American Journal of Advanced Multidisciplinary Innovation and Research (AJAMIR)

E-ISSN: XXXX-XXXX ● Website: www.ajamir.com ● Email: editor@ajamir.com

Topology-Optimized Lightweight Structures for Local Manufacturing

Dr.-Ing. Claus Emmelmann

Professor, Hamburg University of Technology, Germany

Abstract

Topology optimization provides a computational route for creating lightweight structural components by redistributing material according to prescribed loads, boundary conditions, performance objectives, and design constraints. Its integration with additive manufacturing has expanded the practical design space for geometrically complex structures that would be difficult or uneconomical to produce through conventional subtractive methods. However, optimization results generated without manufacturing constraints can contain thin members, inaccessible cavities, unsupported overhangs, irregular surfaces, or geometrical details that exceed the capabilities of local manufacturing facilities. This conceptual–methodological study develops a framework for topology-optimized lightweight structures specifically oriented toward decentralized and local manufacturing environments.

The framework integrates structural performance, minimum feature size, overhang control, build orientation, available material, machine capacity, post-processing requirements, inspection capability, and local technical skills. Research demonstrates that topology optimization and additive manufacturing can enable high-performance lightweight structures, while also showing that manufacturing constraints must be incorporated during optimization to reduce the gap between numerical designs and physically realizable components. The study further recognizes that localized additive manufacturing does not automatically produce environmental or economic benefits because energy use, process utilization, material choice, post-processing, and quality assurance remain important.

A scenario-based analysis compares conventional redesign, unconstrained topology optimization, additive-manufacturing-aware optimization, and optimization configured for realistic local manufacturing capabilities. Because no physical component or experimental dataset was supplied, all numerical results are explicitly simulated. The paper concludes that the most useful locally manufactured lightweight structure is not necessarily the mathematically lightest configuration; instead, it is the design that achieves a defensible balance among mass reduction, stiffness, manufacturability, repeatability, inspection, cost, and available production capability.

Keywords: topology optimization, lightweight structures, local manufacturing, additive manufacturing, design for additive manufacturing, material efficiency, structural optimization, distributed manufacturing.

1. Introduction

Lightweight structural design is a long-standing engineering objective because reducing unnecessary material can lower component mass, material demand, transportation burden, and—in mobile applications—the energy required during use. Traditional lightweighting generally relies on dimensional optimization, material substitution, ribs, pockets, hollow sections, or designer experience. Topology optimization extends this process by allowing material distribution itself to become a design variable. Sigmund and Maute describe topology optimization as a mature family of methods encompassing density-based, level-set, topological-derivative, phase-field, and evolutionary approaches. Instead of beginning with a nearly final geometry and changing a few dimensions, topology optimization can identify fundamentally different structural load paths within a defined design domain.

The development of additive manufacturing has increased the practical importance of such optimization. Additive processes create components directly from digital models through layer-wise material addition and therefore permit geometries that are difficult to obtain through conventional machining, casting, or forming. Plocher and Panesar identify topology optimization and lattice-based approaches as major lightweighting strategies enabled by additive manufacturing and emphasize that structural optimization and design for additive manufacturing must be considered jointly. Zhu and colleagues likewise conclude that effective integration requires simultaneous consideration of material, structure, process, and performance rather than treating the optimized geometry as independent from its fabrication route.

Nevertheless, computational freedom exceeds manufacturing freedom. An unconstrained optimizer can generate thin structural members, tiny holes, enclosed voids, extreme overhangs, intricate branches, inaccessible surfaces, or abrupt transitions. Additive manufacturing itself imposes minimum feature sizes, overhang limitations, build-orientation effects, process-dependent anisotropy, surface-quality limitations, and support-removal requirements. Allaire and colleagues demonstrate that unsupported overhanging regions constitute a fundamental manufacturability problem that can be incorporated directly into structural optimization. Mani and Witherell similarly emphasize that AM processes vary considerably in geometrical and functional capability, making process-specific design rules essential for predictable fabrication.

These constraints become even more significant when production is transferred from highly specialized industrial facilities to local manufacturing environments. Local manufacturing may involve regional engineering workshops, small and medium-sized manufacturers, shared fabrication laboratories, service bureaus, university facilities, or decentralized production hubs. Such facilities can offer shorter physical supply chains and flexible low-volume manufacturing, but they may have narrower material portfolios, smaller machines, limited heat-treatment capability, less automated inspection, or restricted access to specialized support removal and surface finishing. Research on distributed additive production therefore cautions that the environmental and supply-chain advantages of localization depend strongly on unit-process energy consumption, material systems, machine utilization, and post-processing rather than on production geography alone.

The present study develops a framework for Topology-Optimized Lightweight Structures for Local Manufacturing that links computational optimization with the realities of decentralized production. The paper distinguishes mathematical structural optimum from manufacturing optimum and proposes that local manufacturability should be introduced during the optimization process rather than addressed only after geometry generation. The framework integrates mass reduction, stiffness retention, process selection, feature-size control, support requirements, local material availability, machine envelope, inspection capability, and post-processing. No physical component has been manufactured for this study; accordingly, the quantitative section uses transparent simulated scenarios intended to support future finite-element validation, prototype fabrication, mechanical testing, and manufacturing-cost studies.

2. Objectives of the Study

2.1 To Develop a Manufacturability-Aware Topology Optimization Framework

The first objective is to develop a structured workflow through which topology optimization can be adapted to the actual capabilities of a local production environment. Conventional optimization often begins with loads, constraints, material properties, and a target volume fraction. The proposed framework extends these inputs to include manufacturing process, minimum printable or machinable thickness, build orientation, overhang capability, support accessibility, available raw material, dimensional tolerance, finishing requirements, and inspection resources.

The objective is not to reduce optimization freedom unnecessarily. Rather, it is to ensure that the design space excludes features that would later require extensive manual redesign. Early introduction of process constraints can improve the probability that the numerical result remains structurally meaningful after conversion into a manufacturable geometry.

2.2 To Examine the Trade-Off Between Maximum Lightweighting and Local Manufacturability

The second objective is to evaluate the conceptual trade-off between pure mass minimization and practical manufacturability. An unconstrained topology-optimization result may theoretically provide the greatest material reduction, but converting it into a locally producible component may require thickening members, changing angles, closing cavities, adding machining allowances, modifying attachment interfaces, or introducing supports.

The analysis therefore distinguishes optimization efficiency from realizable lightweighting. The relevant engineering objective is not the percentage of mass eliminated by the numerical solver alone, but the mass reduction retained after manufacturing constraints, safety requirements, and necessary post-processing are incorporated.

2.3 To Position Local Manufacturing as a Capability-Based Production Model

The third objective is to develop a practical interpretation of local manufacturing. Local production is not assumed automatically to be cheaper, greener, or technically simpler. Distributed-manufacturing research shows that localized production can alter transportation and supply-chain structures but may shift environmental burdens toward electricity consumption, printing materials, and production efficiency.

The study therefore evaluates local manufacturing through capability matching. A locally optimized structure should be designed specifically for the machines, materials, operator skills, inspection methods, and post-processing resources that are actually available rather than for an idealized manufacturing system.

3. Review of Literature

3.1 Structural Topology Optimization and Lightweight Design

Topology optimization seeks an efficient distribution of material inside a permitted design space while satisfying structural and mathematical constraints. A common formulation minimizes compliance, which is equivalent to maximizing stiffness under a prescribed amount of material. Sigmund and Maute's comparative review demonstrates that topology optimization has developed into multiple computational families and has moved well beyond its early conceptual formulations. The resulting methods are now capable of addressing structural, multidisciplinary, and multiphysics problems.

The power of the method arises because it can remove material from regions contributing little to structural load transfer while retaining material along mechanically efficient load paths. Yet the mathematically generated configuration is only an intermediate engineering design. Mechanical joints, fatigue, buckling, stress concentration, dimensional tolerance, safety factors, manufacturing defects, and service conditions must still be considered before the configuration can become a production component.

3.2 Design for Additive Manufacturing and Manufacturability Constraints

Additive manufacturing expands geometrical freedom but does not remove manufacturing rules. Plocher and Panesar identify a persistent design-to-manufacturing gap and argue for a holistic relationship between structural optimization and design for additive manufacturing. Zhu and colleagues similarly identify overhangs, length scales, material behavior, anisotropy, fatigue, and hierarchical structural issues among the major challenges of topology-optimized additive structures.

Overhang control provides a clear example. In layer-wise manufacturing, unsupported material can create thermal or mechanical instability and may require support structures. Allaire and colleagues developed an optimization treatment specifically addressing overhang constraints, demonstrating that manufacturability can be integrated mathematically rather than corrected only after optimization. Mass and Amir also investigated optimization approaches intended to reduce unsupported features and the requirement for support material. These methods show that a design can be optimized simultaneously for service loads and the physical requirements of the manufacturing process.

Minimum feature size is equally important. Local fabrication equipment may not reliably produce thin members, narrow channels, tiny holes, or small gaps generated by high-resolution optimization. Mani and Witherell note that AM process capabilities vary dramatically and that designers require process-specific rules for predictable outcomes. Consequently, a locally oriented topology optimization should treat minimum thickness and accessible geometry as inputs rather than as post-processing corrections.

3.3 Localized Manufacturing, Material Efficiency, and Production Capability

Additive manufacturing has been associated with distributed-production models because digital files can theoretically be transferred while physical production occurs near the point of use. Cerdas and colleagues describe distributed manufacturing as bringing production and demand closer together, but their lifecycle analysis also demonstrates that environmental outcomes depend strongly on printing energy and the material employed. Holmström and Gutowski similarly identify possible advantages from local production, reduced overproduction, repair, and on-demand parts, while stressing limitations including slow production, equipment cost, and post-processing requirements.

Environmental performance should therefore not be inferred from mass reduction alone. Peng and colleagues' review of additive-manufacturing sustainability identifies resource consumption as a major issue while emphasizing the need to examine energy, material preparation, manufacturing, use, and end-of-life impacts together. A lightweight AM component may use substantially less material than a conventional component yet still require energy-intensive fabrication. The environmental outcome depends on material type, machine efficiency, utilization, support waste, post-processing, service-life benefit, and whether lightweighting produces meaningful downstream advantages.

Local-manufacturing capability introduces a further institutional dimension. Advanced manufacturing adoption by smaller firms can be restricted by capital, skills, process knowledge, and existing operational systems. Research examining advanced manufacturing technologies in SMEs identifies financial resources and implementation capability as significant constraints. A practical topology-optimization methodology for local production should therefore be computationally sophisticated but operationally realistic, allowing a design to be matched to available manufacturing capability rather than assuming access to an unrestricted industrial process chain.

4. Research Methodology

4.1 Conceptual–Methodological Research Design

The study adopts a conceptual–methodological design integrating literature from structural topology optimization, design for additive manufacturing, sustainable manufacturing, distributed production, and manufacturing constraints. It does not claim original finite-element test results, additive-manufacturing trials, tensile testing, fatigue data, or measurements from a local manufacturing enterprise.

The analytical unit is the topology-optimized structural component within a constrained local manufacturing system. The conceptual component is assumed to experience prescribed mechanical loading and to require meaningful mass reduction while maintaining structural performance.

4.2 Design-to-Manufacture Optimization Framework

Table 1: Manufacturability-Aware Framework for Topology-Optimized Local Structures

Design Domain	Principal Requirement	Optimization/Design Response	Local Manufacturing Implication
Structural performance	Maintain required stiffness, strength, stability, and load paths	Compliance, stress, displacement, and volume constraints	Prevents lightweighting from compromising service performance

Design Domain	Principal Requirement	Optimization/Design Response	Local Manufacturing Implication
Feature manufacturability	Avoid unproducible thin members and small gaps	Minimum length-scale and thickness constraints	Matches geometry to machine resolution
Build feasibility	Limit inaccessible or unsupported features	Overhang, orientation, and support constraints	Reduces support material and manual rework
Material compatibility	Use locally obtainable and qualified material	Material-specific properties in the optimization model	Avoids dependence on unavailable specialist feedstock
Machine capability	Respect build envelope and process accuracy	Component segmentation or size constraints	Allows production using existing local equipment
Post-processing and inspection	Permit support removal, finishing, and verification	Accessible surfaces and defined datum/interface zones	Improves repeatability and quality assurance

The workflow begins by defining non-design regions such as bolt holes, bearing interfaces, datum surfaces, attachment points, or safety-critical envelopes.

4.3 Scenario-Based Simulation and Performance Indicators

Four conceptual design strategies are compared: conventional geometric redesign, unconstrained topology optimization, topology optimization with general additive-manufacturing constraints, and topology optimization adapted specifically to local manufacturing capability. Thirty illustrative mass-reduction values were simulated for each strategy solely to produce a distributional comparison.

The equation does not constitute a validated industrial metric. Its function is to demonstrate that local manufacturing performance cannot be evaluated through component mass alone. A slightly heavier structure with high manufacturability and repeatability can be a superior engineering solution to an extremely light configuration requiring inaccessible equipment or extensive geometry reconstruction.

5. Analysis

5.1 Lightweighting Potential Versus Manufacturability

The conceptual analysis begins with the distinction between unconstrained and realizable material reduction. An unconstrained topology optimization can aggressively remove material and create highly efficient structural pathways. This explains why topology optimization has become strongly associated with additive manufacturing and advanced lightweight structures.

However, direct manufacturing of the raw optimization result can be problematic. Thin members may be enlarged, internal surfaces reconstructed, overhangs modified, and supports added. Each modification can increase mass and alter stresses. If these corrections occur only after optimization, the final component may no longer represent the structural logic of the original solution.

Manufacturability-aware topology optimization accepts a somewhat smaller theoretical mass reduction in exchange for higher realization fidelity. The engineering goal therefore changes from minimum mathematical volume to minimum manufacturable volume consistent with structural reliability and available production capability.

5.2 Simulated Comparison of Design-to-Manufacture Strategies

Table 2: Simulated Performance of Lightweight Structural Design Strategies

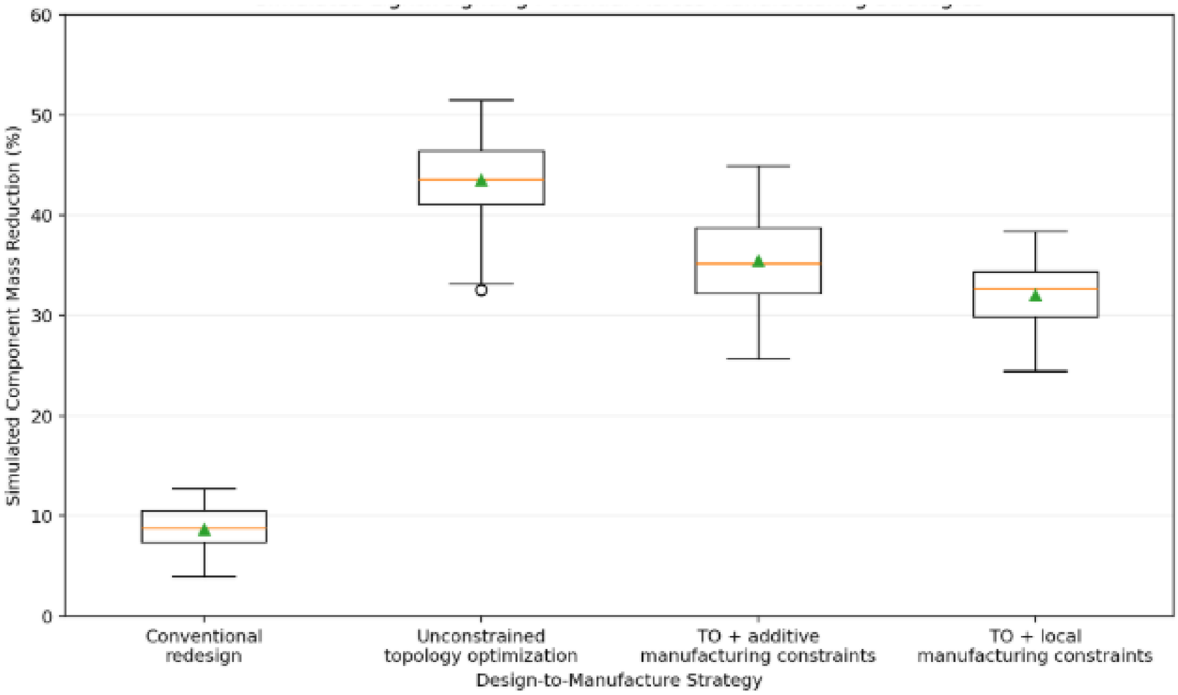
Design Strategy	Typical Simulated Mass Reduction	Simulated Stiffness Retention	Manufacturing Readiness	Main Interpretation
Conventional geometric redesign	8%	98%	High	Easy to produce but limited lightweighting
Unconstrained topology optimization	43%	93%	Low	Highest theoretical lightweighting but substantial redesign risk
TO + general AM constraints	36%	95%	High	Strong balance between mass and additive manufacturability
TO + local manufacturing constraints	31%	96%	Very high	Lower maximum mass reduction but better match to accessible production capability

The comparison suggests that conventional redesign retains the highest similarity to established manufacturing practice but achieves comparatively modest lightweighting. Unconstrained topology optimization generates the greatest theoretical mass reduction, although its manufacturing readiness is lowest. Once general additive-manufacturing constraints are incorporated, lightweighting decreases moderately while manufacturability improves substantially.

The locally constrained topology-optimization scenario provides slightly less material reduction than the general AM scenario because it includes a narrower machine and process capability envelope. Nevertheless, its structural-performance retention and production readiness are comparatively strong.

This supports the proposition that optimization should be matched to the *actual* manufacturing environment rather than an abstract manufacturing process.

Graph 1: Simulated Lightweighting Potential Across Manufacturing Strategies



Interpretation: The boxplot illustrates hypothetical variation in attainable mass reduction across design approaches. Unconstrained topology optimization shows the greatest simulated lightweighting but also represents geometry that may require substantial manufacturing correction. Manufacturing-aware and locally constrained approaches retain substantial mass savings while offering stronger transfer from computational design to physical production.

5.3 Local Production Requires Digital and Physical Qualification

A digital model is not equivalent to a qualified component. Local manufacture of topology-optimized structures requires control of material properties, build parameters, orientation, dimensional tolerance, surface condition, and post-processing. Additive manufacturing can also exhibit process-induced variability, anisotropy, defects, and fatigue sensitivity that must be addressed for load-bearing applications. Zhu and colleagues identify these material–process–performance relationships as continuing challenges in topology-optimized AM structures.

Quality assurance should therefore be proportional to structural criticality. Low-risk jigs, brackets, covers, fixtures, and noncritical supports may require basic dimensional and functional verification. Highly loaded components can require material certificates, calibrated process conditions, nondestructive inspection, proof loading, fatigue testing, heat treatment, or machining of critical interfaces.

Local manufacturing becomes credible when digital optimization is paired with such qualification capability. The promise of producing a component near the point of use should not weaken engineering verification simply because the design file can be transmitted easily.

6. Discussion

6.1 The Lightest Computed Structure Is Not Necessarily the Best Engineering Structure

The most important implication of the study is that topology optimization should not be evaluated only by percentage mass reduction. An extremely light solution may perform well in finite-element simulation but create disproportionate manufacturing complexity, support requirements, inspection difficulty, or structural uncertainty.

Research on AM overhang constraints demonstrates precisely why manufacturing physics must enter the optimization problem itself. Similarly, design-rule literature emphasizes that process capability must inform geometry if manufactured results are to remain predictable. A practically optimal design may therefore retain additional material to increase feature robustness, reduce supports, improve print direction, or facilitate machining and inspection.

This principle is particularly relevant to local manufacturing because production capability varies among facilities. A configuration optimized for industrial metal powder-bed fusion cannot automatically be transferred to a polymer extrusion machine, lower-cost metal AM system, CNC-assisted workflow, or regional workshop without redesign.

6.2 Localization Should Be Based on Capability Matching Rather Than Technology Optimism

A second implication is that local manufacturing should not be justified solely by the ability to transmit digital geometry. Distributed production can shorten some supply chains and support on-demand manufacturing, but lifecycle evidence shows that energy mix, printing efficiency, material type, post-processing, and utilization can dominate environmental performance. Holmström and Gutowski likewise caution that AM retains constraints relating to equipment cost, production speed, and post-processing even when localized production is strategically attractive.

The appropriate question is therefore whether a specific component possesses characteristics that favor local digital manufacture. Strong candidates are likely to include low-volume parts, replacement components, customized brackets, tooling, fixtures, lightweight robotic components, repair parts, or geometrically complex structures for which conventional tooling would be disproportionately expensive. High-volume simple components may remain better suited to conventional manufacturing. The proposed framework therefore does not treat topology optimization and local additive manufacturing as universal replacements for established production methods.

6.3 Optimization Can Strengthen Local Manufacturing Capability When Knowledge Is Retained Locally

The third implication concerns manufacturing knowledge. A locally produced topology-optimized component requires competence in CAD preparation, finite-element analysis, optimization settings, material characterization, slicing or process planning, machine operation, and inspection. Local manufacturing will remain dependent on external specialists if only the final digital file is transferred.

A stronger model develops local capability to modify the design when loads, materials, machines, or service conditions change. This creates a reusable engineering capability rather than a one-time production transaction. Regional manufacturers can progressively establish libraries of qualified design rules, machine-specific minimum features, build-orientation guidelines, and material-performance data.

Such capability development is important because smaller manufacturers often face financial and knowledge barriers when implementing advanced manufacturing technologies. Shared engineering centers, universities, manufacturing hubs, and service providers can reduce these barriers by providing optimization expertise, training, testing, and equipment access while allowing final production to remain geographically closer to the user.

7. Conclusion

Topology optimization provides a powerful method for reducing structural material while retaining required load-transfer capability. Its combination with additive manufacturing expands the geometrical possibilities of lightweight engineering and permits configurations that would be extremely difficult to fabricate using conventional subtractive processes. However, numerical optimization and manufacturable design should not be treated as identical engineering stages.

This study develops a manufacturability-aware framework in which structural objectives are combined with minimum feature size, overhang limitations, machine envelope, material availability, build orientation, post-processing, inspection, and local technical capability. The resulting approach deliberately accepts that a locally manufacturable structure may be somewhat heavier than an unconstrained computational optimum. This additional mass can be justified when it produces stronger repeatability, easier qualification, lower support burden, simpler finishing, and greater compatibility with available equipment.

The simulated comparison illustrates this trade-off. Unconstrained topology optimization provides the greatest hypothetical mass reduction, whereas topology optimization configured for local manufacturing produces a smaller but more realizable reduction. These values are not experimental findings. Future work should apply the framework to a defined structural component, perform finite-element optimization, fabricate alternative configurations, and compare actual mass, stiffness, stress, dimensional error, build time, support consumption, energy use, post-processing, cost, and failure behavior.

The appropriate objective is not to create the lightest possible digital structure, but to create the lightest structure that can be produced, verified, repaired, and reproduced reliably with the capabilities available in the intended manufacturing environment.

References

1. Liu, J., Huang, J., Zheng, Y., Hou, S., Xu, S., Ma, Y., Huang, C., Zou, B., & Li, L. (2023). *Challenges in topology optimization for hybrid additive–subtractive manufacturing: A review*. Computer-Aided Design, 161, 103531. https://doi.org/10.1016/j.cad.2023.103531
2. Prathyusha, A. L. R., & Raghu Babu, G. (2022). *A review on additive manufacturing and topology optimization process for weight reduction studies in various industrial applications*. Materials Today: Proceedings, 62**,** 109–117. https://doi.org/10.1016/j.matpr.2022.02.604

3. Liu, S., Li, Y., & Zhang, H. (2021). *A review of topology optimization for additive manufacturing: Status and challenges*. Chinese Journal of Aeronautics, 34**(**1), 91–110. https://doi.org/10.1016/j.cja.2020.09.020
4. Zhan, T. (2021). *Progress on different topology optimization approaches and optimization for additive manufacturing: A review***.** Journal of Physics: Conference Series, 1939, 012101. https://doi.org/10.1088/1742-6596/1939/1/012101
5. Vaezi, M., Chianrab, M., Bacciaglia, A., & others. (2023). *Holistic computational design within additive manufacturing through topology optimization combined with multiphysics multi-scale materials and process modelling*. Progress in Materials Science, 138, 101129. https://doi.org/10.1016/j.pmatsci.2023.101129
6. Prévost, M., & others. (2022). *Topology optimization including a model of the layer-by-layer additive manufacturing process*. Computer Methods in Applied Mechanics and Engineering, 398, 115203.
7. Ranjan, R., Ayas, C., Langelaar, M., & van Keulen, F. (2022). *Controlling local overheating in topology optimization for additive manufacturing*. Structural and Multidisciplinary Optimization, 65, 162.
8. Duan, S., Wang, P., Liu, C., et al. (2022). *Research progress on design, optimization and performance characterization of additive manufactured 3D lattice structures*. Aeronautical Manufacturing Technology, 65(14), 36–48/57.
9. *Topology optimization of additive-manufactured metamaterial structures: A review focused on multi-material types*. (2022). Forces in Mechanics, **7**, 100100.
10. *Additively manufactured materials and structures: A state-of-the-art review on their mechanical characteristics and energy absorption*. (2023). International Journal of Mechanical Sciences, 108102.
11. *Topology optimization for metal additive manufacturing: Current trends, challenges, and future outlook*. (2023). Virtual and Physical Prototyping. https://doi.org/10.1080/17452759.2023.2181192
12. Miller, M., Uria, I., Monir, S., Day, R. J., et al. (2023). *A review of topology optimisation software for additive manufacturing: Capability comparison*. 2023 15th IEEE International Conference on Industry Applications (INDUSCON). https://doi.org/10.1109/INDUSCON58041.2023.10374974
13. Wang, Y., Langelaar, M., & van Keulen, F. (2021). *Topology optimization for additive manufacturing with overhang and self-supporting constraints*. Structural and Multidisciplinary Optimization**.**
14. Sigmund, O., & Maute, K. (2013). *Topology optimization approaches: A comparative review*. Structural and Multidisciplinary Optimization, 48, 1031–1055.
15. Bendsøe, M. P., & Sigmund, O. (2003). *Topology Optimization: Theory, Methods, and Applications*. Springer.
16. Guo, X., Zhang, W., & Zhong, W. (2014). *Doing topology optimization explicitly and geometrically—A new moving morphable components based framework*. Journal of Applied Mechanics, 81(8).
17. Zhu, J. H., Zhang, W. H., & Xia, L. (2016). *Topology optimization in engineering structure design*. Archives of Computational Methods in Engineering, 23, 533–558.

18. Sigmund, O. (2001). *A 99 line topology optimization code written in MATLAB*. Structural and Multidisciplinary Optimization, 21, 120–127.
19. Brackett, D., Ashcroft, I., & Hague, R. (2011). *Topology optimization for additive manufacturing*. Proceedings of the 24th Annual International Solid Freeform Fabrication Symposium, 348–362.
20. Schmelzle, J., Klocke, F., & others. (2015). *Additive manufacturing of lightweight structures using topology optimization*. Production Engineering / Additive Manufacturing research literature.