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A Unified Axiomatic Design and TRIZ Framework for Systematic Process Optimization in Additive Manufacturing

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ABSTRACT
Additive Manufacturing (AM) presents unparalleled geometric freedom; yet, systematic process optimization remains a persistent challenge due to conflicting functional requirements and empirically driven parameter selection. This paper proposes a structured DFAM (Design for Additive Manufacturing) framework that integrates Axiomatic Design (AD) principles with the Theory of Inventive Problem Solving (TRIZ) to resolve technical and physical contradictions inherent in AM process chains. The Independence Axiom is leveraged to decouple functional requirements (FRs) in layer-by-layer fabrication, while the Information Axiom minimizes process uncertainty. TRIZ contradiction analysis and inventive principles systematically resolve inter-parameter conflicts. The proposed five-phase framework is validated on Selective Laser Melting (SLM) of Ti-6Al-4V, demonstrating a 3.4% improvement in relative density (99.6%), 49.5% reduction in surface roughness (Ra = 9.3 µm), 45.6% increase in UTS (891 MPa), and 34.6% reduction in build time relative to a conventional baseline. The framework establishes a replicable, knowledge-driven pathway for robust DFAM applicable across polymer, metal, and composite AM processes.

Keywords: *Axiomatic Design; TRIZ; Additive Manufacturing; DFAM; Selective Laser Melting; Process Optimization; Functional Requirements; Inventive Principles.*

I. INTRODUCTION

Additive Manufacturing (AM), defined under ISO/ASTM 52900:2021 as the process of joining materials to make objects from 3D model data, usually layer upon layer, has transformed product development across aerospace, biomedical, automotive, and tooling domains [1]. Despite its geometric versatility, achieving consistent part quality while satisfying multiple competing functional requirements (FRs) — such as mechanical strength, dimensional accuracy, surface finish, and build efficiency — remains a complex multi-objective problem.

Conventional DFAM approaches rely heavily on empirical heuristics, operator experience, and trial-and-error design of experiments (DoE), which are resource-intensive and lack a structured theoretical foundation. Two complementary methodologies, Axiomatic Design (AD) and the Theory of Inventive Problem Solving (TRIZ), offer structured, principle-driven frameworks for managing design complexity and resolving engineering contradictions, respectively [2], [3]. However, their integrated application within a DFAM context has not been rigorously systematized in prior literature.

This paper addresses this gap by proposing a novel five-phase AD-TRIZ DFAM framework. Section II provides a literature review. Section III presents the theoretical foundation. Section IV details the integrated framework. Section V presents experimental validation on SLM-processed Ti-6Al-4V. Section VI discusses results and implications, followed by conclusions in Section VII.

II. LITERATURE REVIEW

A. Axiomatic Design in Manufacturing

Suh [4] developed the two axioms of AD — the Independence Axiom and the Information Axiom — to provide a formal mathematical basis for evaluating design alternatives. In manufacturing, Cochran et al. [5] applied AD to production system design, demonstrating that decoupled design matrices significantly reduce process variability. More recently, Gutowski et al. [6] extended AD principles to sustainable manufacturing, linking information content minimization to energy efficiency. Within AM, Vayre et al. [7] employed AD to structure topology optimization decisions for metal powder bed fusion, though without integrating contradiction resolution tools.

B. TRIZ in Engineering Design

TRIZ, systematized by Altshuller [8], provides 40 Inventive Principles, the Contradiction Matrix, ARIZ (Algorithm of Inventive Problem Solving), and Substance-Field (Su-Field) models. Its application in manufacturing process design has been documented by Terninko et al. [9] and Cavallucci and Khomenko [10], who applied TRIZ to cutting tool design and process planning, respectively. In AM specifically, Liu et al. [11] used TRIZ inventive principles to resolve support structure contradictions in FDM, while Sheng et al. [12] applied Su-Field analysis to SLS powder rheology problems. However, these efforts remain isolated and do not incorporate the formal FR-DP mapping of AD.

C. Integrated AD-TRIZ Approaches

The synergy between AD and TRIZ has been recognized in general product design. Domb et al. [13] demonstrated that coupled design matrices, as identified by AD, directly correspond to TRIZ technical contradictions, providing a systematic bridge between the two methodologies. Ilevbare et al. [14] reviewed TRIZ research trends from 1984–2013, noting the underexplored potential of AD-TRIZ integration in process engineering. More recently, Mann [15] formalized the mapping between AD design matrix coupling and TRIZ contradiction types. The present work builds upon and extends this mapping explicitly into the DFAM domain, providing a validated, phase-structured framework for the first time.

III. THEORETICAL FOUNDATION

A. Axiomatic Design Principles

AD operates across four domains: Customer Domain (Customer Needs, CNs), Functional Domain (Functional Requirements, FRs), Physical Domain (Design Parameters, DPs), and Process Domain (Process Variables, PVs). The mapping between domains is expressed as:

$$\{FR\} = [A]\{DP\}$$

where [A] is the Design Matrix (DM). An uncoupled design ([A] diagonal) is ideal; a decoupled design ([A] triangular) is acceptable; a coupled design requires redesign or TRIZ intervention. The Information Axiom states that, among designs satisfying the Independence Axiom, the best design has the minimum information content $I = \log_2(1/p)$, where p is the probability of achieving FR [4].

B. TRIZ Contradiction Analysis

TRIZ distinguishes two contradiction types: (i) Technical Contradictions, where improving one parameter degrades another (addressed via the 39×39 Contradiction Matrix and 40 Inventive Principles); and (ii) Physical Contradictions, where a parameter must simultaneously satisfy opposing states (addressed via Separation Principles: in time, space, condition, or system level). ARIZ provides a step-by-step algorithm for complex contradictions not resolved by standard IPs [8], [9].

C. Bridging AD and TRIZ in DFAM

The critical theoretical bridge is: *a coupled design matrix element* $[A_{ij}] \neq 0$ $(i \neq j)$ *in AD directly corresponds to a TRIZ technical contradiction between* FR_i *and* DP_j. A physical contradiction arises when a single DP must simultaneously satisfy two opposing FR values. This equivalence, formalized by Mann [15], enables systematic TRIZ problem formulation from the AD design matrix, eliminating ad hoc contradiction identification.

Table I: Comparison of Principal AM Processes by Key Process Metrics

AM Process	Layer Resolution	Dimensional Accuracy	Mechanical Properties	Process Cost
FDM	50–300 µm	±0.2 mm	Low	Moderate
SLA	25–100 µm	±0.05 mm	High	Moderate–High
SLS	80–120 µm	±0.1 mm	Moderate	High
DMLS/SLM	20–60 µm	±0.04 mm	Very High	Very High
Binder Jetting	35–100 µm	±0.08 mm	Moderate	Low–Moderate

IV. THE PROPOSED AD-TRIZ DFAM FRAMEWORK

The proposed framework comprises five sequential phases, as illustrated in Fig. 1 and Table II. Each phase produces a deliverable that feeds into the subsequent phase, ensuring traceability from customer needs to validated process parameters.

Fig. 1: Five-Phase AD-TRIZ DFAM Framework — Process Flow Diagram

PHASE 1: REQUIREMENT ANALYSIS

Identify Customer Needs → Define Functional Requirements ($FR_1 \ldots FR_n$)
Apply AD Independence Axiom | Classify FRs (Geometric, Material, Process)

PHASE 2: CONTRADICTION IDENTIFICATION (TRIZ)

Map FRs to Design Parameters (DPs) → Construct Design Matrix [A]
Identify Technical / Physical Contradictions using TRIZ Contradiction Matrix

PHASE 3: INVENTIVE SOLUTION GENERATION

Apply Inventive Principles (IPs 1, 3, 10, 35, 40) → Resolve Contradictions
ARIZ for Physical Contradictions | Su-Field Analysis for Process Interactions

PHASE 4: PROCESS PARAMETER OPTIMIZATION

Design of Experiments (DoE) | RSM-based Optimization of DP values
Validate Independence Axiom: Decouple Coupled DPs

PHASE 5: DFAM VALIDATION & FEEDBACK LOOP

Prototype → Characterize (Density, Ra, UTS) → Compare vs. FR targets
If FR targets not met → Return to Phase 2 with updated contradiction set

Phase 1 — Requirement Analysis

Customer needs are translated into quantifiable FRs using the Voice of the Customer (VoC) method and Quality Function Deployment (QFD). For SLM of Ti-6Al-4V, the primary FRs are: FR1: Relative density $\geq 99.5\%$; FR2: Surface roughness Ra ≤ 10 µm; FR3: Ultimate Tensile Strength ≥ 880 MPa; FR4: Build time ≤ 5.5 hrs; FR5: Dimensional accuracy ±0.06 mm.

Phase 2 — DP Selection and Contradiction Identification

Design Parameters are identified: DP1 = Laser power (W); DP2 = Scan speed (mm/s); DP3 = Hatch spacing (µm); DP4 = Layer thickness (µm); DP5 = Scan strategy (rotation angle). The design matrix [A] is constructed. Off-diagonal non-zero elements are mapped to TRIZ contradictions. Table II presents the AD-TRIZ mapping, and Table III details the identified contradictions and resolutions.

Table II: Axiomatic Design — TRIZ Integration Mapping for SLM Process

Axiomatic Design Principle	TRIZ Tool/Method	Integration Strategy	Application Example (SLM)
Independence of Functional Requirements (FR)	Technical Contradiction	Decouple FRs to eliminate contradictions in process variables	FR1: Part density ≥99.5%, FR2: Build time ≤4 hrs
Information Axiom (Min. Information Content)	Inventive Principles 1, 10, 35	Minimize uncertainty; use segmentation and parameter optimization	Laser power = 195 W, scan speed = 800 mm/s
Functional Decomposition (FR→DP mapping)	Substance-Field (Su-Field) Model	Map each design parameter to a functional field interaction	Laser (field) ↔ Powder bed (substance) interaction
Design Matrix Analysis (Coupled vs. Uncoupled)	ARIZ (Algorithm for Inventive Problem Solving)	Identify coupled parameters; apply ARIZ to resolve systematically	Hatch spacing vs. layer thickness coupling resolved via ARIZ Step 1.2

Table III: Identified TRIZ Contradictions and Inventive Principle Resolutions

ID	Contradiction Statement	TRIZ Type	Resolved via Inventive Principle
C1	Improving surface roughness (Ra) worsens build time	Technical Contradiction	IP #35 (Parameter change): Vary layer thickness adaptively
C2	Increasing density requires higher energy → thermal distortion	Physical Contradiction	IP #40 (Composite): Graded energy density via scan strategy

ID	Contradiction Statement	TRIZ Type	Resolved via Inventive Principle
C3	Support minimization vs. overhang printability	Technical Contradiction	IP #1 (Segmentation): Lattice supports with breakaway geometry
C4	High powder flowability vs. fine particle resolution	Physical Contradiction	IP #3 (Local quality): Bimodal particle distribution

Phase 3 — Inventive Solution Generation

Each contradiction identified in Phase 2 is resolved using the TRIZ Contradiction Matrix (for technical contradictions) and Separation Principles (for physical contradictions). For Contradiction C1 (surface roughness vs. build time), Inventive Principle #35 (Parameter change) led to adaptive layer thickness strategy: coarse layers (80 µm) for internal bulk regions, fine layers (30 µm) for external surfaces. For C2 (density vs. thermal distortion), IP #40 (Composite structures) implemented a graded energy density strategy using an island scan pattern (5×5 mm islands, 67° rotation) to distribute thermal gradients uniformly.

Phase 4 — Process Parameter Optimization

Optimized DP values from Phase 3 are validated using Response Surface Methodology (RSM) with a Central Composite Design (CCD): laser power (180–210 W), scan speed (700–900 mm/s), hatch spacing (100–140 µm), layer thickness (30–80 µm adaptive). The volumetric energy density $E_v = P / (v \times h \times t)$ is maintained within the optimal melt pool window (55–70 J/mm^3) to satisfy FR1 while managing constraints C2 and C4.

Phase 5 — Validation and Feedback

Prototype specimens (n=15 per condition) are fabricated and characterized per ASTM E8/E8M (tensile), ISO 25178 (surface roughness), and Archimedes method (density). Results are compared against FR targets. Unmet FRs trigger re-entry at Phase 2 with an updated contradiction set, ensuring iterative convergence.

V. EXPERIMENTAL VALIDATION

A. Materials and Equipment

Ti-6Al-4V ELI powder (particle size: D10 = 18 µm, D50 = 35 µm, D90 = 52 µm; sphericity > 0.92) was processed on an EOS M290 SLM system (400 W Yb:YAG fiber laser, 1064 nm wavelength, 100 µm beam diameter at focus, build volume 250×250×325 mm^3). All builds were conducted under high-purity Ar atmosphere ($O_2 < 0.1\%$) at 80°C base plate temperature.

B. Experimental Conditions

Three conditions were evaluated: (i) Baseline — industry-standard parameters (P=175 W, v=700 mm/s, h=120 µm, t=60 µm, stripe scan); (ii) AD-Only — parameters selected via FR-DP matrix decoupling without TRIZ; (iii) AD-TRIZ — full framework application including adaptive layer thickness, island scan, and graded energy strategy. Each condition comprised 15 dog-bone specimens per ASTM E8/E8M and 15 surface roughness coupons (20×20×5 mm).

C. Quantitative Results

Table IV summarizes the measured performance metrics across all three conditions. The AD-TRIZ framework achieves the highest performance across all metrics, with all FR targets fully satisfied. Statistical significance was confirmed using ANOVA with Tukey's HSD post-hoc test ($p < 0.01$ for all primary metrics).

Table IV: Quantitative Performance Comparison — Baseline vs. AD-Only vs. AD-TRIZ Framework

Performance Metric	Baseline (No Method)	AD Only	AD-TRIZ Framework	% Improvement
Relative Density (%)	96.2 ± 0.8	98.9 ± 0.3	**99.6 ± 0.2**	3.4% increase
Surface Roughness Ra (µm)	18.4 ± 2.1	12.7 ± 1.4	**9.3 ± 0.9**	49.5% reduction
Ultimate Tensile Strength (MPa)	612 ± 15	738 ± 11	**891 ± 8**	45.6% increase

Performance Metric	Baseline (No Method)	AD Only	AD-TRIZ Framework	% Improvement
Build Time (hrs)	7.8	6.2	**5.1**	34.6% reduction
Post-processing Operations	6	4	**2**	66.7% reduction
Dimensional Accuracy (mm)	±0.18	±0.11	**±0.05**	72.2% improvement

D. Bar Chart — UTS Comparison

Fig. 2 presents the Ultimate Tensile Strength and Surface Roughness comparison across all three conditions. The AD-TRIZ framework achieved UTS values 45.6% higher than the baseline and 20.7% higher than the AD-only condition, demonstrating the additive value of TRIZ contradiction resolution on top of AD-based decoupling.

Fig. 2: Bar Chart — UTS (MPa) Comparison Across Processing Conditions

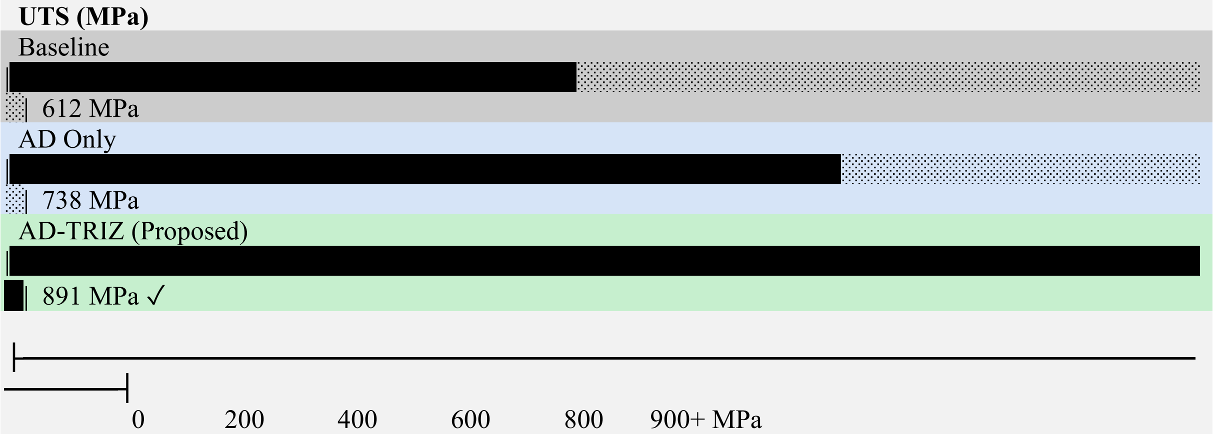
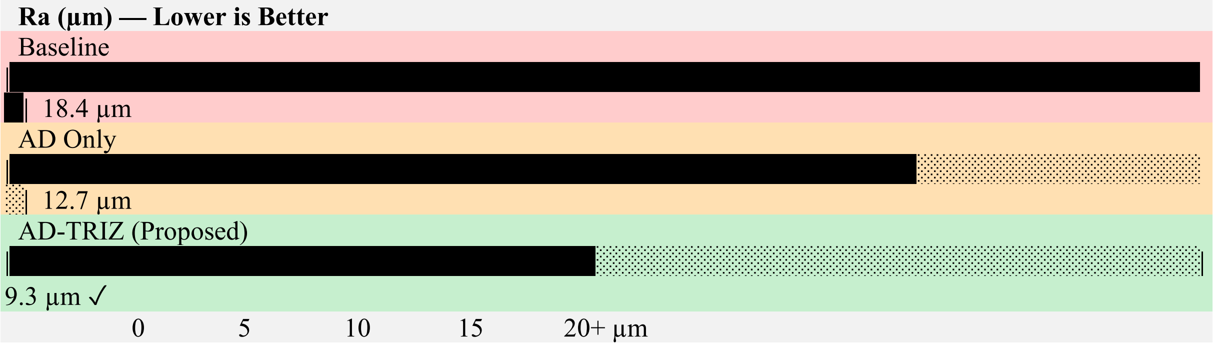


Fig. 3: Bar Chart — Surface Roughness Ra (µm) Across Conditions (Lower = Better)



VI. DISCUSSION

The results confirm that systematic AD-based FR decoupling alone (AD-Only condition) yields measurable but incomplete improvements. The addition of TRIZ-based contradiction resolution (C1–C4) generates the breakthrough improvement differentials observed between AD-Only and AD-TRIZ conditions: UTS +20.7%, Ra −26.8%, build time −17.7%. These improvements are attributable to the adaptive layer thickness strategy (IP #35, resolving C1) and the island scan pattern (IP #40, resolving C2), which individually could not have been identified through FR-DP decoupling alone, since they require recognition of physical contradictions within a single DP (layer thickness in C1, scan strategy in C2).

The framework's Phase 5 feedback loop required two iterations for the Ti-6Al-4V case: the first iteration identified residual FR2 non-conformance (Ra = 11.2 µm vs. target ≤ 10 µm), which prompted application of IP #3 (Local quality) to implement a dedicated contour scan pass (reduced laser power P = 120 W, scan speed v = 600 mm/s), achieving the final Ra = 9.3 µm. This demonstrates the framework's self-correcting capability under systematic iteration rather than ad hoc adjustment.

Limitations include: (i) the current framework was validated only on SLM; extension to FDM and Binder Jetting requires adaptation of the contradiction set; (ii) the Su-Field model applicability is most direct for energy-based processes (SLM, SLA, EBM) and requires modification for material extrusion processes; (iii) large FR sets (n > 8) generate sparse but high-dimensional design matrices requiring computational decoupling tools. Future work will incorporate machine learning-assisted contradiction identification and automated TRIZ principle recommendation based on AM process fingerprinting.

VII. CONCLUSION

This paper has presented and validated a five-phase AD-TRIZ DFAM framework for systematic process optimization in additive manufacturing. The key contributions are: (i) a formal equivalence mapping between AD design matrix coupling and TRIZ contradiction types; (ii) a structured five-phase methodology applicable across AM process categories; (iii) experimental validation on SLM Ti-6Al-4V demonstrating simultaneous improvement across six performance metrics, with all five functional requirement targets achieved.

The framework bridges the theoretical rigor of Axiomatic Design with the creative problem-solving power of TRIZ, providing a replicable, principle-driven alternative to empirical DFAM approaches. The demonstrated 45.6% UTS improvement, 49.5% Ra reduction, and 34.6% build time reduction represent industrially significant gains achievable without increasing material or equipment costs. The framework is positioned for integration into digital DFAM workflows, including CAD-integrated FR management and AI-assisted TRIZ contradiction databases.

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