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Topology Optimized Design for Additive Manufacturing

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Abstract: *Additive manufacturing (AM) has evolved into a disruptive technology enabling the production of lightweight,complex, and customized components across aerospace, automotive, biomedical, and energy industries. Conventional manufacturing often limits structural optimization due to tooling and geometric restrictions, whereas AM offers unprecedented design freedom. Among the strategies for lightweighting, topology optimization (TO) has emerged as a superior method compared to lattice structuring, as it systematically distributes material in accordance with applied loads and constraints. This paper presents a comprehensive study on topology-optimized design for AM, highlighting recent advances up to 2025. The discussion covers the classification of AM processes, their suitability for topology-optimized designs, and the role of support structures in manufacturability. Emerging trends such as space–time topology optimization, AI-assisted algorithms, hybrid lattice-TO approaches, and multi-scale optimization are emphasized. Applications in aerospace brackets, automotive suspension systems, orthopaedic implants, and energy-efficient heat exchangers are reviewed. The findings suggest that topology optimization, when integrated with advanced AM technologies, provides the most effective pathway to achieving lightweight, high-performance, and sustainable designs.*

Keywords*:* Additive Manufacturing, Topology Optimization, Design for AM, Lightweight Structures, Selective Laser Melting, Electron Beam Melting

I. INTRODUCTION

Additive manufacturing (AM), commonly known as three-dimensional (3D) printing, is increasingly recognized as a transformative production technology. Unlike conventional subtractive methods, where material is removed from a solid block, AM builds components layer by layer directly from digital models. This enables the fabrication of complex geometries, internal channels, lattice structures, and topologically optimized parts that are not feasible through traditional processes.

Lightweight design is a critical requirement across industries. In aerospace, reducing mass improves payload efficiency and lowers fuel consumption. In the automotive sector, it enhances energy efficiency and contributes to the transition toward electric mobility. In biomedical applications, lightweight implants improve patient comfort while ensuring biocompatibility and mechanical compatibility with bone. Traditional manufacturing methods impose restrictions on achieving such optimized geometries due to tooling limitations, high costs, and significant material wastage. AM overcomes these barriers by enabling design for additive manufacturing (DfAM), where components are tailored for both performance and manufacturability.

Two primary strategies are used for weight reduction in AM: lattice structuring and topology optimization. Lattice structures rely on repeating cellular patterns to reduce mass while retaining stiffness. They are particularly useful in energy-absorbing applications such as crash structures or biomedical scaffolds. However, lattice designs often suffer from stress concentrations at strut junctions, reduced fatigue life, and increased manufacturability challenges, especially in removing powder from enclosed volumes.

Topology optimization (TO), in contrast, is a computational approach that identifies the most efficient material distribution within a given design space. Methods such as the Solid Isotropic Material with Penalization (SIMP), Evolutionary Structural Optimization (ESO/BESO), and Level-Set Methods (LSM) have been successfully applied to generate non-intuitive, organic shapes optimized for stiffness-to-weight ratio. With the increasing computational capabilities and integration of AI-based solvers in 2025, TO has become faster, more accurate, and more compatible with AM-specific constraints such as minimum feature size, overhang angle, and build orientation.

This paper investigates the suitability of topology-optimized design for additive manufacturing, extending the comparative foundation provided in earlier research. It reviews the evolution of AM processes, materials, and optimization techniques while incorporating recent developments such as space–time topology optimization for multi-axis AM, sintering-aware optimization for binder jetting, and hybrid lattice-TO methods. Furthermore, applications in aerospace, automotive, biomedical, and energy industries are analysed to demonstrate the impact of TO in real-world scenarios. The paper concludes with a discussion of current challenges and potential future research directions, including multi-scale optimization, real-time adaptive TO, and sustainability considerations.

1. Classification of Additive Manufacturing

Additive manufacturing encompasses a diverse range of technologies that differ in feedstock material, energy source, and resolution capabilities. The International Organization for Standardization (ISO) and ASTM classify AM into seven primary categories: material extrusion, powder bed fusion, vat photopolymerization, binder jetting, directed energy deposition, sheet lamination, and material jetting. Among these, powder bed fusion (PBF) techniques—such as Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), and Electron Beam Melting (EBM)—are most relevant for structural topology optimization due to their ability to produce fully dense metallic components with complex geometries.

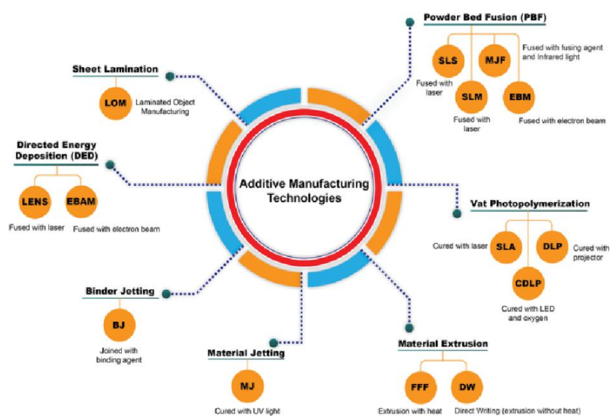

Fig.1. Additive Manufacturing Technologies

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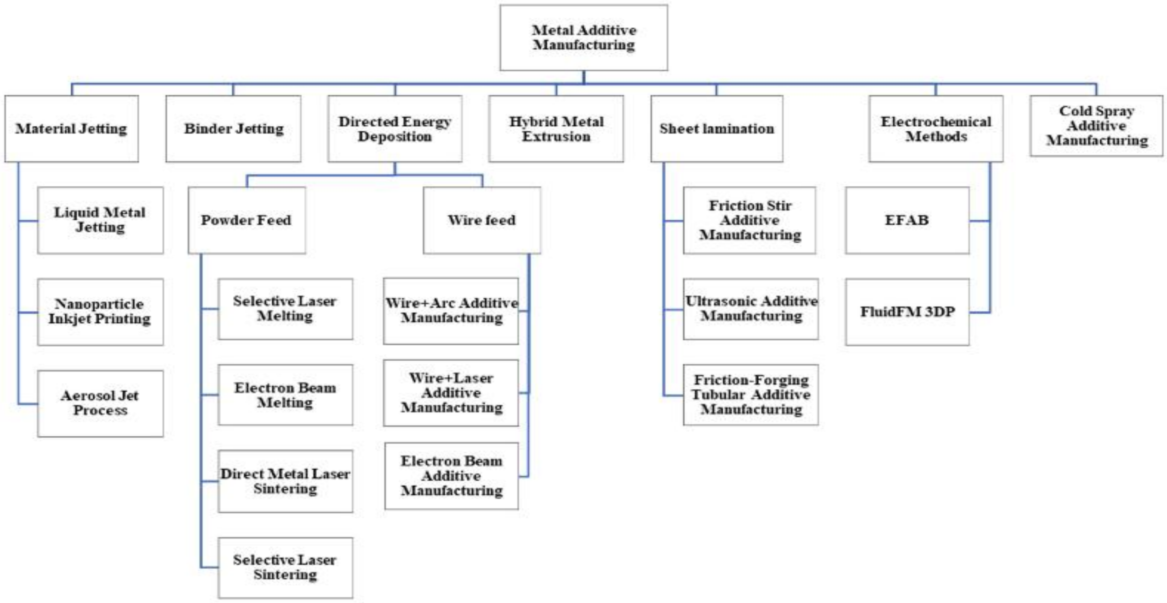

Fig.2. Classification of Additive Manufacturing

1.1. Solid-Based Processes
Material extrusion methods such as Fused Deposition Modeling (FDM) employ thermoplastic filaments (e.g., ABS, PLA, PEEK) extruded layer by layer. While widely used for prototyping and low-load applications, extrusion-based systems have limitations in terms of dimensional accuracy, surface quality, and mechanical strength.

1.2. Powder-Based Processes
Powder bed fusion processes dominate metal AM and remain the preferred choice for topology-optimized components:
- Selective Laser Melting (SLM)
- Direct Metal Laser Sintering (DMLS)
- Electron Beam Melting (EBM)

1.3. Liquid-Based Processes
Vat photopolymerization, particularly Stereolithography (SLA) and Digital Light Processing (DLP), use UV light to cure liquid resins. While these methods are widely used for prototyping, biomedical models, and microfluidics, their application in structural topology optimization is limited due to material brittleness. However, developments in ceramic-loaded photopolymers and toughened resins are expanding their role in functional components.

1.4. Binder Jetting
Binder jetting deposits a liquid binder onto powder layers, followed by curing and sintering. Its key advantages are high build speed and low cost. Traditionally, binder jetting suffered from high shrinkage and porosity during sintering. However, recent research (2024–2025) introduced sintering-aware topology optimization frameworks that incorporate shrinkage models directly into the optimization process, significantly reducing distortion.

1.5. Directed Energy Deposition (DED)
DED involves depositing powder or wire feedstock into a focused energy source (laser, electron beam, or plasma arc). It is particularly suited for repair, refurbishment, and large-scale structural parts. In 2025, DED is being integrated with

hybrid manufacturing systems (additive + CNC machining), enabling near-net-shape fabrication followed by precision finishing.

1.6. Sheet Lamination and Material Jetting

Though less prominent in metal AM, sheet lamination and material jetting serve niche applications. Material jetting enables multi-color and multi-material deposition, useful in biomedical visualization. Sheet lamination, while low-cost, remains limited in mechanical performance.

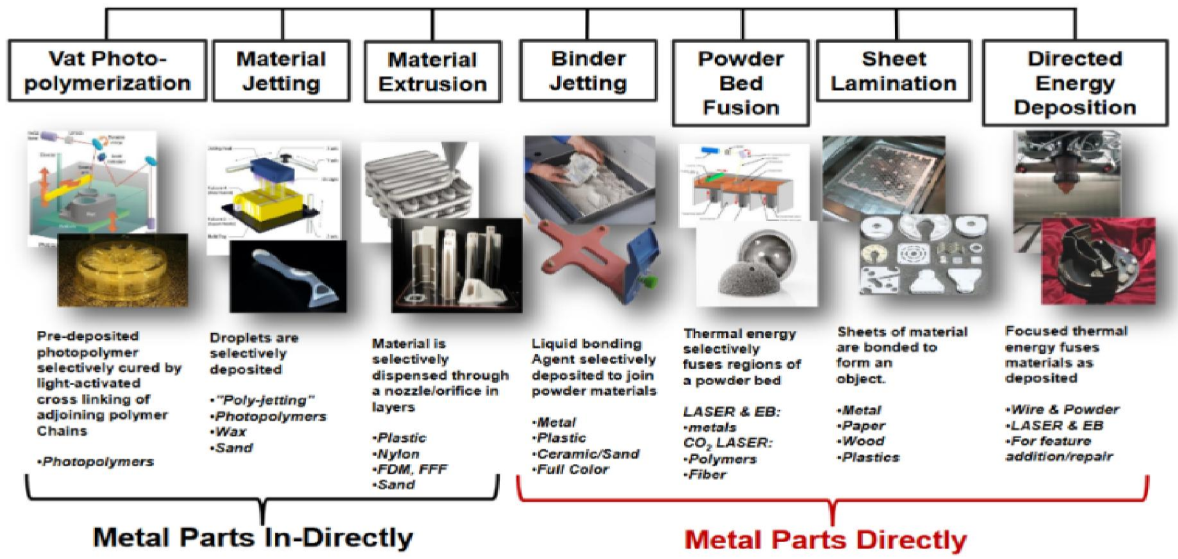

Fig.3. Process with Materials

II. ADDITIVE MANUFACTURING PROCESS CHAIN

The additive manufacturing (AM) process chain consists of sequential stages that transform a digital design into a physical component. Each stage directly influences part quality, cost, and manufacturability. For topology-optimized components, process-chain considerations are particularly important, as optimization often results in non-intuitive geometries that push the limits of AM capabilities.

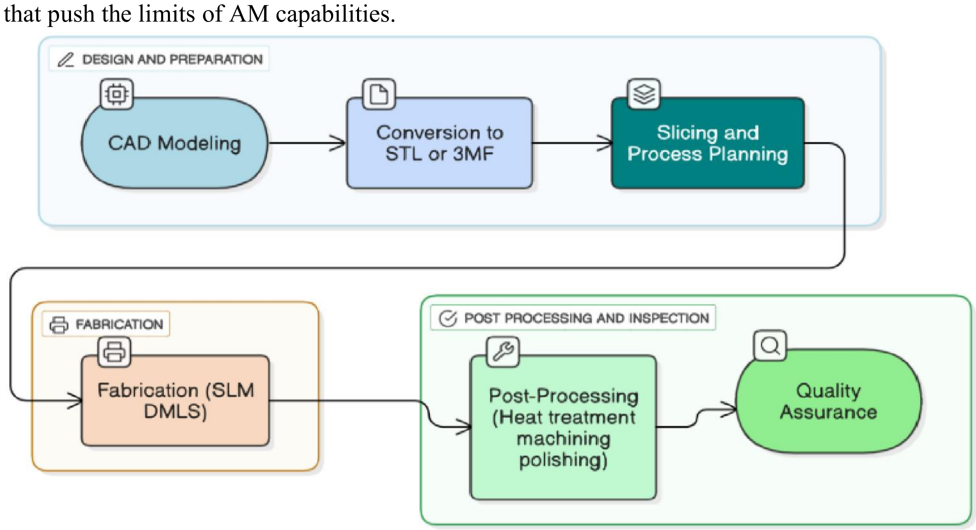

Fig.4. Flow chart of the Pre-Processing to Post- Processing of AM

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2.1. Computer-Aided Design (CAD) Modeling

The process begins with the creation of a CAD model of the component using design software such as Creo, CATIA, or SolidWorks. For topology optimization (TO), the CAD model typically defines the design domain (regions where material can be distributed), the non-design domain (areas reserved for fixtures, holes, or functional requirements), and applied boundary conditions.

2.2. Conversion to STL/AMF

The CAD model is then exported into a neutral file format, most commonly STL (Standard Tessellation Language) or AMF (Additive Manufacturing File). The STL format approximates curved surfaces with triangular facets, while AMF supports richer information such as color, materials, and lattices.

2.3. Slicing and Process Planning

The 3D model is virtually sliced into thin cross-sections corresponding to the layer thickness of the chosen AM process. Toolpaths for lasers, electron beams, or extruders are then generated. Process planning also involves support generation, orientation optimization, and scan strategy definition.

2.4. Fabrication (Additive Manufacturing)

The component is fabricated layer by layer using the selected AM process (SLM, DMLS, EBM, DED, etc.). The success of TO-based designs depends heavily on process reliability, since intricate load paths and thin features must be accurately realized

2.5. Post-Processing

Post-processing is essential for ensuring final quality and functionality. Common steps include:

- Support structure removal (mechanical or chemical).
- Heat treatment to relieve residual stresses.
- Hot isostatic pressing (HIP) to eliminate porosity in metallic parts.
- Surface finishing (machining, polishing, shot-peening, chemical treatments).

2.6. Quality Assurance

The final step ensures that the part meets dimensional, mechanical, and safety requirements. For topology-optimized components, verification is critical since unconventional geometries may exhibit non-standard stress concentrations.

III. MATERIALS IN ADDITIVE MANUFACTURING

The choice of material is a critical factor in additive manufacturing (AM) and directly influences the feasibility of topology-optimized designs. Materials must not only be compatible with the selected AM process but also provide the mechanical, thermal, and chemical properties required by the intended application. Over the past decade, the range of AM-compatible materials has expanded significantly, with metals, polymers, ceramics, and composites now available for industrial-scale use. By 2025, the development of functionally graded materials (FGMs), multi-material deposition systems, and bioresorbable alloys has further expanded the application potential of AM.

3.1. Metallic Materials

Metals remain the primary focus for structural applications in aerospace, automotive, defense, and biomedical industries due to their superior strength, stiffness, and fatigue resistance. Powder bed fusion (PBF) processes such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM) dominate metal AM.

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3.2. Polymeric Materials

Polymers are widely used in extrusion-based and vat photopolymerization processes due to their affordability and design flexibility. While mechanical strength is lower than metals, polymers are valuable for prototyping, tooling, and lightweight functional parts.

3.3. Ceramic Materials

Ceramics are valued for their hardness, wear resistance, and high-temperature performance, but their brittleness poses challenges in AM. Typical applications include biomedical implants (dental, bone scaffolds), aerospace thermal barriers, and electronics.

3.4. Composite Materials

Composites combine polymers, metals, or ceramics with reinforcing fibers or particles to achieve superior properties. Additive manufacturing enables the controlled placement of reinforcements, allowing tailored mechanical performance.

3.5. Emerging Trends in 2025

- Functionally Graded Materials (FGMs): Smooth transitions between metals, polymers, and ceramics for performance optimization.
- Multi-material topology optimization: Allowing simultaneous optimization of material distribution and material type.
- Bioinspired materials: Mimicking bone or nacre structures for toughness and lightweight performance.
- Sustainability-oriented materials: Powders and polymers designed for recyclability and reduced carbon footprint.

IV. METAL AM TECHNOLOGIES FOR TOPOLOGY OPTIMIZATION

For topology-optimized (TO) components to transition from simulation to production, the selected additive manufacturing (AM) process must support the resulting complex geometries. Among the various AM techniques, powder bed fusion (PBF) methods remain the most suitable for structural TO parts, as they offer excellent dimensional control and high-performance mechanical properties. The three dominant PBF technologies are Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM). Each has unique benefits and trade-offs that must be considered when applying TO in aerospace, automotive, biomedical, and energy applications.

4.1. Direct Metal Laser Sintering (DMLS)

DMLS uses a high-power laser to selectively fuse regions of a metallic powder bed. The process works with a wide variety of alloys, including stainless steels, cobalt-chrome, titanium alloys, and tool steels.

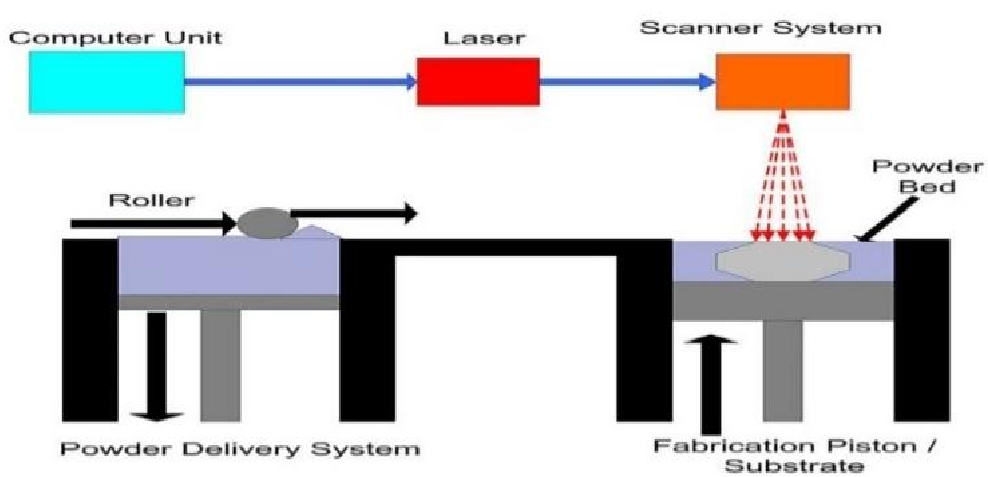

Fig.6. DMLS

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Advantages:
• Excellent dimensional accuracy (~±50 µm).
• Broad material compatibility.
• Good for medium-complexity TO designs.

Limitations:
• Residual stress formation due to high thermal gradients.
• Support removal can be costly for overhang-rich TO geometries.

4.2. Selective Laser Melting (SLM)

SLM is closely related to DMLS but achieves complete melting of the powder, producing fully dense metallic parts with properties close to wrought materials. It is particularly suited for aerospace and biomedical TO parts where strength and fatigue life are critical.

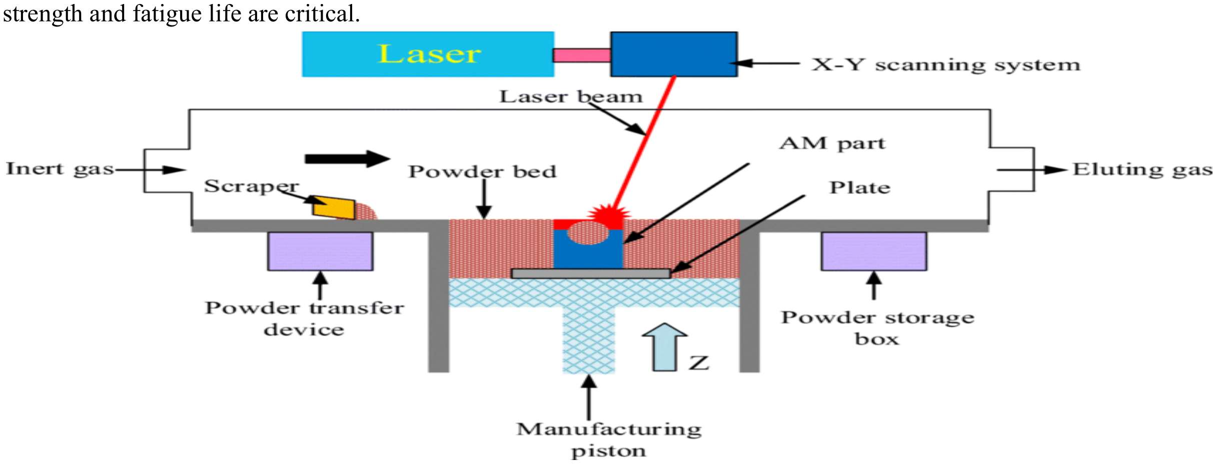

Fig.7. SLM

Advantages:
• Produces near-wrought mechanical properties.
• Fine feature resolution (down to ~30–50 µm).
• Well-suited for complex TO geometries with thin ribs and webs.

Limitations:
• Requires strict environmental control (inert gas).
• Build speed lower than EBM for large components.
• High dependence on support structures.

4.3. Electron Beam Melting (EBM)

EBM employs an electron beam under vacuum to melt metallic powders. It is particularly effective for titanium alloys and widely used in orthopedic implants and aerospace structures.

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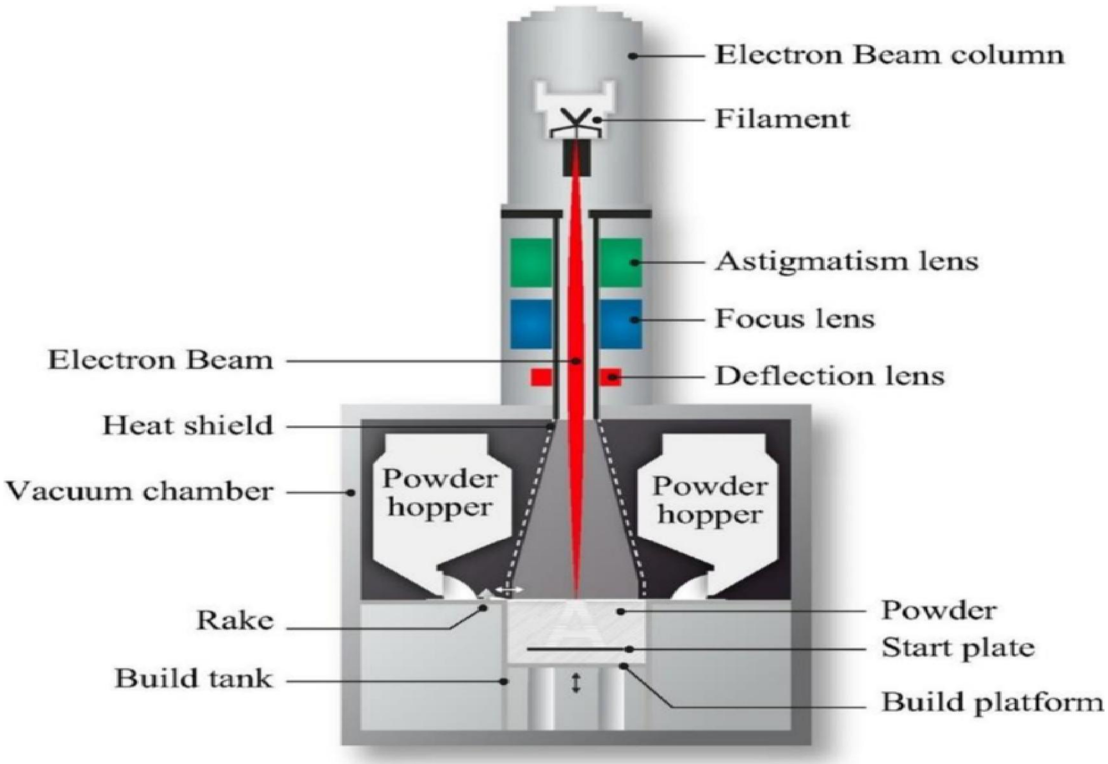

Fig.8. EBM

Advantages:
• High build rates due to elevated powder bed temperature.
• Lower residual stresses compared to laser-based methods.
• Vacuum environment prevents oxidation (ideal for Ti and Ni alloys).

Limitations:
• Surface finish rougher (~±100 µm).
• Limited range of commercially available alloys compared to SLM/DMLS.
• Higher machine and operating costs.

4.4. Comparative Evaluation (2025 perspective)

Parameter	DMLS (2025)	SLM (2025)	EBM (2025)
Feature resolution	~50 µm	~30–50 µm	~80–100 µm
Build speed	Medium	Medium	High
Surface finish	Smooth	Smooth	Rougher
Residual stress	High	High	Low
Material range	Broad	Broad	Limited
Best for TO parts	General-use TO	High-strength TO (aerospace, medical)	Large Ti-alloy TO components

Table.1. Comparison of DMMLS, SLM & EBM

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V. TOPOLOGY OPTIMIZATION FOR ADDITIVE MANUFACTURING

5.1. Fundamentals of Topology Optimization

Topology Optimization (TO) is a computational method that determines the most efficient material layout within a defined design space, subject to given loads, boundary conditions, and constraints. Unlike size or shape optimization, which modify predefined geometries, TO creates entirely new structures by removing inefficient material and reinforcing critical load paths.

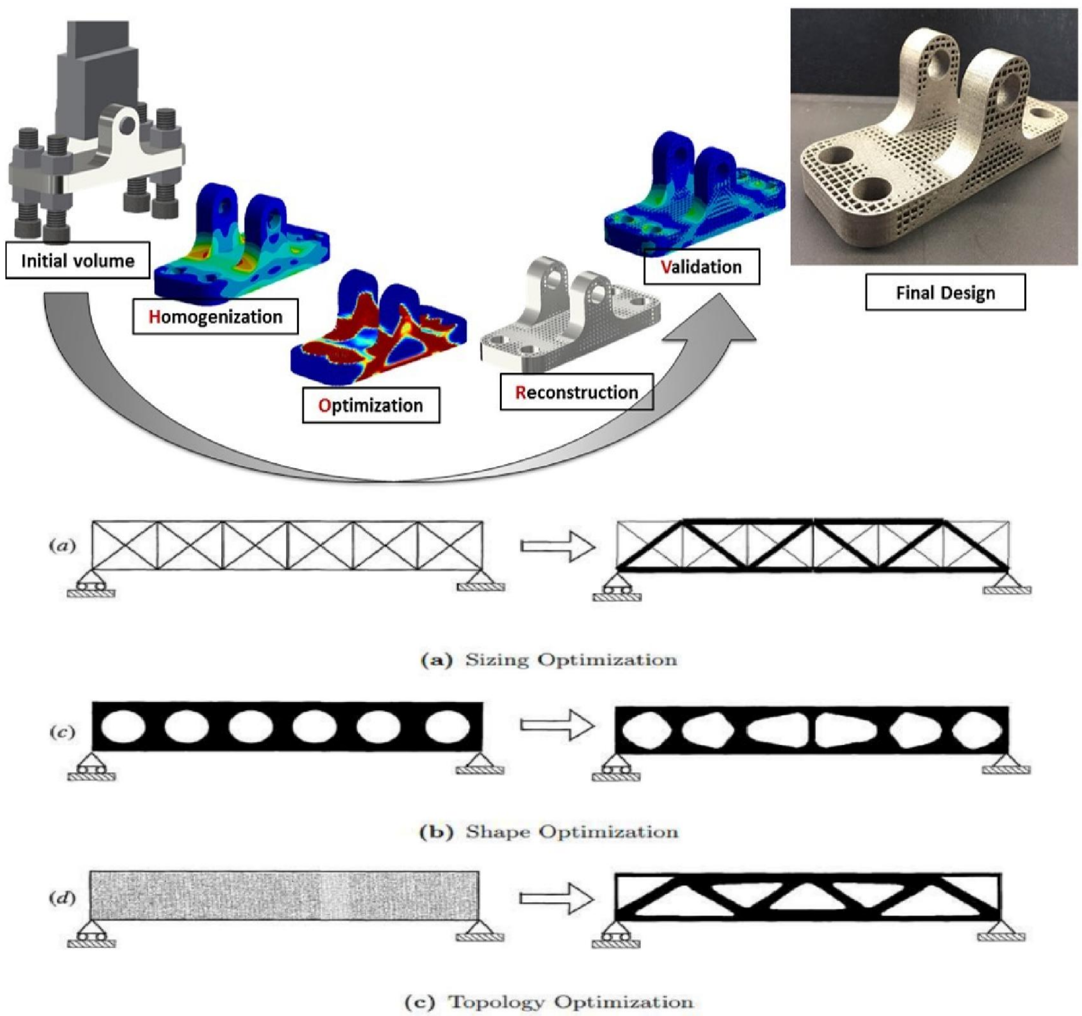

Fig.9. Topology Optimization for Additive Manufacturing

Objective functions commonly used in TO:

- Compliance minimization (maximize stiffness for given volume).
- Mass minimization with strength constraints.
- Frequency maximization (for vibration-sensitive components).
- Multi-physics optimization (thermal + structural).

Constraints:

- Volume fraction.
- Stress or strain limits.

• Manufacturability restrictions (minimum wall thickness, overhang angle, build orientation).

This makes TO an ideal partner for Additive Manufacturing (AM), which can fabricate organic, non-intuitive geometries that conventional processes cannot.

5.2. Classical TO Methods

1. SIMP (Solid Isotropic Material with Penalization):

o The most widely used density-based method.
o Represents material distribution as density values between 0 (void) and 1 (solid).
o Penalization drives intermediate densities toward discrete solid/void states.
o Advantage: Robust, compatible with commercial software (ANSYS, Abaqus, Altair OptiStruct).

2. ESO/BESO (Evolutionary Structural Optimization):

o Iteratively removes low-stress elements and adds material where needed.
o Easy to implement but less efficient for large-scale 3D models.

3. Level-Set Methods (LSM):

o Represent geometry boundaries implicitly with a mathematical level-set function.
o Enable smooth boundaries and direct manufacturability constraints.
o Useful for producing printable TO geometries without extensive post-processing.

4. MMC (Moving Morphable Components):

o Represents geometry as a set of deformable components.
o Allows direct control of feature sizes and manufacturability.
o Emerging method with strong potential for AM applications.

5.3. Recent Advances in TO (2025 Perspective)

• AI-Assisted Topology Optimization:

Machine learning accelerates TO by predicting optimal layouts without full iterative solvers. Neural networks trained on prior TO datasets now provide near-instant initial designs, reducing computational cost by >50%.

• Space–Time TO:

New frameworks account for the build sequence in AM, optimizing not just the final geometry but also intermediate stability during fabrication. This reduces build failures in overhang-heavy TO parts.

• Hybrid TO-Lattice Structures:

TO identifies global load paths, while lattice infill provides local energy absorption and weight reduction. This hybrid approach is gaining traction in crashworthy automotive components and biomedical implants.

• Multi-Scale TO:

Integrates macroscale optimization (overall shape) with microscale optimization (lattice or microstructures). In 2025, commercial software can now run coupled optimizations, enabling hierarchical designs.

• Multi-Physics TO:

Expands beyond structural optimization to include thermal conductivity, fluid flow, and acoustic performance, critical for heat exchangers and aerospace propulsion systems.

5.4. Case Applications of TO in AM

- Aerospace: Satellite brackets, jet engine supports, and turbine blades optimized for maximum stiffness-to-weight ratio. Airbus and NASA reported weight savings up to 45% using TO+AM compared to machined parts.
- Automotive: TO used in suspension nodes and EV battery enclosures, yielding lighter designs with reduced vibration sensitivity.
- Biomedical: Patient-specific implants (hip cups, cranial plates) optimized for both strength and bone ingrowth. Hybrid TO-lattice scaffolds match bone stiffness, improving osseointegration.

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- Energy Systems: Heat exchangers with TO-driven internal channels demonstrate 30–40% higher thermal efficiency due to optimized fluid flow paths.

4.5. Challenges in TO for AM

Despite advances, TO-AM integration faces hurdles:

- Geometry reconstruction: Raw TO results often contain voxel artifacts that require smoothing for manufacturability.
- Support structure dependency: Many TO geometries create overhangs that increase build cost.
- Computational intensity: Large 3D TO models can still require high-performance computing resources.
- Certification issues: TO-generated geometries are unconventional, complicating standard certification and inspection procedures.

VI. SUPPORT STRUCTURES AND DESIGN FOR AM

6.1. Role of Support Structures

In powder bed fusion (PBF) processes such as DMLS, SLM, and EBM, support structures are often required to:

• Anchor overhanging features and prevent collapse.
• Conduct heat away during laser/e-beam exposure to reduce warping.
• Counteract residual stresses caused by rapid thermal cycling.
• Define datum surfaces for dimensional stability.

For topology-optimized (TO) geometries, which often generate organic shapes with thin branches and inclined members, support design becomes a critical determinant of manufacturability and cost.

6.2. Economic Impact of Supports

Supports directly affect the time, material, and post-processing costs of an AM build. The reference work highlighted that support removal can contribute 40–70% of total production cost in certain AM workflows.

• Material cost: Support consumes the same high-value metal powder as the final part.
• Build time cost: Laser/e-beam scan time increases with support volume.
• Post-processing cost: Removal requires machining, EDM, or manual finishing, often labor-intensive.
• Surface finish impact: Contact regions between supports and the part require re-machining or polishing.

6.3. Design-for-AM (DfAM) Strategies for Reducing Supports

Orientation optimization:
• Orienting the part to minimize unsupported overhangs (<45° from horizontal is a typical guideline).
• Aligning critical load paths with the build direction for enhanced strength.
Topology Optimization with Overhang Constraints:
• Modern TO algorithms incorporate minimum overhang angle filters to suppress geometries that would otherwise require excessive supports.
• For example, a rib or web can be reoriented during optimization to remain self-supporting.
Feature size control:
• Enforcing minimum wall thickness ensures that slender TO features are printable and not prone to distortion.
Support-friendly lattice infill:
• Lattices can be designed as self-supporting architectures (e.g., gyroids, TPMS) that reduce or eliminate the need for external support.

6.4. Advances in Support Structures (2025 Perspective)

• AI-driven support prediction:

Machine learning algorithms now analyze CAD/TO results and automatically generate minimum support strategies, balancing cost, printability, and post-processing effort.

• Self-supporting TO:
2025 software integrates self-support constraints directly into topology optimization, enabling "support-free" optimized structures. This is increasingly applied in aerospace brackets where post-processing cost is high.

• Dissolvable and breakaway supports:
Multi-material AM systems can print supports in a different material (e.g., low-melting alloys or soluble polymers), reducing post-processing complexity.

• Functionally graded supports:
Instead of uniform solid supports, graded-density supports are now used. They provide mechanical stability during printing but are easier to remove afterward.

• Integrated support recycling:
Support structures are increasingly designed to be reusable or recyclable, aligning with sustainability goals in AM.

6.5. Case Examples of Support Challenges in TO

• Aerospace TO bracket: Support volume exceeded 60% of part mass when printed without orientation optimization. Redesign with overhang-aware TO reduced supports by 45%, saving ~20% total cost.

• Biomedical hip cup: Organic TO geometry generated deep cavities requiring inaccessible support removal. A hybrid TO + lattice infill design was adopted to achieve self-support.

• Automotive suspension node: Large inclined ribs from TO created stress risers after manual support removal. Incorporating build orientation constraints during TO eliminated this issue.

VII. ADDITIVE MANUFACTURING PROCESS SELECTION FOR TO

The performance of a topology-optimized (TO) design is only as good as the process that fabricates it. While TO can deliver innovative geometries, process choice determines whether the design is feasible, reliable, and cost-effective. For metal TO components, the main contenders remain DMLS, SLM, and EBM, each with trade-offs in terms of resolution, build volume, and economics.

7.1. Process Selection Criteria

The following factors must be considered when selecting an AM process for TO parts:

1. Geometric Resolution and Feature Size
• TO often creates thin ribs, fillets, and organic webs.
• SLM provides the highest resolution (~30–50 µm features), while EBM is limited to coarser features (~80–100 µm).
• If fine details are essential, SLM/DMLS is preferred.

2. Residual Stress and Distortion
• SLM/DMLS introduce high residual stresses due to localized laser heating, requiring stress-relief heat treatment.
• EBM, with elevated powder-bed temperatures, naturally reduces residual stresses, making it advantageous for large, load-bearing TO parts.

3. Surface Finish
• SLM/DMLS produce smoother surfaces, reducing post-processing burden.
• EBM requires additional machining for functional surfaces due to rougher as-built finish.

4. Build Speed and Productivity
• EBM typically achieves faster build rates for bulk titanium parts due to higher energy input.
• 2025 multi-laser SLM/DMLS systems significantly narrowed the productivity gap by enabling parallel scanning.

5. Material Range
• SLM/DMLS: Broad alloy compatibility (aluminum, steel, titanium, Inconel).
• EBM: Primarily titanium and cobalt-chrome alloys, but excellent for high-value biomedical and aerospace parts.

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6. Cost and Sustainability
• EBM: Higher machine cost, but reduced support structures lower post-processing expenses.
• SLM/DMLS: Lower machine cost but higher support volume can inflate overall part cost.
• 2025 trend: AI-driven orientation optimization and powder recycling programs reduce costs and carbon footprint across both laser- and electron-based PBF.

7.2. Updated 2025 Decision Framework

Criterion	DMLS (2025)	SLM (2025)	EBM (2025)
Resolution	Medium (~50 µm)	High (~30–50 µm)	Lower (~80–100 µm)
Residual Stress	High	High	Low
Surface Finish	Good	Very Good	Rougher
Material Range	Broad	Broad	Narrow (Ti, CoCr)
Sustainability (2025)	Medium (powder reuse)	High (AI+ recycling)	High (low support use)
Best Applications	General TO components	High-precision TO parts	Large TO Ti-alloy parts

Table 2. Process Selection Guide for TO Components

VIII. APPLICATIONS OF TO IN ADDITIVE MANUFACTURING

8.1. Aerospace Applications

The aerospace industry is one of the earliest adopters of topology optimization (TO) in additive manufacturing (AM), due to its relentless drive for weight reduction, fuel efficiency, and structural reliability.

• Satellite Brackets & Mounting Structures
Airbus and ESA have demonstrated TO-enabled titanium satellite brackets with 40–50% weight reduction, now commonly fabricated by SLM. The reduced mass directly lowers launch costs, while AM enables integrated cable routing.

• Engine Components
Jet engine housings and turbine brackets optimized by TO have achieved 25% higher stiffness-to-weight ratios. In 2025, hybrid AM systems are printing large-scale TO parts with integrated cooling passages, a step toward full-scale optimized propulsion systems.

• Airframe Joints
TO-designed wing ribs and fuselage joints, previously machined from billet, are now additively manufactured with EBM in Ti-6Al-4V, offering reduced residual stress and faster builds.

8.2. Automotive Applications

Automotive design increasingly leverages TO for lightweighting, crashworthiness, and electric vehicle (EV) efficiency.

• Suspension and Chassis Nodes
TO-AM has reduced the weight of suspension arms and chassis joints by 20–30% without compromising crash safety. By 2025, AI-driven TO tools are standard in motorsport and luxury vehicle design workflows.

• Battery Housings for EVs
TO-optimized battery enclosures now integrate structural stiffness, crash energy absorption, and thermal management, providing multifunctional performance in a single AM-built unit.

• Motorsport Components
Formula E and F1 teams use TO+SLM for ultra-lightweight brackets and heat exchangers, where lead time reduction is as critical as performance.

IX. DISCUSSION

9.1. TO vs. Lattice Structures

Both topology optimization (TO) and lattice structuring are strategies to reduce mass while maintaining performance, but they serve different roles:

• Topology Optimization (TO):

o Excels in defining global load paths, removing inefficient material while maintaining structural integrity.

o Produces near-solid optimized frameworks that are stiff, strong, and load-bearing.

o Best suited for aerospace brackets, automotive joints, and biomedical implants requiring structural reliability.

• Lattice Structures:

o More effective for local performance tuning, such as energy absorption, damping, or promoting bone ingrowth.

o Tend to suffer from stress concentrations at lattice junctions and reduced fatigue strength compared to.

o Best applied in non-critical or semi-structural regions (e.g., energy absorbers, lightweight cores, biomedical scaffolds).

2025 perspective: The consensus is shifting toward hybrid approaches, where TO defines the global framework, while lattices are selectively applied in non-critical or multifunctional regions (thermal management, biological integration, crash energy absorption).

9.2. Future Outlook (Beyond 2025)

1. Hybrid TO-Lattice Design: Global TO + local lattice will become the standard workflow for high-performance lightweighting.
2. AI-Driven TO: Deep learning models will allow near-instant TO predictions, enabling real-time design iteration during CAD modeling.
3. Multi-Material TO: Functionally graded materials (FGMs) will enable seamless transitions between metals, polymers, and ceramics, tailored to local loading.
4. Generative Design Integration: CAD tools will embed TO, lattices, and manufacturability checks natively, reducing the current workflow gap.
5. Space–Time TO: Optimization will consider not just the final geometry but also intermediate stability during the AM build process, reducing failures.
6. Digital Twin Certification: Regulatory pathways will increasingly accept digital twin models of TO-AM parts as evidence of reliability.

X. CONCLUSION

In this paper, we provided a comprehensive evaluation of topology optimization (TO) and lattice structures, highlighting their respective strengths, limitations, and practical considerations. TO offers remarkable design flexibility and material efficiency, while lattice structures enhance mechanical performance and lightweighting. However, both approaches face challenges in manufacturability, certification, and sustainability. Our comparative analysis shows that integrating TO and lattice strategies can deliver synergistic benefits, but careful attention to trade-offs, regulatory compliance, and environmental impact is essential.

The key contributions of this study include a balanced assessment of TO and lattices, identification of critical challenges, and a forward-looking roadmap for future adoption. Moving forward, research and industry efforts should focus on standardization, sustainable design practices, and hybrid TO-lattice approaches to maximize performance while minimizing cost and environmental footprint. Overall, the integration of these advanced design strategies holds significant potential to drive innovation and efficiency in [your field], paving the way for more resilient, sustainable, and high-performance solutions.

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