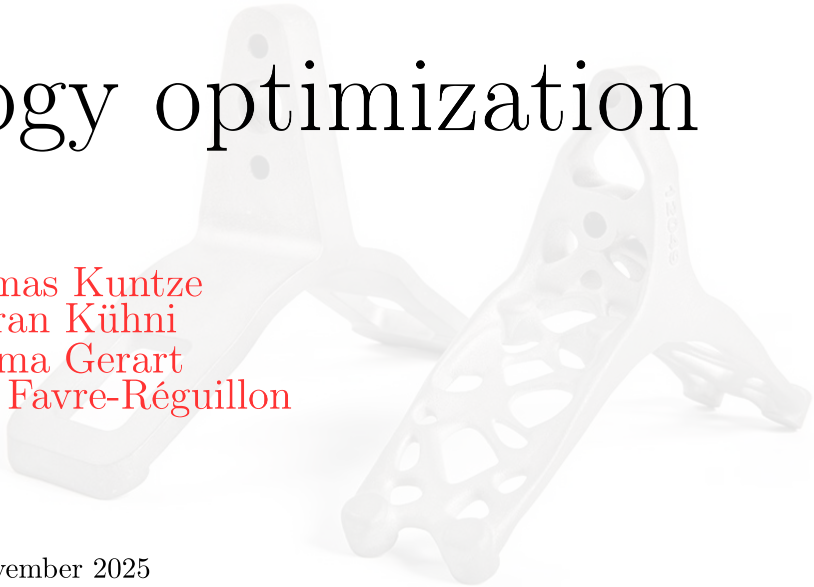
DFAM topology optimization



Thomas Kuntze
Cyran Kühni
Emma Gerart
Mathélyo Favre-Réguillon

November 2025

Contents

Page

Author contributions:

Thomas Kuntze: Section 3 and section 4

Cyran Kühni: Section 7 and section 8

Emma Gerart : Section 2 and section 6

Mathélyo Favre-Réguillon: Section 1 and section 5

1

Introduction

Additive Manufacturing (AM) has and is redefining how engineers conceive, design, and produce parts. By enabling the fabrication of intricate geometries and lightweight structures that were previously unachievable through conventional manufacturing methods, AM has become a key innovation across various industries. As noted by Zhu *et al.*[1] :

> "Additive manufacturing allows engineers to fabricate parts with unprecedented geometric complexity and functional integration, which offers tremendous potential for lightweight design and performance optimisation."

However, the true potential of AM can only be realised when the design process itself is adapted to the specific opportunities and constraints of additive technologies. This mindset is known as **Design for Additive Manufacturing (DfAM)**.

DfAM aims to exploit the unique capabilities of AM including geometric freedom, part consolidation, and customisation; while addressing challenges such as build orientation, support generation, and material anisotropy. It encourages designers to move beyond the traditional "design-to-manufacture" and instead to a "design-to-function" as it is represented in figure 1.1. In practice, this involves integrating process parameters and material behaviour directly into the design stage to achieve parts that are both high-performing and manufacturable.

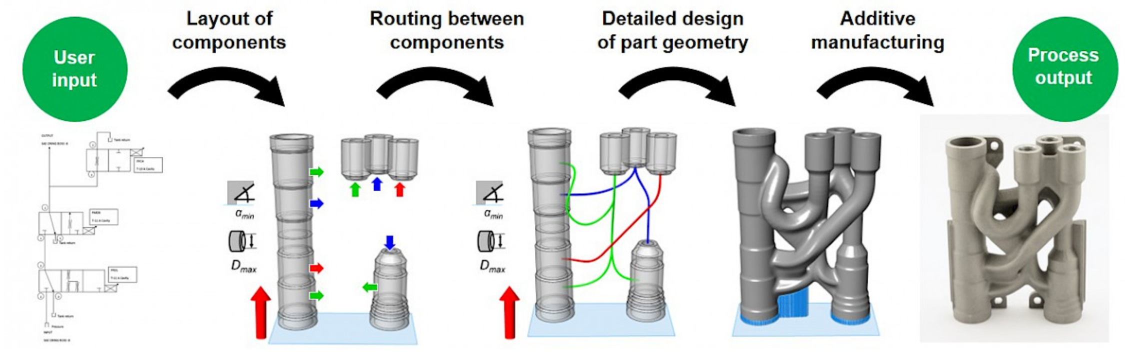


Figure 1.1: Illustration of the Design for Additive Manufacturing process[2].

Within this design framework, **topology optimisation (TO)** has emerged as one of the most powerful computational tools for generating robust structures that minimise material usage while maintaining required mechanical performance. The synergy between DfAM and TO enables the creation of parts that are not only optimised in terms of weight and stiffness but also tailored for additive production constraints. Yet, despite this promising combination, the integration of TO into DfAM workflows still faces numerous challenges, that you'll discover all along this document.

The objective of this literature review is therefore to investigate the role of TO within the broader context of Design for Additive Manufacturing, by analysing recent research developments, methods, and applications. The review seeks to identify the benefits and limitations of current approaches, explore how TO can be effectively implemented in AM environments, and highlight future perspectives relevant to lightweight structural design, with particular interest in applications such as the EPFL Racing Team's mechanical components.

2

Design for Additive Manufacturing

Design for Additive Manufacturing is a methodology aimed at exploiting the unique capabilities of AM processes while accounting for their specific limitations. As highlighted by Diegel et al.[3], AM does not eliminate manufacturing constraints; rather, it transforms them. Consequently, DfAM seeks not only to ensure printability, but to redesign parts so that they gain performance, functionality, or manufacturability benefits that would be unachievable with conventional processes.

2.1 Creating Value Through Additive Manufacturing

A central concept in DfAM is the distinction between *direct part replacement*, *adaptation for AM*, and *true design for AM*. Diegel et al.[3] insist that AM generates value only when the designer fully rethinks the geometry to exploit the freedom offered by the process.

This contrast is illustrated by the manifold example from Renishaw (Fig. 2.1), where a traditionally machined component is first directly reproduced using AM, then adapted, and finally redesigned specifically for additive manufacturing. The comparison highlights the dramatic differences in mass, performance, and functional integration that occur when transitioning from "printing the existing part" to "designing the part for AM."

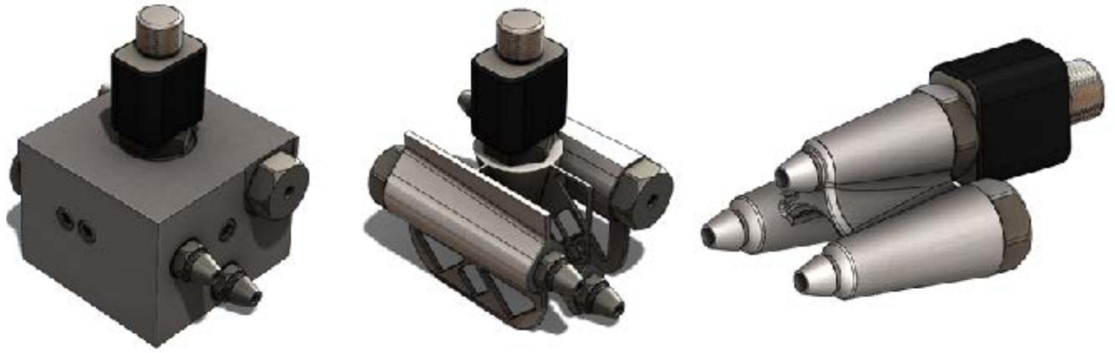


Figure 2.1: Design approaches for manifold: direct replacement, adaptation for AM, and full AM-oriented redesign. Courtesy of Marc Saunders, Renishaw. Reproduced from Diegel et al.[3].

This transition from direct replacement to AM-optimised geometry provides:

- a reduction from 4.6 kg to 1.0 kg when simply adapting for AM (78% weight reduction),
- a further reduction to 0.4 kg when fully redesigning the part (91% reduction),
- improved internal flow paths,
- reduced envelope size and easier assembly.

This example demonstrates that AM becomes strategically relevant when it enables weight reduction, part consolidation, internal features, or performance improvements that cannot be achieved with subtractive manufacturing.

2.2 Fundamental Design Principles

Chapter 3 of Diegel et al.[3] introduces seven core design rules that structure the DfAM workflow.

The first principle is to minimise the need for support structures. Supports increase material consumption, build time, surface finishing effort, and thermal distortion risks. Designing self-supporting geometries or choosing a suitable build orientation helps mitigate these drawbacks.

The second principle concerns build orientation. Orientation simultaneously affects the amount of support material, mechanical anisotropy, surface roughness, and process stability. Thus, orientation must be selected through a compromise between mechanical performance and manufacturability.

A third principle aims to reduce post-processing. Although AM enables high geometric freedom, certain surfaces must remain accessible for machining, polishing, or powder removal. Ignoring these requirements can significantly complicate finishing operations.

A fourth principle is to reduce build time. Build height along the Z-axis is a dominant factor: taller parts require more layers, thus increasing fabrication time. Heavy mass accumulations, dense infill regions, and unnecessary solid volumes likewise extend the build duration. Lower overall height and lightweight design strategies therefore contribute to cost efficiency.

Further rules address material usage and geometric quality. Sharp transitions, thick sections, and non-optimised reinforcements may introduce thermal deformation or stress concentrations. Once key manufacturing constraints are controlled, designers should take advantage of AM-specific opportunities by integrating lattice structures, topology-optimised shapes, or multi-functional features.

2.3 Managing Anisotropy and Mechanical Behaviour

A central point highlighted by Diegel et al.[3] is that all AM processes exhibit inherent anisotropy. Layer-by-layer fabrication typically results in weaker inter-layer bonding, making the direction perpendicular to the layers the most critical mechanically. Designers therefore need to align principal load directions with the strongest material axes, or otherwise compensate through geometry or material selection.

This consideration must be included from the earliest design stages, as it affects both performance targets and orientation decisions.

2.4 Economic Considerations in Design for Additive Manufacturing

Economic performance is integral to the DfAM workflow. Several time-dependent stages of the AM process (heating, cooling, powder handling) are independent of the design. However, the design strongly influences:

- laser scanning time or deposition time,
- the total volume of supports,
- the quantity of melted material,
- the ease of powder evacuation,
- the complexity of post-processing.

Thus, a well-designed AM component reduces build time, material consumption, and finishing requirements without compromising mechanical or functional performance. Diegel et al.[3] underline that “printable” is not synonymous with “optimised”; achieving optimal AM performance requires deliberate design choices.

3

Topology Optimization

Topology Optimization is a computational methodology dedicated to finding the best possible distribution of material within a prescribed design domain in order to maximize structural performance under given constraints. Since the pioneering work of Bendsøe and Kikuchi[4] and its consolidation by Bendsøe and Sigmund[5], TO has become one of the most influential tools in structural mechanics and generative design. With the rise of AM, TO has transitioned from an academic technique to a practical design enabler, as AM technologies can fabricate the complex geometries that arise naturally from TO algorithms. TO is a key way to take full advantage of AM. It helps create lighter parts, combine functions, and explore complex shapes. In modern DfAM workflows, it is used early as a creative tool to generate efficient and innovative designs.

3.1 Topology Optimization within DfAM

The integration of TO within DfAM reflects a strong synergy. TO generates efficient and often non-intuitive structural layouts, while AM enables their fabrication without the geometric constraints typical of machining or casting. TO-driven redesigns commonly achieve mass reductions of 30–60% in aerospace and automotive applications. Beyond lightweighting, TO enables part consolidation and the integration of internal features such as conformal cooling channels, which would be infeasible with traditional processes.

AM therefore turns TO from a purely conceptual tool into something that can be used effectively in practice. Conversely, TO provides a systematic approach to exploit AM's geometric freedoms early in the design process. A design workflow is proposed in which TO, simulation, and AM process planning form an iterative loop.

Manufacturing feedback including distortion prediction, support requirements, or optimal build orientation can be reinjected into the TO formulation, making the workflow cyclic rather than sequential. In this context, TO is not simply an optimisation tool but a generative engine adapted to the constraints and opportunities of AM. To illustrate how iterative refinement or changing optimisation parameters affects the resulting geometry, Fig. 3.1 shows several TO outcomes obtained for the same short cantilever problem but with different minimum length scales. As the filter radius decreases, finer structural features appear and the layout becomes more complex. This reflects how repeated optimisation cycles or relaxed manufacturing constraints can progressively enrich the structural design.

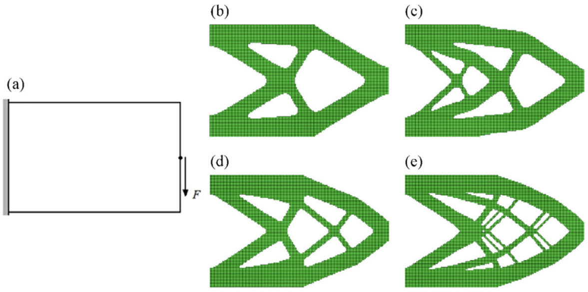


Figure 3.1: Multiple designs of a short cantilever obtained by changing the filter radius $r_{\min}$: (a) load and support conditions; (b) $r_{\min} = 4.5$; (c) $r_{\min} = 3.0$; (d) $r_{\min} = 2.0$; (e) $r_{\min} = 1.0$. From Y. M. Xie[6].

3.2 The TO Design Loop

The classical TO workflow comprises three stages: (1) definition of the optimisation problem, (2) iterative numerical optimisation and (3) geometric interpretation and preparation for manufacturing. In a DfAM context, these steps become more tightly coupled to AM constraints.

Problem definition includes specifying the design domain, loads, material behaviour, objectives and constraints. Industrial-scale TO problems may involve **10^4 to 10^7** degrees of freedom. Non-design regions are often required to accommodate interfaces, fasteners or regions in contact with AM support structures.

During numerical optimisation, the structure is analysed via finite elements and sensitivities are computed typically with adjoint methods that scale independently of the number of design variables[7]. Convergence is typically reached within **50–200 iterations** depending on the penalty scheme, filtering strategies and mesh resolution. Spatial or sensitivity-based filters are commonly employed to enforce minimum feature sizes and suppress numerical artefacts.

Post-processing prepares the raw TO output for AM by smoothing voxelised boundaries, enforcing minimum printable features and reconstructing CAD geometry. Subsequent AM-specific steps include build orientation, support estimation, mesh repair and slicing. These manufacturing considerations motivate the need for manufacturing-aware TO formulations.

3.3 Families of Topology Optimization Algorithms

Different TO algorithms offer distinct advantages in terms of geometric accuracy, numerical robustness and ability to incorporate AM-related constraints. The three families most relevant for DfAM applications are discussed below.

3.3.1 Density-Based Methods (SIMP)

Density-based approaches, and particularly the SIMP (Solid Isotropic Material with Penalization) method, are the dominant topology optimization formulations in both academia and industry. The structure is represented through a continuous density field, enabling efficient gradient-based optimization across large meshes. A key advantage of SIMP for AM is the possibility to enforce geometric regularity via filtering and projection operators, which control minimum feature sizes, eliminate checkerboarding and produce near-binary designs. Directional filters make it possible to integrate AM-specific constraints such as minimum overhang angles[8]. Due to its maturity and flexibility, SIMP is widely implemented in commercial solvers.

3.3.2 Evolutionary Methods (ESO/BESO)

Evolutionary Structural Optimization (ESO) and its bidirectional extension (BESO), introduced by Xie and Steven[10], iteratively remove or add elements based on strain energy criteria. These methods naturally produce crisp void–solid boundaries and are well suited for rapid conceptual exploration.

However, ESO/BESO generally exhibit less geometric regularity than density-based methods and require supplementary smoothing to obtain manufacturable surfaces. Their integration of complex AM constraints is more limited, although recent studies have extended BESO to incorporate directional overhang restrictions. Computational costs are typically higher due to the non-smooth nature of element activation.

3.3.3 Level-Set Methods

Level-set TO represents geometry implicitly via a signed distance function whose zero-level set defines the structural boundary. Boundary evolution is driven by shape sensitivities, yielding smooth and well-defined geometries without the need for projection operators. This makes level-set methods particularly appealing for AM, where surface quality and geometric continuity are critical.

Geometric constraints such as minimum thickness, curvature limits, or overhang conditions can be incorporated directly into the evolution equation, providing a powerful framework for manufacturing aware optimisation. The main drawback is the increased algorithmic complexity, including periodic reinitialisation or remeshing, which makes large-scale implementations more demanding than SIMP-based approaches.

4

Rules and Constraints of TO

Topology Optimization (TO) in a DfAM context requires not only ensuring structural performance but also guaranteeing that the generated geometry can be fabricated reliably using a given additive manufacturing process. Manufacturing constraints need to be included early in the optimisation process. Otherwise, the result may be a design that looks optimal on paper but cannot actually be printed. These constraints shape the design space, influence the convergence of TO algorithms, and ultimately determine the feasibility of the resulting topology.

This chapter reviews the categories of constraints most relevant to DfAM-oriented TO, expanding and refining the structure proposed in the initial document, and incorporating quantitative design rules[3].

4.1 Structural and Mechanical Constraints

Traditional TO problems impose structural constraints to ensure that optimized geometries meet mechanical requirements. These include maximum stress limits, maximum displacements, stiffness thresholds, and natural frequency constraints. Such constraints ensure mechanical safety and are essential when TO is applied to load-bearing components in aerospace, automotive, or tooling applications.

Stress-constrained TO, for example, requires controlling local peak stresses, often handled through aggregation functions or local stress penalization. These structural constraints remain foundational, but in DfAM, they must be complemented by manufacturability constraints that directly affect printability.

4.2 Geometric Constraints

Geometric constraints govern the spatial and morphological characteristics of the optimized topology. They ensure that TO outputs are coherent, mesh-independent, and suitable for downstream processes.

A key geometric constraint is the **minimum feature size**, enforced to avoid fragile thin members that cannot be printed. Morphological filters, density filters and projection functions are commonly used for this purpose[8]. These filters also help prevent checkerboard patterns and isolated elements, improving manufacturability.

Connectivity constraints prevent the creation of isolated volumes or floating elements that would be unprintable. For AM, additional geometric criteria, such as avoiding enclosed voids where powder cannot escape, play a major role and must be treated explicitly in the TO formulation.

4.3 Manufacturing Constraints for Additive Manufacturing

Manufacturing constraints represent the core of DfAM-oriented TO. They capture the fundamental physical and geometric limitations inherent to AM processes. The following subsections integrate quantitative guidelines.

4.3.1 Minimum Printable Feature Size

Minimum wall thickness is one of the most critical AM constraints. In Laser Powder Bed Fusion (PBF-LB/M, 5.3.8), report the following recommended minimums for common alloys[3]:

- Stainless steel: **1.0 mm** recommended (0.3 mm absolute minimum).
- Aluminium: **1.0 mm** recommended.
- Titanium: typically **0.8–1.0 mm**.

Thin, extended unsupported walls are prone to distortion during the melt pool solidification process. Filters and projection operators in TO can enforce these limits directly by guaranteeing a minimum length scale.

These thickness limits also depend strongly on the specific metal AM process, as PBF-LB/M, EBM, and metal binder jetting impose different thermal conditions, powder characteristics, and melt pool behaviours that affect the minimum printable wall thickness.

4.3.2 Overhang Angle Constraints

Overhang angles below a certain threshold require support material in PBF-LB/M. Quantitative limits exist for maximum unsupported overhang angles. (measured from the horizontal) [3]:

- Stainless steel: **60°**
- Titanium: **60°**
- Aluminium: **45°**

As shown in Fig. 4.1, parts remain stable at angles of 50° and 45°, begin to degrade at 40° and 35°, and collapse almost completely at 25° and 20°, illustrating the critical role of overhang angle in determining printability.

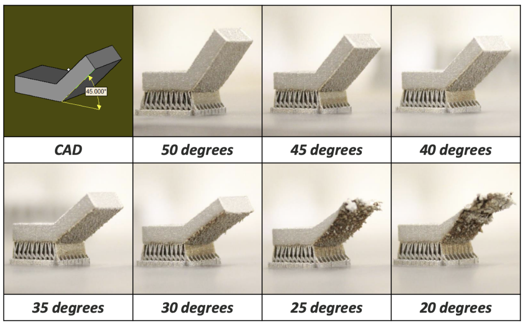


Figure 4.1: Self-supporting angles. Courtesy of David Bentley, Protolabs, *A Deep Dive into Metal 3D Printing*[9].

TO algorithms can integrate overhang constraints using directional derivatives or gradient penalization aligned with the build direction. Level-set TO offers natural ways to embed these constraints by controlling boundary evolution angles.

4.3.3 Unsupported Holes

For horizontal circular holes, diameters below **8 mm** can generally be printed without supports. Beyond this threshold, deformation tends to occur, or supports become necessary. Figure 4.2 illustrates this behaviour by showing a series of horizontally printed holes. Small diameters remain stable and self-supporting, whereas larger holes begin to sag and deform, eventually requiring internal support structures.

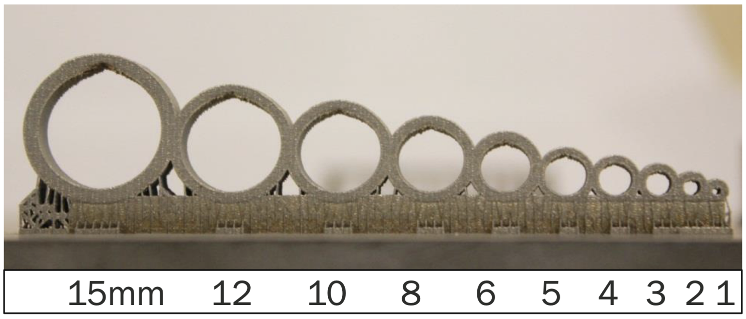


Figure 4.2: Horizontal holes printed without support material. Courtesy of David Bentley, Protolabs, *A Deep Dive into Metal 3D Printing*[9].

TO constraints related to minimum curvature or maximum span length can be used to ensure that such holes remain within printable limits.

4.3.4 Clearance and Powder Removal Constraints

In metal AM, powder evacuation places strict limits on internal geometries. Clearances must be sufficient to allow trapped powder to escape, especially when designing internal channels or lattice-filled regions.

Typical minimum clearances are:

- **0.2 mm** for tight clearances in SLA systems(5.3.3),
- **0.2–0.4 mm** clearances required for powder removal in PBF-LB/M(5.3.7).

TO may incorporate such constraints by enforcing minimum void-channel widths and ensuring access paths remain open.

4.3.5 Build Orientation Constraints

Build orientation plays an important role in mechanical anisotropy, surface quality, and recoater stability. Risks include potential collisions between the part and the recoater blade when orientations exceed machine capacity. TO methods increasingly incorporate build-direction parameters so that load paths align with optimal printing directions, improving fatigue resistance.

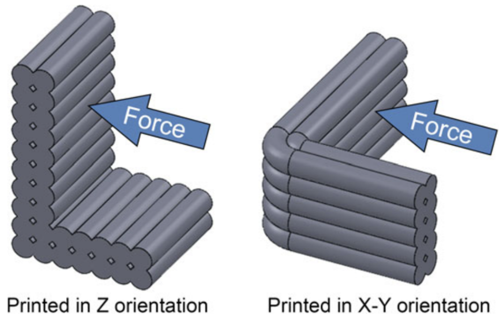


Figure 4.3: Influence of build orientation on mechanical behaviour: the same geometry shows different strength when printed in Z or X–Y orientation. From Diegel et al. [3].

Orientation-aware TO constraints may modify the stiffness tensor or add directional penalties, ensuring structural members align with optimal printing paths. As illustrated in Fig. 4.3, the same geometry can exhibit significantly different mechanical behaviour depending on whether it is printed in the Z direction or in the X–Y plane, due to the inherent anisotropy generated by the layer-wise deposition process. In the Z direction, when the force is applied, the interfaces between the individual layers are loaded in tension, which weakens the material. In contrast, when the part is printed in the X–Y orientation, the material exhibits far fewer discontinuities along the loading direction, resulting in a much better resistance to the applied force.

4.4 Process and Material Constraints

AM introduces thermo-mechanical phenomena such as residual stresses, warping, heat accumulation and microstructural anisotropy. TO may couple thermo-mechanical simulations with optimization to anticipate distortions before fabrication. This approach improves accuracy for thin-walled or large components.

4.5 Boundary and Interface Constraints

Boundary constraints ensure that optimized geometries maintain correct interfaces with assemblies, support plates or post-machining operations. These include:

- enforcing machining allowances,
- preserving functional interfaces (bolt holes, mating surfaces),
- ensuring accessibility for post-processing.

Such constraints ensure that the optimized geometry can be integrated into real product development workflows.

5

AM and TO Implementation

Rather than being treated as two separate domains, TO and AM are now connected through software capable of generating, validating, and fabricating highly optimized geometries. This section explores how this integration is achieved through modern engineering tools and manufacturing processes, detailing their roles, limitations, and applications.

5.1 From Optimization to Fabrication

For a topology-optimized design, several steps are required before the component can be physically produced (figure 5.1). Topology optimization typically produces a grayscale density field or voxel-based geometry, which must then be transformed into a manufacturable model. This process includes geometry reconstruction, smoothing, defeaturing, and the addition of manufacturing constraints (such as minimum feature size or overhang angle). Modern softwares enable these operations by combining finite element (FE) solvers with computer-aided design (CAD) and build simulation tools.

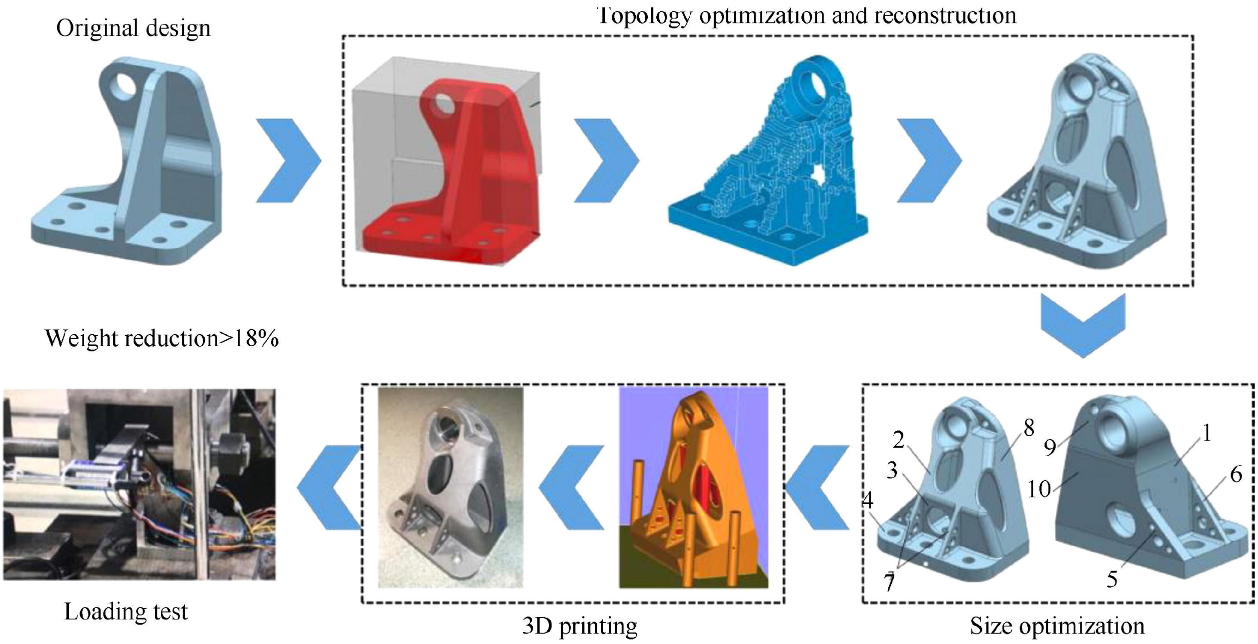


Figure 5.1: Optimization process of the part: from the original design to the produced part [1]

5.2 Software Tools for Topology Optimization

In recent years, the development of these software platforms has significantly improved the integration of TO. These tools allow engineers to define design domains, apply loads and boundary conditions, and automatically compute optimal material layouts while considering additive manufacturing (AM) constraints. The choice of software depends on the desired accuracy, computational cost, and the degree of coupling between design, simulation, and manufacturability.

5.2.1 Altair Inspire [11]

Altair Inspire is one of the most used platforms for topology optimization and generative design. It allows engineers to define loads, constraints, and design domains through a CAD-based interface, then automatically computes optimal material layouts.

Figure 5.2: Altair

A key advantage of Altair Inspire is its built-in consideration of manufacturing constraints such as symmetry, draw direction, overhang angles, and minimum member thickness; which ensures AM feasibility directly within the optimisation loop. The software supports both metallic and polymer-based additive processes and includes integrated validation modules for structural and modal analysis, making it particularly effective.

5.2.2 nTopology [12]

nTopology represents a new generation of engineering design tools built around implicit modelling and field design principles.

Unlike traditional CAD systems based on Boundary Representation (B-Rep), where geometry is defined by explicit surfaces, edges, and vertices forming the boundary of a solid, nTopology adopts a fundamentally different approach by using mathematical fields to represent geometry.

Figure 5.3: nTop

Note – Difference between B-Rep and Field-Based Modeling [13]

In B-Rep modeling, each shape is described by its outer skin through a collection of surfaces such as planes, cylinders or patches. While this method is effective for conventional design, it becomes limiting when dealing with complex or highly detailed structures such as lattice frameworks or organically optimized parts. Transitions between different geometries, or between optimized and manufacturable regions, often require manual surface reconstruction or meshing, which can lead to discontinuities.

In contrast, nTopology represents geometry as continuous scalar fields, which are mathematical functions defining properties such as material density or distance throughout space. This field-based representation allows continuous transitions between different regions or design features without the need for remeshing or connecting surfaces. As a result, nTopology enables a direct workflow from topology optimization results to manufacturable designs.

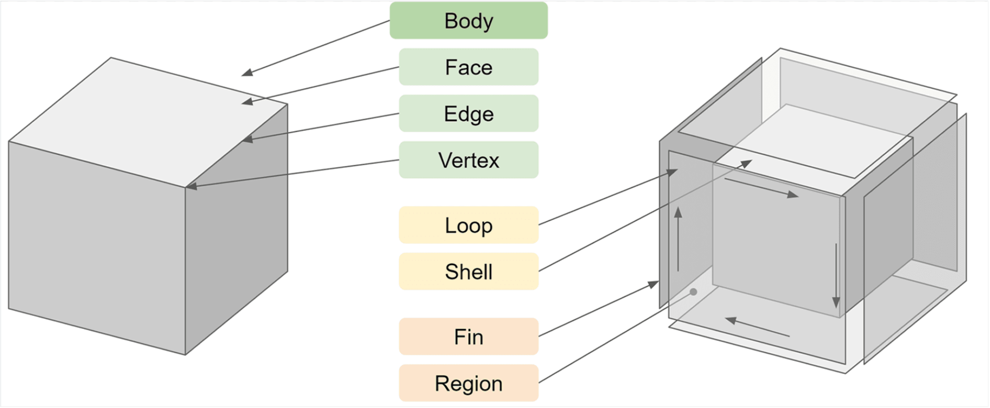


Figure 5.4: Illustration of B-Rep entities compared with the implicit solid representation.

This strength combine TO outputs with advanced lattice, shell, and material design, making it ideal for high-performance lightweight structures. Moreover, nTopology provides automated workflows for support generation, heat dissipation optimisation, and overhang reduction.

5.2.3 Autodesk Fusion 360 Generative Design [14]

Autodesk Fusion 360 incorporates a generative design module that shares many principles with TO, but is more focused on manufacturability and multi-objective exploration. The platform allows users to define load cases, design constraints, and multiple manufacturing methods simultaneously. It then produces a set of feasible designs that satisfy both performance and process constraints. While it uses similar numerical foundations to TO, its integration with cloud computing enables large-scale design exploration. This makes it particularly valuable for industrial applications where engineers must balance weight, cost, and manufacturability. The generated models are directly exportable to AM build preparation software such as *Autodesk Netfabb*, thus creating a continuous workflow from optimisation to printing.

Figure 5.5: Autodesk

5.2.4 Siemens NX [15]

Siemens NX integrates topology optimisation, design validation, and AM process simulation within a single environment. The software enables to run TO analyses, followed by direct conversion of the results into parametric CAD geometry. NX also evaluate residual stresses, distortions, and print orientations. This makes it particularly suited for aerospace and automotive sectors where TO must be validated under tight tolerance and certification constraints.

Figure 5.6: Siemens

5.2.5 ANSYS [16]

ANSYS software also offer robust topology optimization modules focused on finite element accuracy and simulation-driven design. ANSYS integrates TO within its parametric design language, allowing automatic reanalysis and shape refinement based on physical responses. This software is highly used in academic research and industrial prototyping to validate TO methodologies on benchmark structures.

Figure 5.7: Ansys

5.2.6 3DEXPERIENCE [17]

3DEXPERIENCE from Dassault Systèmes provides an integrated environment that connects design, simulation, and manufacturing in a single collaborative platform. Its topology optimization tools are available directly, enabling engineers to perform optimization and design refinement inside the native CAD environment. This integration allows users to define functional specifications, apply loads and constraints, and generate optimized lightweight structures while maintaining full associativity with the parametric model. By ensuring that geometry updates automatically propagate through the entire design process, 3DEXPERIENCE supports efficient iteration cycles and facilitates seamless transition from concept design to production.

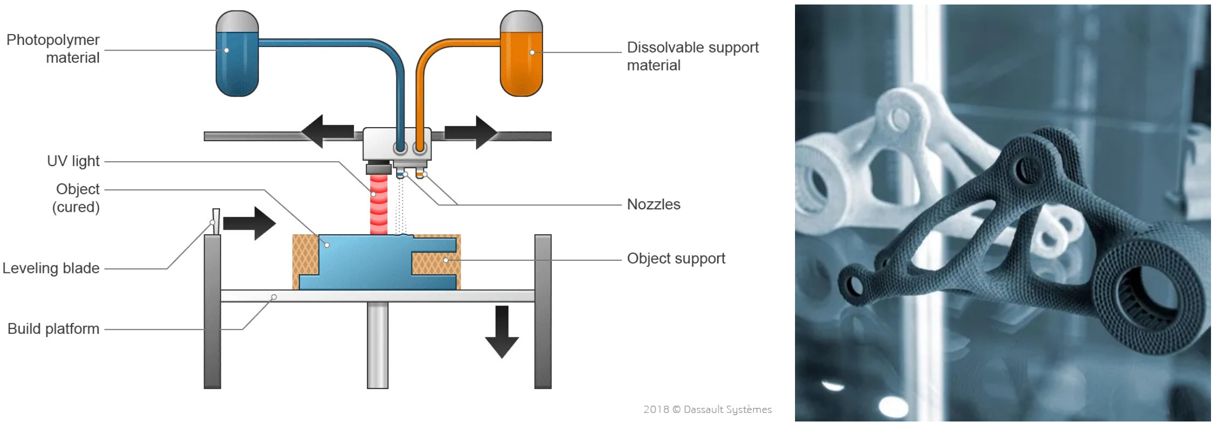
Figure 5.8: 3DX

5.3 Additive Manufacturing Machines and Production Technologies

The manufacturing of topology-optimized (TO) components relies heavily on additive manufacturing (AM) processes capable of resolving the intricate geometric features generated by optimization algorithms. Thin struts, branched load paths, internal voids, and spatially varying thicknesses are all typical of TO results and cannot be reproduced using traditional subtractive methods. Nevertheless, the ability to fabricate such geometries varies significantly from one AM process to another, depending on achievable resolution, material behaviour, thermal constraints, and the need for support structures. This section reviews the main AM processes used for the fabrication of TO components, ordered from the least to the most industrially adopted, with emphasis on their suitability for transforming mathematically optimized designs into functional parts.

5.3.1 Photopolymer Jetting [18]

Photopolymer Jetting builds parts by jetting microscopic droplets of UV-curable resin, which solidify instantly under UV light.



(a) PolyJet printing principle. **(b)** Topology-optimized piece [19]

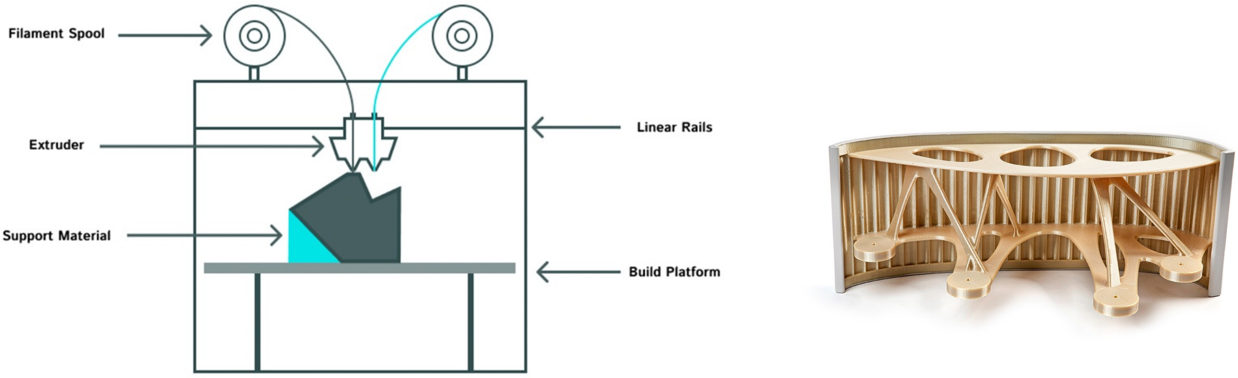
Figure 5.9: Photopolymer Jetting technology: (a) process; (b) TO example part.

Thanks to its very fine layer thickness, typically around 15–80 µm on many machines, and a surface finish capable of achieving roughness on the order of 1 µm in optimal conditions, PolyJet is very efficient for visualising geometries (figure 5.9b). Designers often use it to inspect thin branches, junctions, or regions where manufacturability may be critical.

Despite its precision, Photopolymer Jetting remains unsuitable for structural TO components because the printed polymers exhibit low stiffness, poor thermal resistance, and long-term instability. For this reason, this method is mostly used during early design stages, where complex TO shapes must be visually assessed rather than mechanically validated.

5.3.2 Fused Deposition Modeling (FDM) [20]

Fused Deposition Modeling produces parts by extruding thermoplastic filaments layer by layer.



(a) FDM extrusion process. **(b)** Airbus Spacer Panel [21]

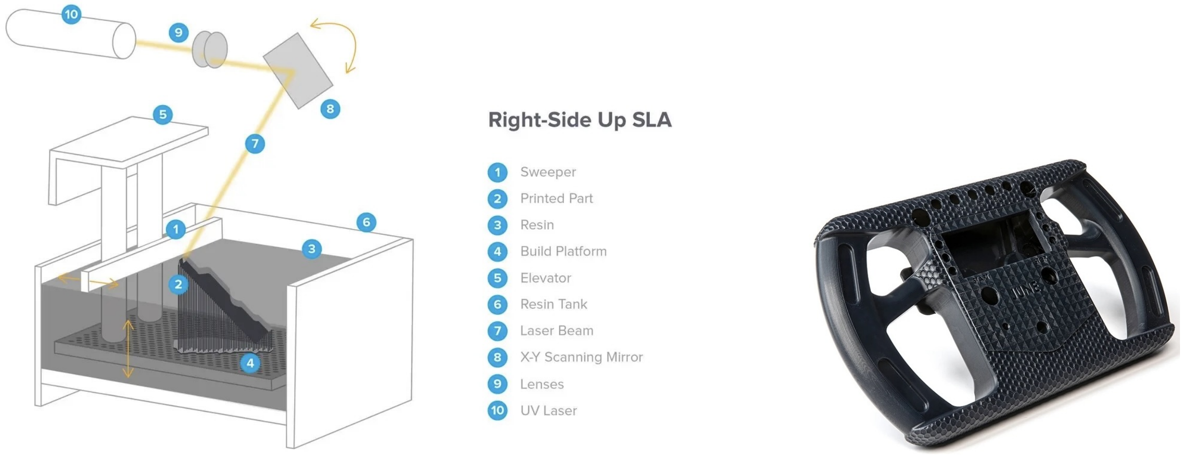
Figure 5.10: FDM technology: (a) process; (b) TO example part.

The spacer panel (figure 5.10b) produced in ULTEM 9085, marked Airbus' first use of 3D printing for a cabin part and delivered a 15% reduction in weight compared to the conventional panel.

Its simplicity and low cost make it widely adopted for early-stage TO prototypes. FDM is effective for evaluating overall shape, assembly constraints, and gross topology. However, the relatively coarse resolution, pronounced anisotropy, and material limitations (typically ABS or PLA) prevent faithful reproduction of thin TO features. For these reasons, FDM is used almost use for non structural but lightweight custom items .

5.3.3 Stereolithography (SLA) [22]

SLA uses a UV laser to selectively cure liquid resin layer by layer (50–100 µm). Two architectures exist: the top-down approach, where the build platform moves downward into the resin vat, and the bottom-up approach, where the part is lifted upward from a transparent window—each influencing accuracy, peel forces, and achievable part size.



(a) SLA principle with UV-laser curing. **(b)** Automative prototyping [23]

Figure 5.11: SLA: (a) process; (b) TO example part.

Because the laser can be steered with extreme precision (better than 25 µm), SLA achieves excellent surface quality and geometrical fidelity, enabling accurate reproduction of thin branches, small junctions, and intricate TO geometries. However, SLA parts are made from photopolymers with inherently brittle behaviour, limited thermal resistance, active post-processing and aging sensitivity. These drawbacks restrict SLA to prototyping applications (figure 5.11b.

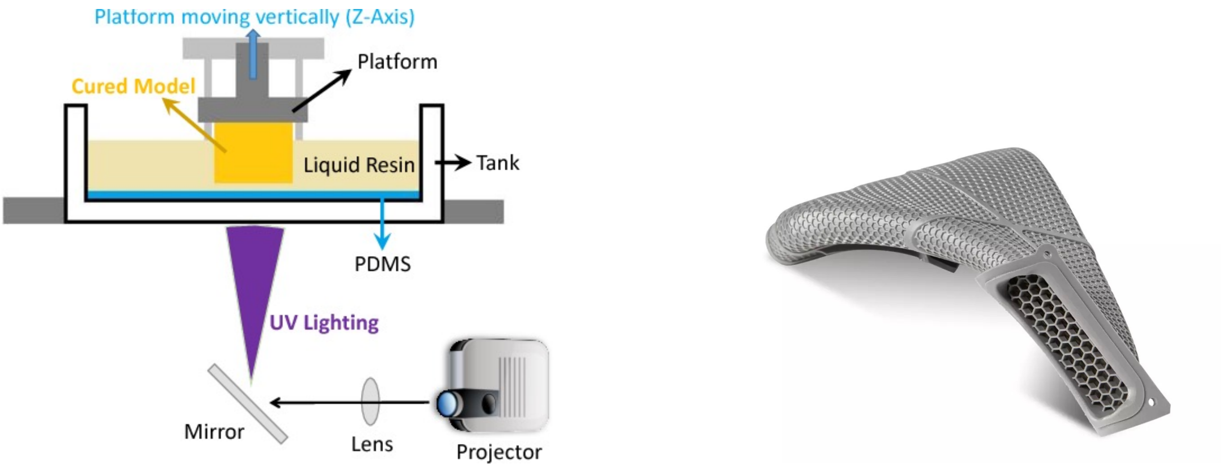
Note – Electroplating of SLA Parts for Stiffness Enhancement [24]

Electroplating consists of depositing a thin metallic layer (typically copper or nickel) onto an SLA part after applying a conductive coating. According to Formlabs, even a relatively thin metal layer (150 µm) can increase stiffness by a factor of up to **4** and tensile strength by **3** compared to the uncoated resin. The improvement is particularly strong in bending: a coated Rigid 10K beam showed a deflection reduction from **1.05 mm** to **0.44 mm** under a 100 N load.
Because electroplating strengthens the surface (where most stresses are concentrated), it is highly effective for topologically optimized geometries, which naturally exhibit high surface-to-volume ratios. This makes electroplating a cost-efficient way to produce stiff, lightweight, TO-derived prototypes without resorting to full metal AM.

Figure 5.12: TO part with electroplating for reinforcement

5.3.4 Digital Light Processing (DLP)[25]

Digital Light Processing cures entire resin layers simultaneously using a projected image.



(a) DLP layer projection system.

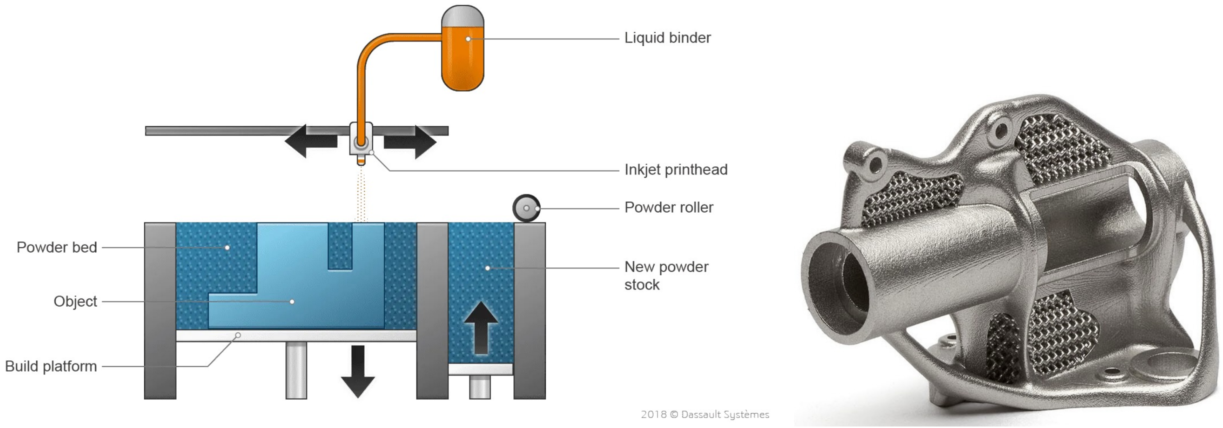
(b) TO piece using DLP[26]

Figure 5.13: DLP: (a) process; (b) TO example part.

This methods improves printing speed (4-5× faster than SLA)[27] and ensures uniform curing. DLP is compatible with polymer, ceramic-filled, or metal-filled resins, giving it unique versatility for TO studies. However, its resolution is generally 2 times lower than SLA, and the build volume is often smaller (12×). While capable of reproducing moderately complex TO geometries, DLP struggles with the details of highly optimized structures.

5.3.5 Binder Jetting (BJ)[28]

Binder Jetting selectively deposits a liquid binder onto a powder bed to form a fragile "green" part, which is then sintered.



(a) Binder Jetting deposition mechanism.

(b) Azoth robotic application[29]

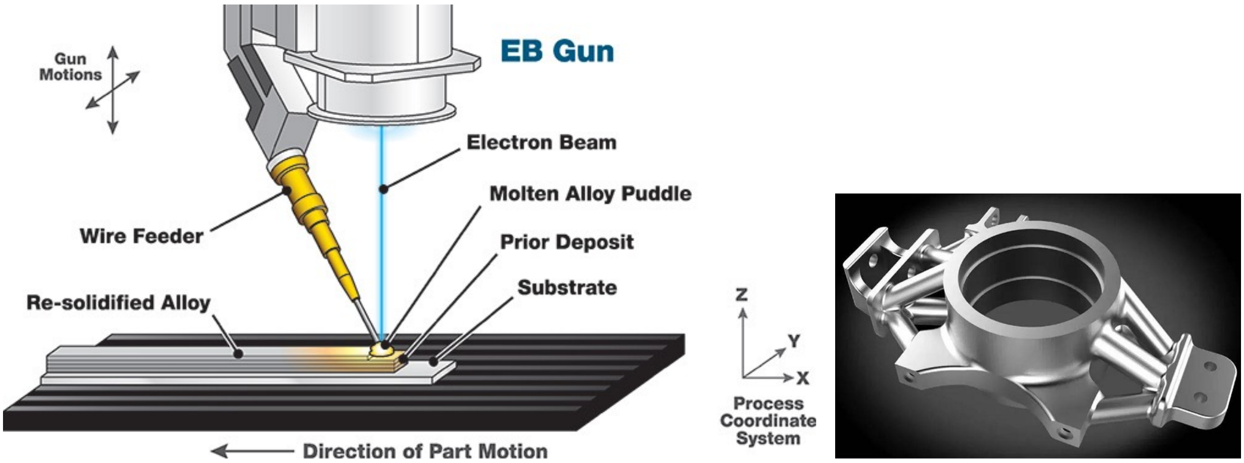
Figure 5.14: Binder Jetting: (a) process; (b) TO example part.

This process is inherently faster than melting-based AM (27× faster than L-(M)PBF)[30], and it requires no support structures ; an important advantage when dealing with internal cavities or lattice infills in TO designs. After sintering, relative densities of 96–98 % are typical for common metal powders (e.g., stainless steel) without additional infiltration.

However, sintering introduces significant volumetric shrinkage (often 15–20 %), which can compromise dimensional precision, particularly in thin, topology-optimized features. Also, unless further densification is carried out, the mechanical properties remain below those from fusion-based processes.

5.3.6 Directed Metal Deposition (DMD)[31]

Directed Metal Deposition feeds metal powder or wire directly into a melt pool created by a laser.



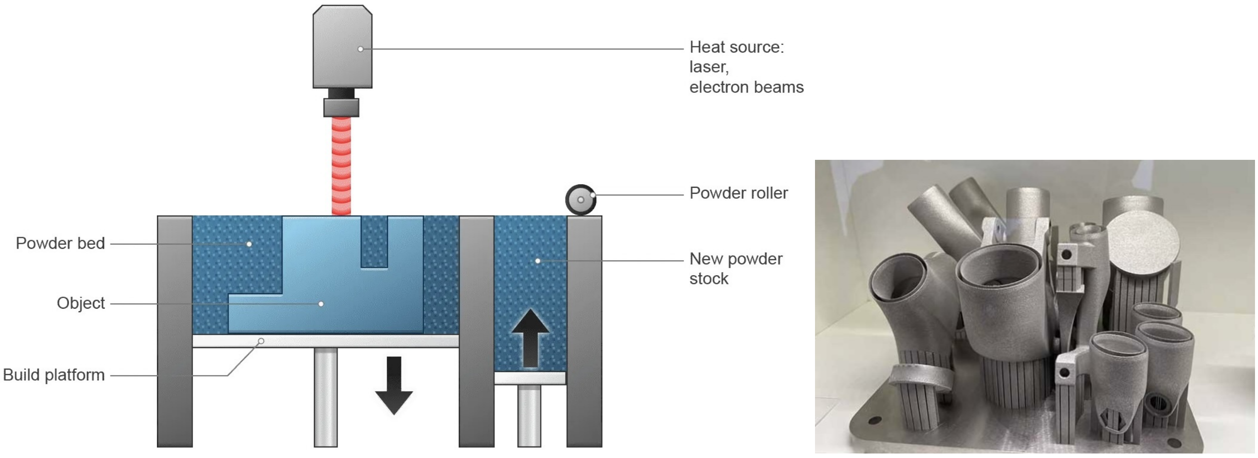
(a) DMD: laser and powder feed. **(b)** Automative TO via DMD[32]

Figure 5.15: DMD: (a) process; (b) TO example part.

The process offers large working volumes (can reach 0.20 m^3)[33] and high deposition freedom, allowing the fabrication of oversized TO components or reinforcement of existing structures. Yet, the melt pool size typically lies in the order of several hundred micrometres, which restricts the resolution of very fine TO features. Thermal stresses can be large, and surfaces are often rough, making DMD more suitable for structural, large-scale TO nodes than for fine lattice geometries.

5.3.7 Electron Beam Powder Bed Fusion (E-PBF)[34]

Electron Beam Powder Bed Fusion melts metal powder with an electron beam inside a vacuum chamber.



(a) E-PBF operating under vacuum. **(b)** TO E-PBF aerospace structure[35]

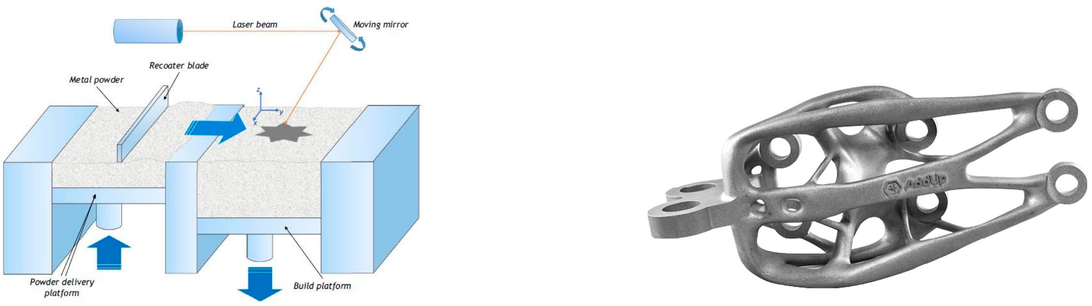
Figure 5.16: E-PBF: (a) process; (b) TO example part.

The preheating of the powder bed (up to hundreds of °C) significantly reduces residual stresses, which is a major benefit for certain TO geometries. Typical layer thicknesses in E-PBF are in the range of 50–150 µm. In some high-performance alloys (e.g., Ti-6Al-2Sn-4Zr-2Mo), as-built tensile strengths can reach about 914 ± 8 MPa.

Still, because E-PBF systems have a relatively large melt zone and 2× lower resolution compared to laser PBF, very fine TO struts (e.g., below 300 µm) may not be reproduced accurately. Surface roughness is also high, and only a limited set of alloys can be processed due to vacuum requirements.

5.3.8 Laser Metal Powder Bed Fusion (L-(M)PBF) [36]

Laser Powder Bed Fusion is the reference process for manufacturing metal topology-optimized parts.



(a) Laser PBF selective melting. **(b)** Aircraft floor bracket [37]

Figure 5.17: Laser Metal Powder Bed Fusion: (a) process; (b) TO example part.

With typical layer thicknesses between 50 and 80 µm, L-PBF offers an trade-off between build speed (10 mm^3/s) and precision. In Ti-6Al-4V, parts made by LPBF have achieved ultimate tensile strengths (UTS) in the range of 1,000–1,250 MPa. The laser spot size in many commercial systems is on the order of 0.1–0.5 mm, which enables the reproduction of fine, optimized lattice structures. Still, L-(M)PBF requires supports for overhanging geometry, and extensive post-processing (e.g., heat treatment, machining, surface finishing) is usually necessary to reach final mechanical performance.

5.3.9 Discussion

The choice of AM process strongly conditions how a topology-optimized design can be manufactured. Metal PBF systems remain the main industrial route for structural TO parts, while BJ and DED technologies offer alternatives when cost or scale becomes dominant. Polymer processes are mainly used for early validation of shapes. Table 5.1 below summarizes the different AM processes ordered by their typical relevance and usage for topology-optimized components.

Table 5.1: Comparison of additive manufacturing processes for topology-optimized parts.

Process	TO Suitability	Remarks / Limitations
PolyJet	Good (visual models)	Excellent accuracy, multi-material capabilities; weak and aging photopolymers.
FDM	Limited	Low resolution and strong anisotropy; mainly for preliminary TO shape validation.
SLA	Excellent (prototypes)	Very high accuracy; materials are brittle and can age; electroplating possible for hybrid TO demonstrators.
DLP	Moderate–Good	Fast but slightly less accurate than SLA; smaller build volumes; good for demonstrators.
Binder Jetting	Moderate	Very fast, no supports; shrinkage and lower density limit suitability for fine or high-performance TO parts.
DMD	Limited–Moderate	Large deposition freedom; poor resolution and high thermal stresses.
E-PBF	Very Good	Fast, low residual stresses; limited resolution and only vacuum-compatible alloys.
L-(M)PBF	Excellent	Best resolution and mechanical performance; requires supports and build size constraints.

6

Advantages and Limitations of TO

TO is now a key tool in modern engineering design, especially when combined with AM. It allows engineers to explore material layouts and geometries that achieve the best structural performance for a given set of constraints. It opens up new possibilities for lightweight, high-performance, and functionally integrated components. However, despite its great potential, several challenges. The following sections summarize the main advantages and limitations of TO in the context of design and manufacturing.

6.1 Advantages

TO enables an optimal distribution of material, so that less material is used for the same structural performance (or improved performance for the same mass). This is widely highlighted as one of the main benefits of combining TO with AM.

TO enables an optimal distribution of material, reducing mass while meeting stiffness or strength constraints. This benefit becomes even more significant when paired with AM, which can manufacture the complex, hollowed-out, or lattice-based geometries commonly produced by TO. AM allows light-weighting strategies (e.g., topology-optimized seat frame reduced from 16.2 kg to 3.1 kg), as seen in figure 6.1, which TO directly supports by naturally removing unnecessary material.

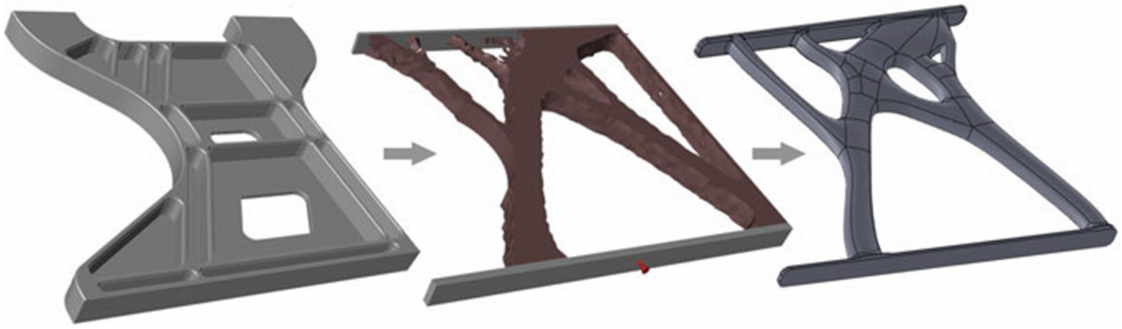


Figure 6.1: CNC-machined aircraft seat frame (left), rough topology optimized version (center), and finished design (right) [3]

Because AM enables intricate geometries, TO can generate designs with internal lattice structures, optimized load paths, and organic topology that were impossible with classical subtractive/manufacturing methods.

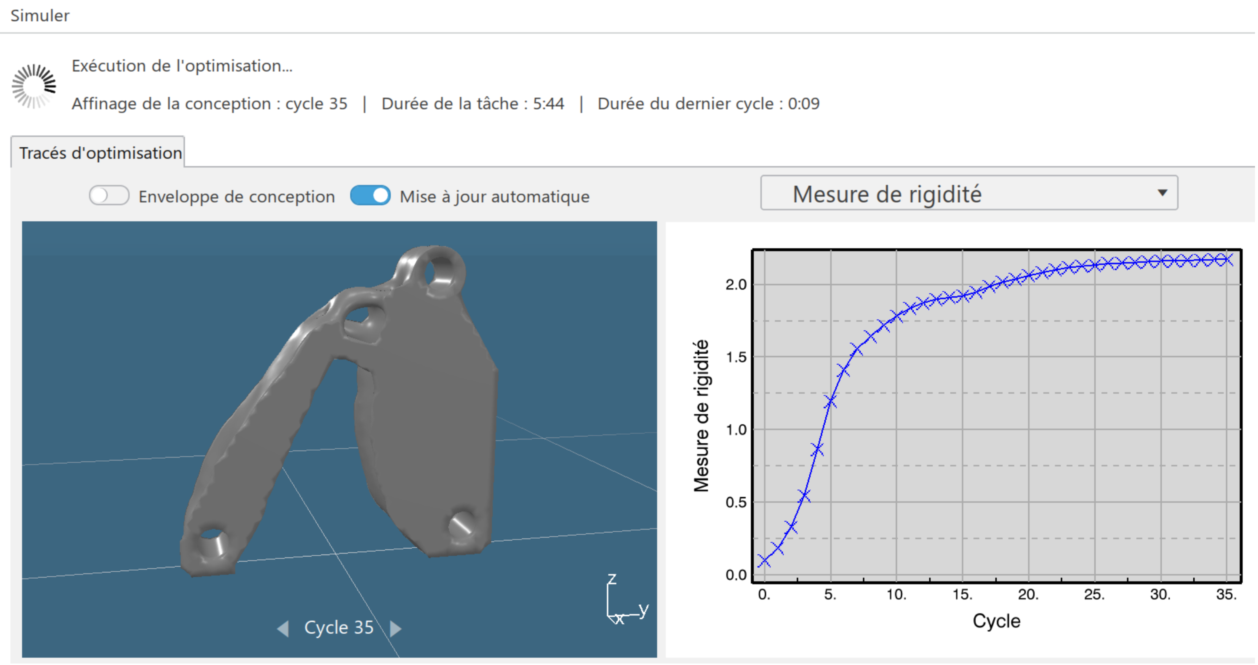
Combining TO with AM allows for the consolidation of assemblies into single parts—reducing joints, interfaces, fasteners, assembly steps, and potentially improving fatigue performance.

Especially when weighted with DfAM mindset, TO can integrate multiple functions into one part.

6.2 Limitations

Topology optimization (TO) often requires fine mesh resolution, large numbers of iterations, and sometimes the coupling of multiple physics (e.g., structural, thermal, or process simulations). These factors can make the computational cost significant.

The raw output of a TO process is rarely directly manufacturable. Optimized shapes may include thin ligaments, small isolated features, unsupported overhangs, or enclosed voids that complicate powder evacuation or part cleaning. Such geometric characteristics can exceed the capability of current additive manufacturing (AM) processes and typically require geometric interpretation, smoothing (see figure 6.2), or redesign to ensure manufacturability.



Simuler

Exécution de l'optimisation...

Affinage de la conception : cycle 35 | Durée de la tâche : 5:44 | Durée du dernier cycle : 0:09

○ Enveloppe de conception ● Mise à jour automatique

Mesure de rigidité

Figure 6.2: Rough first result after topological optimization

Material and process uncertainties also introduce discrepancies between TO predictions and the as-built part. Additively manufactured components may exhibit anisotropy, residual stresses, porosity, or variations in mechanical properties depending on build orientation, scan strategy, and post-processing. By contrast, many TO formulations assume idealized or simplified material behaviour, which can create a gap between the optimized design and its real-world performance.

Even when TO and AM enable high-performance geometries, the resulting part often still requires post-processing (machining, heat treatment, surface finishing) and validation (mechanical testing) to meet quality or certification requirements, adding time and cost.

Industrial guidelines, standards, and best practices for combining TO with AM remain less mature than for conventional manufacturing. This contributes to reluctance or slow adoption in some sectors due to perceived risk, cost, or gaps in in-house expertise.

Finally, if TO is performed without a proper Design for Additive Manufacturing (DfAM) mindset; i.e. without incorporating manufacturing, material or assembly constraints into the optimization—the mathematically optimal shape may still be impractical. The purpose of TO is precisely to integrate such constraints during optimization, and when they are omitted or poorly formulated, the resulting design can create downstream issues rather than eliminating them.

7

Case Study: EPFL Racing Team

Topology optimization is used mainly in high-performance fields such as aerospace, motorsport, and biomedical engineering, thanks to its ability to deliver stiff, lightweight designs. Today, we even see some road cars using such parts:

Figure 7.1: Suspension arm of the Bugatti Tourbillon road car [38]

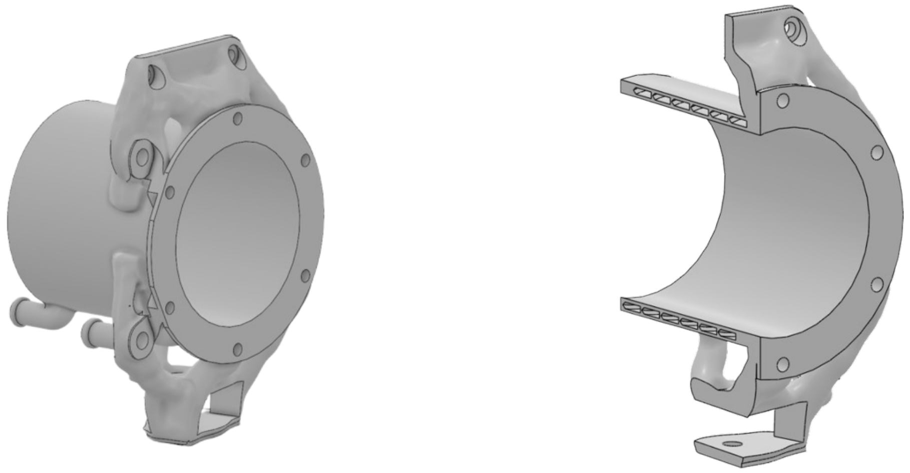
The Figure 7.1 show the suspension arm of the Bugatti Tourbillon, a road car released in 2024. The "bonelike" design clearly reveal the use of topological optimization for weight saving while ensuring the required stiffness.

7.1 The upright

To better understand how a part like this is created, from concept to design, manufacturing, and post-processing, we chose to study a component produced by the EPFL Racing Team.

7.1.1 Functionality

The upright is the central element of the suspension system: the two wishbones and the push-rod connect to the entire wheel wheel assembly only through this single part. It therefore transmits, via the chassis, all the forces applied at the tyres during the main driving phases, acceleration, braking, and steering. In addition to this primary function, the upright do also integrate the motor (four in total, one in each wheel) and the cooling jacket around it to promote heat exchange between the heavily loaded motors and the circulating cooling. Since the upright must also provide a cooling function, which is best realized with internal channels (see figure 7.2b) that are practical to manufacture only with additive manufacturing, it was natural to consider topology optimization. This approach lets us fully exploit the design freedom of 3D printing, reducing mass while preserving stiffness and integrating efficient, conformal cooling paths.



(a) Isometric view **(b)** Sectional view

Figure 7.2: Front upright of the EPFL Racing Team

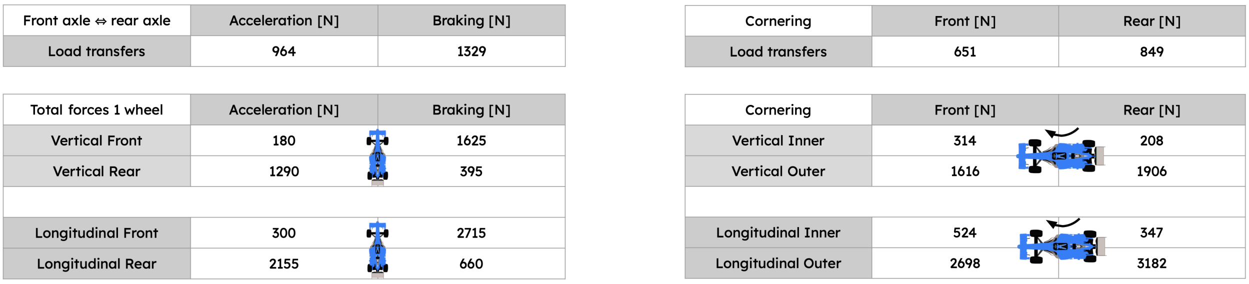
7.2 Why topological optimization ?

Now that we know what the upright is, it is natural to ask why apply topology optimization to this part. Building on the discussion above about why additive manufacturing is appropriate for this component, the upright is subjected to very high loads during all driving phases, so it must be sufficiently stiff to withstand them, but it should be done with care because if one load cased is forget it could lead to the destruction of the part at the first corner. At the same time, it is an unsprung mass, not supported by the suspension like the chassis. In a race car, reducing unsprung mass sharpens suspension response, helping the car react more quickly to bumps and keeping the tyre in more consistent contact with the ground leading to improve the grip, one of the most important aspect of a race car. To search always more performance and for the challenge it bring, it was chose to build this part using topological optimization.

7.3 Workflow

7.3.1 Load Cases & Forces

The first step is to define all load cases that your part is subject to. In the figure 7.3 below, the forces you can see are the one that are going to be set in the software to compute and creat the part, therefore you need to make sure that they realistic otherwise the part will not be resistant enough.



Front axle ⇔ rear axle	Acceleration [N]	Braking [N]
Load transfers	964	1329

Total forces 1 wheel	Acceleration [N]	Braking [N]
Vertical Front	180	1625
Vertical Rear	1290	395
Longitudinal Front	300	2715
Longitudinal Rear	2155	660

Cornering	Front [N]	Rear [N]
Load transfers	651	849

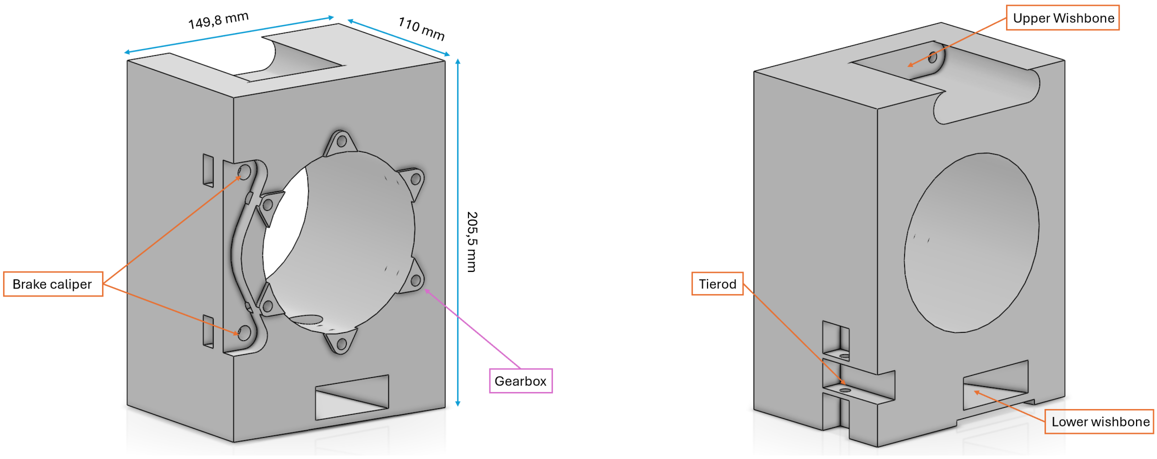
Cornering	Front [N]	Rear [N]
Vertical Inner	314	208
Vertical Outer	1616	1906
Longitudinal Inner	524	347
Longitudinal Outer	2698	3182

(a) Acceleration and Braking forces **(b)** Cornering forces

Figure 7.3: Acceleration, braking and cornering forces

7.3.2 Design Space

Now that the forces are computed, the second step is to model the optimization space using CAD software (*3DExperince*). The objective is to make it as large as possible to allow for maximum freedom during optimization, while making sure that the design space do not interfere with surrounding components.



(a) Front view **(b)** back view

Figure 7.4: Space design of the front right upright

The design space, as you can see on the picture above, includes all the space that the TO can use as well as the space it cannot not touch (part not in green and white on figure 7.5). Here it is principally the suspension pick point, the housing for the motor, the fixation for the gearbox (GB) and the brake calipers position (see figure 7.4).

7.3.3 Simulations & Results

Once you have your design space, it's time to run the TO simulation. First, apply the forces, moments, and boundary conditions that your part is subject to. You can build different simulations for your different cases, which will allow you to superpose the solutions to obtain one that is stiff enough to resist. Different types of objectives can be used for TO. Here, this was done by choosing **"Maximize stiffness with mass constraints"**. The user has to set a goal of weight compare to the design space model (in percentage or an absolute value), the software is going to calculate a feasible solution that maximize the stiffness of you part while making sure the weight is under the constraint set beforehand.

(a) Braking **(b)** Acceleration

Figure 7.5: Forces, Moment and Boundary condition for Braking and Acceleration case

In figure 7.5 the green arrows are the forces, in purple are the moments, and in orange (at the bottom) the boundary conditions. The green/ white space is the space the TO is allowed to use.

The time of simulation can vary in function of the mesh size and order, number of load cases and constraints and the physique complexity of your part inside the design space constraint. When the simulation is finish you get your results:

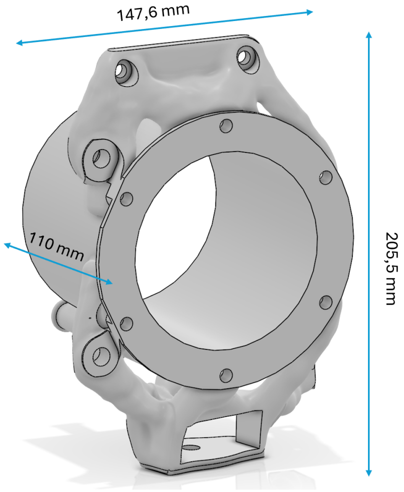


Figure 7.6: Front upright final design

Figure 7.6 shows the final iteration of the design, obtained after numerous trials and refinements. The cooling jackets were not produced by topology optimization, it was added afterward. To make sure that the design hold all the different load cases, some FEM simulations where made for each one of them (See I.B).

7.4 Manufacturing

7.4.1 Manufacturer & material

The front and rear part were manufactured in Switzerland with the help of an EPFLRT sponsor : Protoshape. ProtoShape, founded in 2012, has been a Swiss pioneer in generative manufacturing as a service provider using Laser Metal Powder Bed Fusion (see section 5.3.8). The parts were built using a Selective Laser Melting machine, the SLM 280. The material used was AlSi10Mg, an aluminum alloy commonly employed in metal additive manufacturing alongside superalloys such as Inconel (IN718) and titanium (Ti6Al4V), due to its lightweight nature and good thermal properties.

7.4.2 Post-processing

As you can imagine, due to the complex shape of the part, it was not printable without using supports (see figure 7.7) . After discussion with the manufacturer, the interior of the cooling jackets was design to have no supports inside when the front face was printed, otherwise it would have been impossible to remove afterward.

Figure 7.7: Printing supports of the upright

The printing time was approximately 20 hours per upright. After printing, the support structures were removed using mechanical tools such as chisels, scrapers, as well as a flat screwdriver and a hammer. To meet the required dimensional tolerances, such as the diameter of the motor housing, the flatness of the gearbox mounting surface, and the alignment of the screw holes, post-printing machining operations were performed. These ensured the necessary precision and proper fit of the components. To remove residual powder and improve surface quality, the part was subjected to sandblasting and glass blasting, resulting in a clean, uniform finish suitable for inspection and assembly. Finally, to guarantee the stiffness of the part, it was cured for 2 hours at 300 °C.

7.4.3 Weight comparison

To conclude, let us talk about the weight saving of the new part compared to the previous part. The previous upright was not combine to the cooling jacket, so, to be more realistic, it was add together with the upright during the process of weighting.

(a) LRT5 upright **(b)** LRT4 upright

Figure 7.8: Weight comparison between LRT5 and LRT4 rear uprights

The final weight of the LRT4 rear upright combined with the cooling jacket is 1.282kg (fig 7.8b)and the LRT5 rear upright 0.861kg (fig7.8a), which is a saving of 0.421kg (33%) on unsprung mass. For the EPFL Racing Team, it was the first time that the upright was manufactured using this type of process. Due to the importance of this part not braking, a high safety factor of more than 3 was used(see I.C). Both the rear and front uprights were a great success and did not fail during two years of intensive use. A future objective of the team is to design a new upright with better cooling integration (for example no 90° bend at the inlet), while further reducing the weight of the part to seek always more performance.

8

Conclusion and Future Perspectives

The integration of Design for Additive Manufacturing (DfAM) into the design workflow has emerged as a key enabler to fully exploit the capabilities of Additive Manufacturing (AM). AM is not an innovative production method, but a technology that requires rethinking the entire design approach. Geometric freedom, functional integration, and material efficiency become central tools, and when combined with DfAM strategies, topology optimization, and lattice structures, they enable performance levels unattainable with conventional manufacturing. Weight savings, fewer components, streamlined assembly, and enhanced design flexibility illustrate how this approach can fundamentally reshape product development.

However, this freedom does not eliminate constraints. AM introduces its own limitations: material anisotropy, sensitivity to building orientation, mandatory post-processing, residual stresses, distortion, and challenges related to powder removal or inaccessible internal cavities. The results demonstrate the need for a multidisciplinary approach that combines design, simulation, process expertise, and experimental validation. Furthermore, the difficulty of converting topology optimized geometries into clean, manufacturable CAD models highlights the current gaps in digital tools and the need for more mature industrial standards.

Ultimately, DfAM has become an essential skill to convert the theoretical potential of AM into practical, industrially viable solutions. The benefits are significant, but their capture requires methodological rigor and complete mastery of the digital and manufacturing workflow. Future developments lie in the convergence of multi-scale optimization, process simulation, automated geometric clean-up, and the establishment of robust design standards. As these tools and methods continue to evolve, they will improve the reliability, repeatability, and industrial adoption of AM-optimized components, paving the way for increasingly high-performance applications in aerospace, automotive, medical, and high-end engineering sectors.

APPENDIX I

Upright Appendix

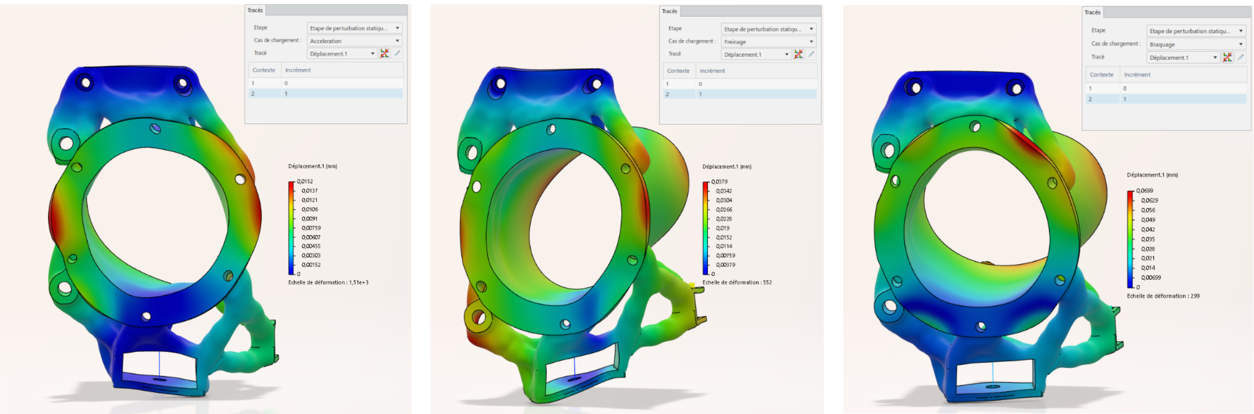
I.A AlSi10Mg properties

Parameter	Symbol	Value	Unit
Young's modulus	E	73 000 – 74 000	MPa
Yield strength	σ_y	271	MPa
Poisson's ratio	ν	0.33	–
Density	ρ	2.67×10^{-3}	kg/mm^3
Coefficient of thermal expansion	α	$1.9 - 2.52 \times 10^{-5}$	1/K
Thermal conductivity	λ	130 – 150	W/(m·K)
Specific heat capacity	c_p	910 – 920	J/(kg·K)

Table I.1: Constitutive properties of the AlSi10Mg alloy

I.B Simulations

I.B.1 Front upright



Tracés

Etape: Etape de perturbation statiqu...
Cas de chargement : Acceleration
Tracé: Déplacement.1

Contexte	Incrément
1	0
2	1

Tracés

Etape: Etape de perturbation statiqu...
Cas de chargement : Freinage
Tracé: Déplacement.1

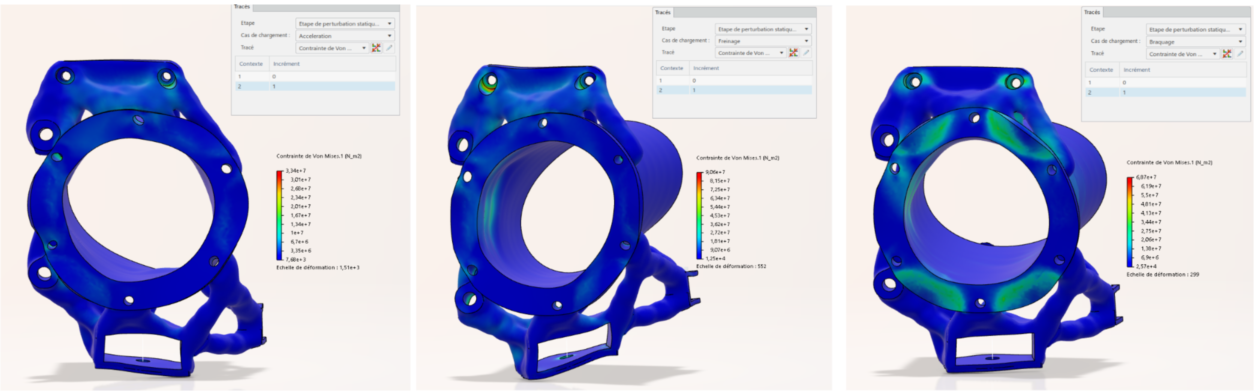
Contexte	Incrément
1	0
2	1

Tracés

Etape: Etape de perturbation statiqu...
Cas de chargement : Braquage
Tracé: Déplacement.1

Contexte	Incrément
1	0
2	1

Figure I.1: Front Displacement results for accleration, braking and cornering



Tracés
Etape: Etape de perturbation statiqu...
Cas de chargement : Acceleration
Tracé: Contrainte de Von ...

Contexte	Incrément
1	0
2	1

Echelle de déformation : 1,51e+3

Tracés
Etape: Etape de perturbation statiqu...
Cas de chargement : Freinage
Tracé: Contrainte de Von ...

Contexte	Incrément
1	0
2	1

Echelle de déformation : 552

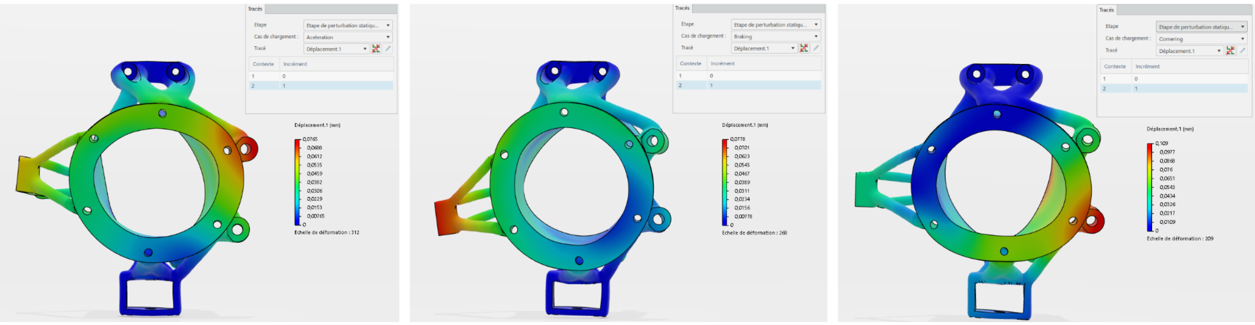
Tracés
Etape: Etape de perturbation statiqu...
Cas de chargement : Braquage
Tracé: Contrainte de Von ...

Contexte	Incrément
1	0
2	1

Echelle de déformation : 299

Figure I.2: Front Von Mises results for accleration, braking and cornering

I.B.2 Rear upright



Tracés
Etape: Etape de perturbation statiqu...
Cas de chargement : Aceleration
Tracé: Déplacement.1

Contexte	Incrément
1	0
2	1

Echelle de déformation : 312

Tracés
Etape: Etape de perturbation statiqu...
Cas de chargement : Braking
Tracé: Déplacement.1

Contexte	Incrément
1	0
2	1

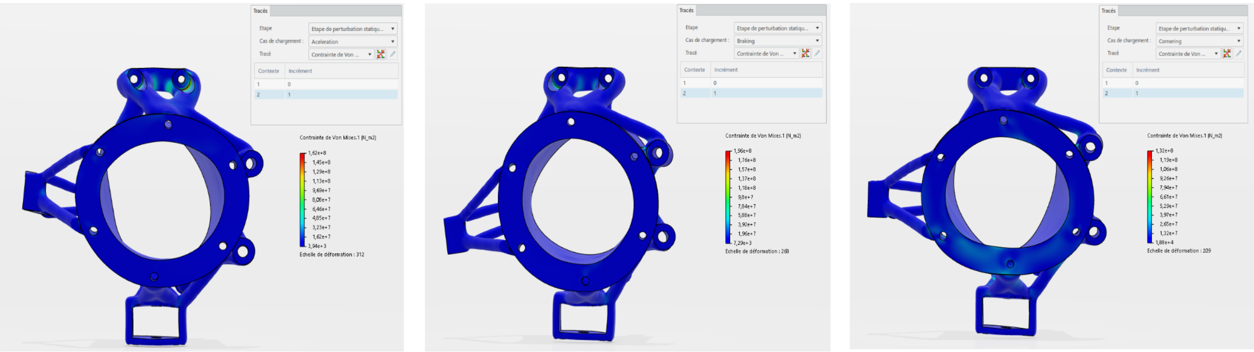
Echelle de déformation : 268

Tracés
Etape: Etape de perturbation statiqu...
Cas de chargement : Cornering
Tracé: Déplacement.1

Contexte	Incrément
1	0
2	1

Echelle de déformation : 209

Figure I.3: Rear upright Displacement results for accleration, braking and cornering



Tracés
Etape: Etape de perturbation statiqu...
Cas de chargement : Aceleration
Tracé: Contrainte de Von ...

Contexte	Incrément
1	0
2	1

Echelle de déformation : 312

Tracés
Etape: Etape de perturbation statiqu...
Cas de chargement : Braking
Tracé: Contrainte de Von ...

Contexte	Incrément
1	0
2	1

Echelle de déformation : 268

Tracés
Etape: Etape de perturbation statiqu...
Cas de chargement : Cornering
Tracé: Contrainte de Von ...

Contexte	Incrément
1	0
2	1

Echelle de déformation : 209

Figure I.4: Rear upright Von Mises results for accleration, braking and cornering

I.C Security factor

To calculate the security factor, we are going to take the worst case: front upright braking case:

$$n = \frac{\sigma_y}{\sigma_{vM,max}} = \frac{271\text{MPa}}{90.6\text{MPa}} = 3.01$$

Bibliography

[1] Jie Zhu, Wei Zhang, and Jun Zhou. A review of topology optimization for additive manufacturing: Status and challenges. https://www.sciencedirect.com/science/article/pii/S1000936120304520, 2021. Chinese Journal of Aeronautics, Volume 34, Issue 2, Pages 540–558.

[2] Inspire AG. Design for additive manufacturing (dfam). https://www.inspire.ch/en/research-for-the-industry/manufacturing-processes-quality/additive-manufacturing-3d-print-design-for-am/design-for-am/, 2025. Accessed: 2025-11-01.

[3] Olaf Diegel, Axel Nordin, and Damien Motte. A practical guide to design for additive manufacturing. https://link.springer.com/book/10.1007/978-981-13-8281-9, 2020.

[4] M. P. Bendsøe and N. Kikuchi. Generating optimal topologies in structural design using a homogenization method. https://www.sciencedirect.com/science/article/pii/0045782588900862, 1988.

[5] Martin P. Bendsøe and Ole Sigmund. Topology optimization: Theory, methods and applications. https://link.springer.com/book/10.1007/978-3-662-05086-6, 2003.

[6] Yi Min Xie. Generalized topology optimization for structural design. https://www.google.com/search?client=safari&rls=en&q=Generalized+Topology+Optimization+for+Structural+Design&ie=UTF-8&oe=UTF-8, 2025.

[7] Ole Sigmund. A 99 line topology optimization code written in MATLAB. https://link.springer.com/article/10.1007/s001580050176, 2001.

[8] J. K. Guest, J. H. Prévost, and T. Belytschko. Achieving minimum length scale in topology optimization using nodal design variables and projection functions. https://onlinelibrary.wiley.com/doi/10.1002/nme.1064, 2004.

[9] Bentley David. A deep dive into metal 3d printing: Optimize design through part geometry, surface finish, secondary operations, and other considerations. https://s3.amazonaws.com/static.projects.hackaday.com/4550211684955915058.pdf, 2020. DMLS Process Engineer, Proto Labs.

[10] Y. M. Xie and G. P. Steven. A simple evolutionary procedure for structural optimization. https://www.sciencedirect.com/science/article/pii/004579499390035C, 1993.

[11] Altair Engineering Inc. Altair inspire – topology optimization and generative design software. https://altair.com/inspire, 2024. Accessed: November 2025.

[12] nTopology Inc. Topology optimization capabilities. https://www.ntop.com/software/capabilities/topology-optimization/, 2025. Accessed: 2025-11-04.

[13] Blake Courter. B-rep vs. implicit modeling: Understanding the basics. https://www.ntop.com/resources/blog/understanding-the-basics-of-b-reps-and-implicits/, March 2019. Accessed: 2025-11-07.

[14] Autodesk Inc. Fusion 360 generative design overview. https://www.autodesk.com/products/fusion-360/blog/topology-optimization-and-autodesk-fusion/, 2023. Accessed: November 2025.

[15] Siemens Digital Industries Software. Siemens nx additive manufacturing and topology optimization. https://plm.sw.siemens.com/en-US/nx/manufacturing/additive-manufacturing/am-design/, 2024. Accessed: November 2025.

[16] Inc. ANSYS. Ansys topology optimization | lightweighting & shape optimization. https://www.ansys.com/applications/topology-optimization, 2025. Accessed: 2025-11-08.

[17] Dassault Systèmes. Topology optimization – 3dexperience online store. https://www.3ds.com/store/topology-optimization, 2025. Accessed: 2025-11-08.

[18] Dassault Systèmes. Material jetting – 3d printing process guide. https://www.3ds.com/make/guide/process/material-jetting, 2025. Accessed: 2025-11-15.

[19] Xometry. Material jetting 3d printers – guide and applications. https://www.xometry.com/resources/3d-printing/material-jetting-3d-printers/, 2025. Accessed: 2025-11-15.

[20] LSRPF. What is fused deposition modeling (fdm)? https://www.lsrpf.com/fr/blog/what-is-fused-deposition-modeling, 2025. Accessed: 2025-11-16.

[21] Materialise. Airbus 3d printing inspiration case – cabin panel in ultem 9085. https://www.materialise.com/en/inspiration/cases/airbus-3d-printing, 2025. Accessed: 2025-11-16.

[22] Formlabs. The history of stereolithography: 3d printing origins. https://formlabs.com/blog/history-of-stereolithography-3d-printing/, 2025. Accessed: 2025-11-16.

[23] Materialise. Stereolithography – industrial 3d printing technologies. https://www.materialise.com/en/industrial/3d-printing-technologies/stereolithography, 2025. Accessed: 2025-11-16.

[24] Formlabs. Résistance du métal : Stratégies et exemples d'utilisation pour la galvanoplastie de pièces sla. https://3d.formlabs.com/livre-blanc-resistance-du-metal-strategies-exemples-utilisation-pour-galvanoplastie-de-pi
2025. Accessed: 2025-11-16.

[25] Additive Manufacturing Lab University of Zurich. Dlp technology (digital light processing) – amf uzh. https://www.amf.uzh.ch/en/additive-manufacturing/our_technologies/dlp.html, 2025. Accessed: 2025-11-16.

[26] Jellypipe. Newly available dlp technology. https://www.jellypipe.com/en/blog-news/newly-available-dlp-technology/, 2025. Accessed: 2025-11-16.

[27] Formlabs. Resin 3d printer comparison: Sla vs dlp. https://formlabs.com/blog/resin-3d-printer-comparison-sla-vs-dlp/, 2025. Accessed: 2025-11-16.

[28] Dassault Systèmes. Binder jetting – 3d printing process guide. https://www.3ds.com/make/guide/process/binder-jetting, 2025. Accessed: 2025-11-16.

[29] Azoth 3D. What is metal binder jetting? https://www.azoth3d.com/what-is-metal-binder-jetting/, 2025. Accessed: 2025-11-16.

[30] AMFG. Metal binder jetting: All you need to know. https://amfg.ai/2019/07/03/metal-binder-jetting-all-you-need-to-know/, 2019. Accessed: 2025-11-16.

[31] Inc. Sciaky. What is directed energy deposition (ded) 3d printing? https://www.sciaky.com/additive-manufacturing/what-is-ded-3d-printing, 2025. Accessed: 2025-11-16.

[32] EBM MACHINE. Top 3 pros and cons of directed energy deposition. https://ebeammachine.com/top-3-pros-and-cons-of-directed-energy-deposition/, 2024. Accessed: 2025-11-16.

[33] Metal-AM. Large-scale ded systems and build envelopes. https://www.metal-am.com/, 2024. Overview article and industry examples; accessed: 2025-11-16.

[34] Dassault Systèmes. Powder bed fusion – 3d printing process guide. https://www.3ds.com/make/guide/process/powder-bed-fusion, 2025. Accessed: 2025-11-16.

[35] EBM Machine. How to master the powder bed fusion process. https://ebeammachine.com/how-to-master-the-powder-bed-fusion-process/, 2025. Accessed: 2025-11-16.

[36] MDPI. Metals 2021, 11, 158. https://www.mdpi.com/2075-4701/11/1/58, 2021. Accessed: 2025-11-16.

[37] AddUp Solutions. Aircraft floor bracket – reducing time mass with topology optimization. https://addupsolutions.com/applications/aircraft-floor-bracket/, 2023. Accessed: 2025-11-16.

[38] Jamie Edkins. New bugatti tourbillon revealed: 277mph chiron replacement is an engineering marvel. https://www.carwow.co.uk/news/7780/new-bugatti-tourbillon-revealed-chiron-replacement, 2024. Accessed: 2025-11-17.

[39] A. Alfaify et al. Sustainability and design for additive manufacturing: A review. https://www.sciencedirect.com/science/article/pii/S0959652620336106, 2020. Journal of Cleaner Production, Volume 270, 122383.

[40] N. Chtioui, R. Gaha, and A. Benamara. Design for additive manufacturing: Review and framework proposal. https://www.sciencedirect.com/science/article/pii/S2405896321002457, 2021. Procedia CIRP, Volume 99, Pages 73–78.

[41] X. Wang, M. Jiang, and Z. Zhou. Review on design for additive manufacturing: Process awareness and material considerations. https://www.sciencedirect.com/science/article/pii/S0264127519306021, 2019. Additive Manufacturing, Volume 27, Pages 80–92.

[42] R. Lynn, C. Saldana, T. Kurfess, N. Reddy, T. Simpson, K. Jablokow, T. Tucker, S. Tedia, and C. Williams. Toward rapid manufacturability analysis tools for engineering design education. https://www.sciencedirect.com/science/article/pii/S2351978916301056, 2016. Procedia Manufacturing, Volume 5, Pages 1183-1196.

[43] A. Moreno Nieto and E. Sánchez. Design for additive manufacturing: Tool review and a structured survey of cae tools. https://www.mdpi.com/2076-3417/11/4/1571, 2021. Applied Sciences, Volume 11, Issue 4, Article 1571.

[44] Puntozero 3D. Lattice structures – design for additive manufacturing. https://www.puntozero3d.com/en/services/lattice-structures/, 2023. Accessed: 2025-11-02.

[45] Unionfab. Design for additive manufacturing (dfam): Maximize 3d printing's potential. https://www.unionfab.com/blog/2023/11/dfam-design-for-additive-manufacturing, 2023. Published: November 18 2023; Last updated: October 18 2024.

[46] Issam El Khadiri, Maria Zemzami, Nhan-Quy Nguyen, Mohamed Abouelmajd, Nabil Hmina, and Soufiane Belhouideg. Topology optimization methods for additive manufacturing: a review. `https://doi.org/10.1051/smdo/2023015`, 2023. Int. J. Simulation and Multidisciplinary Design Optimisation, 14(12), 2023.

[47] Engineering Product Design. What is topology optimization? `https://engineeringproductdesign.com/knowledge-base/topology-optimization/`, 2024. Accessed: 2025-11-02.

[48] Marcel Langelaar. An additive manufacturing filter for topology optimization of print-ready designs. `https://link.springer.com/article/10.1007/s00158-016-1522-2`, 2017. Structural and Multidisciplinary Optimization, 55(5), 871–883, 2017.

[49] Formlabs. Le b.a-ba de l'optimisation topologique: comment utiliser des modèles algorithmiques pour concevoir des pièces légères. `https://formlabs.com/fr/blog/optimisation-topologique/`, 2025. Accessed: 2025-11-02.

[50] Grégoire Allaire. *Shape Optimization by the Homogenization Method*. Springer, 2012.