

Machine-Capability Studies for Additive Manufacturing: Repeatability, Reproducibility, Nested Variation and Acceptance

Designing capability evidence around the actual variance hierarchy of additive production

Juan Segurola

3Dresyns by Resyner Technologies S.L.

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

ER-344 · Engineering Review · Version 0.5 · 28 September 2026

Abstract

Additive production contains nested sources of variation: feature within part, part within build, position within build, build within machine, machine within site and site within organisation. Repeatability examines variation under nominally unchanged conditions; reproducibility introduces declared sources such as operator, machine, day or site. Orientation and position can create deterministic dimensional or cure differences. Cp/Cpk-type summaries can be useful only when the measured distribution, specification basis and stability assumptions are defensible. A reference geometry improves comparability across machines, while production parts test the specific requirement set. Qualification therefore depends on preserving the measured state, configuration and exception history needed to distinguish these mechanisms in production rather than relying on nominal recipe identity alone.

Keywords: machine capability; additive manufacturing; repeatability; reproducibility; nested variation; acceptance; variance components

1. Significance and scope

Additive production contains nested sources of variation: feature within part, part within build, position within build, build within machine, machine within site and site within organisation. The engineering question is how repeatability, reproducibility and nested sources of variation should be measured so that machine capability claims are tied to defined acceptance limits rather than isolated test builds. The review focuses on evidence that supports repeatable manufacturing decisions and excludes proprietary recipes, supplier-specific settings and undocumented operator heuristics.

1.1 Corpus boundary

ER-344 owns statistical studies used to characterise machine and production capability in additive manufacturing. It does not own generic test-method precision studies, supplier lot qualification or product-specific design allowables. ER-343 owns machine-health monitoring and ER-345 owns build-layout and scheduling effects; ER-344 owns statistical capability and acceptance architecture.

2. Capability starts with a variance hierarchy

Additive production contains nested sources of variation: feature within part, part within build, position within build, build within machine, machine within site and site within organisation. A study that collapses these levels into one standard deviation cannot identify the dominant source or support transfer decisions [1-3].

3. Repeatability and reproducibility answer different questions

Repeatability examines variation under nominally unchanged conditions; reproducibility introduces declared sources such as operator, machine, day or site. Both are required when the intended use includes multiple printers or production shifts. The design must match the decision rather than inherit terminology from gauge studies without adaptation [1,2].

4. Build position is a structured factor

Orientation and position can create deterministic dimensional or cure differences. Randomising specimens without recording position destroys information. Capability studies should map the build field sufficiently to distinguish systematic spatial effects from random part-to-part noise [2,3].

5. Acceptance indices require distribution discipline

Cp/Cpk-type summaries can be useful only when the measured distribution, specification basis and stability assumptions are defensible. Non-normal tails, censoring, drift and mixed populations should be handled directly rather than hidden by a single capability number [1,3].

6. Reference artefacts and production parts play different roles

A reference geometry improves comparability across machines, while production parts test the specific requirement set. Capability evidence is strongest when a stable reference artefact diagnoses the equipment and representative parts confirm that the result transfers to the real geometry [1-3].

7. Qualification architecture

The protocol should predefine factors, randomisation, replication, measurement uncertainty, variance model and acceptance logic. Re-running only failed cells until the average passes invalidates the design. Outliers require a documented assignable cause before exclusion [1-3]. Monitoring and control literature also reinforces the need to distinguish process signals from controlled outputs when selecting the study variables [4].

8. Evidence hierarchy and transfer

A one-machine study can establish local repeatability; multi-machine and multi-build studies are needed for fleet claims. Round-robin guidance is useful when sites or organisations are compared because it forces separation of study design from observed variability [1-3].

Table 1. Qualification matrix for machine-capability studies for additive manufacturing.

Variance level	Example source	Study requirement
Within part	Feature-specific error	Multiple measurands
Within build	Position/orientation	Mapped locations
Between builds	Day, vat, setup	Replicated builds
Between machines	Calibration/hardware state	Nested machine factor
Between sites	Environment/procedure	Controlled transfer study

9. Interpretation matrix

For machine-capability studies, an apparent capability loss may arise from machine drift, gauge variation, build-position effects or sampling structure. Nested variance decomposition and an adequate measurement-system study are required before the printer itself is assigned as the dominant source.

Table 2. Diagnostic interpretation matrix for machine-capability studies.

Statistical symptom	Risk	Correct response
High within-build spread	Position or local process effect	Model position explicitly
Stable mean, drifting variance	Degrading consistency	Variance monitoring
Mixed distributions	Hidden machine or lot classes	Stratify before capability index
Apparent high capability	Spec much wider than measurement	Check measurement uncertainty

10. Limitations and evidence gaps

Capability estimates are sensitive to sampling design, measurement uncertainty, build layout and the hierarchy of nested variation. Many additive-manufacturing studies use too few machines, builds or positions to separate these effects robustly. Capability indices should therefore be reported only when the measurement system and variance structure are adequate for the stated acceptance decision.

11. Conclusions

Machine capability in additive manufacturing is a variance-decomposition problem before it is a capability-index problem. Repeatability, reproducibility, build position and measurement uncertainty must be separated well enough to support the intended acceptance decision. Capability evidence is strongest when reference artefacts and production-relevant features lead to the same conclusion about process stability.

References

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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.