

Human-Factors Methods in Additive Manufacturing and Safety Evidence for Photopolymer Processing: Separate Evidence Layers and the Missing Join

Lifecycle assurance and responsible innovation

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Abstract

Human-factors methods and photopolymer-processing safety evidence currently occupy separate evidence layers in the controlled source set. One source applies cognitive-ergonomics and human-error methods to fused-deposition modelling, while the other reviews occupational hygiene across AM processes and includes vat photopolymerisation among multiple process categories [1,2]. Neither source joins workload, interfaces or error recovery to photopolymer processing specifically. This review therefore treats the missing join as the principal result. It shows how human-factors methods may define questions for photopolymer workflows without transferring FDM findings, while safety evidence remains limited to the occupational-exposure scope supported by the multi-process review. A task-level study design links observed actions, error recovery and synchronised exposure context without assuming a causal effect from either layer alone.

Keywords: human factors · additive manufacturing · photopolymer processing · safety evidence · workload · interfaces · error recovery

1. Scope and ownership

ER-485 separates two questions: what human-factors methods can examine in AM, and what safety evidence exists for photopolymer processing. It does not transfer FDM workload, interface or human-error findings to vat photopolymerisation.

2. Two evidence layers

Source [1] is an AM human-factors case study in fused deposition modelling using cognitive-ergonomics and human-error analysis methods [1]. Source [2] is a multi-process occupational-hygiene review that includes vat photopolymerisation within its broader AM coverage [2]. The first supplies methods in an FDM setting; the second supplies safety/exposure context that includes VPP. No controlled source provides the combined photopolymer-specific human-factors study.

3. What can transfer: the question structure

Methods such as task decomposition, workload assessment and structured human-error analysis can define how a workflow is examined. Their methodological role can therefore inform study design. The numerical or task-specific findings of an FDM case, however, remain attached to that FDM context and are not treated as photopolymer evidence here [1].

4. What cannot transfer: FDM findings

An observed workload, interface problem, error mode or recovery route in one AM process cannot be assumed to occur in another. Photopolymer workflows have different material handling, exposure controls, cleaning and post-processing steps. This article names those as reasons to require direct study, not as evidence that any particular human-factors effect occurs.

5. Safety evidence for photopolymer processing

The occupational-hygiene review includes vat photopolymerisation among multiple AM process categories [2]. It therefore supports keeping exposure and occupational-safety questions in scope. Because it is multi-process, the article does not convert every general AM hazard statement into a VPP-specific finding.

6. The missing join

The central evidence gap is a study that measures human-factors variables in an actual photopolymer-processing workflow while also preserving the relevant safety and exposure context. Without that join, the corpus has a method source on one side and photopolymer-relevant safety coverage on the other, but no direct evidence connecting them.

7. Minimum direct study

A future study should identify the workflow, operators or operator class, task sequence, interfaces, workload method, error taxonomy, recovery opportunity, training state, safety controls and the process state being observed. Outcomes should be linked to specific tasks rather than aggregated into a generic AM score.

8. Error recovery

Recovery is an important human-factors question because a workflow can tolerate an error if it is detected and corrected before it affects safety or quality. The controlled sources do not establish recovery performance for photopolymer processing. A future study should therefore observe detection, interruption, correction and escalation explicitly rather than infer them from procedure documents.

9. Safety boundary

ER-485 does not replace chemical-hazard, exposure-limit or process-safety reviews. Safety evidence is used only to preserve the context in which human-factors performance would have to be studied. No quantitative VPP exposure value is introduced from source [2] beyond its controlled scope.

10. A task-level design for the missing study

The proposed study would follow a bounded photopolymer workflow from preparation through handling, post-processing and disposition. Each task would have a start condition, required information, operator action, completion condition and opportunities for detecting a deviation. This decomposition would identify what must be observed without assuming that a human-factors result from another manufacturing route transfers to the workflow.

For a hypothetical post-processing task, the study could distinguish identifying the correct job, selecting the applicable instruction, configuring equipment, transferring the part, recording completion and responding to a discrepancy. An error at one step and a successful recovery at a later step should remain separate observations. Counting only final rejected parts would miss recovered errors; counting every initial error as a product failure would ignore recovery.

The observation method should state whether performance was routine, supervised, simulated or deliberately interrupted. A task performed while being observed may not represent all routine conditions. Operator experience, workload context and familiarity with the equipment should be retained so that comparisons are not reduced to an unexplained average score.

11. Measure the safety context without conflating endpoints

A joined human-factors and exposure study would synchronise task observations with the relevant exposure measurements while respecting their different meanings. A recorded procedural deviation does not establish an exposure, and an exposure measurement does not identify operator error as its cause. The proposed design would preserve equipment state, controls, task timing and sampling conditions alongside the behavioural observations.

A useful comparison could evaluate a defined interface or instruction change against the same task endpoints. It would need to account for learning and order effects: improved performance in a second trial could reflect practice rather than the change under study. The study should state how the comparison addresses that possibility and where it remains unresolved.

Recovery performance could be described through detection, interruption, correction and escalation events, with the relevant time and evidence retained. The goal is to establish which part of the workflow supports or obstructs a controlled outcome. This develops a direct research design for photopolymer processing without attributing a measured workload, error frequency or exposure reduction to a workflow that has not been studied.

Supplementary critical engineering analysis: Task-centred human-factors assessment: Risk assessment should follow actual tasks rather than broad job titles. Resin receipt, cartridge transfer, vat filling, support removal, washing, transfer to post-cure and waste handling expose workers to different combinations of contact, aerosols, manual handling and procedural complexity. A task analysis should record the operator action, credible deviation, hazardous state, detection opportunity and recovery measure. The resulting hazard controls must be evaluated against observed work practices, not merely documented standard operating procedures.

Evidence for intervention effectiveness: Training completion is a process record, not evidence that a safeguard works. More informative endpoints include observed adherence, spill incidence, near-miss classification, time to detect abnormal states and whether a control remains usable under workload. Protective measures require their own maintenance and reassessment programme. General human-factors research is transferable as a method, but quantitative effect sizes cannot be assumed for a particular photopolymer workplace without direct measurement.

Additional critical synthesis: evidence, applicability and qualification: Task analysis with measurable endpoints: A human-factors study of photopolymer production should treat filling, resin recovery, part removal, cleaning, post-cure and waste transfer as separate tasks. Each task has different opportunities for skin contact, inhalation, manual handling or accidental mix-up. A task map should record normal operation, foreseeable deviation, detection signal and feasible recovery action. A generic staff survey cannot replace direct observation of the process, because workers may correctly describe a procedure while operating under conflicting time or access constraints.

Separating exposure outcomes from usability outcomes: Near-miss counts, compliance observations and task completion time measure different things from chemical exposure. A reduced task time does not demonstrate reduced inhalation or dermal contact. Similarly, a lower area monitor reading does not prove that hand contact has been controlled. Evaluation should define outcome families in advance and preserve the conditions under which each was measured. Protective equipment and ventilation are relevant, but hierarchy-of-controls reasoning asks whether hazardous steps can also be eliminated, enclosed or mechanically constrained. The cited general occupational AM literature does not provide a facility-specific effectiveness coefficient for these interventions.

Study design for intervention evaluation: Before-after comparisons can be confounded by workload, production mix and operator familiarity. A stronger evaluation records those variables, keeps observation definitions fixed and, where possible, uses comparable tasks or sites. Rare serious events may require leading indicators such as observed exposure pathways and control failures rather than waiting for an injury count. Reporting negative or null results helps avoid selecting only favourable demonstrations. The engineering deliverable is a repeatable protocol for testing controls, not an unsupported claim that a particular training intervention guarantees safety.

Critical evidence synthesis: Human factors: task-level study design and control effectiveness: Photopolymer safety cannot be inferred from the existence of an instruction sheet. A usable human-factors study observes tasks under realistic interruptions, hand-offs and abnormal conditions, such as changing a resin container, clearing a spill or removing a partially cured part. The relevant endpoints include error occurrence, correct execution of recovery steps, contact opportunities, duration and frequency of tasks, and reliance on memory rather than engineered controls. Different operators and experience levels should be represented so that an intervention does not appear effective solely because expert users performed the trial.

Improved task completion and reduced chemical exposure are related but not interchangeable outcomes. A newly designed workflow may reduce errors yet shift exposure from one task to another; direct task-based sampling or validated exposure proxies are necessary to evaluate that claim. Intervention studies should identify their comparator, learning effects, observation bias and the duration over which benefits persist. A hierarchy of controls remains important: training can support but not substitute for effective enclosure, ventilation and safer work organisation.

12. Limitations

The evidence is split by process and purpose. Source [1] is FDM-specific for human factors; source [2] is multi-process for occupational hygiene. The missing photopolymer-specific join is therefore a real evidence gap rather than a space filled by analogy.

Human-factors qualification under realistic interruptions: Operator error should not be interpreted solely as an individual failing. Task sequence, ambiguity in instructions, alarm salience, time pressure, workbench organization and the accessibility of batch information all influence error opportunity. A useful assessment identifies the decision points at which incorrect material selection, inadequate washing, wrong cure settings or release of an unqualified build could occur. These hazards should be ranked using consequence and detectability, not frequency estimates imported from unrelated industries.

Validation should use representative scenarios including interruptions, handover between shifts, similar packaging and ambiguous display states. Independent observers may record omissions, recovery time and whether procedural controls prevented propagation of an error into a released part. The intervention itself must be evaluated: an added checklist can reduce omission while also increasing workload or encouraging mechanical completion. Human-factors evidence supports improving safeguards, not removing the need for technical acceptance testing of the finished material.

13. Conclusions

Human-factors methods in AM are available, and occupational-safety evidence includes photopolymer processing within broader AM reviews [1,2]. What is missing is direct measurement of human factors inside a photopolymer workflow. The correct engineering response is to carry the methods forward as study tools while keeping the FDM findings and the photopolymer safety evidence in separate layers until a direct study joins them.

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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