLP exposure is projected over each layer, but this does not imply that doubling part count always leaves cycle time unchanged: part height, recoating, separation, support architecture and cleaning throughput also matter. A realistic utilisation denominator should use available scheduled machine capacity after maintenance and downtime, while achieved loading should be measured per validated production mix. These are separate from the fraction of accepted parts.

The resulting bottleneck may lie downstream rather than at the printer. For example, an additional exposure unit could increase green-part output but not accepted throughput if washing or dimensional verification remains capacity-limited. Claims about scale economies should identify the limiting resource, the required number of operator interventions and any change in sampling or traceability burden. Capacity simulations should be checked against at least a representative set of observed production runs.

14. Sensitivity, scenario transfer and decision quality

A one-way sensitivity chart is useful for identifying influential variables but cannot capture correlated shifts in material price, build loading and yield. Transparent economic decisions should combine physically plausible ranges with scenario dependencies. For example, changing orientation to increase nesting density may also alter support consumption, optical exposure and removal labour. Treating those variables as independent can create combinations that a validated process cannot achieve. Break-even analysis must document both the selected comparator and the assumptions about demand and quality acceptance.

The direct VPP study [2] evaluates crossover and payback metrics across specified scenarios. Its results justify adopting that methodological framework, not adopting one universal crossover volume. For a product-specific business case the required transfer study would select geometries representative of the target catalogue, record measured post-processing time, identify saleable-output acceptance criteria, and re-estimate all machine- and site-specific rates. Sensitivity outputs should report the thresholds at which the preferred route changes, alongside evidence confidence for each input.

15. Evidence gaps and a minimum validation experiment

The present literature base is still too narrow to pool costs across machines, resins or applications. An informative qualification experiment would track a defined part family over multiple independent builds and operators, recording build occupancy, pre- and post-processing times, consumable volumes, energy, rework and rejected output. A cost ledger would then reconcile actual outlays with those observations. The comparison should be repeated at different loading levels while maintaining equivalent inspected quality. This design is proposed as an engineering validation protocol, not a claim that such production trials were carried out for this article.

The distinction between model verification and economic validation is essential. A spreadsheet can be internally correct yet inaccurate when its inputs omit production holds, repeated washing, inspection or idle capacity. External validity requires a representative production environment and an uncertainty interval around measured quantities. Decisions should state whether the published result is a prospective scenario, a calibrated process model or a retrospective account of incurred expenditure.

Sensitivity and uncertainty in economic comparisons

The relevant functional unit is a conforming, accepted component rather than a printed build or a litre of resin. An economic comparison becomes misleading when one route reports cost per attempted build while another reports cost per accepted article. The numerator must therefore account for part and support mass, auxiliary consumables, washing, drying, post-cure, machine occupation, inspection, rejected parts and rework where these are included in the defined system boundary. Accounting convention and measured activity must be identified separately. Results derived for sacrificial patterns or investment-casting workflows cannot be applied directly to end-use photopolymer components without a process-boundary reconciliation.

A decision-grade sensitivity analysis should vary utilisation, batch occupancy, failed-build probability, post-processing labour and the basis used to allocate overhead. These drivers can interact: a short exposure cycle is not economically advantageous if washing or inspection limits completed throughput, and apparent material efficiency can be offset by support removal or non-recoverable wash-liquid consumption. The review therefore distinguishes the published, process-specific economic observations from an analytical framework suggested for future site-level study. It does not imply that the cited studies establish a universal photopolymer cost function.

Cost sensitivities must be tested as coupled scenarios

Unit cost is not a property of a printer in isolation. A decision-grade comparison specifies the accepted output unit, model mix, build occupancy, operator attendance, post-processing effort and rejected output. These quantities interact: increasing build occupancy may reduce nominal exposure cost per article while increasing separation or handling loss. An attribution model that changes only utilisation and fixes yield implicitly excludes this mechanism and should be labelled as a partial sensitivity analysis.

For a controlled comparison, report at least two operating states: an observed baseline and a feasible stressed state with documented queueing, recovery and inspection delays. Carry the same labour, machine-hour and material-accounting boundaries across both states. The analyst should distinguish the marginal economics of accepting one further order from the full cost of sustaining a site. The former can omit fixed committed costs for a short decision horizon; the latter cannot. Neither accounting frame validates another without reconciliation.

A useful review table would locate each input by provenance: time study, production log, supplier quotation, engineering assumption or externally published benchmark. The resulting sensitivity ranking is conditional on that provenance and on the chosen decision horizon. Where the source evidence is from a different AM modality, it can motivate a variable to measure but cannot supply a photopolymerisation-specific numerical coefficient without a transfer argument.

16. Limitations

The original metal-oriented anchor [1] was inspected only to the extent stated in the earlier version. A direct open-access VPP techno-economic study [2] was additionally assessed for its process stages, variables and scenario-dependent findings. Its investment-casting-pattern cost observations do not establish costs or performance for other end uses. No proprietary cost records or original production dataset were generated for this review.

17. Conclusions

Photopolymer techno-economic analysis must use a declared functional unit, measured accepted-output yield, realistic resource utilisation and complete post-processing boundaries. Direct VPP evidence [2] shows the value of route- and scenario-specific cost models, while also delimiting transfer to other product classes. A useful engineering review should explain uncertainty and capacity constraints rather than treating any reported crossover volume as universal.

References

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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 dataset was generated.

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