

Advances in 3D Printing Research Based on Topology Optimization

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Abstract. Topology optimization is an advanced structural design approach in the field of industrial engineering that optimizes the form of material distribution while maintaining structural strength. 3D printing is an advanced manufacturing technology that creates objects layer-by-layer by dividing a three-dimensional object into two-dimensional planes and stacking them on top of each other. In 3D printing, topology optimization can achieve lightweighting, and improve structural strength and performance, while reducing printing time and cost, providing a whole new range of possibilities for 3D printing manufacturing. At present, the industrial manufacturing industry is increasingly adopting 3D printing technology to fabricate complex objects that cannot be achieved by traditional manufacturing methods, whose flexibility and degree of freedom bridge the gap between topology-optimized and actual fabricated structures. This paper reviews recent research on 3D printing methods based on topology optimization techniques, discusses the basic manufacturing requirements and limitations of 3D printing considering topology optimization, briefly reviews practical applications of 3D printing techniques based on topology optimization in the field of industrial design, and explores the limitations of the existing applied methods and the possibilities of future work. It has far-reaching implications for the combination of topology optimization and 3D printing techniques and their application in different industrial fields.

Keywords: Topology optimization, 3D printing, Manufacturing constraints, Industrial design.

1. Introduction

3D printing, also referred to as additive manufacturing (AM), is a process that involves the layering of three-dimensional entities into a variety of two-dimensional planes using slicing software and bondable raw materials such as metal powders, plastics, and resins to achieve the preparation of structures by accumulating materials layer by layer from the bottom up [1]. 3D printing can be classified into a variety of methods, including selective laser sintering (SLS), selective laser melting (SLM), stereo lithography apparatus (SLA), electron beam selective melting (EBSM), and electron beam fusion (EBF), depending on the type of material and the form of applied heat source.

The accelerated advancement of 3D printing technology has transformed the design and manufacturing of products in the field of industrial engineering today. 3D printing technology can rapidly and accurately produce models with complex shapes, expanding the degree of freedom in manufacturing and design. 3D printing not only saves on finished products and shortens the manufacturing cycle, but also requires little or no manufacturing skills on the part of the fabricator.

In engineering design, topology optimization is a sophisticated structural design technique that is frequently employed to achieve the most idealized structural configuration. This is accomplished by adjusting the structural morphology, optimizing the distribution of materials, minimizing the number of materials used while preserving the structure's strength, and satisfying specific loading conditions, performance, and constraints and requirements.

Since the design region for topology optimization is global, the overall structure is subject to geometric topological deformation. The iterative nature of topology optimization dictates that its results produce complex geometric configurations that are often difficult to produce through traditional manufacturing methods. Designers often have to make secondary designs to the optimization results based on manufacturing techniques and experience, which usually damages the optimality of the structure or even makes the structure perform worse than the original configuration

[2]. As a result, there is a large discrepancy between the structures designed through topology optimization methods and those adopted for actual engineering and manufacturing.

3D printing technology narrows this discrepancy, making it possible to fabricate structures with complex geometrical configurations at multiple geometrical scales from micro to macro, while reducing printing time and cost without damaging the optimality of the structure.

The iterative approach to topology optimization and the nature of the optimization algorithm also introduces new limitations when using topology optimization methods for 3D printing. Considering the inherent nature of 3D printing and the various process parameters, as well as the manufacturing accuracy of the equipment, the topology-optimized structures are almost impossible to directly perform additive manufacturing [3], and 3D printing is not suitable for manufacturing all the complex topologies that have been designed. Therefore, it is crucial to impose 3D printing constraints in topology optimization. This paper analyzes the solutions proposed in the existing literature for the constraints in terms of structural dimensions, material properties, overhang angles, and connectivity, and discuss the limitations and challenges of the existing methods.

3D printing technology has greatly broadened the freedom of styling design for industrial products, and topology optimization ensures optimal structural strength at the same time. This paper discusses the practical applications of 3D printing technology based on topology optimization in industrial design in recent years, an in-depth investigation of the specific application methods and effects in structure and function, product styling, and other aspects, and discusses the future development trend of this technology. Through a systematic literature review, this paper aims to provide a relatively comprehensive analysis of the new requirements and corresponding solutions brought by 3D printing for topology optimization, with the intention of providing new ideas and inspiration for the development of engineering design and manufacturing fields.

2. Classification of Topology Optimization Methods

The research topic of topology optimization is primarily separate into continuum topology optimization and discrete structure topology optimization based on the type of independent variables used in optimization methods. Continuum topology optimization is a method that involves modifying continuous parameters, such as mass density [4], to discretize the material of the optimization space into a limited number of units. This procedure utilizes gradient information to update the parameters of the independent variable. Discrete structure topology optimization is based on creating a base structure consisting of a finite number of units in the design space, then eliminating or adding material elements according to an algorithm to constitute the final topology scheme [4].

2.1. Topology Optimization of Continuum Structures

Depending on the way the optimization algorithm inscribes the topology, continuum structural topology optimization is classified into density cell methods and boundary evolution methods.

The density cell approach assumes the introduction of a material with a density variable between 0 and 1, converting the structural topology optimization problem into a problem of optimal distribution of materials. It has a simple program implementation and is computationally efficient, but cannot account for intermediate-density materials. Compared to the boundary evolution method, the density cell method suffers from numerical instabilities such as grayscale cells, checkerboard format, mesh dependence, and local extremes [5].

Solid Isotropic Material with Penalization (SIMP) is a common method for density cell methods, where a penalty factor is introduced to penalize the intermediate densities so that the intermediate density values are clustered towards the ends and the density of the material is allowed to be continuously distributed between 0 and 1. SIMP employs re-filtering to deal with tessellated lattice phenomena, unclear structural boundaries, grid dependence, and other common problems of density cell class methods.

Boundary evolution optimization methods are usually based on level-set functions to inscribe structural boundaries. The level set method (LSM) uses a boundary description model (BDM) to handle the structural topology, where the demarcation line between materials and voids in the design space is expressed as a level set of continuous functions, and the structural boundaries are defined by the equivalent contours or surfaces of the high-dimensional functions. The LSM usually produces clear structural boundaries without the problem of grayscale cells, but the results obtained using the LSM depend heavily on the initial values, which leads to less than optimal convergence speeds. Resulting in a speed of convergence that is often less than optimal, and a large number of iterations are often required in the optimization process [6].

2.2. Topology Optimization of Discrete Structures

Discrete structural topology optimization is mainly solved by employing different optimization algorithms based on the base structure approach.

Evolutionary Structure Optimization (ESO) and the subsequent development of Bi-directional Evolutionary Structural Optimization (BESO) are a class of topology optimization commonly used methods based on discrete variables. ESO/BESO uses a discrete finite element mesh as the independent variable, with 0 or 1 of the structural cell density value representing the presence or absence of structural materials, the corresponding optimization criterion is determined according to the optimization objective, and the addition and deletion of mesh cell materials are realized according to the criterion.

Compared with the traditional structural optimization method, the ESO/BESO method does not have the problem of algorithmic difficulties that are often encountered in the traditional structural optimization method. It is more versatile and can solve the size optimization problem for various types of structures, as well as shape and topology optimization at the same time. The disadvantages are the lack of convergence, the initial design region must be large enough, and the computation is very time-consuming.

3. Core Requirements for Topology Optimization-Based 3D Printing Technology

The optimization of structural design is facilitated by topology optimization; yet, however, the intricate geometries that arise from this optimization are frequently challenging to fabricate using conventional manufacturing techniques. The capabilities of 3D printing surpass those of conventional manufacturing techniques by offering unparalleled design flexibility, allowing the creation of structures with intricate geometric shapes and a wide range of geometric scales from micro to macro measurements. However, although 3D printing effectively solves the problem of poor manufacturability of complex topologies, it remains imperative to enforce the manufacturing limitations of 3D printing in order to achieve the integration of structural design and manufacturing by enhancing the constraints of the manufacturing process [7].

3.1. Structural Dimension Requirements

3.1.1. Minimum size requirement

Topological arrangements frequently generate minuscule rod-shaped branches that are impractical for printing if the minimum dimensions of the rods are less than the laser beam diameter. In the context of additive manufacturing using powder laser sintering technology, if the minimal dimension of the internal structure, after topology optimization, is smaller than the diameter of the laser beam, the resulting minimum size of the printed part will surpass the initial design size determined by the topology optimization [8].

Within the context of density-based topology optimization, density filtering is a very efficient technique for restricting the minimum length scale.

Wang et al. [9] proposed an improved robust topology optimization scheme based on parametric Heaviside functions, which achieves the minimum size control of components and holes and guarantees convergence of both global and local meshes.

For SIMP topology optimization, Zhou et al. [10] proposed a density gradient method to limit the minimum length scale by identifying solid and empty phases, which is computationally inexpensive and easy to apply.

Yang et al. [11] further compared three gradient operators by imposing a minimum size constraint in the robust formulation, and the results showed that the Prewitt operation can compute the density gradient more accurately when boundary corrections are considered.

In the field of LSM topology optimization, Xia and Shi [12] proposed the rapid marching approach for constructing a structural skeleton. This method is employed to eliminate incorrect small geometric features by imposing constraints on the distance between the border and the skeleton. The objective is to achieve minimal length dimension control.

Wang et al. [13] implemented an efficient connection state (ECS) control technique using a virtual component skeleton (VCS). This method incorporates a mobile deformable component (MMC) to determine the minimum length scale based on the minimum thickness. This allows for precise adjustment of the minimum length scale regardless of the geometric properties of the component.

Currently, the minimum print size of industrial 3D printing devices is already small, but the minimum size constraint methods for small and medium-sized 2.5-axis 3D printers with low fineness are seldom considered.

Length scale control methods in topology optimization have reached a level of maturity where geometric size restrictions are now included into commercial software like Ansys Discovery and Altair OptiStruct, which provide many innovative structural optimization methods and a wide range of fundamental manufacturing constraints for conventional processes, composites, and 3D printing. As shown in Fig. 1, when a minimum length scale is imposed, the non-fabricable branches disappear [14].

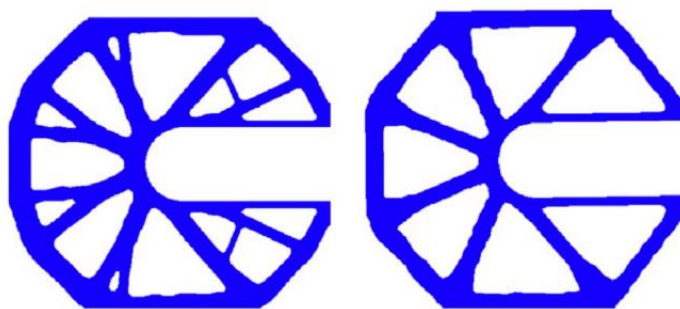


Fig. 1 Topology optimization of C-clamps in Altair OptiStruct [14].

3.1.2. Maximum size requirement

The maximum size requirement of the structure refers to the limitations imposed by 3D printer manufacturability on the maximum size of the printed part. Specifically, if the maximum geometric size of the structure is larger than the size of the molding cavity of the device, the part cannot be integrally manufactured as a whole.

Bai [15] combined a mapping method with a robust optimization method to penalize the density of central units in the structure that do not satisfy the maximum size constraint, achieving control over the maximum size of the structure without introducing any constraints.

Liu [16] developed a length-size recognition and segmentation algorithm based on the structural skeleton, which realized the dynamic limit size control of the structure by recognizing and segmenting the structural skeleton and regulating the length scales of the components based on the real-time state of the structural skeleton.

Fernandez et al. [17] proposed a density-based maximum size control method that uses two aggregation functions, p-mean and p-norm, to aggregate and highly constrain the local constraints,

reducing the introduction of holes in the optimal design and improving the manufacturability of maximum size-constrained components.

The new methods of feature size control for specific additive manufacturing processes such as multi-head printing and printing direction accuracy still remain to be improved. Therefore, there is a certain development space for researching new methods for clear structure, stable convergence, specific accuracy control, and precise feature size control.

3.2. Material Performance Requirements

3.2.1. Topology optimization design based on material anisotropy

The layer-by-layer manufacturing characteristics of 3D printing technology make the mechanical properties of microstructures anisotropic [18], resulting in different tensile strengths of materials in different directions, and the direction of stress-bearing needs to be considered when topology optimization is carried out. Reasonable planning of deposition paths and construction directions, and the design of topologies that consider the anisotropy of materials can effectively improve the load-bearing capacity and service life of the structure [8].

Liu et al. [19] used multiple level-set functions to represent the sliced contour of each layer and realized the synergistic optimization of material anisotropy and self-supporting constraints through deposition path planning based on contour offset and skeleton extraction.

Yang et al. [20] verified that the anisotropy in terms of stiffness, ultimate strength, and fracture location is caused by surface mass irregularities in the microstructural branches of the lattice by testing the mechanical properties of SLM printed titanium materials with multi-scale lattice structures.

Li et al. [21] collaboratively optimized the build orientation and topology by quantifying the printing parameters as a function of material anisotropy correlation and introducing the experimental data on anisotropy into an elastic matrix.

The current consideration of topological models for material anisotropy is overly simplified and idealized. There is still certain room for improvement in constructing quantitative correlations between specific manufacturing process parameters and material properties and improving the numerical stability and computational efficiency of optimization.

3.2.2. Topology optimization design based on manufacturing defects

Products manufactured by 3D printing technology have a significant thermal gradient during the rapid heating and cooling of each layer [18], which is prone to significant accumulation of residual thermal stresses within the structure, leading to geometrical deformations such as deformation, warping, and cracking of the part. Therefore, manufacturing defects such as residual stresses and deformations need to be considered in topology optimization.

Takezawa et al. [22] developed an optimization method for the distribution of lattice volume fraction by applying the intrinsic strain method layer by layer to form a recursive relationship to control the residual deformation through the output of the effective elastic modulus.

Zhang et al. [23] developed a parallel computational framework for the intrinsic strain method and density topology optimization to design a support structure with better rigidity under gravity loading and residual stresses to reduce the deflection of the printing cantilever before and after cutting, which improved the residual deformation of the structure.

Current research on residual stresses focuses on the study of delamination deformation by the intrinsic strain method but does not quantify the effect of contour scanning on surface residual stresses. In addition, the influence of the thermal effect of different 3D printed part geometries on the intrinsic strain value is rarely addressed in current studies. Future studies should consider the different thermal accumulation processes experienced by different height layers, so as to improve the accuracy and efficiency of the prediction of residual stress and deformation of parts.

3.3. Structural Molding Requirements

3.3.1. Overhang angle requirements

Large overhanging structures require additional support structures to hold up the overhanging portions and keep the component from deforming or collapsing because of the layer-by-layer processing characteristic of 3D printing. The support structure is removed by machining after fabrication, which increases the material cost, printing time, and difficulty of post-processing. By designing effective self-supporting structures with an awareness of the length constraints and overhang angle, one can reduce the need for support structures while enhancing the structure's manufacturability.

Based on the Heaviside projection integral function, Qian [24] proposed an overhang angle constraint method based on projected perimeter constraints and density grayscale to eliminate gradient-based global constraints for internal and external supports and avoid the phenomenon of boundary unprintability.

On this basis, Wang and Qian [25] converted the optimized design's lower limit constraint on the overhang angle into a gradient-based global constraint in the direction of construction and the density field used to represent the part simultaneously, thereby satisfying the part's self-supporting overhang angle constraint.

Langelaar [26] proposed an amplitude-modulated hierarchical filtering procedure that acts as a simplified hierarchical printing simulator, where geometries violating the overhang angle constraints are effectively excluded from the design space, enabling fully self-supporting optimized designs.

Fu et al. [27] expanded upon Langelaar's concept of hierarchical filtration by integrating existing additive manufacturing filters with a novel solid isotropic microstructure penalty method (SIMP) that was developed using elemental volume fractions. This approach demonstrates the seamless design of self-supported topologies.

The current self-supporting topology method based on cellular mesh projection and filtering suffers from deficiencies such as boundary oscillations and a large loss of structural performance after optimization. The use of a boundary evolution-based overhang constraint control method results in a smaller loss of structural performance but poor structural continuity. The topology optimization control method that synergistically optimizes the overhang length and inclination angle has certain development prospects.

3.3.2. Connectivity requirements

After the 3D printed part is fabricated, the unmelted metal powder and support material cannot be removed from the fully enclosed printed part, requiring secondary corrections or structural partitioning for fabrication, which greatly increases fabrication difficulty and cost. Considering the overall structural connectivity and eliminating closed voids are crucial for the manufacturability of the structure [14].

Topology optimization design considering structural connectivity constraints mainly starts from eliminating holes, constructing hole-boundary connection tunnels, and realizing hole self-support [8].

Luo et al. [28] used a nonlinear virtual temperature field (N-VTM) to identify the closed voids, applied multiple filtering to identify the overhanging interfaces of the closed voids, and controlled the overhanging angle based on the constraints of logarithmic function to design the structure with self-supporting closed voids with less sacrifice of structural performance.

Xiong et al. [29] proposed a BESO-based method to achieve structural connectivity control by selectively generating the shortest connecting tunnels to connect the internal cavities to the structural boundaries, as shown in Fig. 2. The method synergistically considers the structural strength, build direction, dimensional constraints, and forming constraints and can generate material distributions similar to those of free topology optimization, with less sacrifice to the structural performance.

Zhou and Zhang [30] proposed a side-constraint method for eliminating closed voids in feature-driven topology optimization by restricting the centroids with void features outside the intended domain by side constraints without adding further nonlinear constraints. The method improves

structural connectivity, but the choice of relevant parameters directly affects the accuracy of the computation.

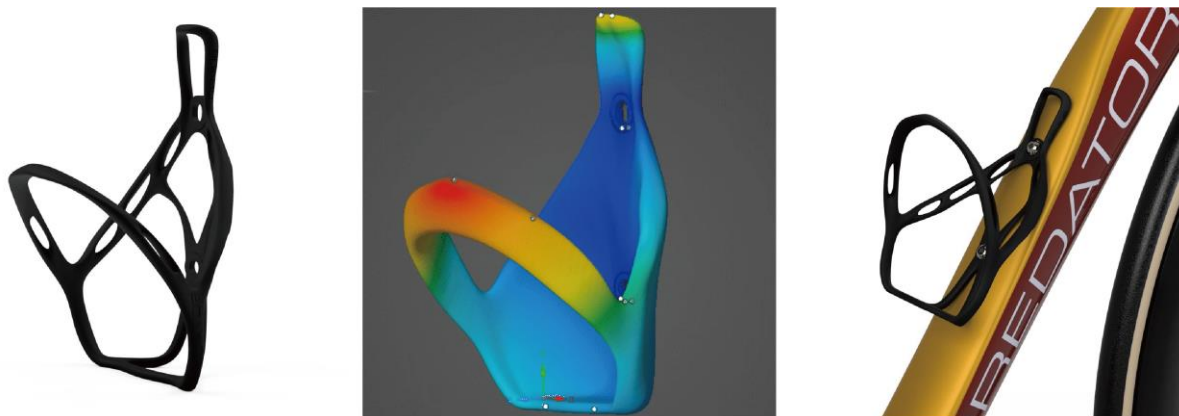


Fig. 2 Genius Water Bottle Cage Product Diagram and Stress Analysis Diagram [31].

Among many current methods, constructing the shortest connecting tunnels and realizing self-support of closed holes can effectively reduce the loss of structural performance. However, the elimination of closed holes tends to sacrifice certain structural performance, making it difficult to achieve similar structural performance as free topology optimization, while additional finite element analysis procedures increase the computational cost. Existing connectivity optimization methods are often based on a single topology optimization feature. Connectivity optimization methods that synergistically consider structural strength, dimensional constraints, and forming constraints have certain development prospects.

4. Application of 3D Printing Technology in Industrial Design Based on Topology Optimization

Industrial design needs to consider multiple dimensions such as human-machine functionality, human-computer interaction, user psychology, product life cycle, etc., and synthesize the requirements of mechanical structure and people's aesthetic needs to design. The current trend of applying 3D printing based on topology optimization in the field of industrial design is to carry out multi-level optimization based on structural constraints. First, determine the internal space that needs to be topologically optimized, and topologically optimize the overall support structure; then refine the internal minimum composition structure to ensure the optimization of the intrinsic function and structure; and finally combine the constraints of 3D printing on topology optimization, and manufacture it through 3D printing one-piece molding. From the perspective of both structural and functional design and product styling design dimensions, 3D printing technology based on topology optimization has already had numerous mature application examples in a wide range of industrial fields.

4.1. Applications in Structural and Functional Design

In the field of sports accessories, Predator Cycling has designed Genius Water Bottle Cage for bicycles through Ansys Discovery simulation driver software, as shown in Fig. 2. Unlike traditional water bottle cages that can only fit water bottles from the top, this product can be placed at an incidence angle close to 45 degrees, making it easy to reach. In addition, the water bottle cage uses SLA-printed resin material to satisfy the lightweight, durability, and grip requirements and is flexible enough to be bent and twisted.

In the field of aerospace, Airbus Group has manufactured the A320 nacelle hinge bracket and the cable bracket on the front wing of the A350 XWB vertical stabilizer by means of metal laser sintering. The optimization of strength and weight reduces construction and installation time, reduces fuel consumption, and improves flight efficiency.

In the field of rail transportation, TGM Lightweight Solutions Engineering Services used Altair HyperWorks software for topology optimization, rapid material efficiency improvements, and wall thickness optimization to reduce the weight of rail containers by 20% and the weight of the entire vehicle up to 600 kg.

In the field of automotive manufacturing, the Renault F1 team uses SLS technology to manufacture the electronic cooling ducts of its Formula 1 cars from carbon fiber-reinforced nylon. By optimizing the structure and reducing the weight of the components, the performance and speed of the vehicles were significantly improved.

In the field of biomedicine, Simright's MinSole software based on finite element topology optimization technology for the optimal design of point structure, as shown in Fig. 3, achieved the design, optimization, and manufacturing of orthopaedic insoles of integrated solutions. MinSole utilizes the characteristics of the point structure of its own high specific stiffness, and high specific strength, to ensure that the insoles of the mechanical properties of the lightweight as well as the cushioning and energy absorption effect meet the flat shoes. MinSole fulfills the medical needs of many medical fields such as flat feet, diabetic feet, long and short legs, etc., and also meets some of the manufacturing requirements of 3D printing technology with the requirement of a clear powder process.



Fig. 3 MinSole automated insole dot structure optimization model [32].

4.2. Application in Product Styling Design

In the field of household products, Joris Laarman's design of aluminum gradient chair adopts a multi-layer optimization approach, as shown in Fig. 4. The chair optimizes the design of the overall support structure with a continuous structure topology, which enhances the structural strength and improves the connectivity of different parts; meanwhile, it optimizes the design of the internal truss infill structure with a discrete structure topology, which reduces the weight and material consumption through more open units. Aluminum gradient chair takes into account the stress characteristics of different regions, which provides a new reference for product design.

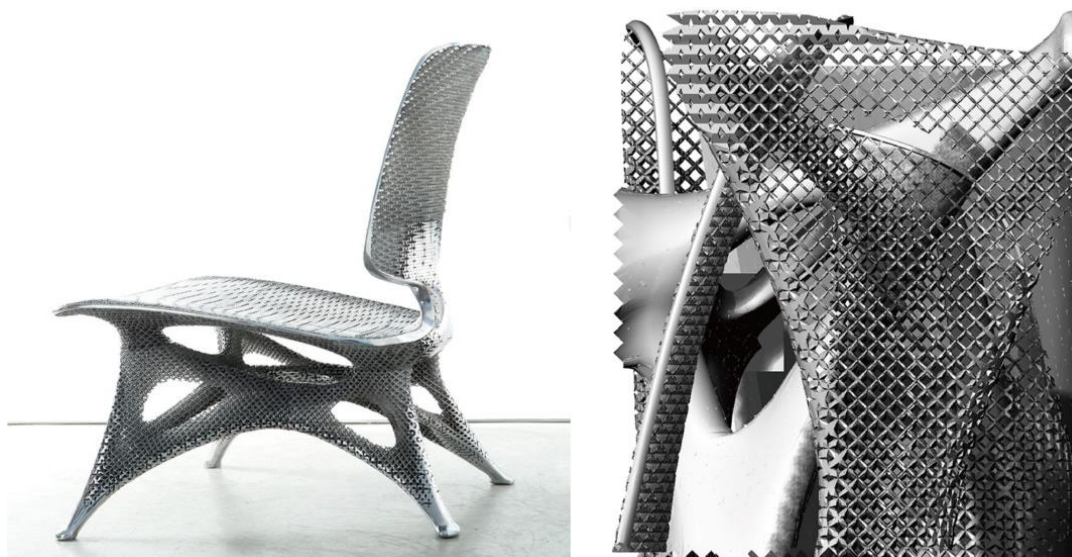


Fig. 4 Aluminum gradient chair Material distribution structure [33].

In automotive manufacturing, Airbus APWorks Light Rider uses Altair HyperWorks software for finite element analysis and topology optimization of the frame structure design as shown in Fig. 5. The optimization process involves three key steps, namely creating the optimal shape given the boundary conditions, deriving the geometry from the optimized results, and dealing with 3D printing-specific manufacturing constraints [34]. The Light Rider saves weight and material costs, reduces assembly time, improves productivity, and provides a new reference for integrating additional functionality into components in automotive manufacturing.

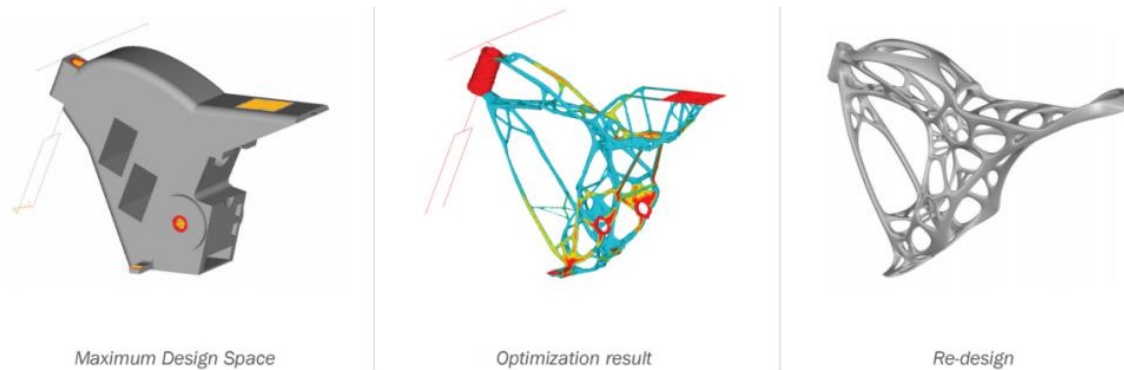


Fig. 5 Light Rider product diagram and optimization process diagram [34].

In the field of amenities, Studio-oberhauser's NIDO is the first wine rack 3D printed in concrete. By integrating reinforcing steel rods during the printing process, it optimizes weight, space, cost, and material usage, while enhancing structural stability, enabling precise measurement and planning design, and facilitating the advancement of powder bed printing technology in the industrial design sector.

5. Conclusion

The deep integration of topology optimization and 3D printing technology contributes to the fabrication and production of high-performance, high-strength, multifunctional, and lightweight structures, reduces printing time and cost, and opens up entirely new possibilities for industrial engineering and manufacturing, making it a popular and attractive research direction today and in the future.

Based on the overview of 3D printing technology and the principles of topology optimization, this review discusses the principles of the commonly used methods such as SIMP, LSM, ESO/BESO, etc., in the topology optimization of continuum and discrete structures, and analyzes the advantages and disadvantages of each method. Based on the layer-by-layer cumulative fabrication characteristics of 3D printing technology and its own fabrication constraints, this review summarizes the core requirements and challenges of 3D printing technology for topology optimization in terms of structural dimensions, material properties, and structural molding constraints. Combined with specific examples from the literature, this review presents an outlook on possible future research directions based on the current state of research.

By analyzing in detail the design ideas, topology optimization logic, and manufacturing process of product cases in different industrial fields, such as transportation, rehabilitation aids, and household products, this review demonstrates the specific applications and development trends of 3D printing technology based on topology optimization in the two aspects of structural and functional design and product styling design, proves the important value of this technology in improving product performance, reducing cost and shortening production cycle.

Although this review provides a comprehensive analysis of the applications of topology optimization-based 3D printing technology in industrial design, there are still some limitations. Existing applications tend to be based on a single vertical and there is still a contradiction between the aesthetic properties of the external shape and the functional and structural properties of the product.

Cross-domain industrial design with product performance and assembly as the primary design constraints can maximize the potential of product structure and performance optimization and has a broad development prospect. Meanwhile, the review mainly focuses on analyzing the engineering and manufacturing domains that can be quantitatively described, and qualitative issues such as market acceptance of industrial products, user preference, and practical operation in mass production are not explored.

Future research should further explore the application potential of topology optimization and 3D printing technology in different industrial fields, combined with the research of emerging materials and processes, to achieve the integrated design of materials, structures, processes, and performance. When referencing topology optimization additive manufacturing technology within the field of industrial design, it is important to strengthen interdisciplinary cooperation, combining knowledge from the fields of design, materials science, and mechanical engineering, to achieve a more comprehensive product innovation in aesthetic and engineering multi-dimensions, which has a wide range of application prospects.

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