Title:

“Introduction to design optimization & Design of Lightweight Structures for Additive Manufacturing”

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The millstones in history of CAD

PRONTO developed by Patrick Hanratty, “the father of CAD/CAM” (1957)

‘**Sketchpad**, A Man-Machine Graphical Communication System’ Ivan Sutherland, 1963

Versprille’s NURBS invention, which formed the basis for modern surface modeling (1970)

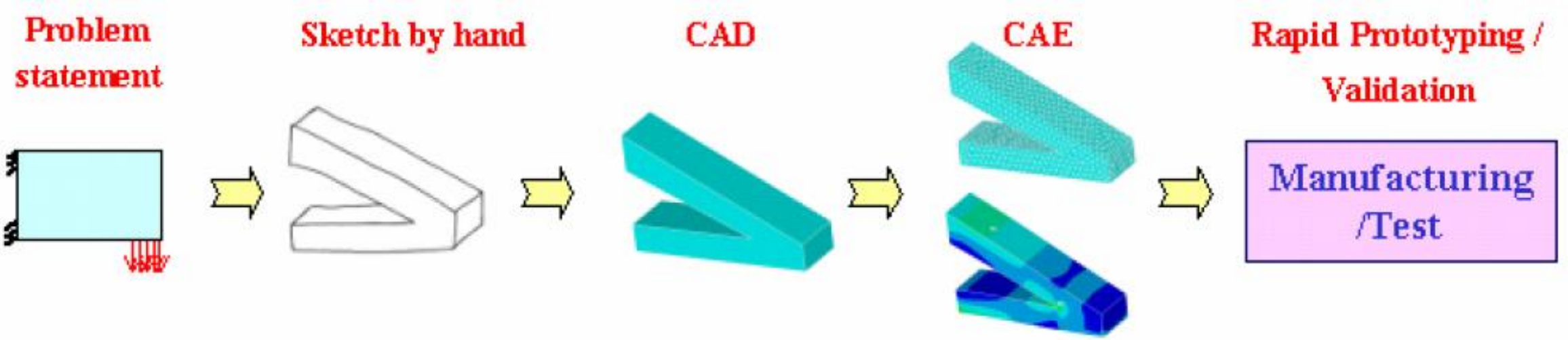
PADL (Part and Assembly Description Language) by Grayer, Lang and Braid (1970)

ADAM, a basis for commercial CAD software systems, was released in 1972

CATIA (Computer-Aided Three-Dimensional Interactive Application) (1977)
The founding of **Autodesk** and subsequent release of **AutoCAD** (1981)

Pro/ENGINEER was released in 1987

‘Traditional’ Product Design Process

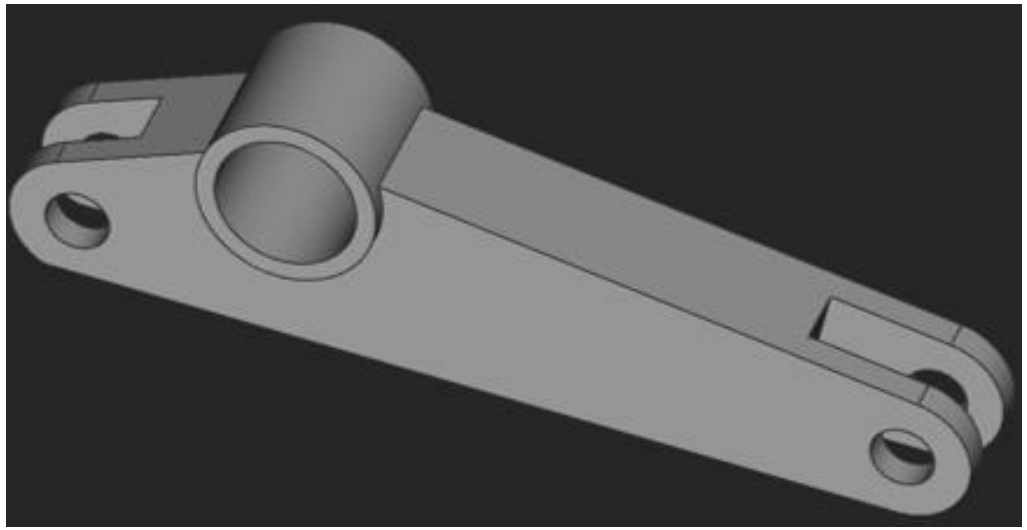


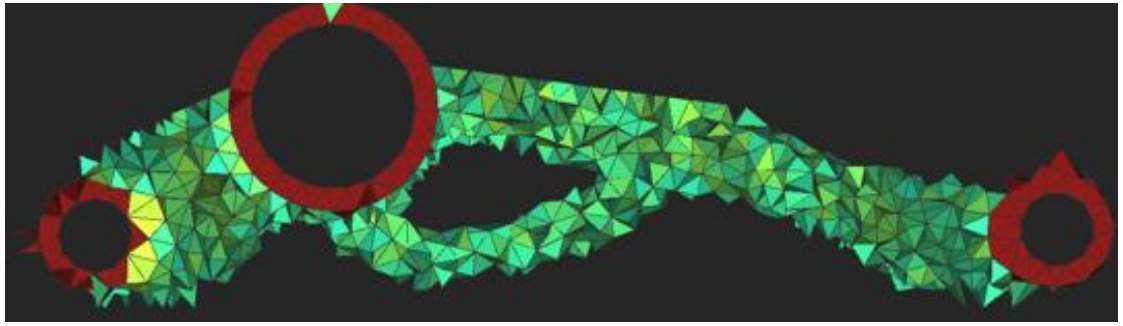
Source: Weck, (2004)

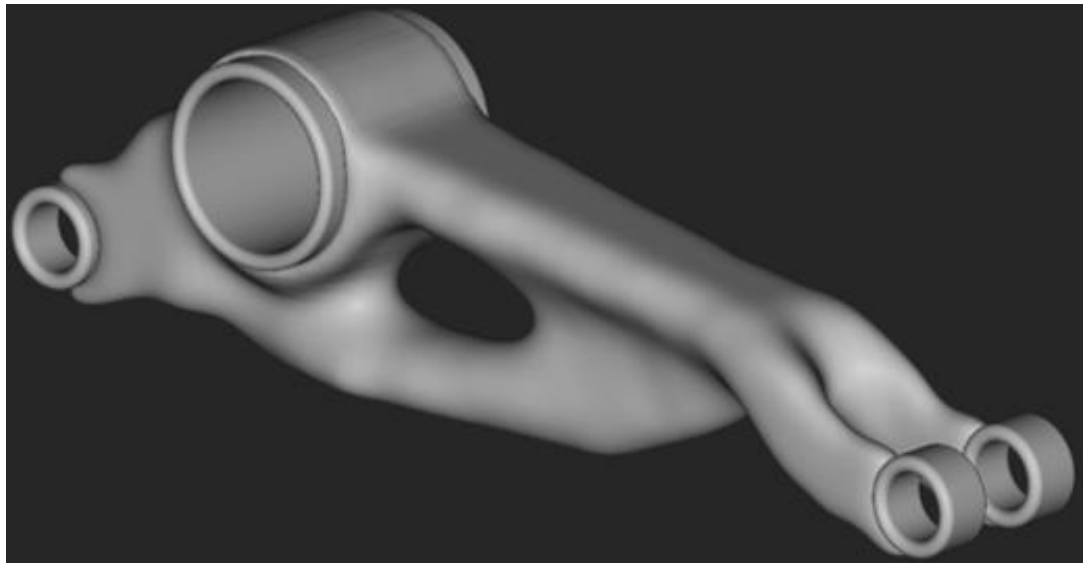
Product Design & Additive Manufacturing

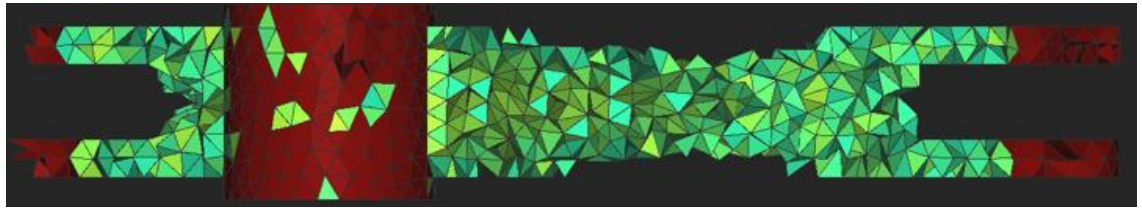
- The recent advances in Additive Manufacturing create great prospects for both researchers and industry
- Based on important advantages such as the possibility to manufacture complex geometries, the technology is being continuously developed and improved
- Despite the manufacturability achievements in the field of Design for Additive Manufacturing (DfAM) many challenges remain
- Many researchers try to create and evaluate innovative lightweight structures that are based on the great advantages of additive manufacturing and overcome manufacturing constraints

‘Nowadays’ Product Design Process



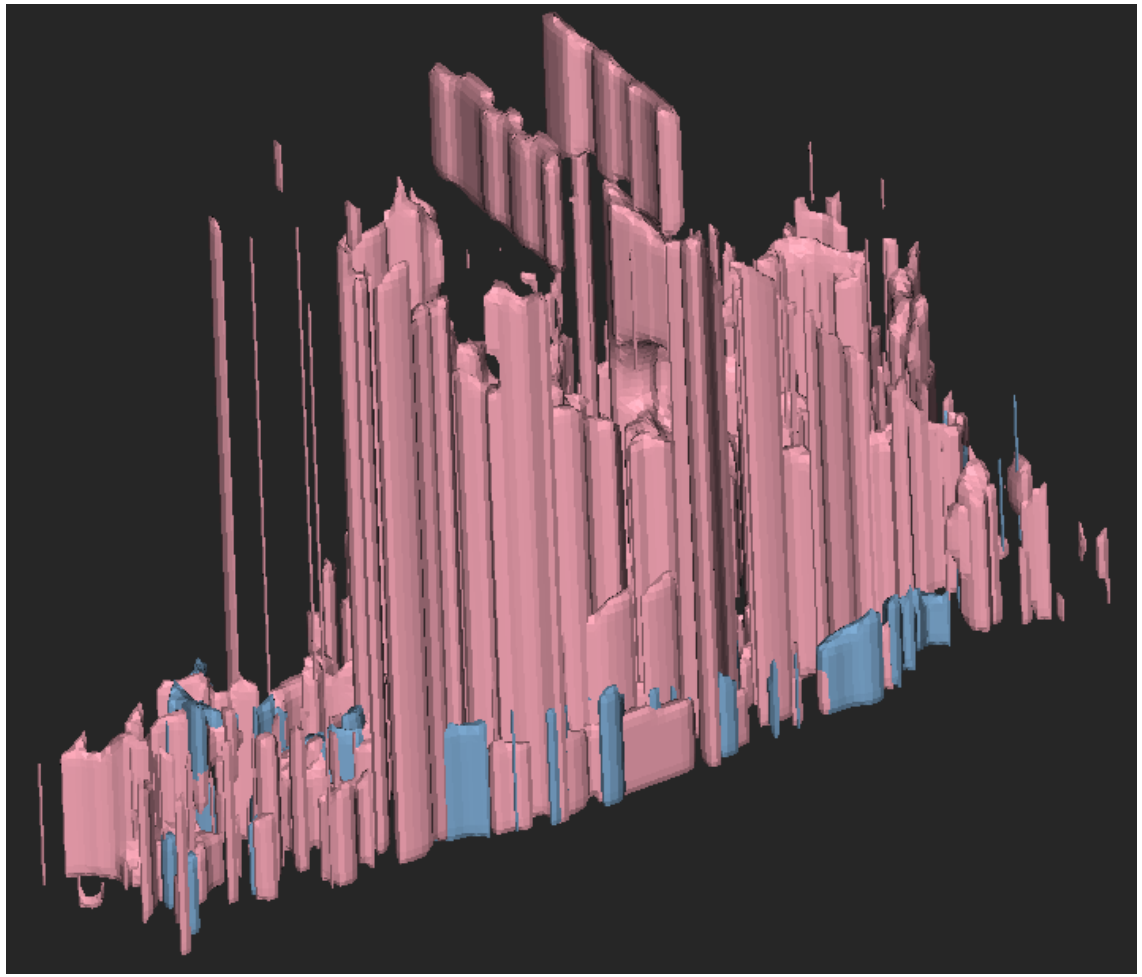


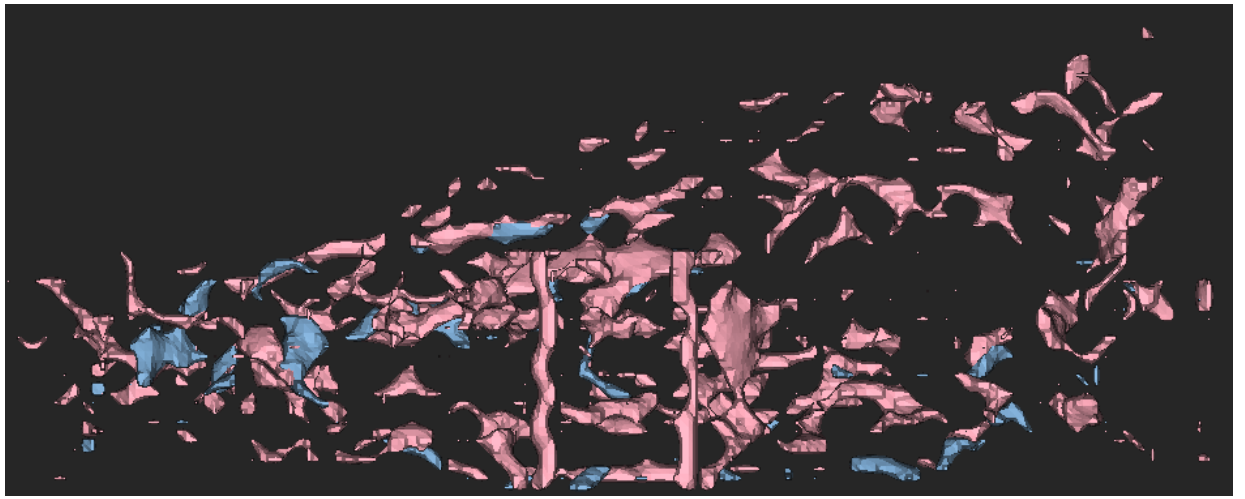


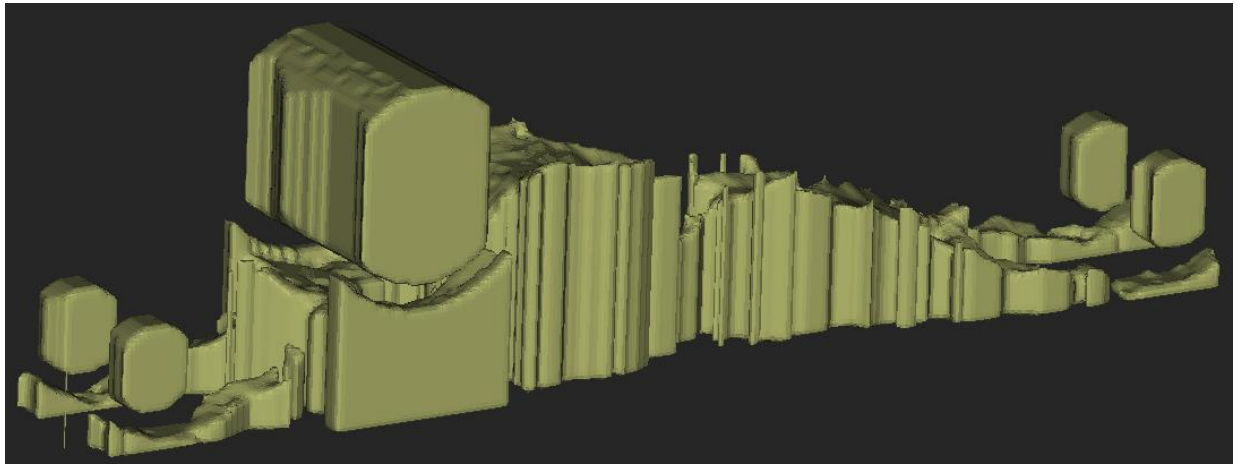


Ioannis Ntintakis, ‘Design of Lightweight structures for Additive Manufacturing

Support Structure Optimization







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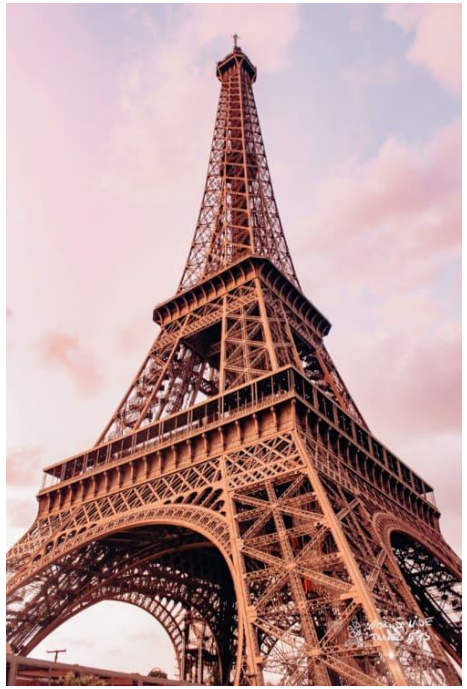


"The art of structure is where to put the holes"

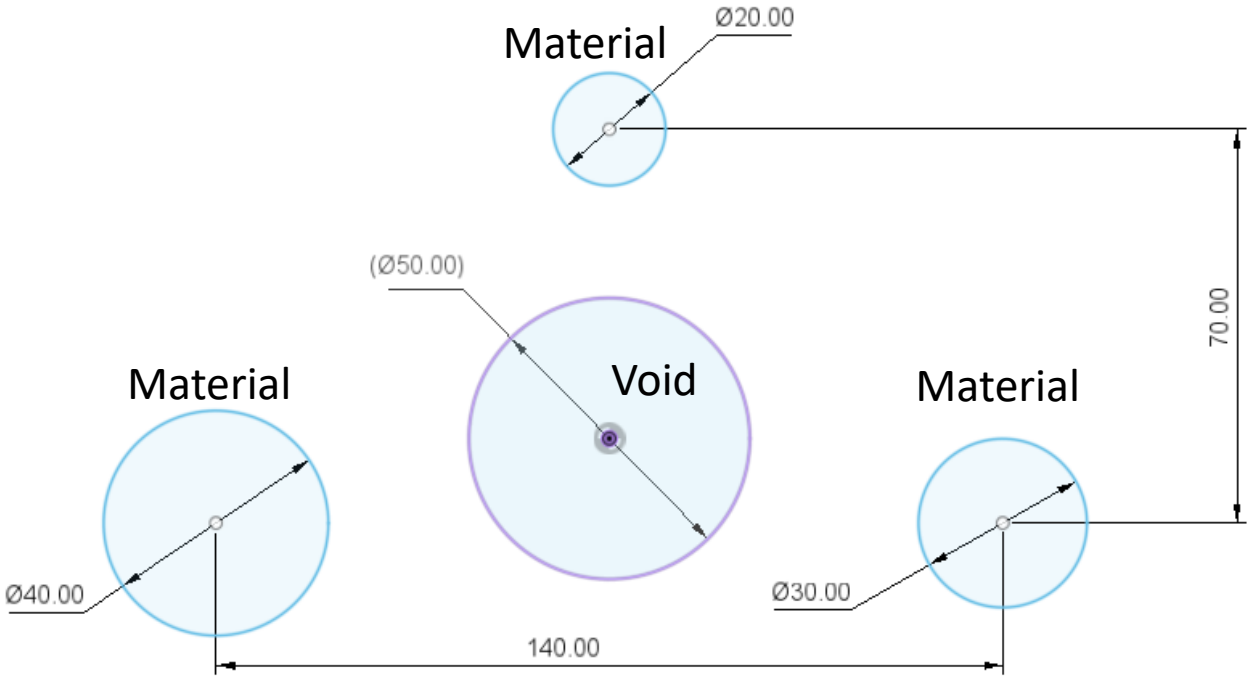
Robert Le Ricolais (1894-1977)

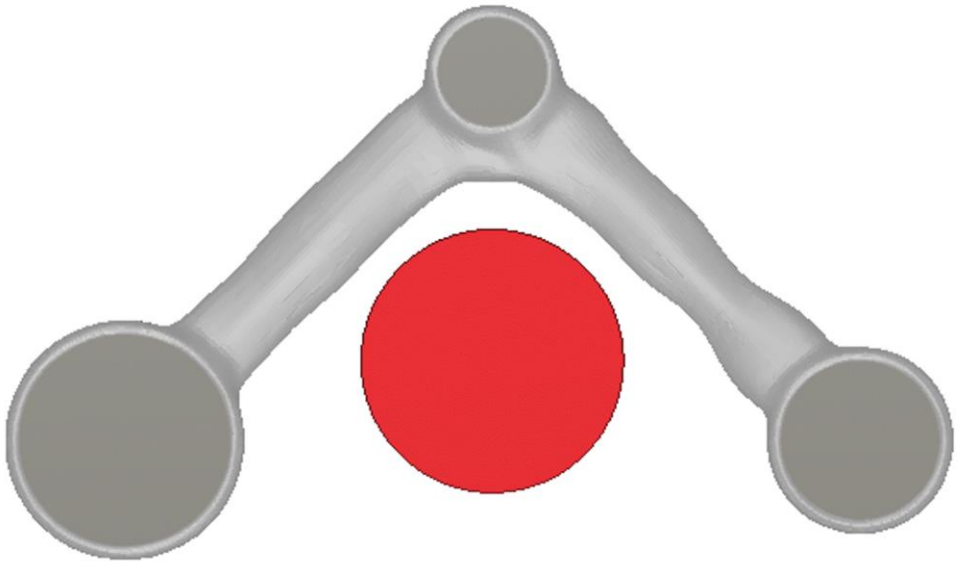
The "father of space structures."

structural engineer and architect

Design Problem Statement

Design Variables





Optimize design – Design Variables

Design Variables must be expressed as a function of variables (X) also constraints have to be included in this function

This function is known as **Objective Function** $f(\mathbf{x})$

Objective Function $f(\mathbf{x})$ can be:

maximized (**max**)

or

minimized (**min**)

Objective Function minimization

$$\begin{aligned} &\text{Minimize} && f(\mathbf{x}) \\ &\textit{Subject to} && g(\mathbf{x}) \le 0 \\ & && h(\mathbf{x}) = 0 \end{aligned}$$

$f(\mathbf{x})$: Objective function to be minimized

$g(\mathbf{x})$: Inequality constraints

$h(\mathbf{x})$: Equality constraints

$\mathbf{x}$: Design variables

Source: Weck, (2004)

Computational Mechanics

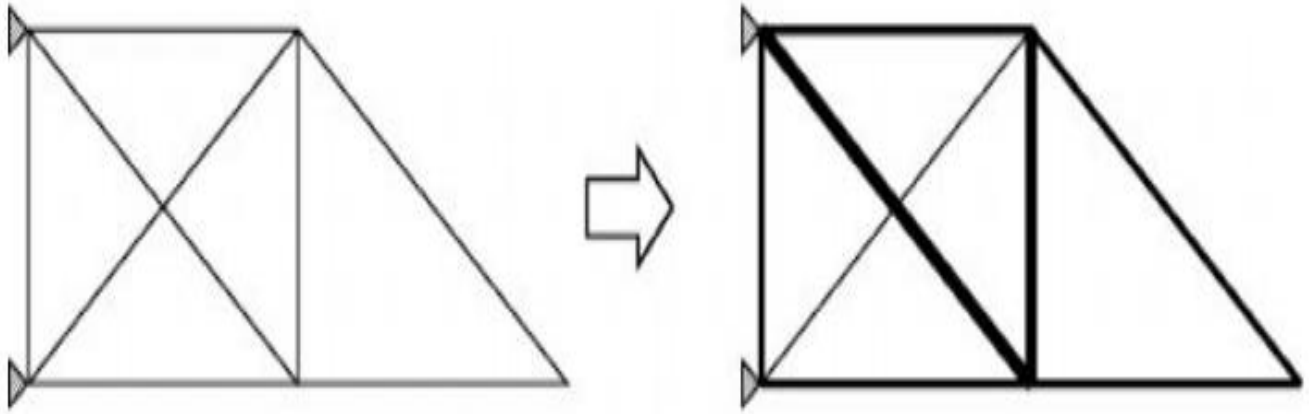
Computational mechanics is the scientific area that uses numerical methods to approximate the solution of engineering problems

Traditionally, the problems of engineering were solved either analytically or experimentally, computational mechanics is the alternative that allows us to consider more complicated structures

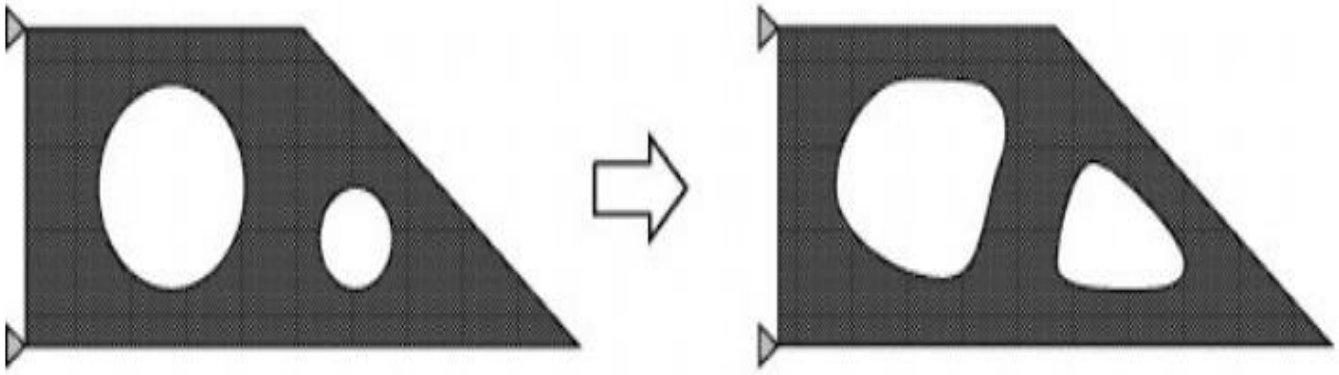
The development of computers over the last few decades has enabled engineers to approach problems that were impossible to solve in the past either because of the large size or the large amount of computing time required

Computational Mechanics - Structural Optimization-

Size Optimization



Shape Optimization



Ioannis Ntintakis, 'Design of Lightweight structures for Additive Manufacturing

Source: Stava et al., 2012

Computational Mechanics - Structural Optimization-

Topology Optimization

Is a mathematical method which spatially optimizes the distribution of material within a fixed and predefined design domain

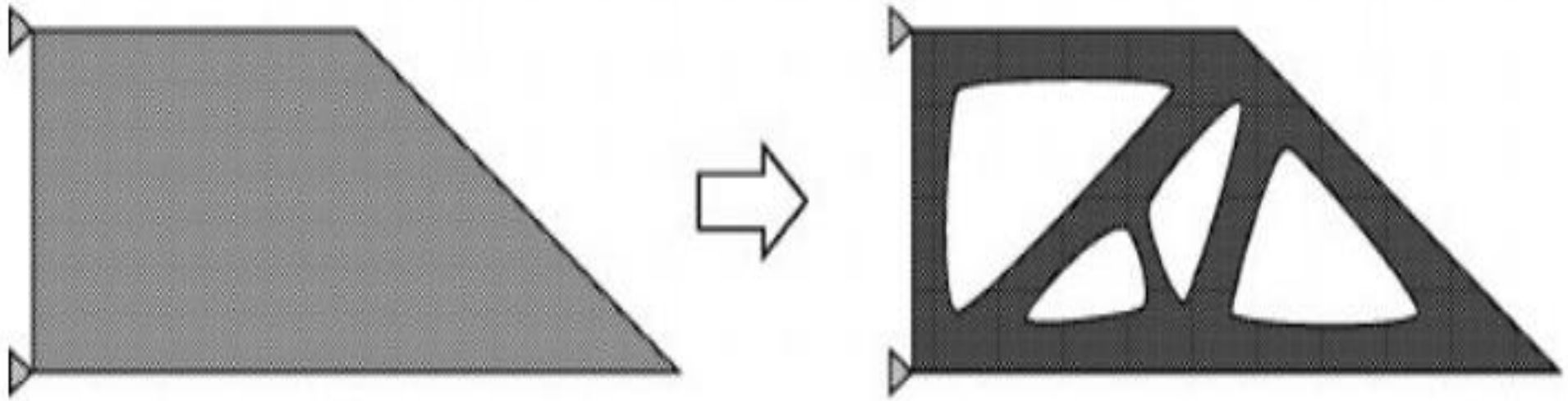
The objective is to find the optimal design solution so that boundary conditions and design constrains to be satisfied

Source: Haslinger and Mäkinen, 2003

Computational Mechanics - Structural Optimization-

Topology Optimization

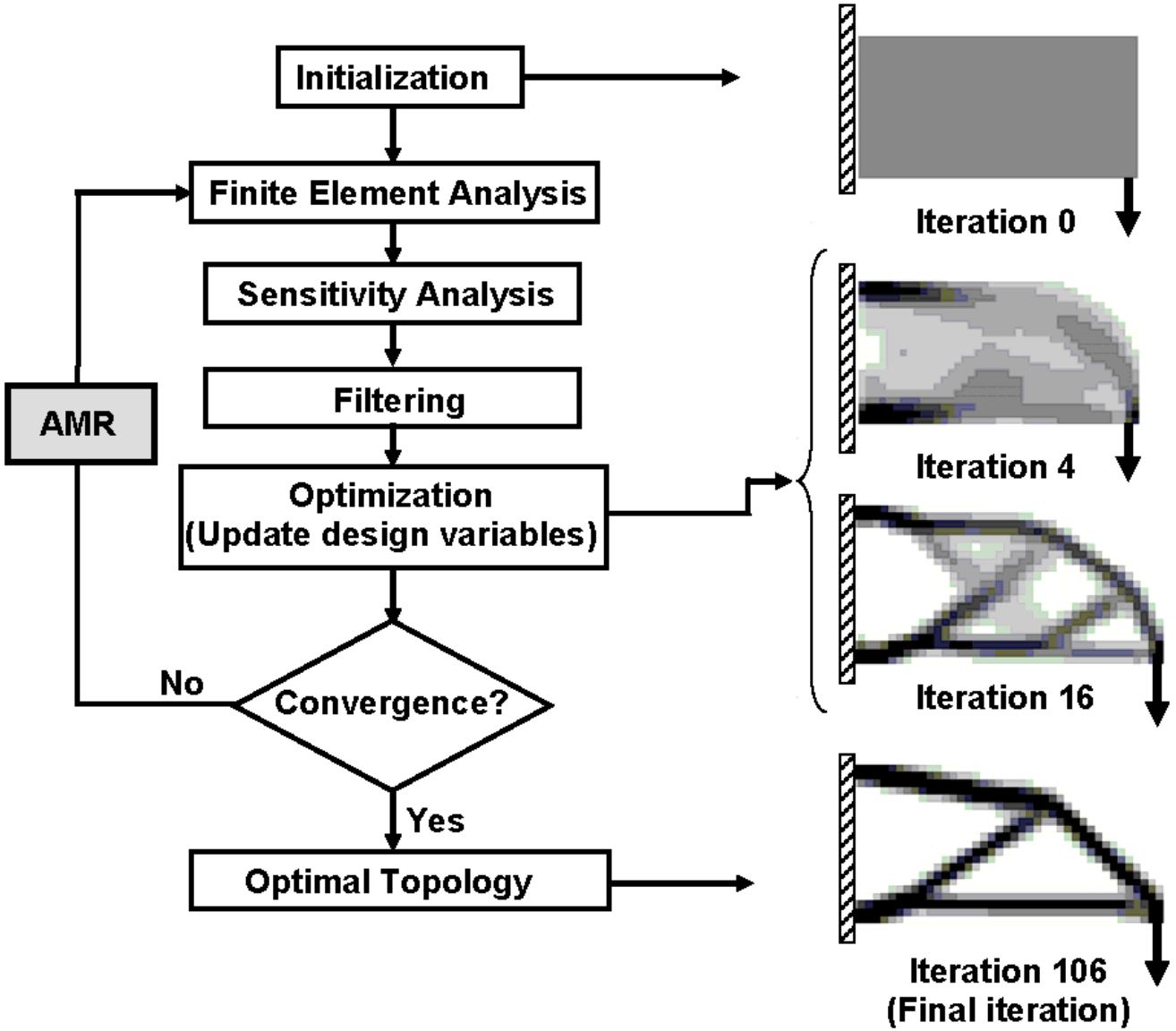
In this form of structural optimization, the shape and size of structure elements change



Source: Haslinger and Mäkinen, 2003

Topology Optimization Algorithm (T.O.)

Dynamic adaptive mesh refinement

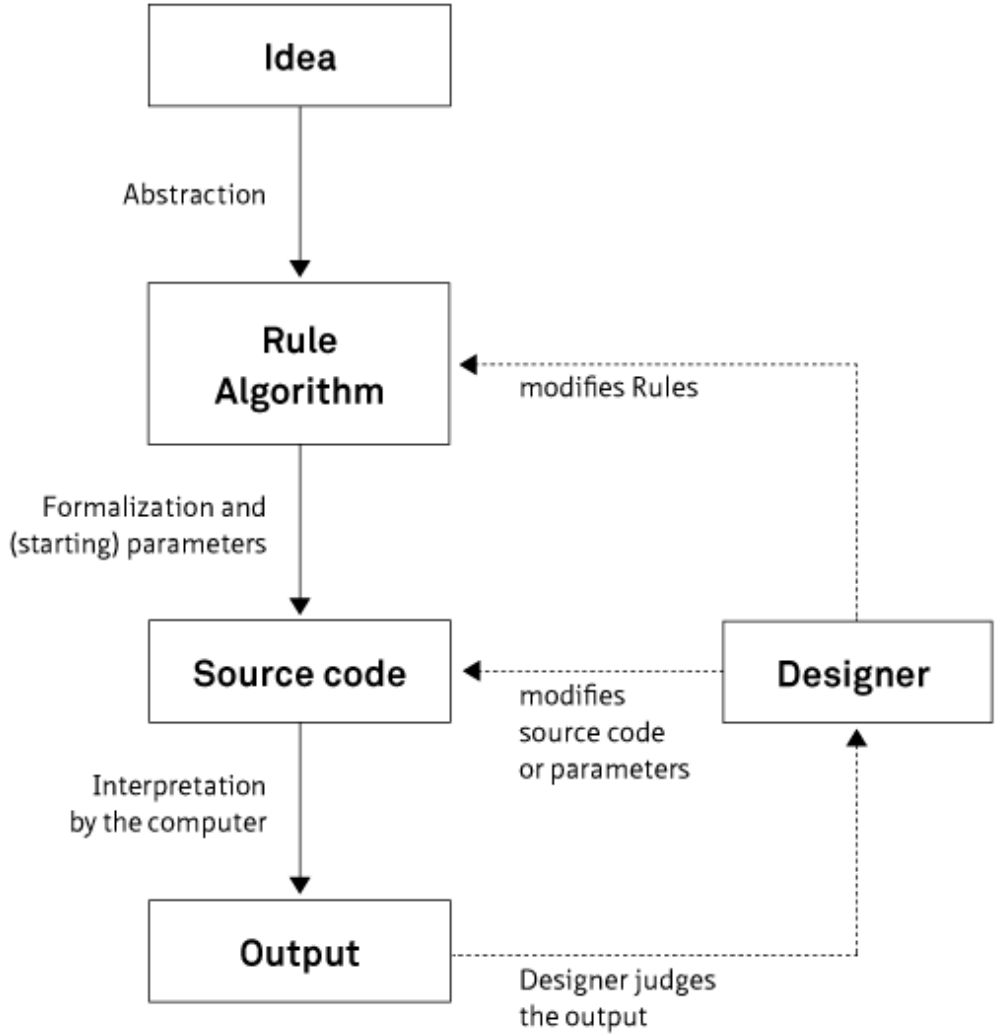


$$\min_{\forall e\ \rho_e \in [\rho_0,1]} \mathbf{f}^T\mathbf{u}$$

$$\text{s.t.} \begin{cases} \mathbf{K}(\boldsymbol{\rho})\mathbf{u} = \mathbf{f} & \text{for } x \in \Omega \backslash \Omega_0, \\ \mathbf{u} = \mathbf{u}_0 & \text{for } x \in \Omega_0, \\ \sum_e \rho_e V_e \le V_0, \end{cases}$$

Source: Proceedings of the 6th IASS-IACM 2008, Ithaca2008, Cornell University, Ithaca, NY, USA

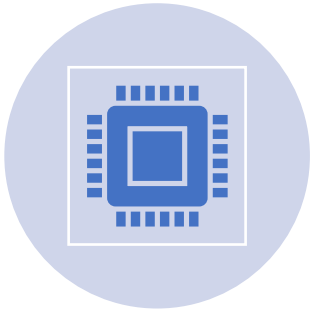
Generative Design Process



Topology Optimization Vs generative Design

T.O. creates only one design that's been optimized for structural integrity based on existing criteria

G.D creates lots of designs in an evolutionary way



Topology Optimization is suitable when you have a set space and overall idea and just need the computer to make it as lightweight as possible

Generative Design is mainly used when the whole shape is unknown so the program will give us a lot of options, taking into consideration things like the desired material and manufacturing method.

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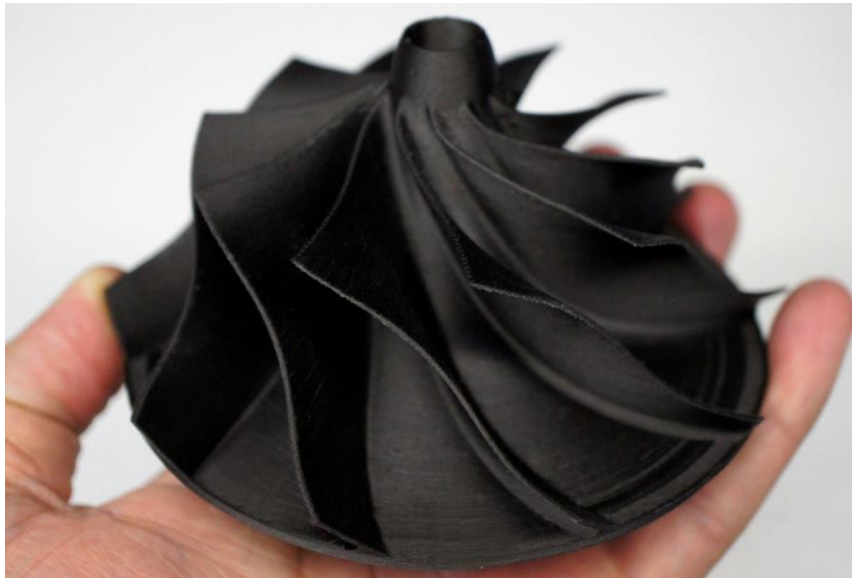
Example –Chair AI-

Source: Designboom

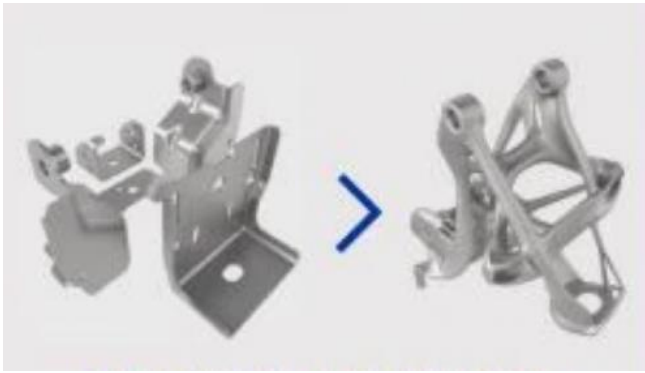
Source: createdigital

Example in automotive industry –Chaos Pr-



Source: Spyros Panopoulos

Example in automotive industry –General Motors-

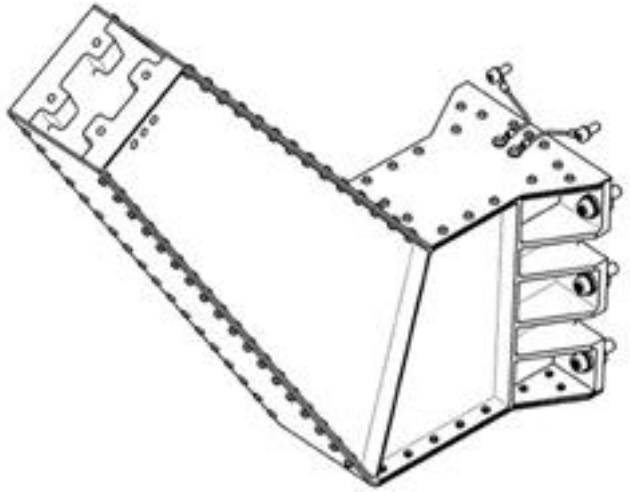


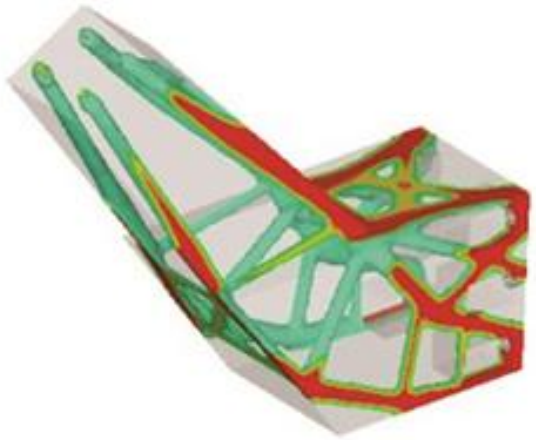
Source: General Motors

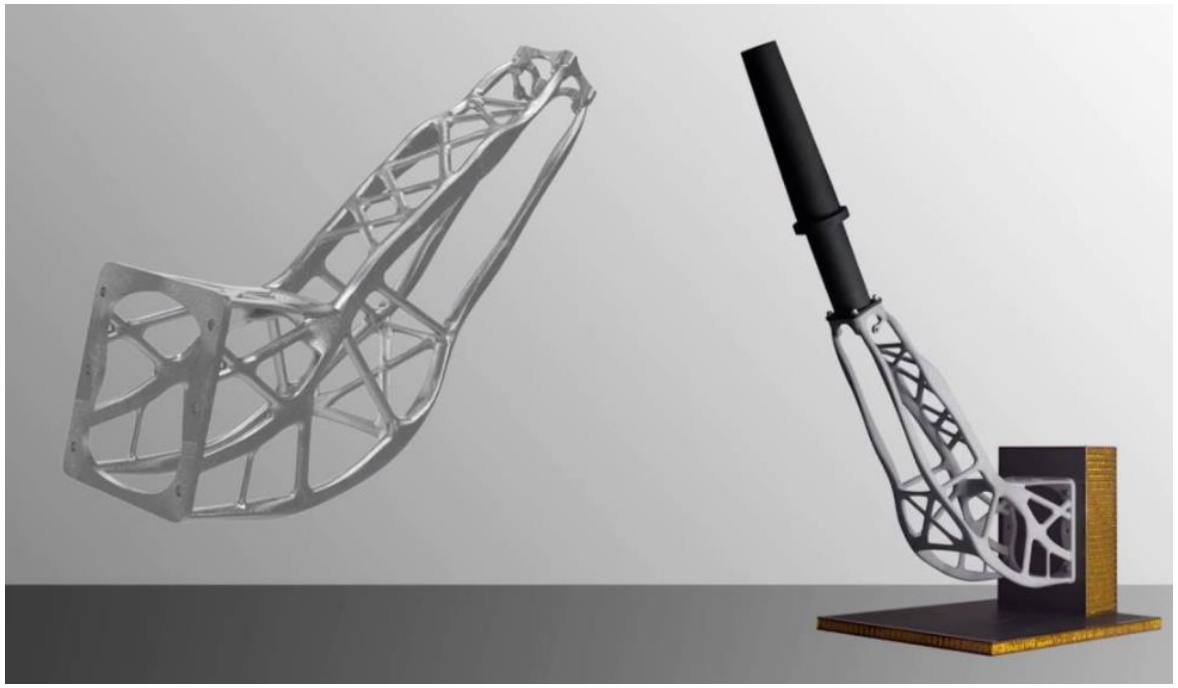
Example in aviation industry – Airbus-

Source: Airbus

Example in space industry –NASA-

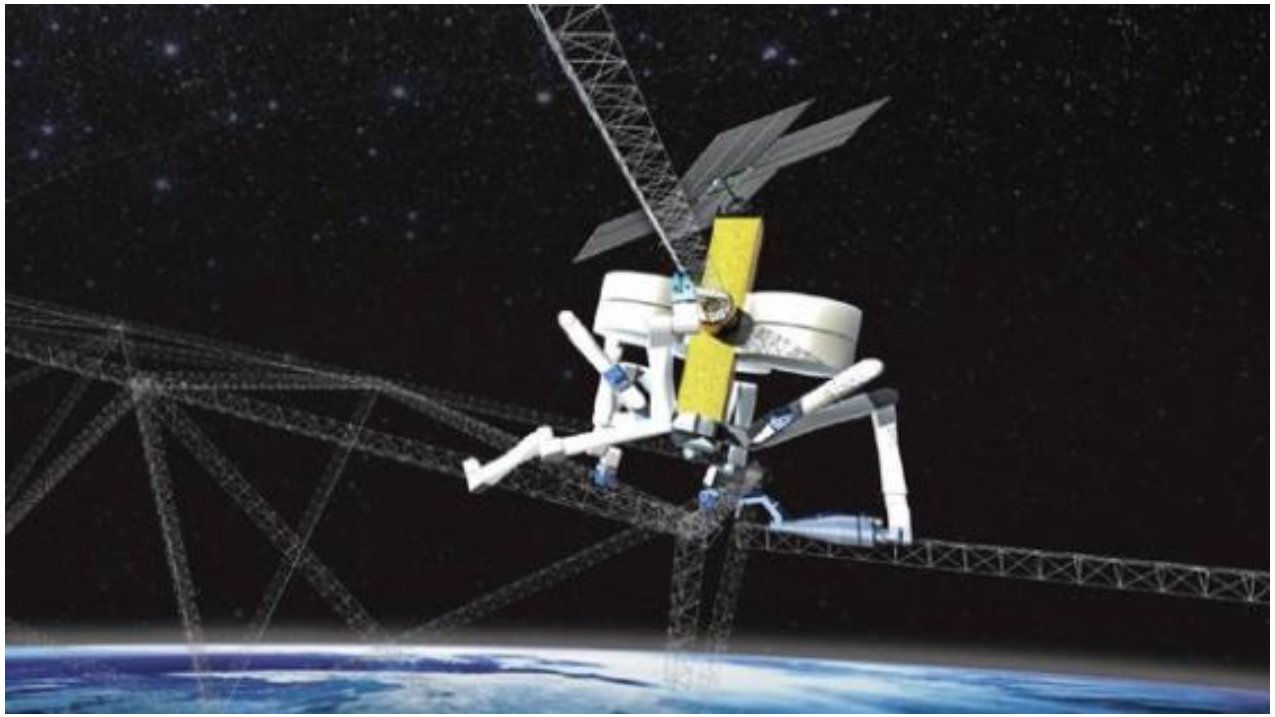


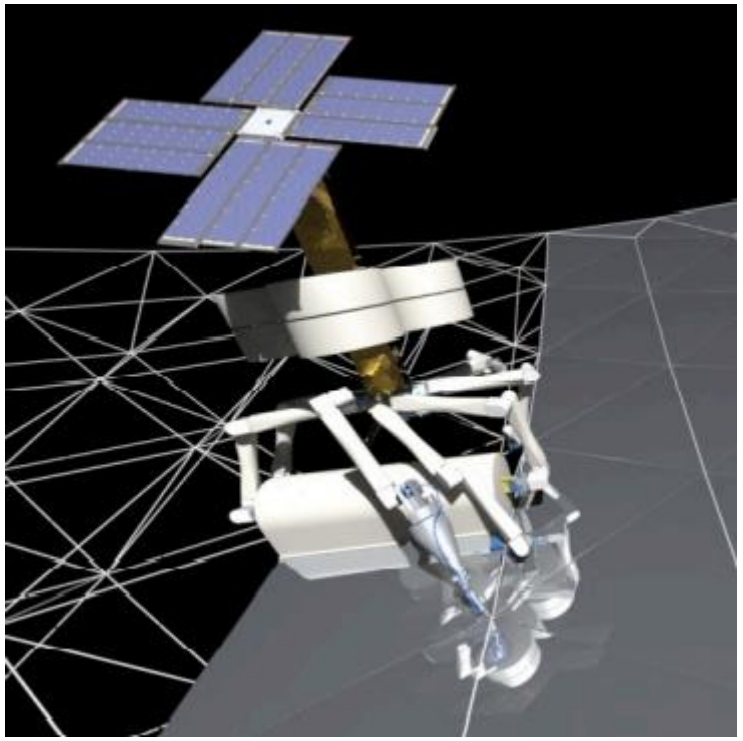




Source: Ruag

Example in space industry –NASA-





Source:NASA

Optimize Design Iterations

I. Ntintakis, G.E. Stavroulakis (2020)

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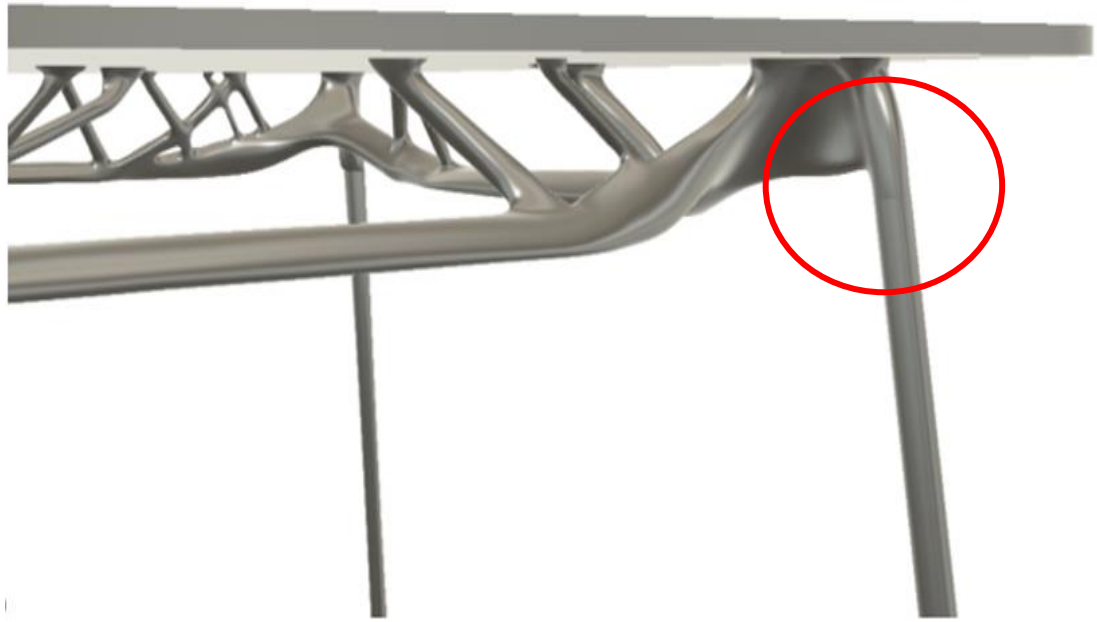
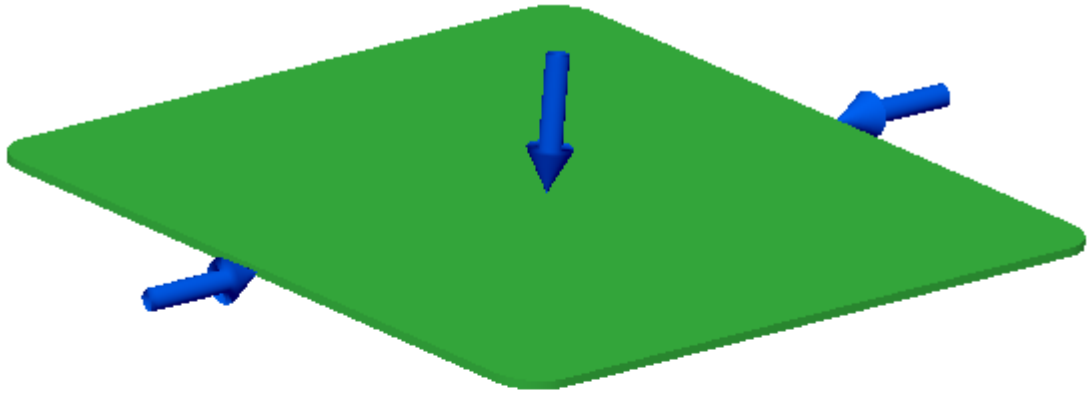
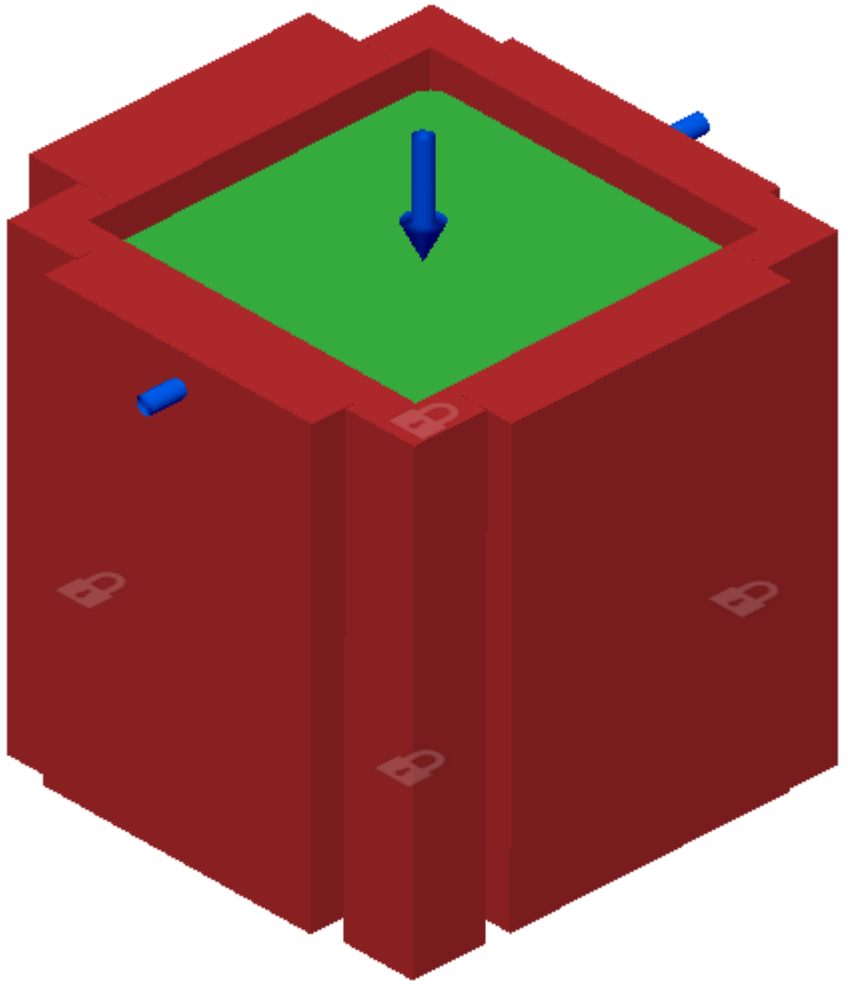
Optimize Design Iterations



I. Ntintakis, G.E. Stavroulakis (2020)

Optimize Design Iterations

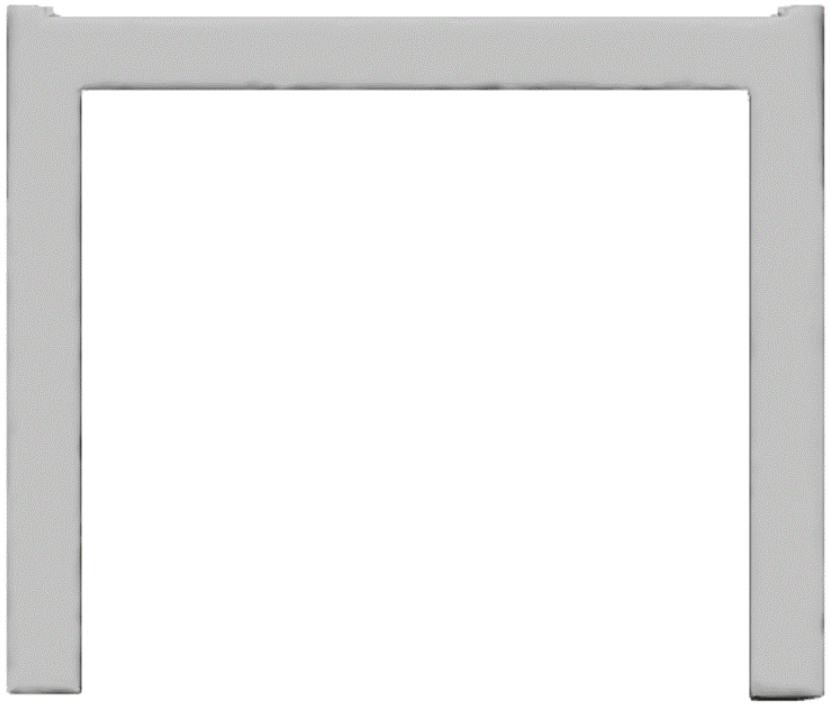




I. Ntintakis, G.E. Stavroulakis (2020)

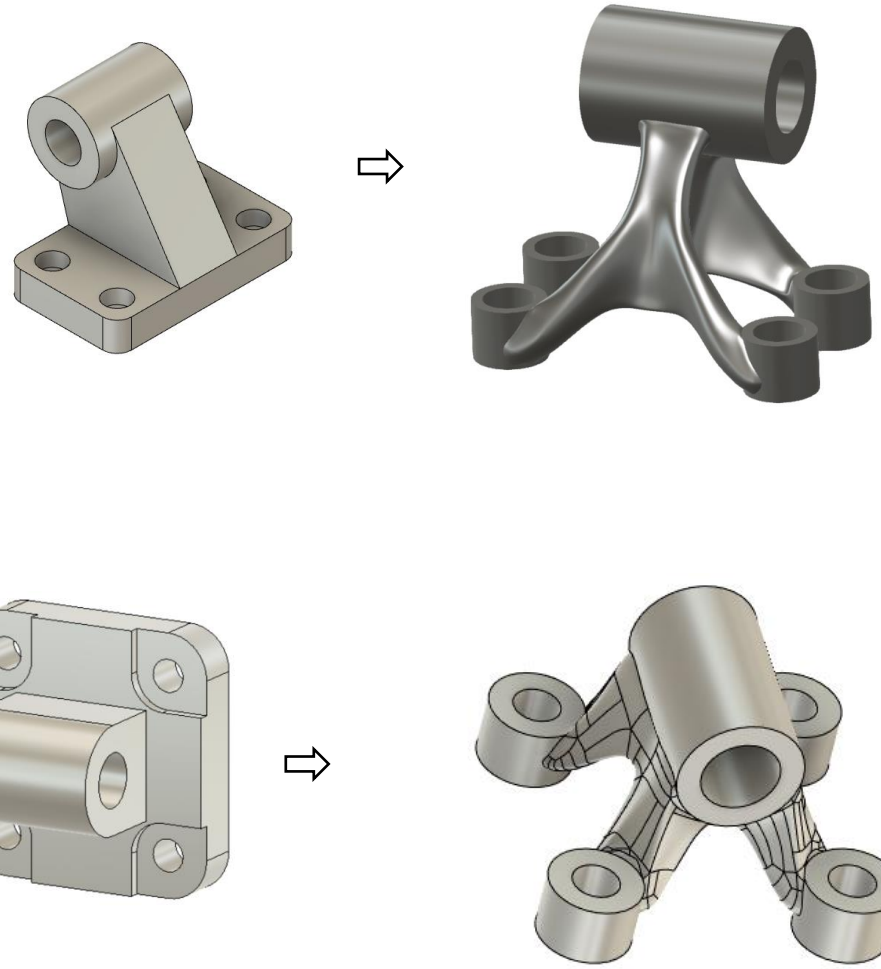
Optimize Design Iterations

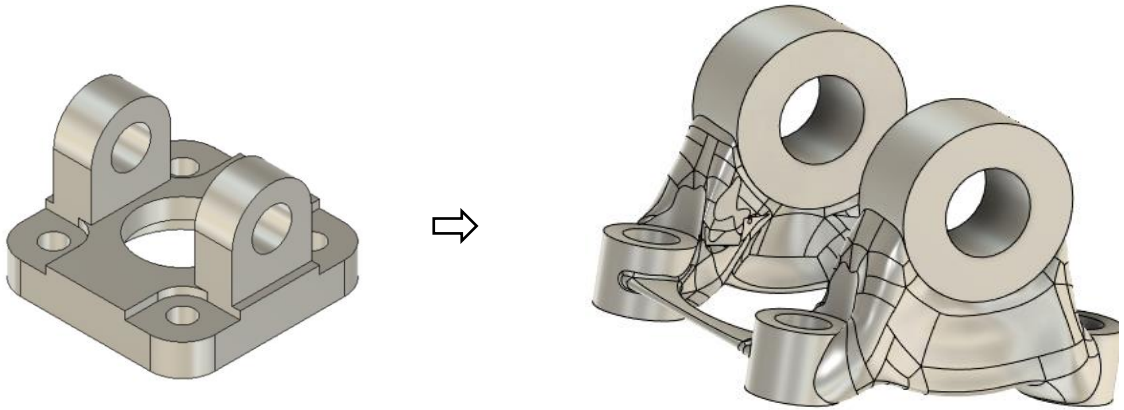
Initial Shape



Source: Ntintakis, el. al, (2020)

G.D. Mechanical Parts





Source: Ntintakis, el. al, (2020)

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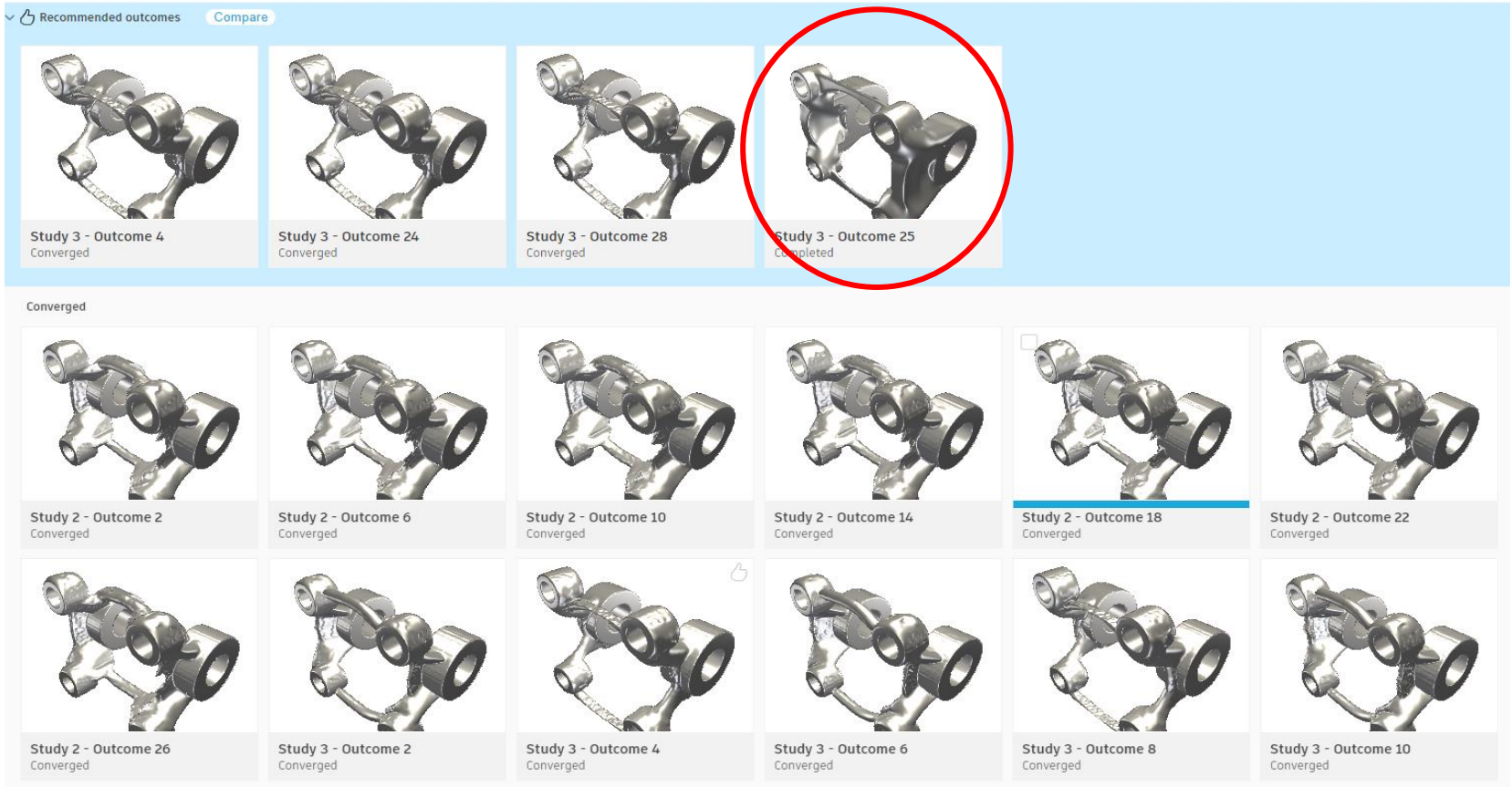

Volume (mm^3)	11,428.72
Mass (kg)	0.031
Max von Mises stress (MPa)	72.4
Factor of safety limit	2
Min factor of safety	3.8
Max displacement global (mm)	0.01

Source: Ntintakis, el. al, (2020)

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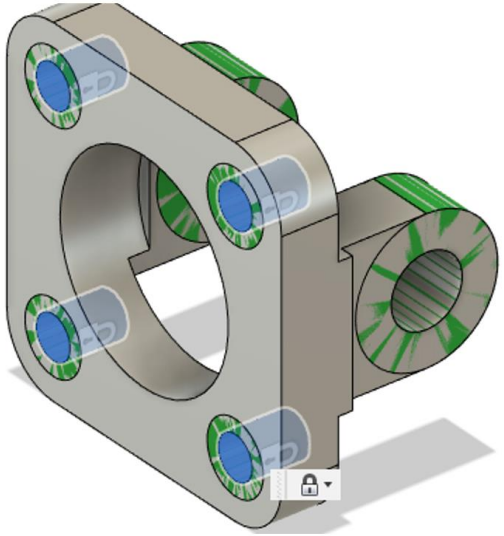
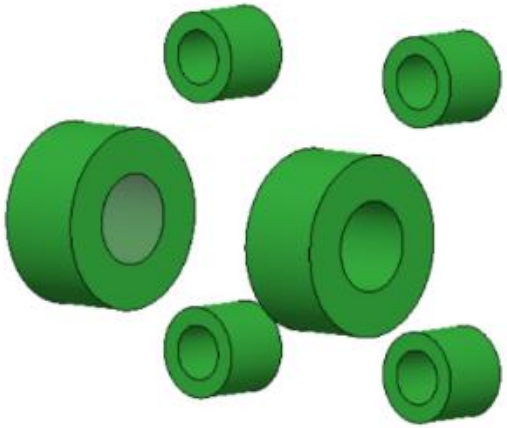
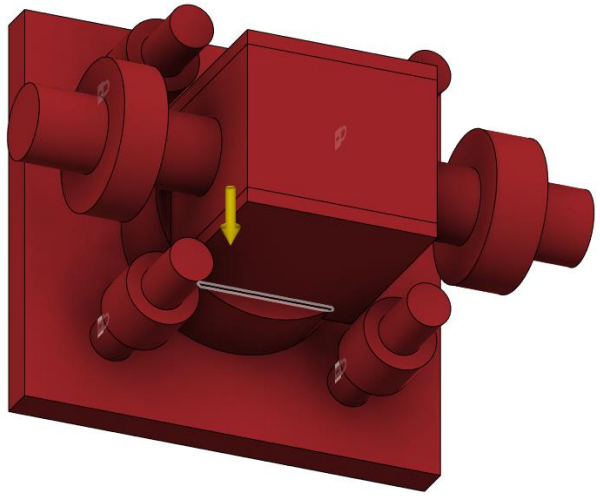
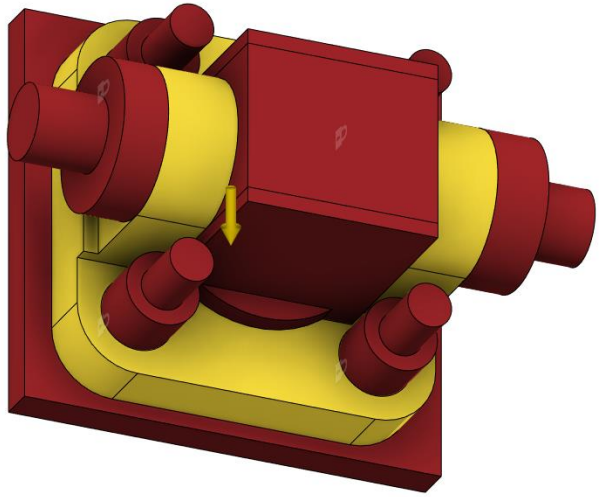
G.D. Mechanical Parts









Source: Ntintakis, el. al, (2020)

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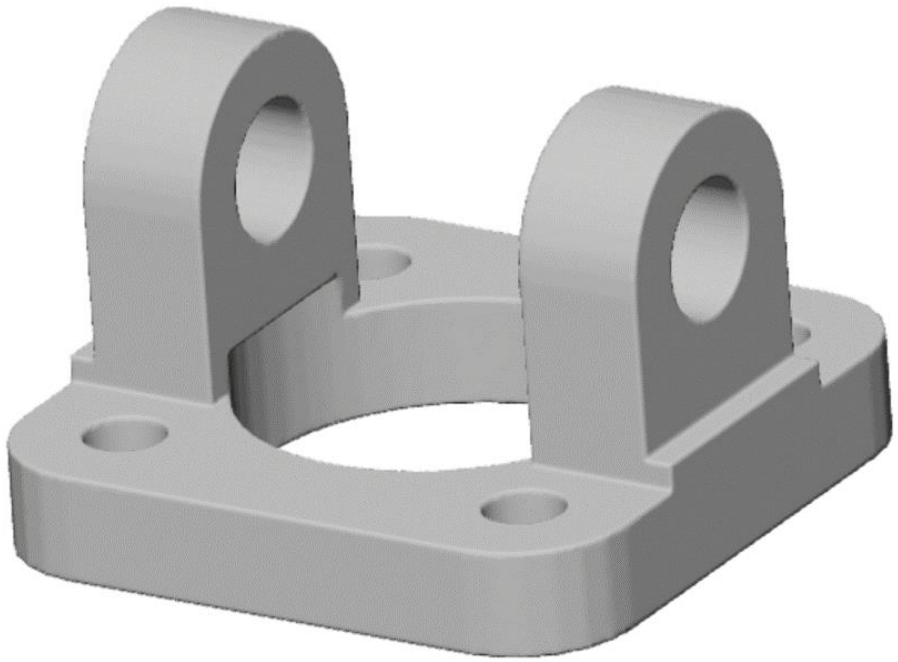
Optimize Design Iterations

Initial Shape



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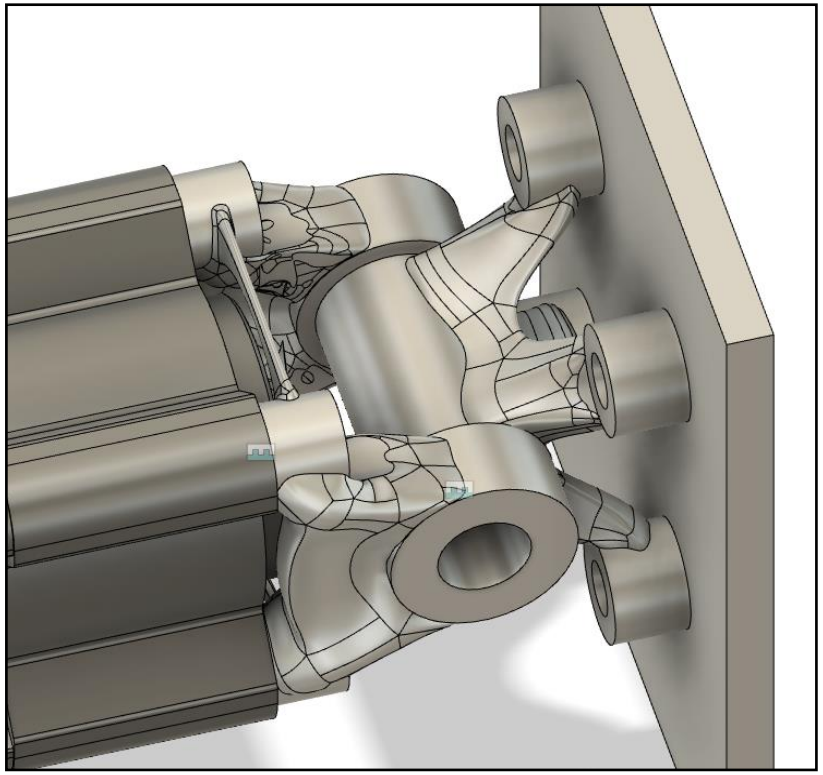

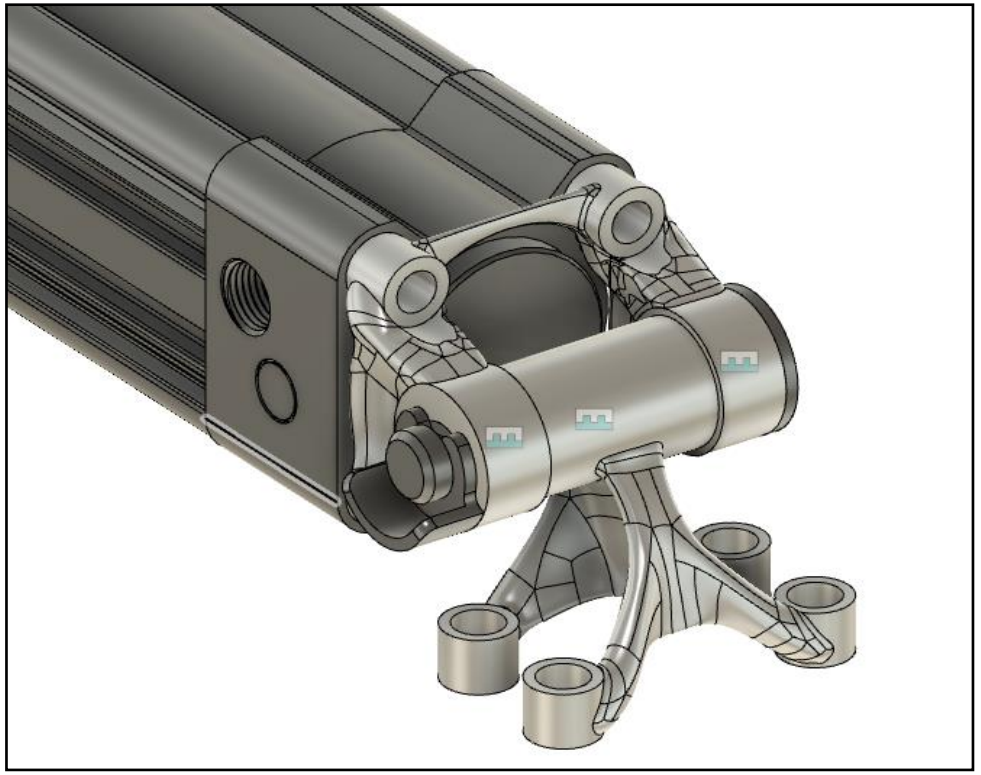

Source: Ntintakis, el. al, (2020)

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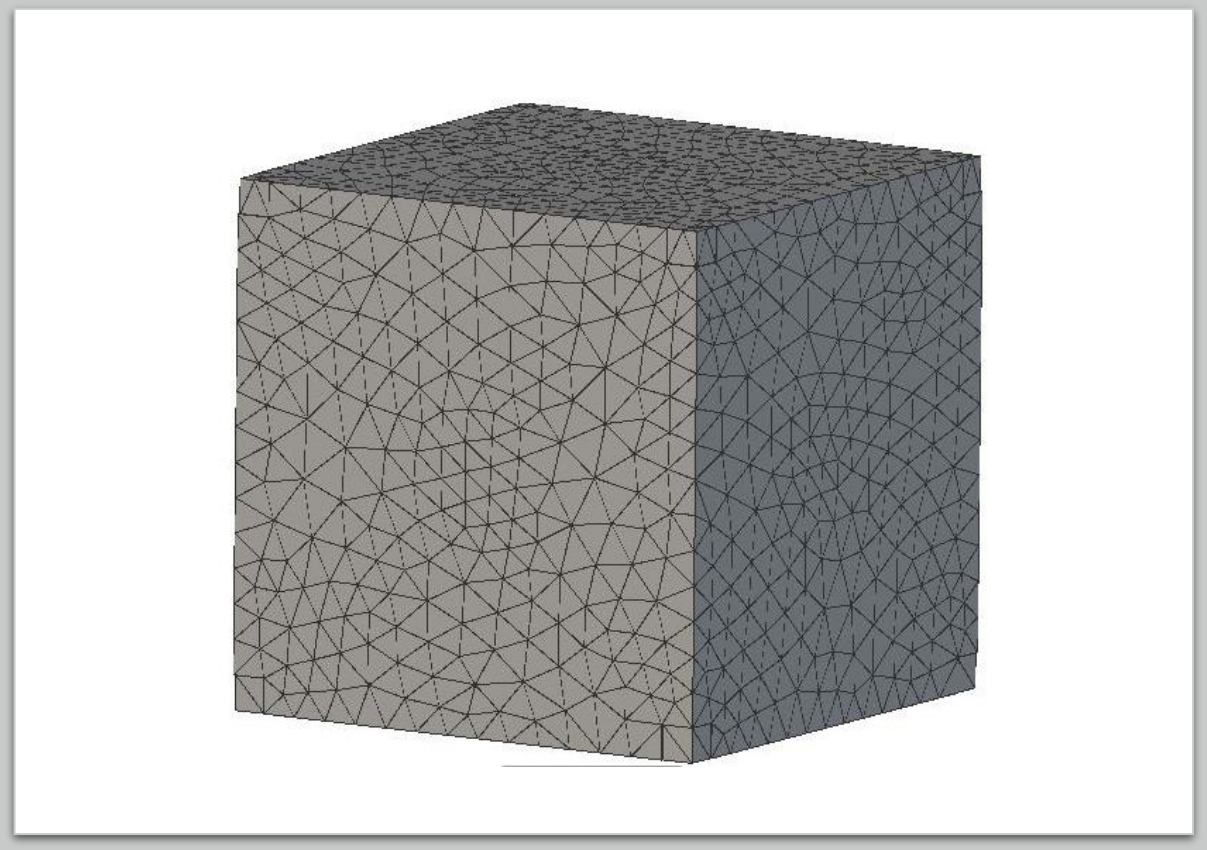
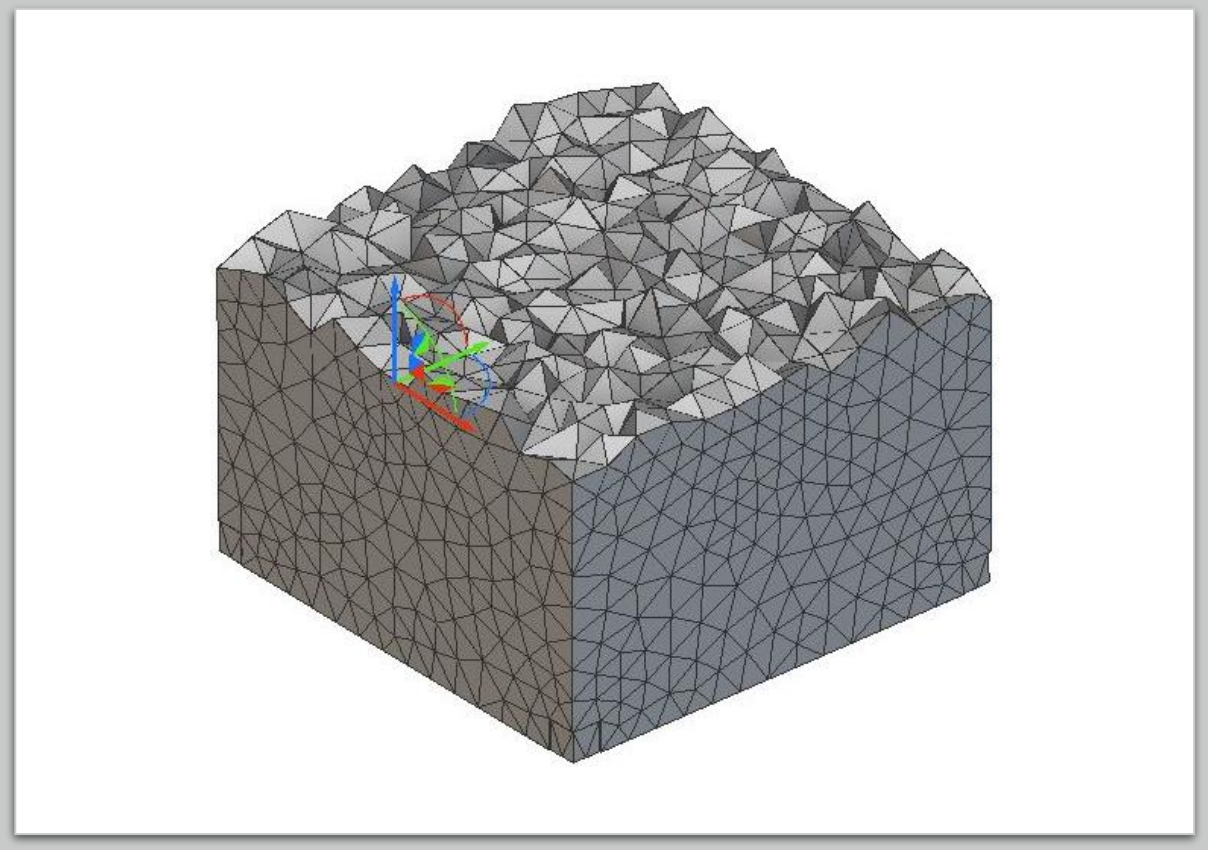
Design of Infill Microstructure for AM

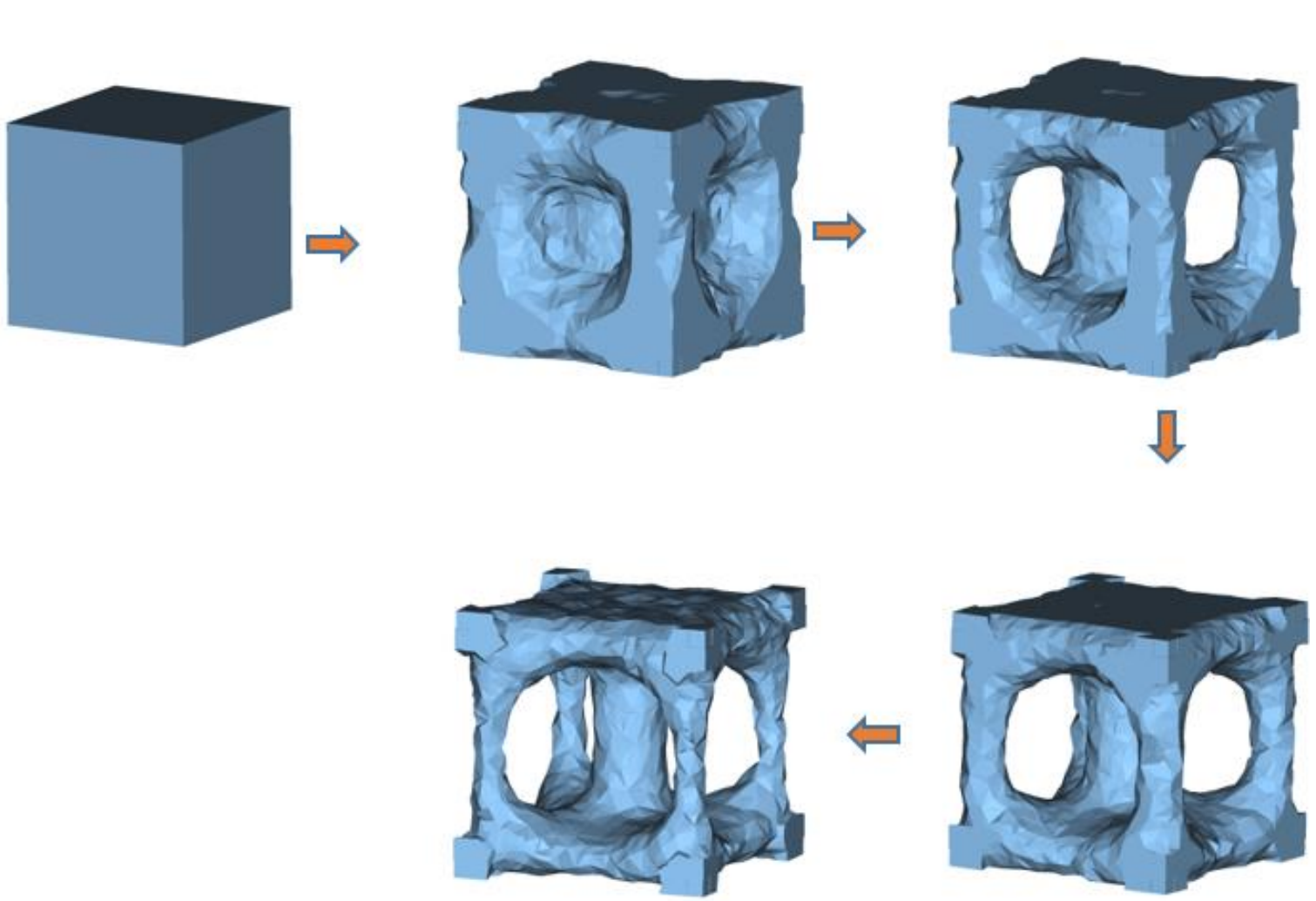
Cubic Design Space 15×15×15 mm

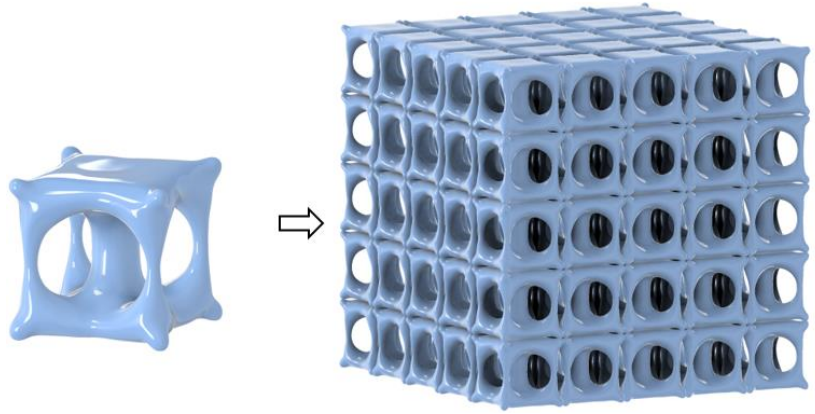
25.781 Tetrahedral Elements

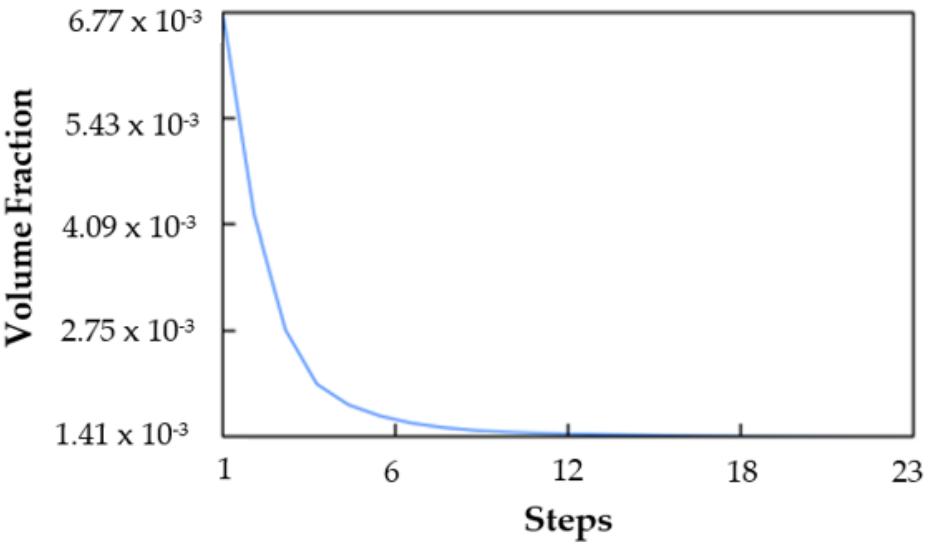




Design of Infill Microstructure for AM







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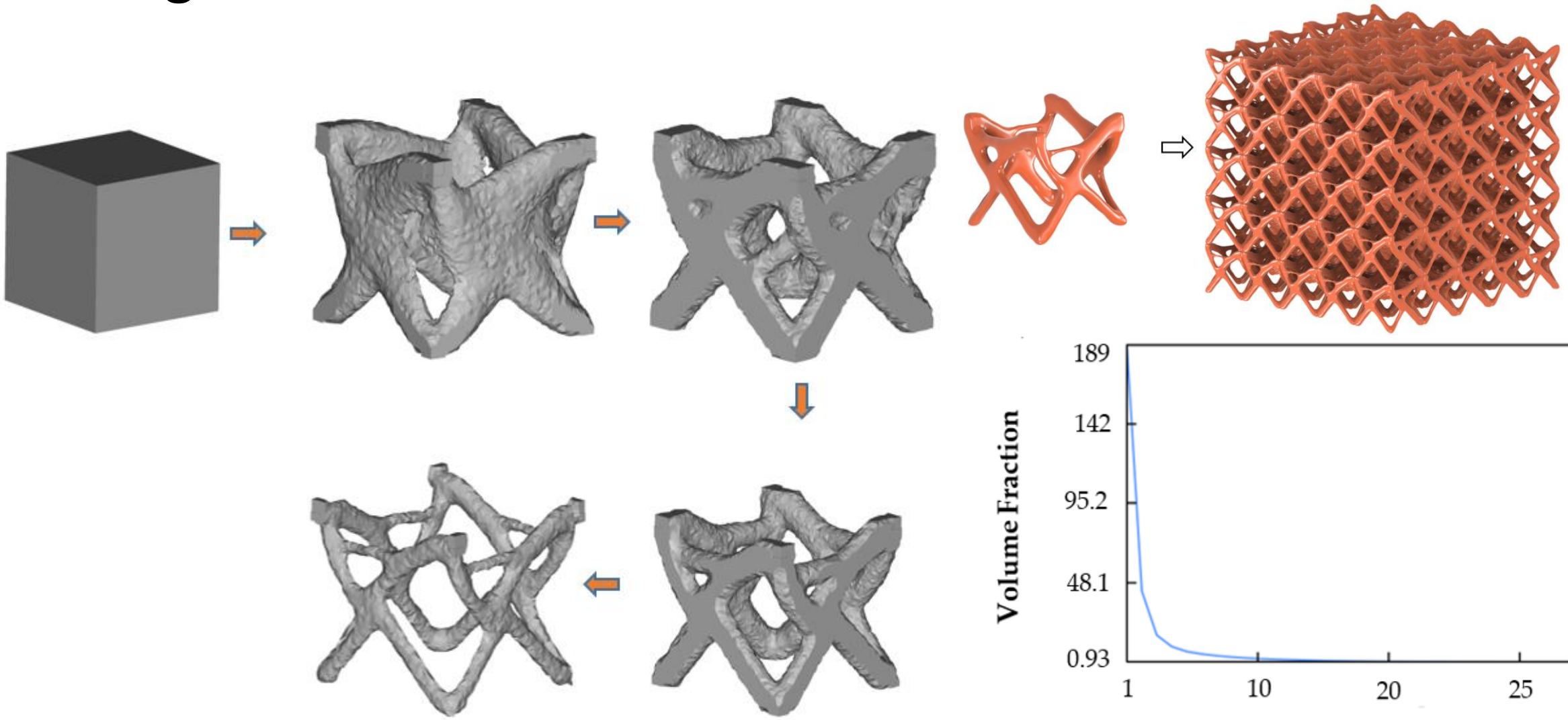
Design of Infill Microstructure for AM



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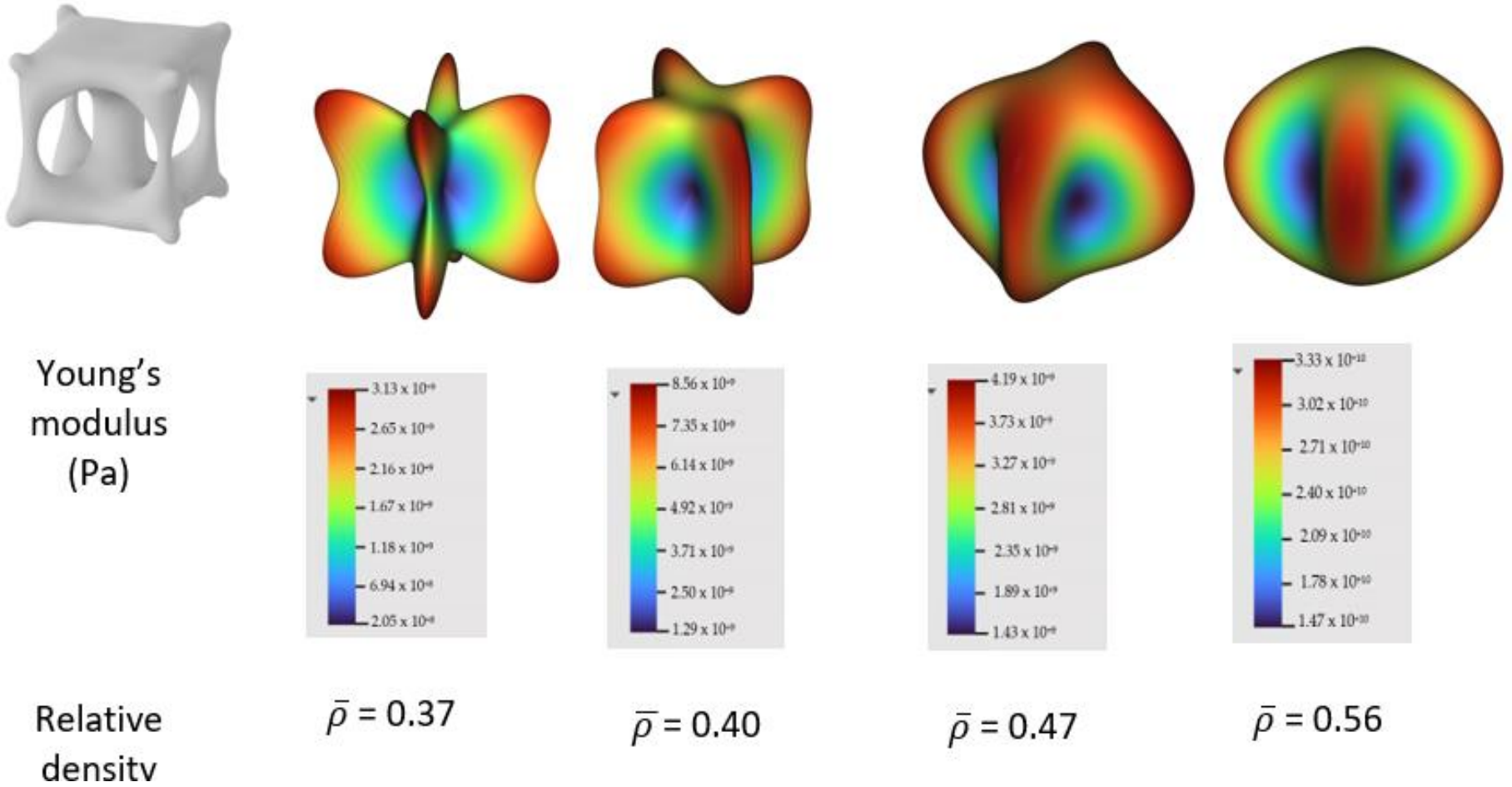

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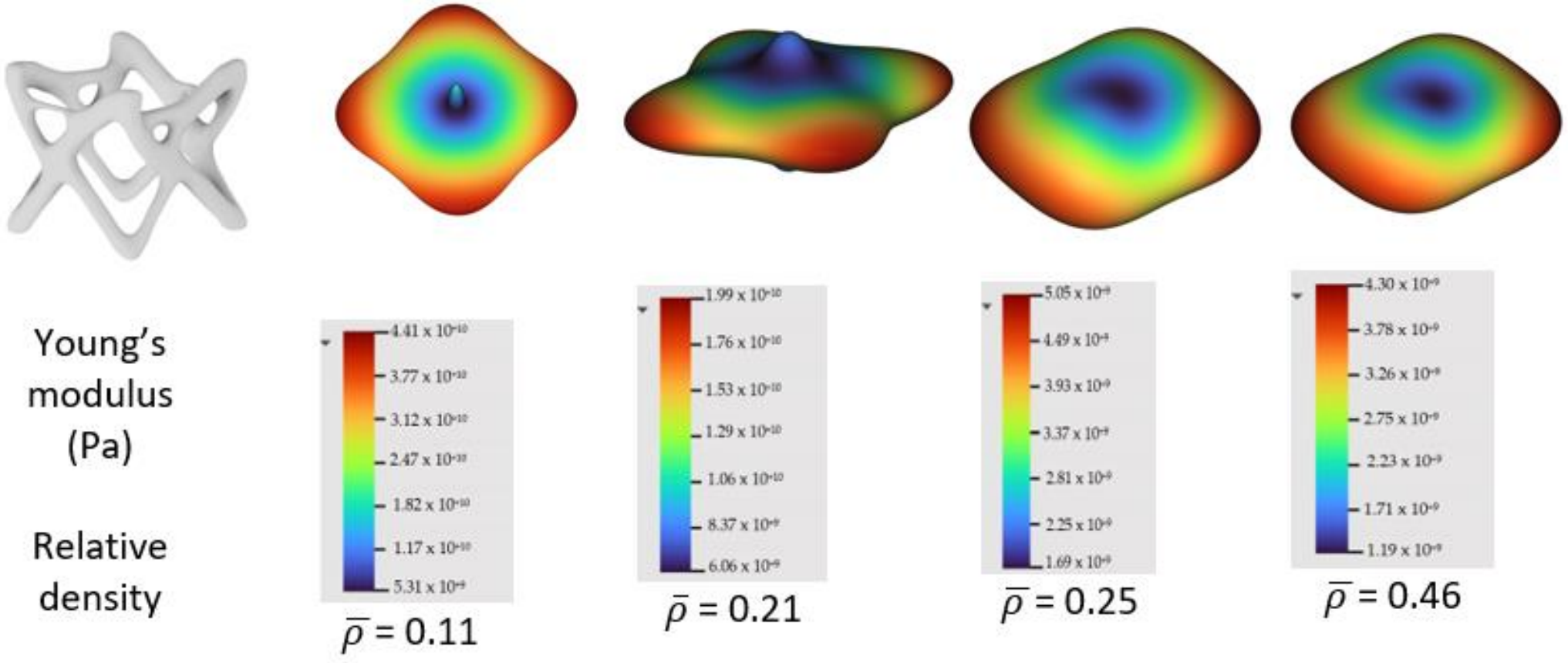

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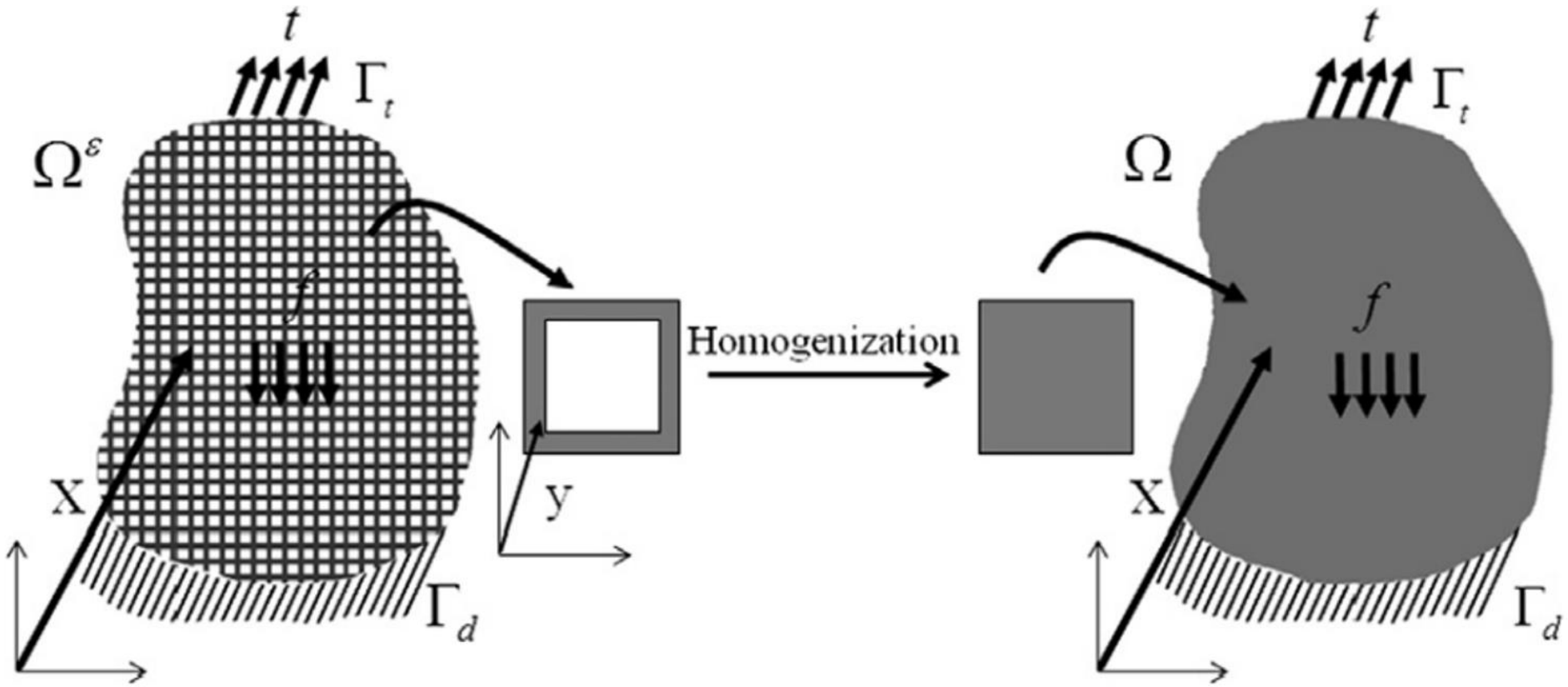
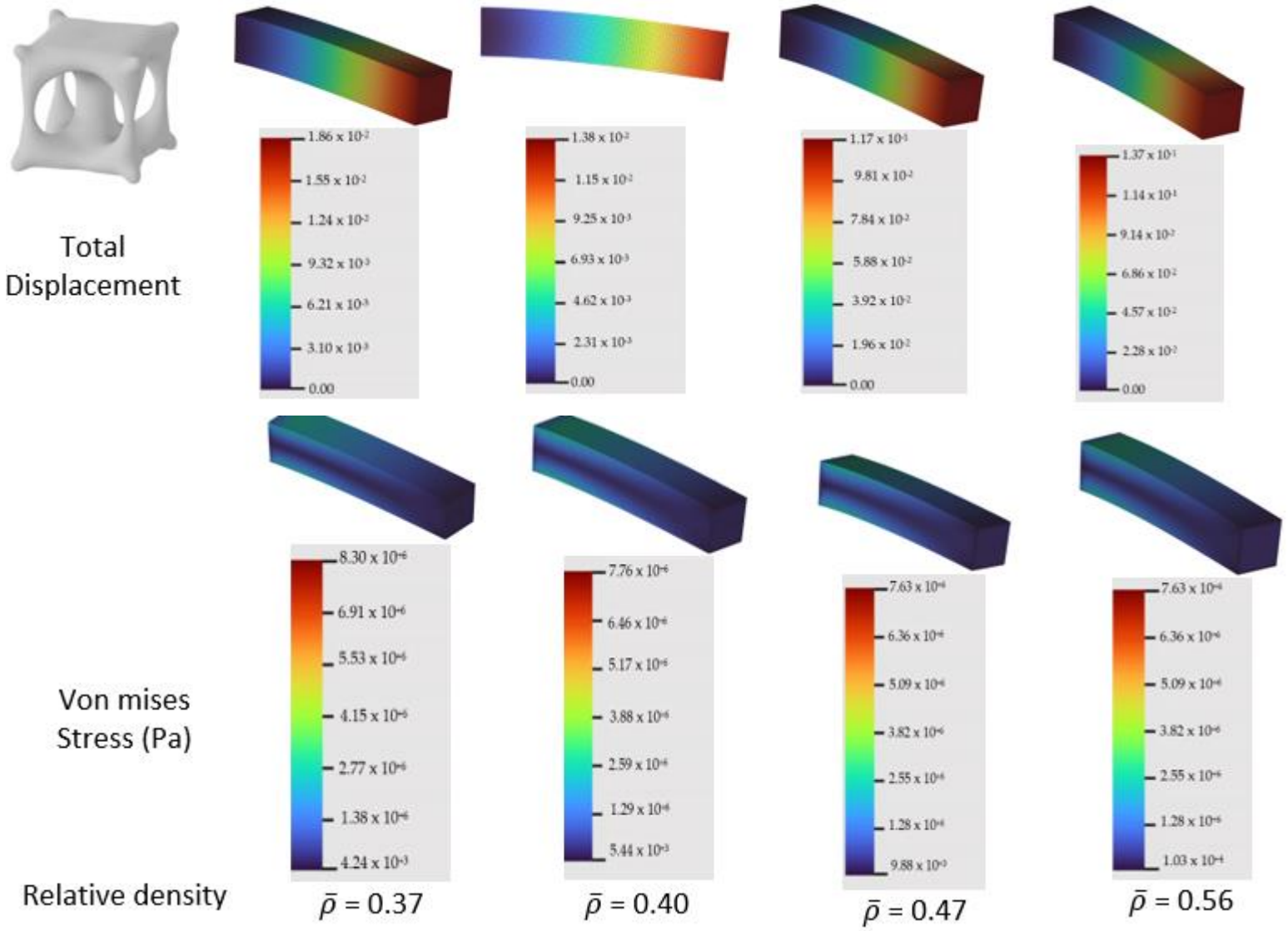
Lattice Homogenization



Evaluation of Homogenized Lattice in a cantilever model



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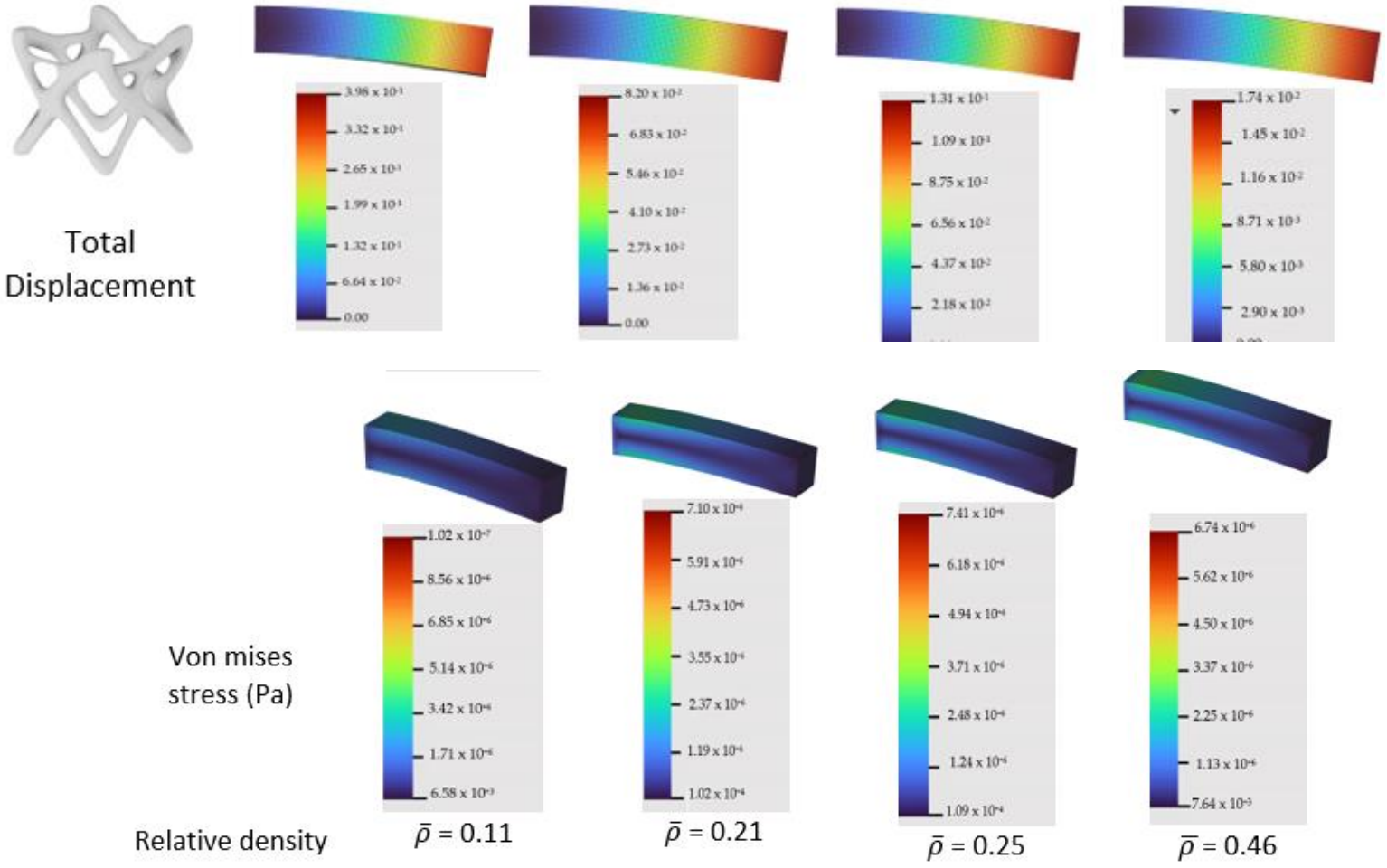
Design of Infill Microstructure for AM



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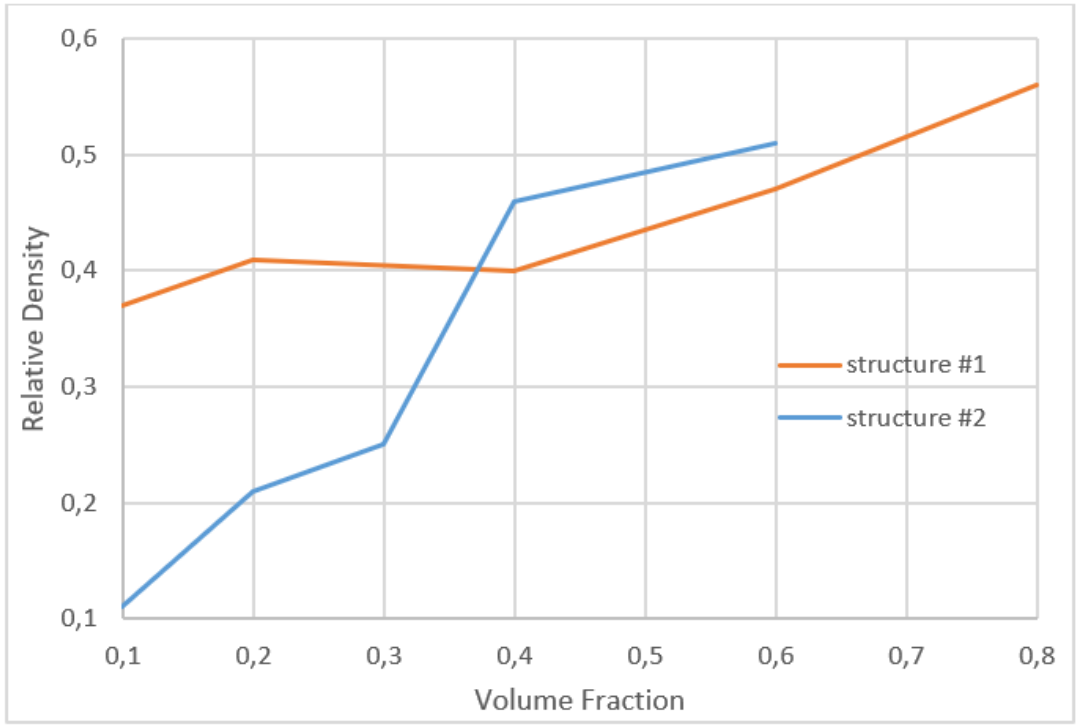
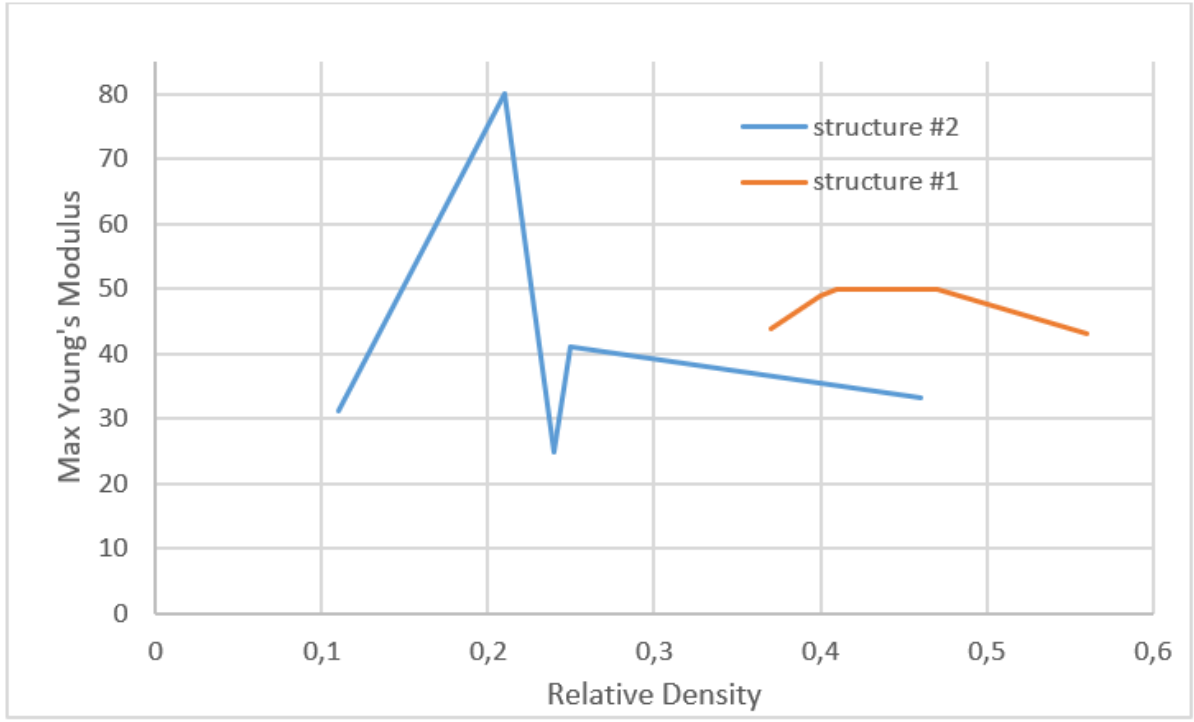
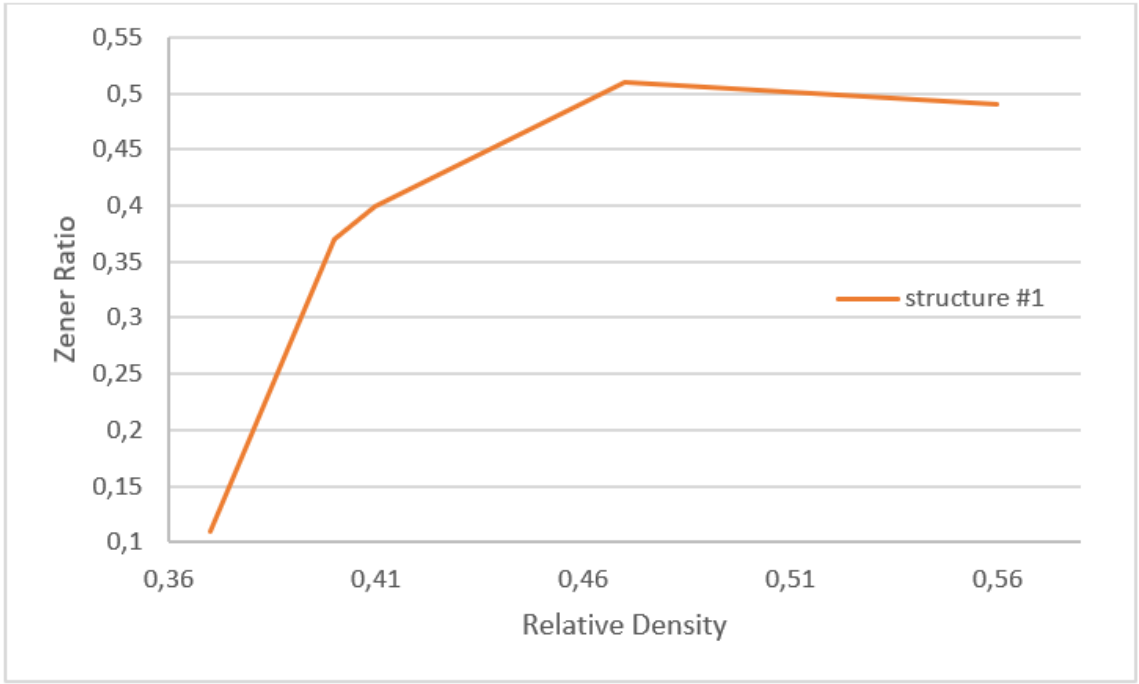
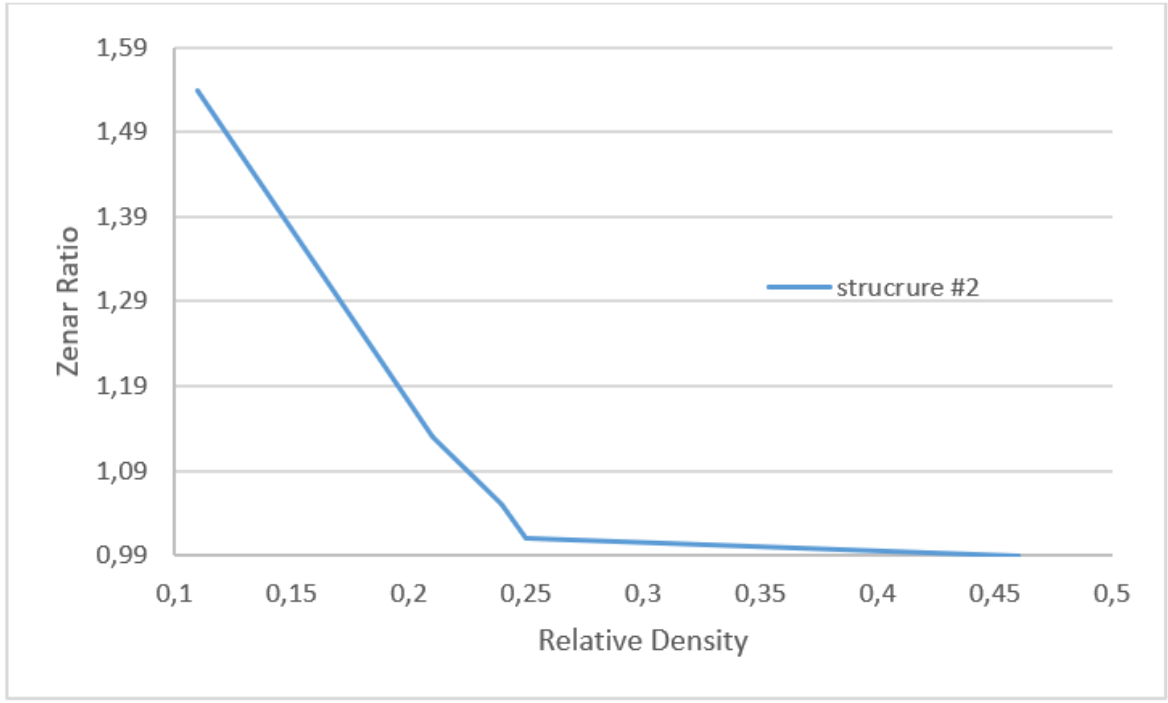


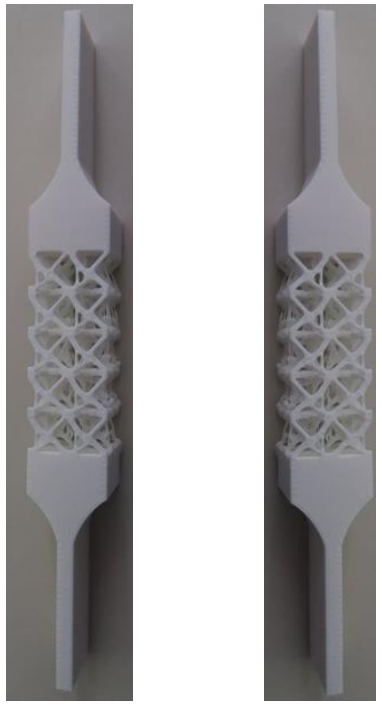


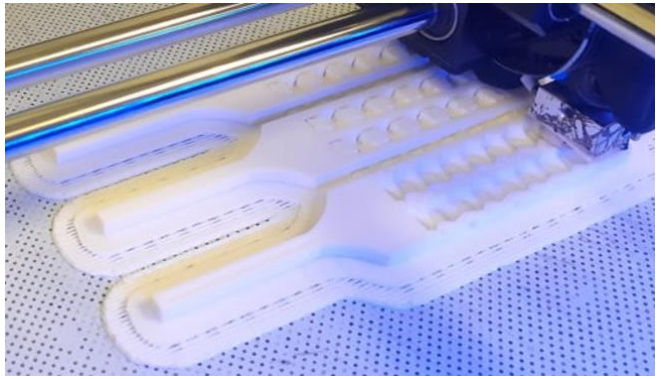
Lattices Isotropy

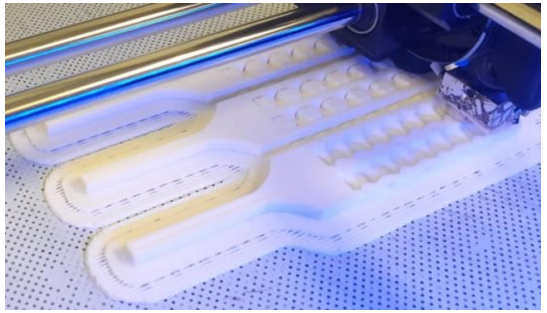




Lattice Structures Printing







0° 45° 90°

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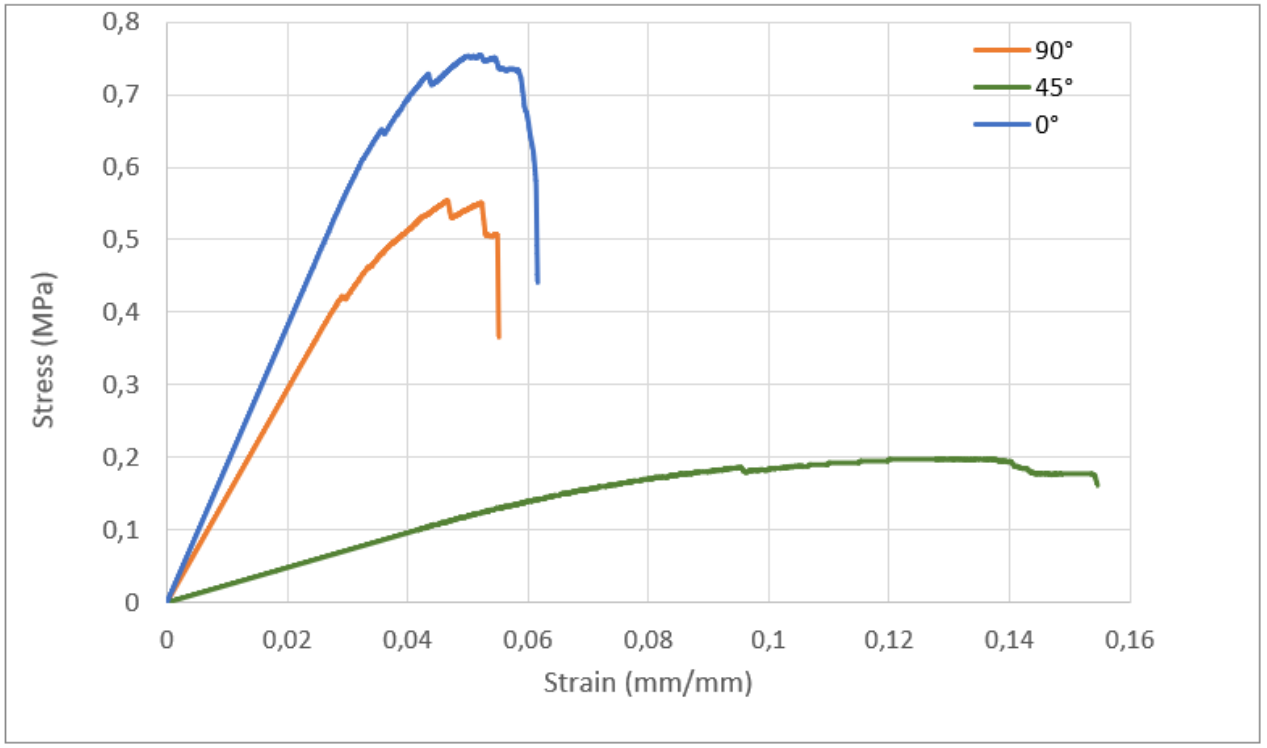
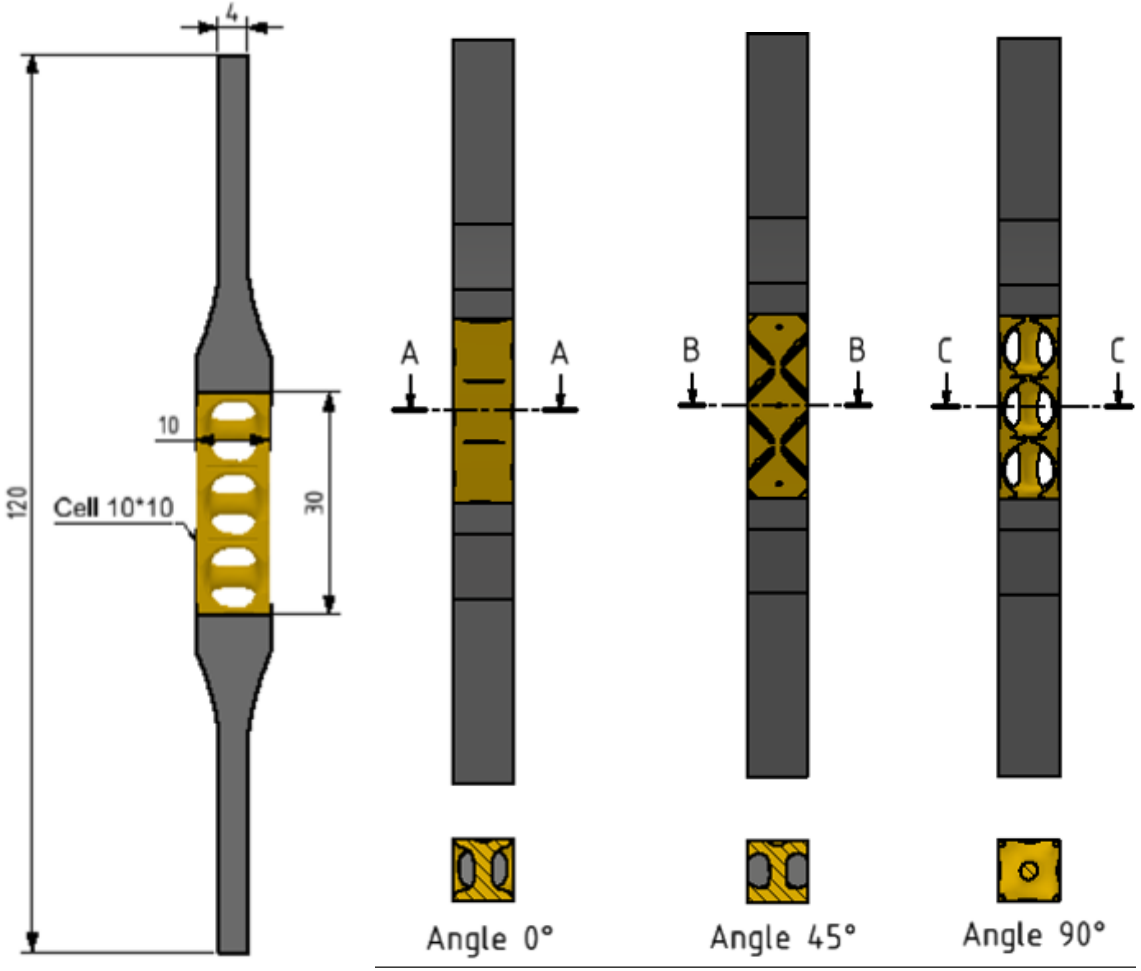
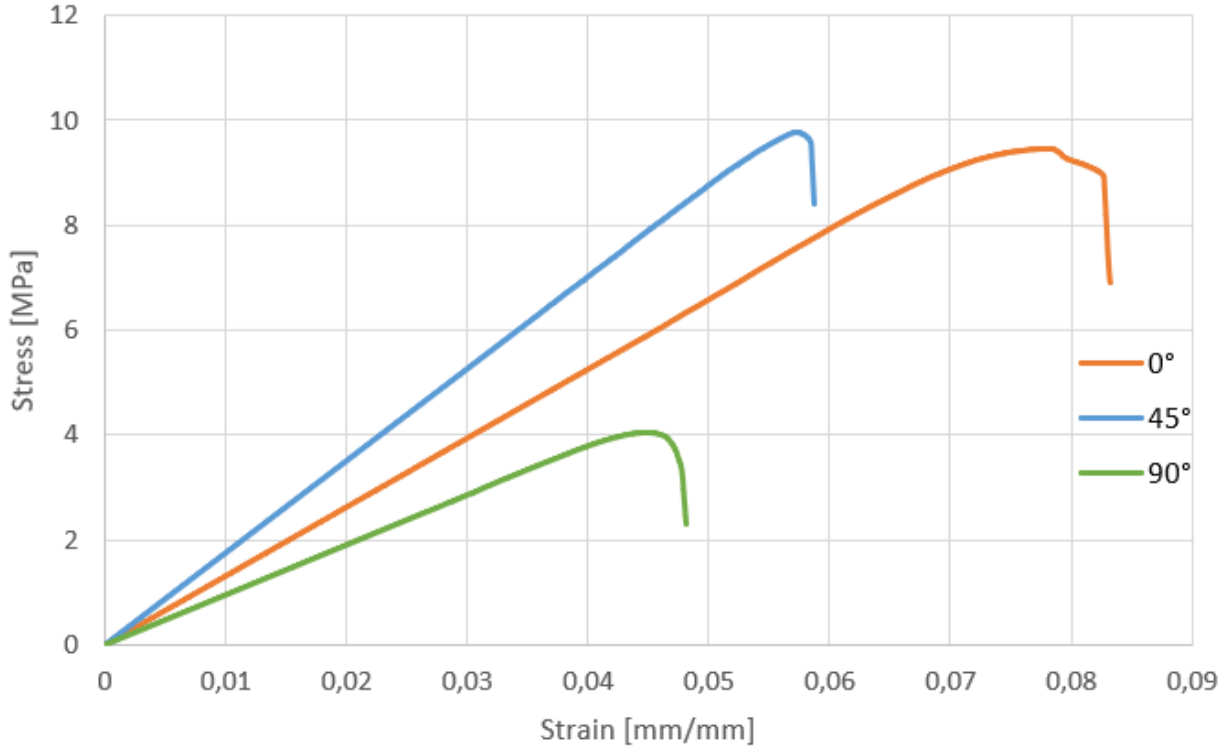


Design of Infill Microstructure for AM





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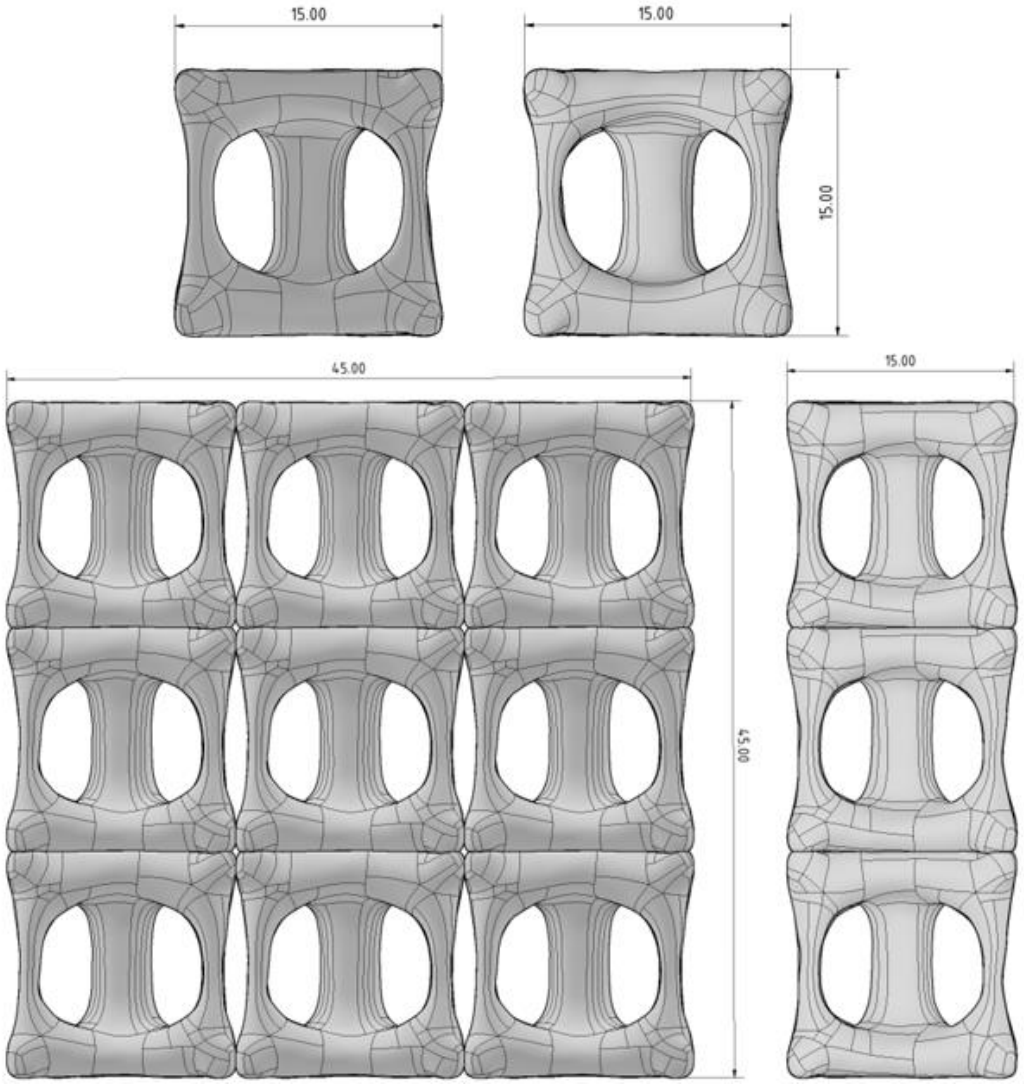

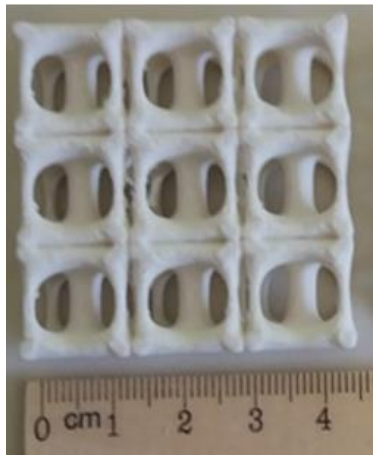

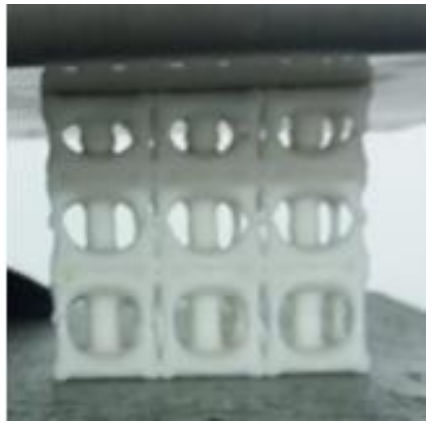

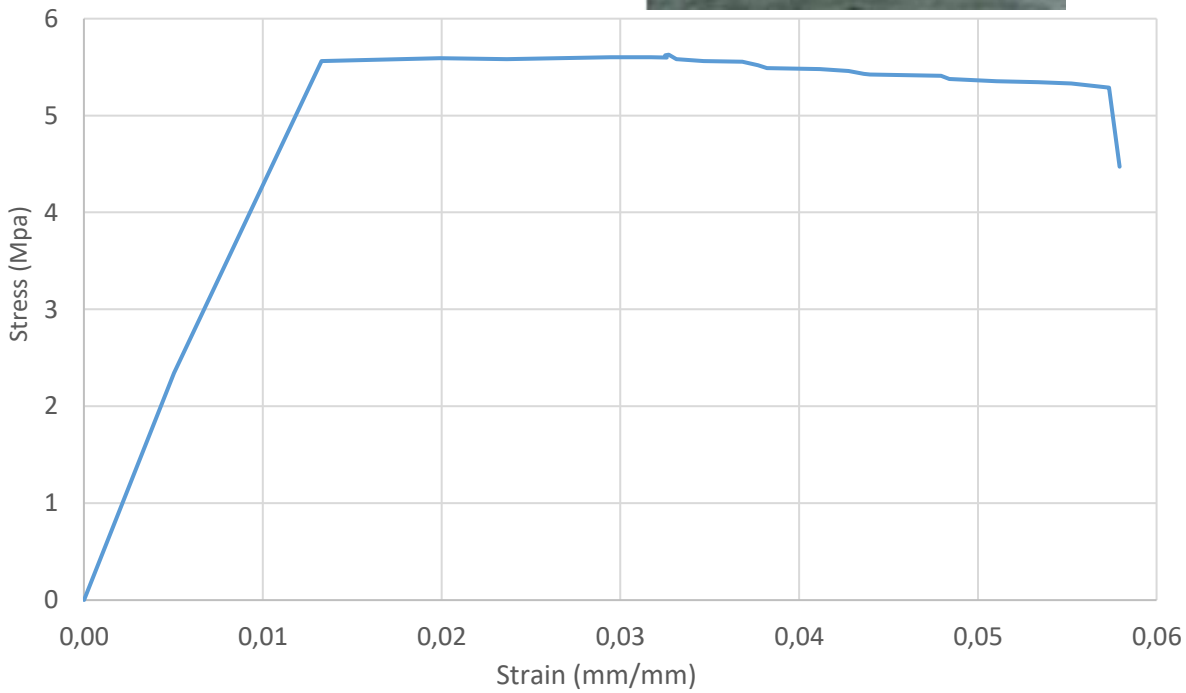

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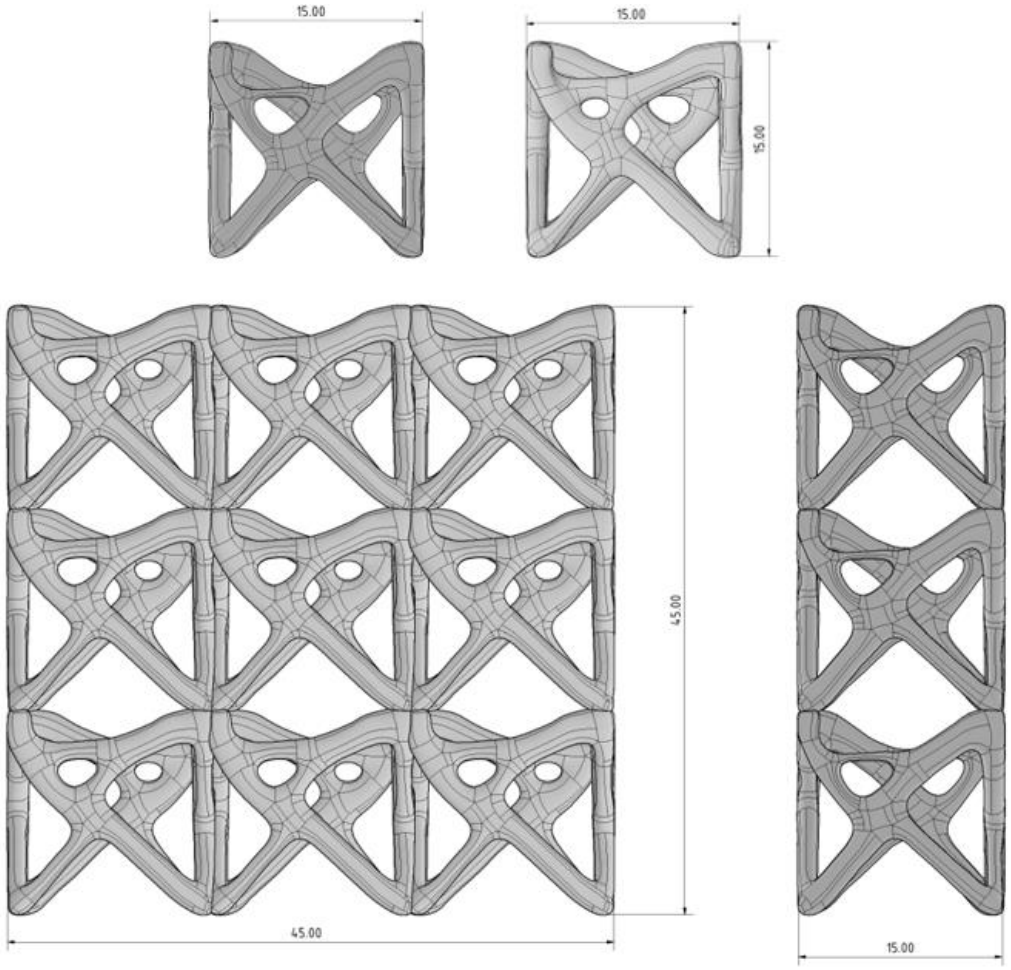

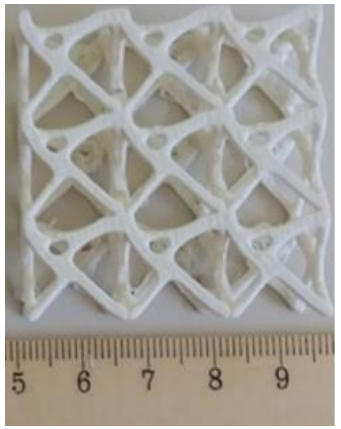

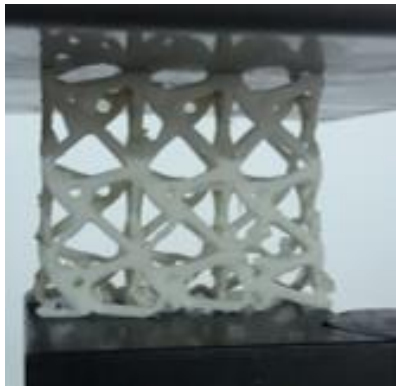

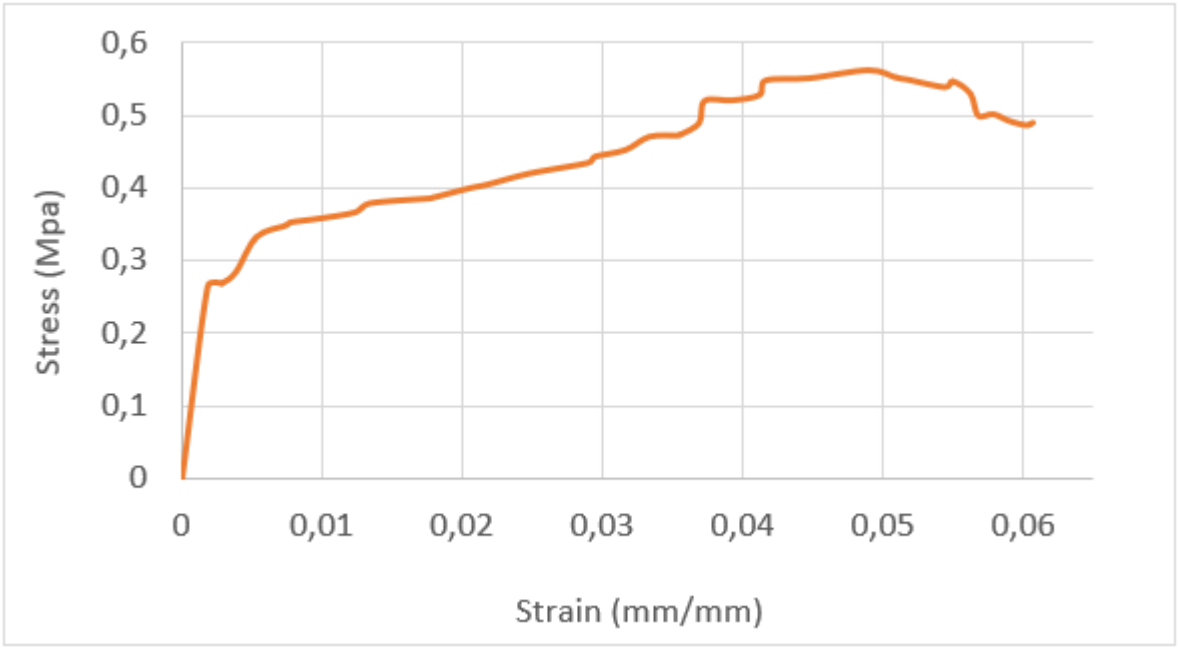

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Conclusions

- Topology optimization and generative design are promising and well-developed tools for the design of consumer products or mechanical components
- Additive Manufacturing is the appropriate fabrication method than can be coupled with TO & GD with excellent positive benefits for designers/engineers
- The hybrid approach of topology optimization and homogenization leads to identify the isotropy of lattice structures

Conclusions

- The proposed microstructures were evaluated by taking into account the isotropy with the help of Zener's ratio and the modulus of elasticity
- The anisotropy of lattices were approved experimentally
- Generative Design is an effective tool from the early stage of product design
- Multi-criteria definition in GD study
- The generative models are fully editable

Thank you for Your Attention!!!

Questions?

Ioannis Ntintakis

Email: ntintakis@hmu.gr

Our new Special Issue:

"Innovative Design with Additive Manufacturing, Topology Optimization and Cellular Microstructure"

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