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Optimization approaches in design for Additive Manufacturing

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Introduction

Additive Manufacturing (AM) technologies introduce a completely new approach for the design of customized and optimized parts; AM allows producing complex parts with a limited increase in production cost and time. Thanks to that, optimization approaches such as size, shape, and topology optimization are being re-discovered, since the models resulting from these methods are challenging to be produced with traditional manufacturing techniques.

These methods enable designers to reinvent solutions of different structural problems with the aim of obtaining improved mechanical characteristics and higher overall performances, especially the reduction of weight that comes with these new geometries.

High computational resources and advanced Computer-Aided Engineering software make possible to perform the optimization in the conceptual design stage, where the design has not yet been refined to a specific topology. Doing so, the different resulting shapes present suboptimal designs that will drive the following design phases.

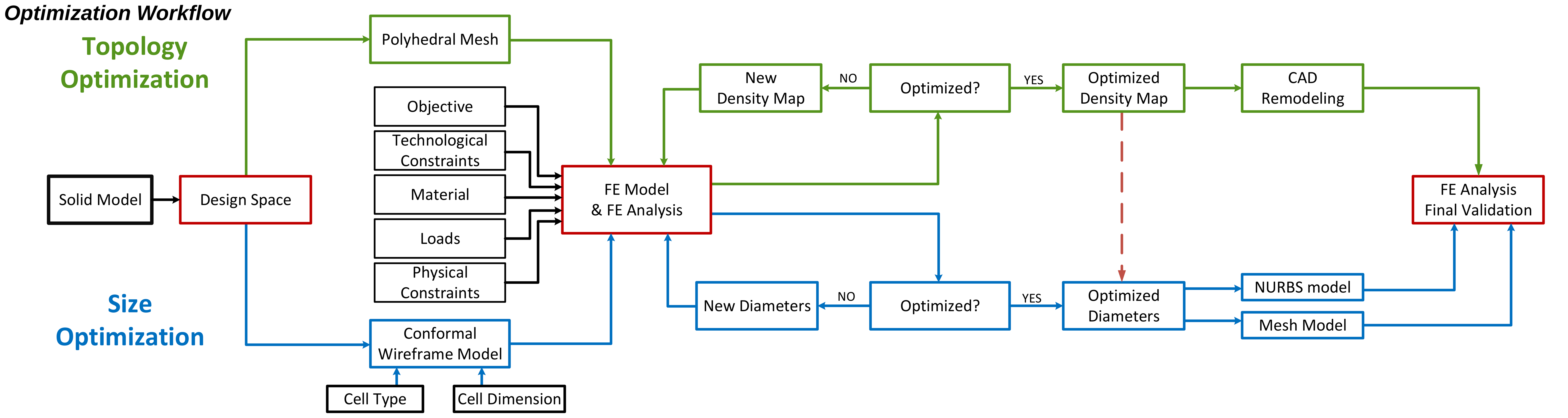
Functional requirements → **Conceptual design** → **Optimization Design Method** → **Detailing + Validation**

The aim of this work is to illustrate the possibilities of new design procedures in relation with AM potentialities and limits.

Different geometric modeling opportunities and structural optimization techniques are presented: commercial software is used to perform topology optimization and redesign of the optimized results. As alternative, a novel method, developed by the research group, allows to design conformal lattice structures with size optimization performed on the beams, which consents to automatically obtain a smooth mesh model.

The proposed workflow is validated on a set of test cases, adopting different design methods based on Lattice structures, PolyNurbs, and parametric CAD to reach innovative solutions.

Optimization Workflow



Topology optimization → material is arranged in order to find the best distribution under a set of boundary conditions and respecting the structural and dimensional performances requirements.

The goal of the optimization can be to maximize the stiffness, imposing a desired reduction of mass; these targets are reached varying the density of each element of a polyhedral mesh, which is related to the mechanical properties.

As a result, a density map is obtained, which is contoured to a specific level of density (threshold), obtaining a mesh surface. The optimized mesh of the design space is taken as an "inspiration" to the further modeling of the part in a CAD environment, often operated manually. In conclusion Finite Element Analysis is needed to verify that the stress conditions are respected. As an alternative, the density map can be used to assign the dimension to the elements of a lattice structure.

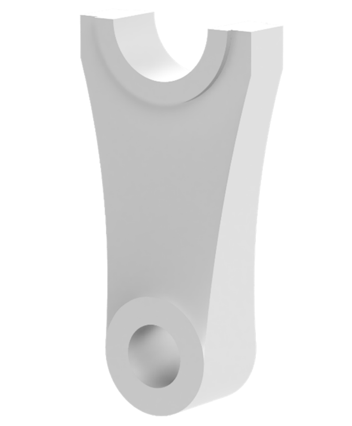
Size Optimization→ a conformal wireframe is obtained specifying the unit cell type and the minimum cell size; then, a size optimization is performed on the beams built on the wireframe, taking in consideration boundary conditions and manufacturing constraints, such as minimum beam diameter and pore size for depowdering. As a result, the optimal diameter of each beam is obtained.

A lattice structure is then modeled from the wireframe and the optimized diameter. This can be done with two different modeling approaches: a mesh modeling method and a NURBS modeling method. In the NURBS modeling method, the beams are modeled by cylinders with spherical caps; the method needs Boolean operations that require high computational resources, and the lattice obtained presents sharp edges at nodal points

The mesh modeling method exploits the Catmull-Clark subdivision surface algorithm to obtain smooth surfaces starting from a coarse mesh; this allows to reduce stress concentration, especially at nodal points, enhancing the mechanical properties and the fatigue life of the lattice, without the needs of additional filleting operations.

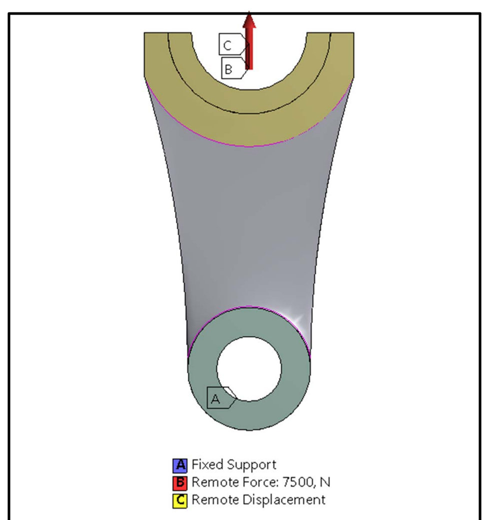
Case Studies

Piston Rod	Material	ρ [g/cm3]	E [Gpa]	YS [Mpa]	UTS [Mpa]	Safety Factor	σ_{adm} [Mpa]
	AlSi11Cu2Fe	2,7	71	140	240	1,5	93,3

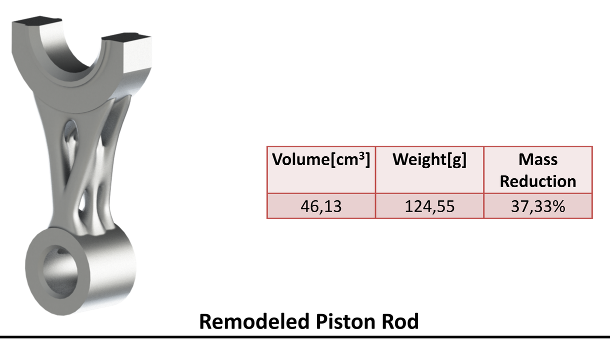


Volume[cm³]	Weight[g]
73,61	198,75

Piston Rod

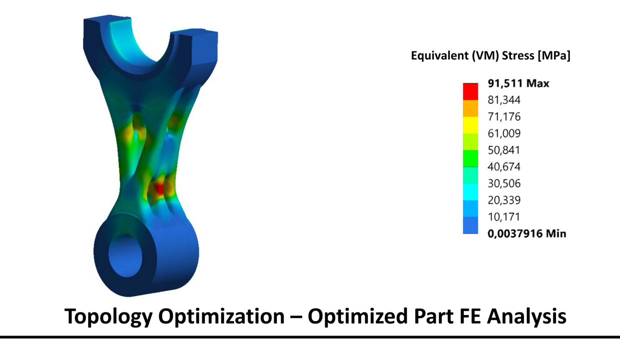


Boundary Conditions

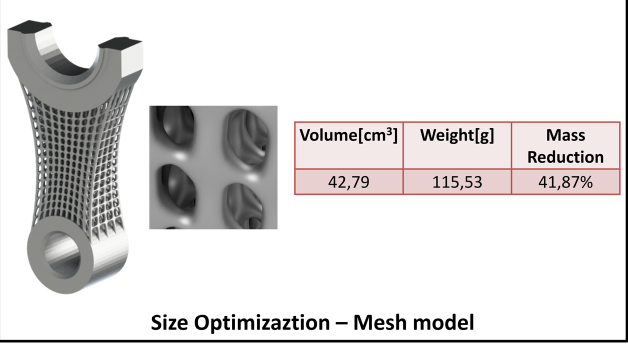


Volume[cm³]	Weight[g]	Mass Reduction
46,13	124,55	37,33%

Remodeled Piston Rod

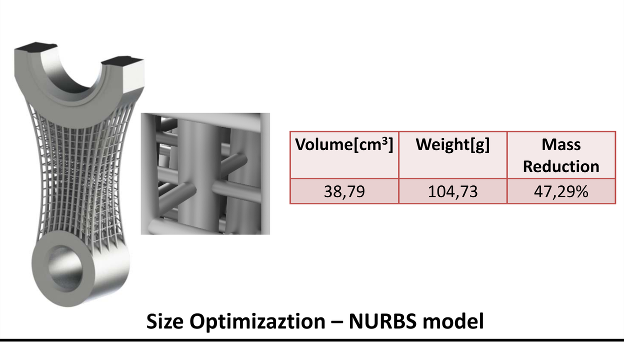


Topology Optimization – Optimized Part FE Analysis



Volume[cm³]	Weight[g]	Mass Reduction
42,79	115,53	41,87%

Size Optimizaztion – Mesh model



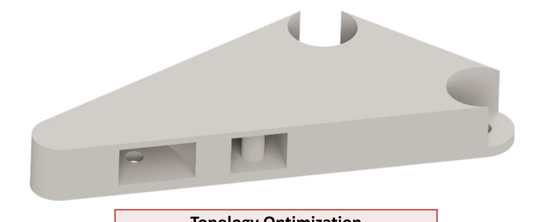
Volume[cm³]	Weight[g]	Mass Reduction
38,79	104,73	47,29%

Size Optimizaztion – NURBS model

Ship Barber	Material	ρ [g/cm³]	E [Gpa]	YS [Mpa]	UTS [Mpa]	Safety Factor	σ_{adm} [Mpa]
	Ti6AlV	4,429	110	786	862	1,5	524

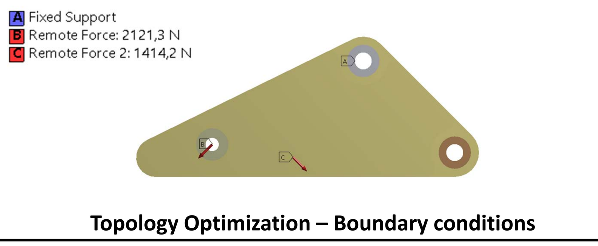
Volume[cm³]	Weight[g]	Number of parts
58,251	257,9	5

Original Ship Barber Model

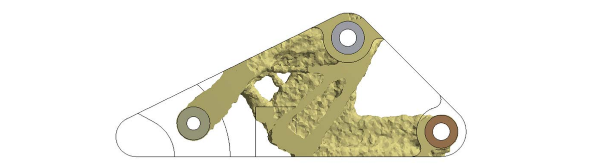


Topology Optimization	
Objective	Minimize Mass
Response Constrain	Global VM Stress 500 MPa (SF1,5)

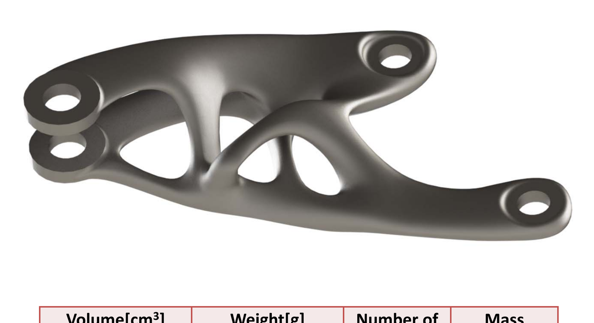
Ship Barber Design Space



Topology Optimization – Boundary conditions

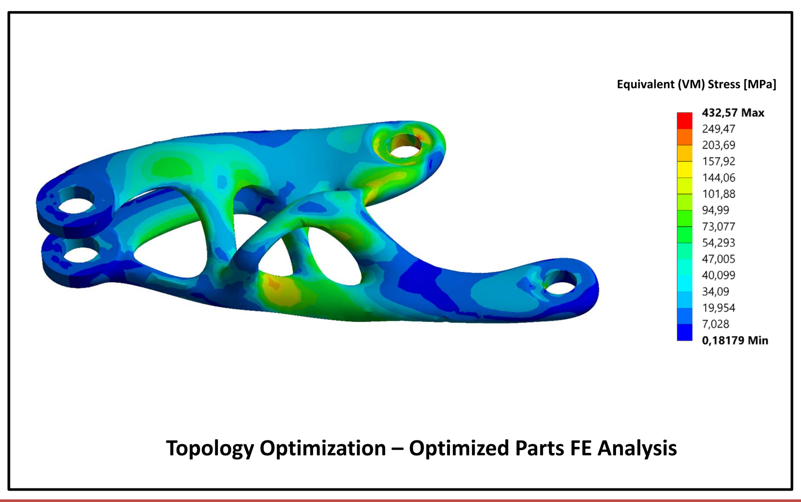


Topology Optimization – Topology Density



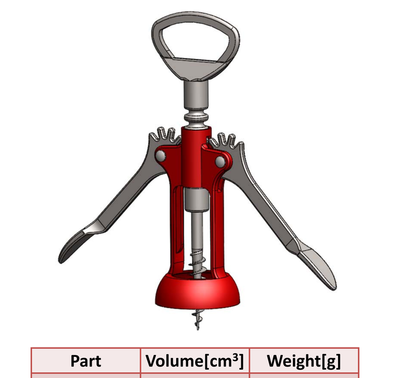
Volume[cm³]	Weight[g]	Number of parts	Mass reduction
46,347	205,27	1	20,4%

Remodeled Ship Barber



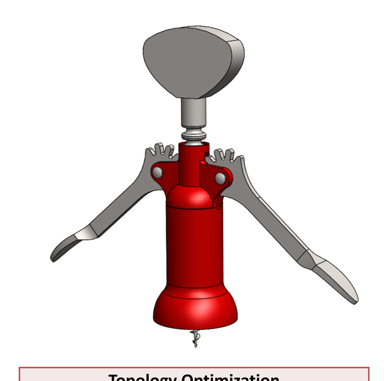
Topology Optimization – Optimized Parts FE Analysis

Corkscrew	Material	ρ [g/cm³]	E [Gpa]	YS [Mpa]	UTS [Mpa]	Safety Factor	σ_{adm} [Mpa]
	SS316L	7,99	190	494	624	1,5	329,3



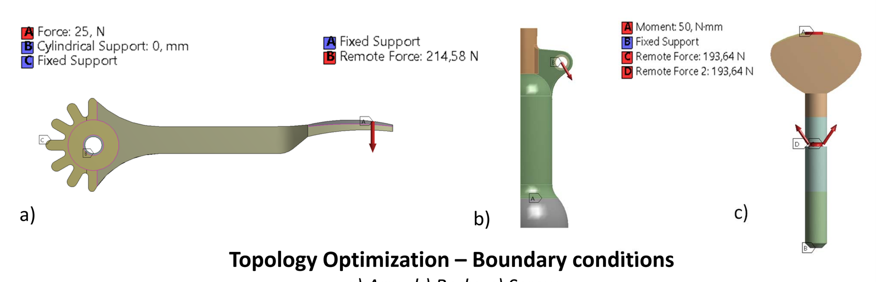
Part	Volume[cm³]	Weight[g]
Arm(x1)	3,164	25,28
Body	7,629	60,95
Screw	9,85	78,70
TOTAL	23,807	190,21

Original Corkscrew Model

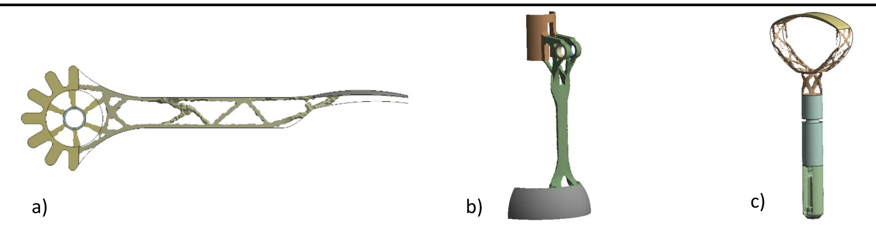


Topology Optimization	
Objective	Minimize Compliance
Response Constrain	85% Mass Reduction

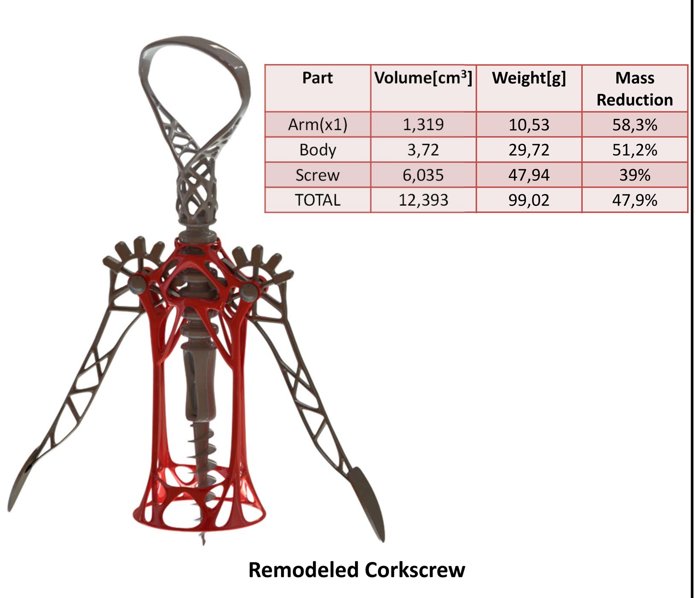
Corkscrew Design Space



Topology Optimization – Boundary conditions
a) Arm; b) Body; c) Screw

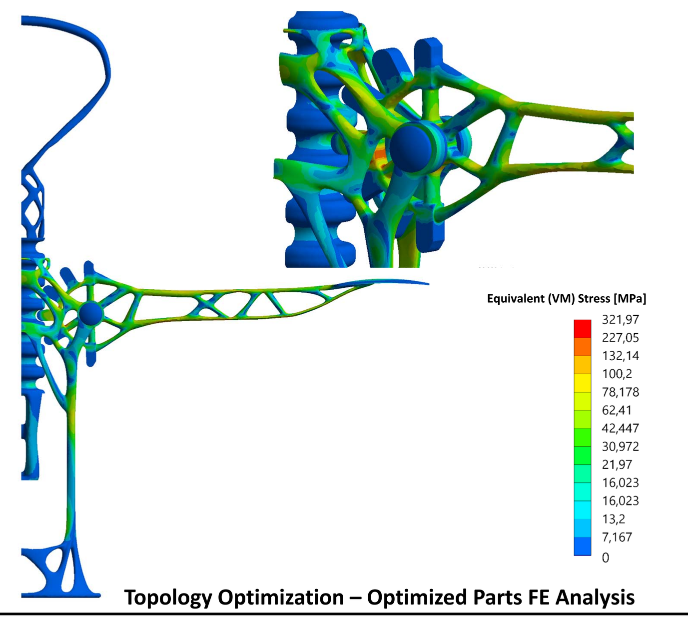


Topology Optimization – Topology Density
a) Arm; b) Body; c) Screw



Part	Volume[cm³]	Weight[g]	Mass Reduction
Arm(x1)	1,319	10,53	58,3%
Body	3,72	29,72	51,2%
Screw	6,035	47,94	39%
TOTAL	12,393	99,02	47,9%

Remodeled Corkscrew



Topology Optimization – Optimized Parts FE Analysis

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