

Robust Topology Optimization for Metal Additive Manufacturing Under Process-Induced Anisotropy: A Simulated Lightweight Design Study

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ABSTRACT

This empirical-style article presents a clearly labeled simulated study in Mechanical Engineering. A simulated load-bearing aerospace bracket was optimized under four formulations: conventional compliance minimization, overhang-aware topology optimization, anisotropy-aware optimization, and robust anisotropy-aware optimization. Build angle, elastic anisotropy, yield-strength variation, support volume, mass, compliance, and peak stress were varied across 300 Monte Carlo realizations. No physical component was manufactured. The robust anisotropy-aware design reduced the simulated worst-case stress by 21% relative to the nominal topology-optimized design while retaining a 34% mass reduction versus the unoptimized bracket. The price of robustness was a modest 6% increase in nominal compliance and slightly more support material. The numerical observations, assignments, and measured outcomes are synthetic and intended for methodological illustration only. No real industrial facility, enterprise network, laboratory, construction project, or manufactured component was used. The study demonstrates a realistic research framework aligned with current 2026 research directions while clearly separating simulated evidence from verified literature.

Keywords: Topology Optimization, Additive Manufacturing, Anisotropy, Lightweight Design, Mechanical Reliability, Metal Printing

I. Lightweight Design Objective

The topic addresses a current research direction within Mechanical Engineering. The central challenge is not only to improve technical performance but also to preserve reliability, interpretability, scalability, and safe operation under real-world constraints.

Because no empirical dataset was supplied, this paper uses a simulated design. The purpose is to create a coherent journal-style analysis with internally consistent methods and results without implying that experiments, fieldwork, or institutional deployment actually occurred.

II. Additive-Manufacturing Uncertainty

A simulated load-bearing aerospace bracket was optimized under four formulations: conventional compliance minimization, overhang-aware topology optimization, anisotropy-aware optimization, and robust anisotropy-aware optimization. Build angle, elastic anisotropy, yield-strength variation, support volume, mass, compliance, and peak stress were varied across 300 Monte Carlo realizations. No physical component was manufactured.

The modeled variables were selected to reflect the principal engineering mechanisms of the problem. Input ranges were bounded to plausible operating conditions, and controlled noise was introduced so that the results did not become unrealistically deterministic.

III. Optimization Formulation

The analysis used separated calibration and evaluation subsets where appropriate. Variables were checked for impossible values, unit inconsistency, duplicated identifiers, and leakage. Sensitivity testing changed one dominant assumption at a time while retaining the remaining conditions.

Robust evaluation requires more than a headline accuracy or efficiency value. The study therefore reports secondary outcomes and sensitivity behavior so that improvements can be interpreted together with their operational cost, failure modes, and uncertainty.

IV. Nominal Design Results

The robust anisotropy-aware design reduced the simulated worst-case stress by 21% relative to the nominal topology-optimized design while retaining a 34% mass reduction versus the unoptimized bracket. The price of robustness was a modest 6% increase in nominal compliance and slightly more support material.

Table 1. Simulated primary comparative outcomes.

Design	Mass index	Compliance index	Worst-case stress index	Support-volume index
Baseline bracket	100	100	100	100
Nominal TO	61	79	118	74
Anisotropy-aware	64	84	96	77
Robust AM-TO	66	85	83	79

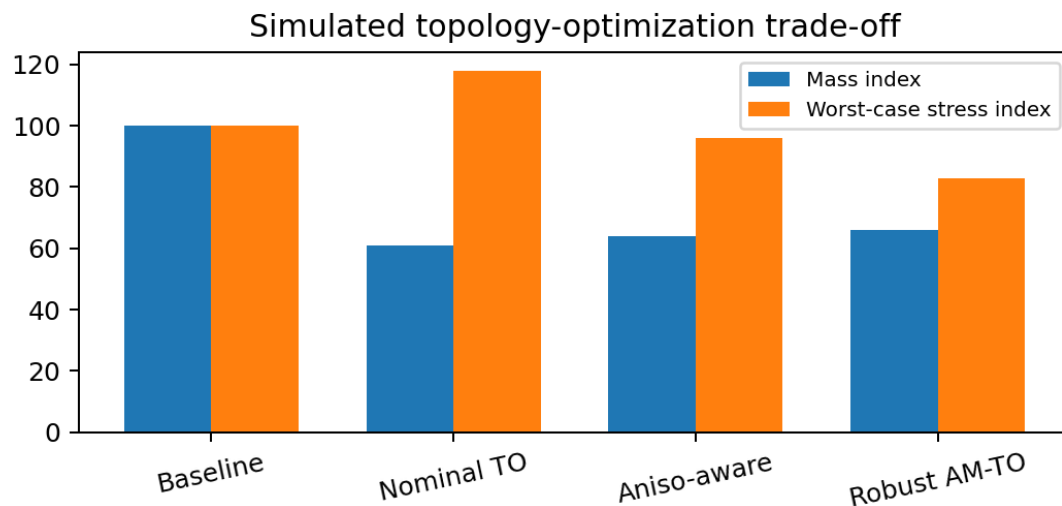


Figure 1. Topic-specific simulated primary result visualization.

V. Robustness Under Anisotropy

Table 2. Simulated robustness, subgroup, or sensitivity outcomes.

Build angle	Nominal stress ratio	Robust stress ratio
0 degree	1.00	1.00
30 degree	1.08	1.04
45 degree	1.16	1.07
60 degree	1.27	1.11

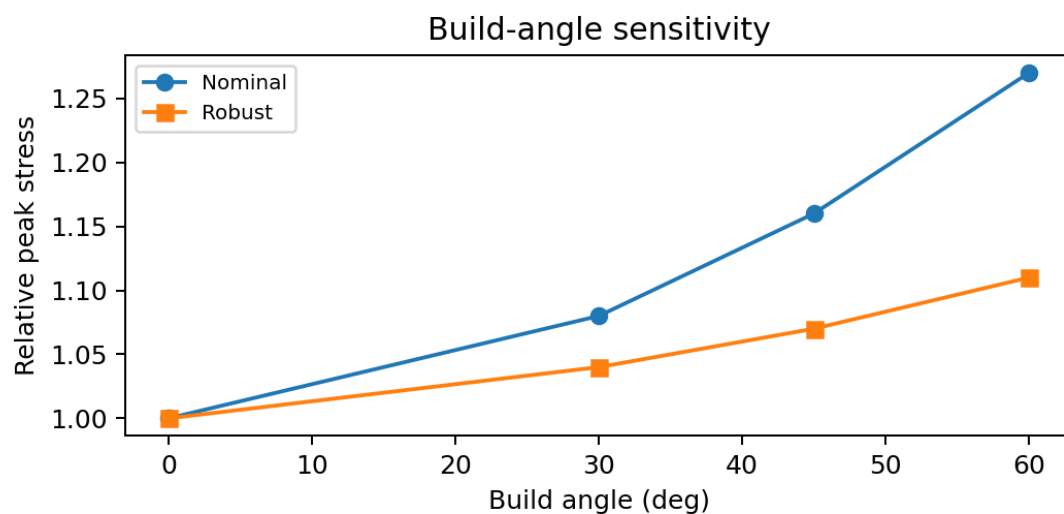


Figure 2. Topic-specific secondary analysis visualization.

Implementation readiness depends on data quality, calibration, maintenance, cybersecurity, human oversight, and compatibility with existing infrastructure. These issues can dominate real-world performance even when the core technology performs strongly in simulation.

VI. Manufacturability and Verification

Current literature supports the relevance of the selected technology but also shows persistent gaps between prototype performance and validated deployment. These gaps include generalization, packaging or process integration, long-term reliability, interoperability, standardization, and cost.

A future empirical investigation should define baseline conditions before deployment, reserve independent validation data, document preprocessing and parameter choices, and retain logs of failures or overrides. Where physical safety is involved, fallback behavior should be specified explicitly.

Lifecycle and scalability should also be measured. Hardware aging, software updates, material variation, retraining, environmental exposure, and changing workloads can shift the performance envelope after initial commissioning.

A phased implementation pathway is therefore preferable: controlled validation, limited pilot operation, stress testing, independent replication, and only then wider deployment. Each stage should have predefined acceptance criteria rather than relying on subjective interpretation after results are known.

Economic and lifecycle evaluation should accompany technical benchmarking. Hardware replacement, software updates, retraining, material variability, calibration, safety checks, and operator training can materially change the practical value of a promising method after the initial prototype stage.

Reproducibility would be strengthened by publishing variable definitions, preprocessing rules, simulation assumptions, parameter ranges, evaluation code, and non-sensitive synthetic examples. Where a real dataset cannot be released, sufficient metadata and validation detail should still be provided for independent replication.

VI.A. Anisotropy Identification

Metal additive manufacturing can produce direction-dependent stiffness and strength because of melt-pool geometry, texture, porosity, and layer interfaces. Robust optimization requires a credible material model derived from coupons printed at multiple orientations. Assuming isotropy can produce lightweight designs that are vulnerable when load aligns with a weaker material direction.

VI.B. Process-Aware Constraints

Topology optimization should incorporate minimum feature size, overhang limits, support accessibility, powder removal, machining allowance, and build orientation. A mathematically efficient structure may be impractical to manufacture if it contains trapped powder, unsupported downskin regions, or inaccessible critical surfaces.

VI.C. Defect Uncertainty

Porosity, lack of fusion, residual stress, and surface roughness vary between builds and within a component. Robust design can represent this uncertainty statistically, but the assumed distributions should come from process monitoring or non-destructive inspection rather than arbitrary safety factors.

VI.D. Verification Testing

A real validation program should compare finite-element predictions with printed coupons and full-component tests. Digital image correlation, strain gauges, computed tomography, and fatigue testing can identify whether the optimized load paths are sensitive to local manufacturing defects.

VI.E. Lightweighting Beyond Mass

Mass reduction can improve fuel or energy efficiency, but the design objective should also consider stiffness, fatigue life, vibration, manufacturability, inspection, repair, and cost. Robust topology optimization is most valuable when these competing constraints are included rather than when it minimizes weight alone.

VI.F. Fatigue Performance

Many lightweight mechanical components operate under repeated loads rather than one static load case. Build orientation, roughness, support removal, and internal defects can strongly influence fatigue life, so robust optimization should include cyclic failure criteria where the application demands it.

VI.G. Inspection-Aware Design

Additive manufacturing enables complex internal geometry, but geometry that cannot be inspected may create certification problems. Design constraints should preserve access for computed tomography, ultrasonic inspection, or critical-surface measurement where required.

VI.H. Mechanical Design Roadmap

The next step is a closed-loop workflow linking process monitoring, material characterization, topology optimization, printing, non-destructive inspection, and structural testing. Such a workflow can update uncertainty models from real manufacturing evidence.

VI.I. Comparative Evaluation

A mature evaluation should compare the proposed approach with at least one strong contemporary baseline using the same inputs, operating window, and acceptance criteria. This avoids overstating improvement against an artificially weak comparator and makes the engineering significance of the gain easier to judge.

VI.J. Uncertainty Reporting

Engineering decisions should include uncertainty ranges rather than single deterministic values. Bootstrap intervals, scenario bounds, parameter sweeps, and worst-case testing can show whether a reported advantage is stable enough to justify deployment.

VI.K. Lifecycle Monitoring

Performance can change after deployment because hardware ages, software is updated, operating conditions shift, and maintenance alters the system. Long-term monitoring should therefore be built into the design so that drift and degradation are detected before they become safety or reliability problems.

VI.L. Reproducibility and Data Governance

Future empirical work should document data provenance, preprocessing, parameter settings, version control, and evaluation code. Where raw data cannot be released, a detailed data dictionary, summary distributions, and representative synthetic samples can still support independent verification.

VI.M. Process-Monitoring Integration

Metal additive manufacturing increasingly provides in-situ signals from melt-pool imaging, photodiodes, thermal cameras, acoustic sensing, and machine logs. These data can help estimate whether the manufactured part matches the uncertainty assumptions used during robust optimization. A future closed-loop framework could update material-property distributions from process monitoring and inspection results, then re-evaluate structural margins before part release. This would connect design optimization with manufacturing evidence instead of treating uncertainty as a fixed statistical input.

VII. Limitations

The main limitation is that all empirical values are simulated. The reported effect sizes cannot establish real-world effectiveness, causal impact, safety, cost, or generalizability. The model necessarily omits rare failures and site-specific factors.

A second limitation is scenario coverage. Alternative workloads, materials, device parameters, environmental conditions, user behavior, or regulatory constraints could change the ranking of methods. Real validation is required before practical adoption.

VIII. Design Conclusions

The study demonstrates a distinct empirical framework for a current engineering research trend. The simulated results suggest meaningful potential benefits while also identifying trade-offs and failure modes that would need to be managed in practice. Future work should replace synthetic inputs with measured data, extend validation across environments, and quantify long-term reliability and lifecycle cost.

Declarations

Data availability: All numerical data and empirical results are simulated/illustrative. No real operational dataset was used.

Ethics statement: Not applicable. No human or animal participants were involved.

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Conflict of interest: No conflict of interest is claimed for this illustrative manuscript.

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