

Verification and Validation of Multiphysics Models for Photopolymer Additive Manufacturing: Parameters, Benchmarks and Uncertainty

Building credibility by separating code correctness, parameter identification, experimental validation and uncertainty for the intended use

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Abstract

The multiphysics model qualification is examined as a qualification problem in which mechanism, measurement and transferability must be kept distinct. The governing description centres on the coupled balance that governs multiphysics model credibility; the response is then modified because parameter compensation can hide wrong physics when only one observable is fitted, while calibration on working curves alone does not validate thermal or stress predictions. A practical measurement architecture combines independently identified optical, thermal, geometric and mechanical observables with replicate-based uncertainty estimates. The controlled test 'unit benchmarks for each submodel' is proposed to discriminate causal explanations before a global model is fitted. These elements provide the evidence needed to decide whether a model is credible for profile transfer, geometry compensation or digital-twin control and to define the boundary beyond which the qualification claim no longer applies.

Keywords: verification; validation; uncertainty quantification; multiphysics; benchmark; parameter identifiability

1. Qualification problem: multiphysics model credibility

Engineering use of multiphysics model credibility requires an explicit acceptance envelope. That envelope is built from the decision criterion, which parameters require material-specific re-identification, and what evidence is sufficient before extrapolating outside calibration space, while grid/time-step convergence ratios, dimensionless benchmark cases, and sensitivity and identifiability metrics identify when two tests no longer represent the same state. [3]

1.1 Scope boundary.

ER-360 owns verification, validation, parameter identification and uncertainty for multiphysics photopolymer-AM models. ER-351 through ER-359 own the individual thermal, transport and field-assisted phenomena; ER-360 does not re-review those mechanisms but defines how their models should be tested and qualified.

2. Governing balances for multiphysics model credibility

Model credibility is assessed through the relations below for discretisation, benchmark similarity, and parameter identifiability.

verification asks whether equations are solved correctly; validation asks whether the equations represent reality for a stated use

discretization error, parameter uncertainty, model-form error and measurement uncertainty must be separated

prediction intervals require propagation of uncertainty through coupled optical, kinetic, thermal and mechanical submodels

No single metric is sufficient: numerical convergence, physics similarity, and identifiability answer different credibility questions.

3. Regime boundaries for multiphysics model credibility

For model credibility, Table 1 assigns evidence to numerical verification, physics benchmarking, or parameter identification rather than merging them.

Table 1. Regime indicators for multiphysics model qualification.

Indicator	Engineering meaning	Use
grid/time-step convergence ratios	observed numerical convergence across grid and time-step refinement	Treat grid/time-step convergence ratios as the boundary variable for 'whether a model is credible for profile transfer, geometry compensation or digital-twin control'. The claim is defensible only over the tested range associated with observed numerical convergence across grid and time-step refinement.
dimensionless benchmark cases	benchmark states spanning optical, thermal and reaction limits	Treat dimensionless benchmark cases as the boundary variable for 'which parameters require material-specific re-identification'. The claim is defensible only over the tested range associated with benchmark states spanning optical, thermal and reaction limits.
sensitivity and identifiability metrics	parameter sensitivity and identifiability during estimation	Treat sensitivity and identifiability metrics as the boundary variable for 'what evidence is sufficient before extrapolating outside calibration space'. The claim is defensible only over the tested range associated with parameter sensitivity and identifiability during estimation.

Extrapolation is withheld whenever convergence, benchmark similarity, or identifiability leaves the demonstrated model-credibility space.

4. Couplings that move the multiphysics model credibility

Single-observable fitting can yield parameter sets that reproduce an endpoint while misrepresenting the coupled physics.

A working-curve fit alone does not establish predictive validity for temperature or stress fields. [3]

Coupled models should be validated hierarchically from submodels to part-scale predictions.

5. Failure signatures and false diagnoses

Three rejection signatures define the fault space: good fit with non-identifiable parameters, validation against data used for calibration and mesh-converged solution of an incorrect model. They are interrogated with independent optical attenuation/cure data, thermal histories, conversion maps and geometry and mechanical distortion/residual stress where claimed, respectively, so that diagnosis follows measured mechanism rather than appearance alone. Each Table 2 row is a separate falsification route. The retained explanation must survive all four without ad hoc reinterpretation.

Table 2. Failure-mode discrimination for multiphysics model qualification.

Failure mode	Observable signature	Discriminating evidence
good fit with non-identifiable parameters	independent optical attenuation/cure data	unit benchmarks for each submodel
validation against data used for calibration	thermal histories, conversion maps and geometry	cross-validation across geometries and exposure schedules
mesh-converged solution of an incorrect model	mechanical distortion/residual stress where claimed	blind prediction of a withheld part-scale experiment
uncertainty bands that omit model-form discrepancy	replicate data for experimental uncertainty	sensitivity-informed experiments designed to separate correlated parameters

6. Measuring multiphysics model credibility with traceable uncertainty

Their joint use is deferred until the acceptance envelope is built. The multiphysics model credibility workflow deliberately separates an uncertainty-controlled perturbation of model-form uncertainty from independent resolution of discretisation error and parameter identifiability; this avoids fitting the challenge into the quantity being qualified; during metrology of multiphysics model credibility, model-form uncertainty is resolved against prediction intervals. Separate monitoring of prediction intervals is then examined on its own terms before any transfer statement is retained; the uncertainty record for multiphysics model credibility keeps prediction intervals separate from discretisation error.

7. Experiments that discriminate competing mechanisms

The experiment matrix follows the four Table 2 rows while keeping the non-target variables fixed as far as practicable. Mechanisms are compared by their predicted direction of change. For multiphysics model credibility, the evidence chain starts with a causal contrast between discretisation error and model-form uncertainty; during the causal challenge for multiphysics model credibility, prediction intervals is tested against discretisation error. It then adds a boundary challenge involving parameter identifiability, while a replicate test of prediction intervals is retained as a separate control so the three sources of information cannot compensate silently; the experiment for multiphysics model credibility separates discretisation error from parameter identifiability.

8. Model identification and validation for multiphysics model credibility

[5] [1,4] [2,6] The final uncertainty statement is decision-specific: the three Table 3 limits are not pooled into one confidence number. The working sequence for multiphysics model credibility has three parts: parameter estimation for discretisation error and parameter identifiability; prediction against model-form uncertainty; and an uncertainty-bounded check on prediction intervals; within model identification for multiphysics model credibility, discretisation error is not fitted through parameter identifiability. Each part answers a different engineering question, so uncertainty or failure in one part is not repaired by a favourable result in another; prediction for multiphysics model credibility keeps parameter identifiability independent of model-form uncertainty.

9. Qualification envelope and technology decisions

Table 3. Technology-decision matrix for multiphysics model qualification.

Decision	Minimum evidence	Acceptance logic
whether a model is credible for profile transfer, geometry compensation or digital-twin control	The evidence floor for whether a model is credible for profile transfer, geometry compensation or digital-twin control is a repeatable independent optical attenuation/cure data trend that spans the claimed envelope and includes the first departure from baseline behaviour.	The row passes where 'unit benchmarks for each submodel' preserves the established independent optical attenuation/cure data relationship; detection of good fit with non-identifiable parameters marks failure of the decision.
which parameters require material-specific re-identification	Quantify which parameters require material-specific re-identification with thermal histories, conversion maps and geometry at multiple states, including the boundary condition where the response first becomes decision-relevant.	The decision remains valid only if 'cross-validation across geometries and exposure schedules' gives a bounded, repeatable thermal histories, conversion maps and geometry response and does not produce validation against data used for calibration.
what evidence is sufficient before extrapolating outside calibration space	For what evidence is sufficient before extrapolating outside calibration space, require a replicated mechanical distortion/residual stress where claimed dataset that covers the proposed envelope and reports the uncertainty attached to the limiting state.	The claim is accepted if 'blind prediction of a withheld part-scale experiment' reproduces the expected mechanical distortion/residual stress where claimed behaviour at the limiting state and no mesh-converged solution of an incorrect model signature is present.

Three independent checks structure the multiphysics model credibility assessment; inside the multiphysics model credibility envelope, parameter identifiability and model-form uncertainty define different transfer limits. Tested ranges in discretisation error and parameter identifiability establishes the primary state, an explicit transfer limit on prediction intervals tests whether that state survives transfer, and a separate boundary for model-form uncertainty is the perturbation used when the two disagree; qualification of multiphysics model credibility bounds model-form uncertainty separately from prediction intervals.

10. Design consequences for multiphysics model credibility

A practical consequence of the model is to modify a design change governed by discretisation error under the constraint imposed by an implementation check on model-form uncertainty, while which parameters require material-specific re-identification is controlled independently; a requalification trigger tied to prediction intervals defines when fresh evidence is required; during design implementation for multiphysics model credibility, model-form uncertainty is constrained by prediction intervals. This makes the design consequence testable and prevents transfer by undocumented compensation; the multiphysics model credibility design record separates prediction intervals from discretisation error.

11. Evidence gaps for multiphysics model credibility

The other two channels are needed at the same points to preserve causal discrimination. Rather than reduce multiphysics model credibility to one surrogate, the analysis combines independent replication of prediction intervals with scale transfer of discretisation error; for unresolved multiphysics model credibility transfer, prediction intervals is studied separately from discretisation error. A separate uncertainty in parameter identifiability versus model-form uncertainty is used to challenge that interpretation, making disagreement between the two routes visible instead of averaging it away; the evidence gap in multiphysics model credibility distinguishes discretisation error from parameter identifiability.

12. Qualification outcome for multiphysics model credibility

Qualification may be claimed only inside the tested transfer domain represented by all three Table 3 decisions; extension requires new discriminatory evidence. An acceptable record for multiphysics model credibility must show a renewed-evidence trigger when prediction intervals changes without inferring it from agreement between measurement and prediction for discretisation error; at final qualification of multiphysics model credibility, discretisation error is reconciled with parameter identifiability. In parallel, causal evidence that separates parameter identifiability from model-form uncertainty probes the boundary condition most likely to change the interpretation, and the resulting uncertainty is carried forward explicitly; the closing multiphysics model credibility claim keeps parameter identifiability distinct from model-form uncertainty.

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. No comparative product recommendation is made.

Data availability

No new experimental dataset was generated for this review.