DESIGNING WITH TOPOLOGY OPTIMIZATION

Pierre DUYSINX

LTAS – Automotive Engineering

Academic year 2021-2022

LAY-OUT

- Introduction
- Design process loop
- Design methodology using topology optimization
- Numerical applications
- Conclusion

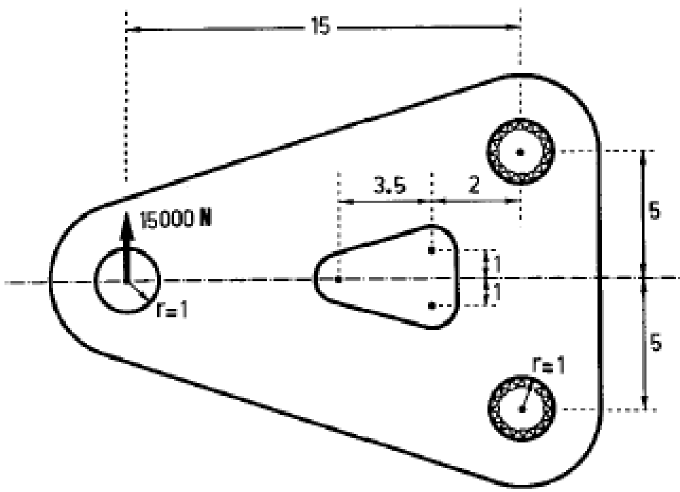
MOTIVATION

MOTIVATION

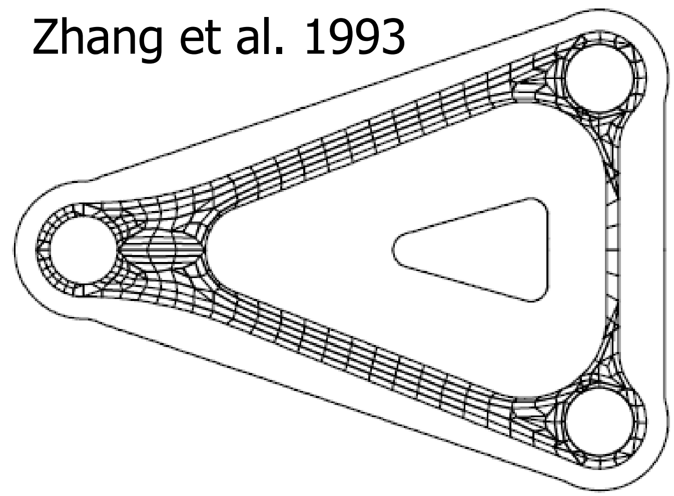
- Morphology of component has a great influence on the final performance
- Unappropriated choice of topology can limit the final satisfaction of the specifications
- Engineers used to trust in their intuition or former knowledge of the topic and empirical choices
- Need for new methods to replace empirical choice or trial-and-error process ➔ topology optimization
- Topology optimized components can reach gains of 50 to 100% in terms of overall performance

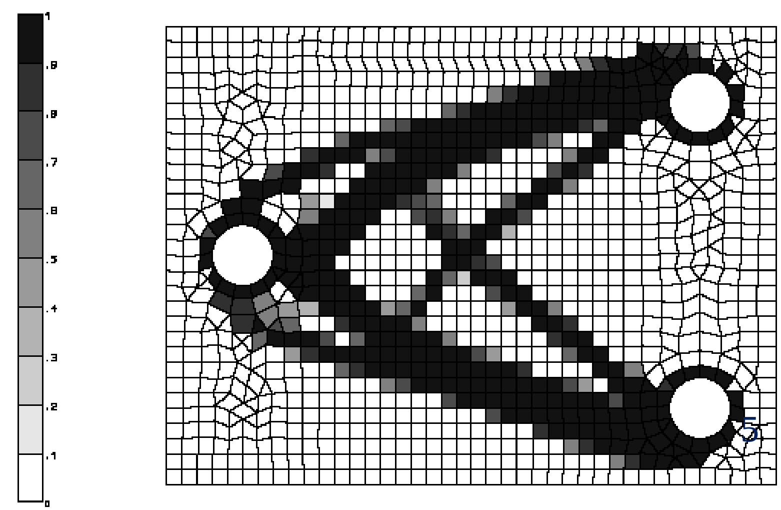
MOTIVATION

- CAD approach does not allow topology modifications



Zhang et al. 1993





A better morphology by topology optimization (Duysinx, 1996)

PLACE OF TOPOLOGY OPTIMIZATION IN THE DIGITAL DESIGN CHAIN

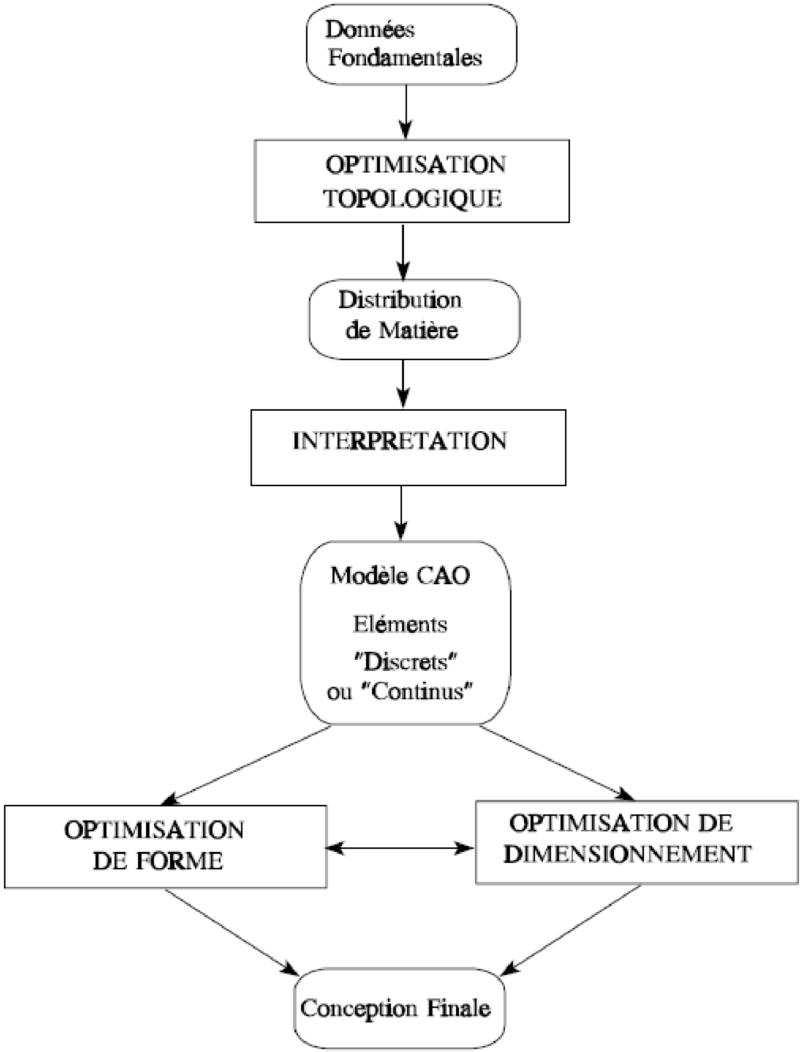
A PRELIMINARY DESIGN TOOL

- Topology optimization is a **preliminary design tool** that must be followed by additional steps of design and verifications.

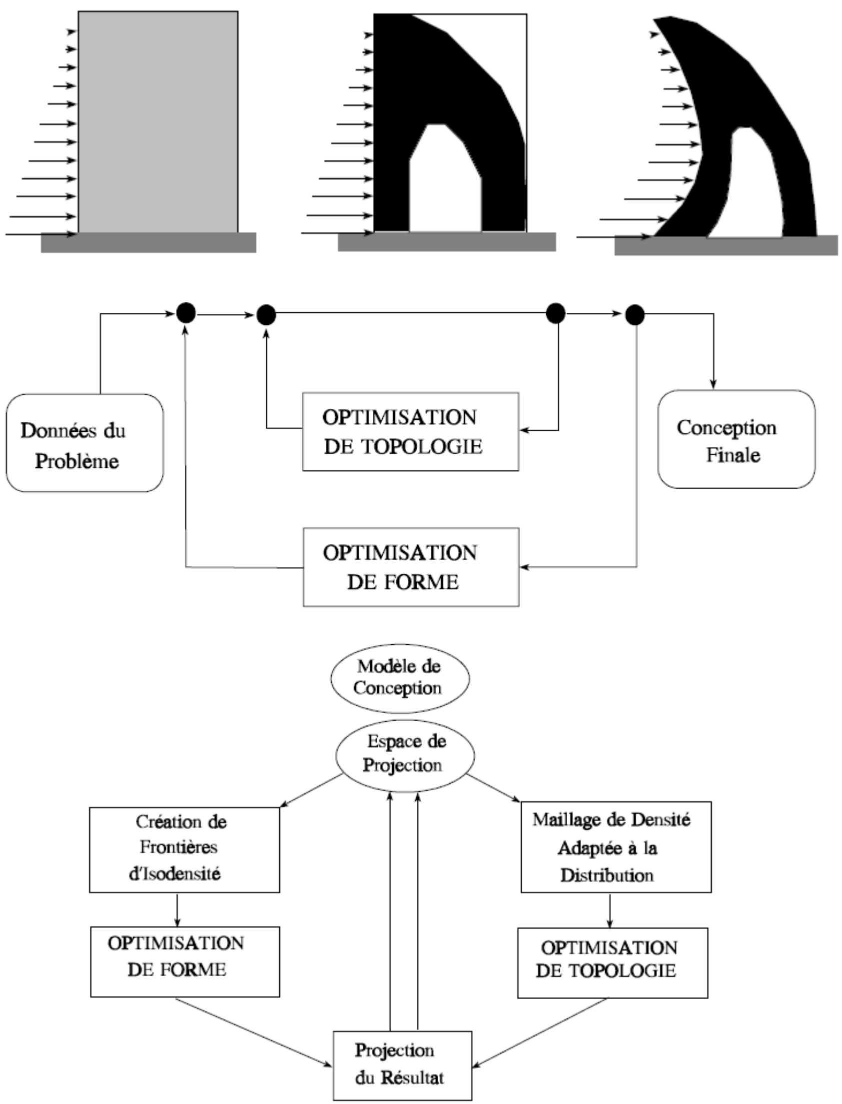
- Topology optimized results must be post treated:
  - Optimized results are not black-and-white pictures. They include intermediate density regions or microstructures. Microstructures can not be manufactured using classic manufacturing processes.
  - Topology optimization consider only a subset of design specifications. ➔ Additional simulations.
  - Simulation and fabrication often require smooth boundary contours ➔ interpretation and reconstruction of a parametric CAD model

A PRELIMINARY DESIGN TOOL

- Continuous design chain
  - Topology optimization has to determine a good morphology
    - Global criteria
    - Boundary conditions
    - Linear analysis?
  - Shape and sizing optimizations has to refine the design to cope with the full specification booklet
    - Local constraints
    - Non linear simulation
    - Manufacturing…



INTEGRATION OF SHAPE AND TOPOLOGY



- Shape of design domain can change topology and vice-versa
- Non continuous mapping between optimized topology and design domain shape (Bruyneel)
- Interlaced shape and topology optimization processes (Maute & Ramm, 1994)
- Simultaneous shape and topology optimization (Kuci, 2018)

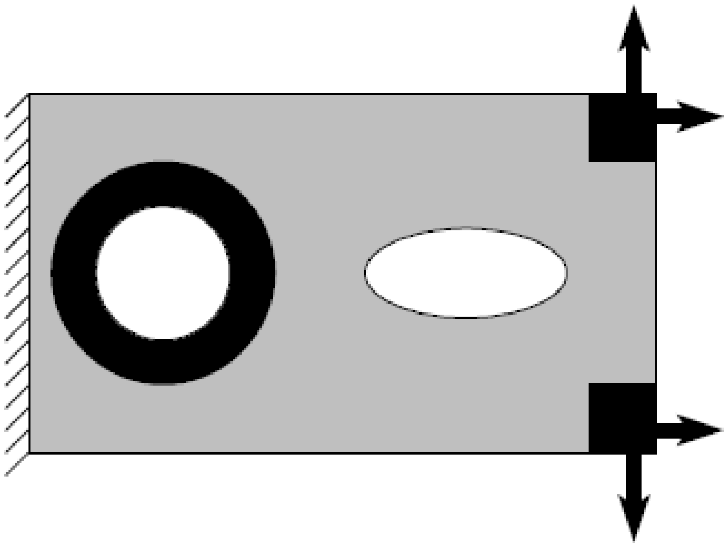
METHODOLOGY FOR TOPOLOGY OPTIMIZATION PROJECT

METHODOLOGY

- Carrying out successfully a topology optimization process requires a structured methodology
- Accounting correctly for the problems specifications:
  - Boundary conditions
  - Load cases
  - Symmetry conditions
  - Problem formulation
- Selecting appropriated TO process parameters:
  - Power penalization,
  - Volume constraints,
  - Filter parameters: density and thresholding functions
  - Material interpolation laws
  - Finite element discretization
- Optimization algorithms

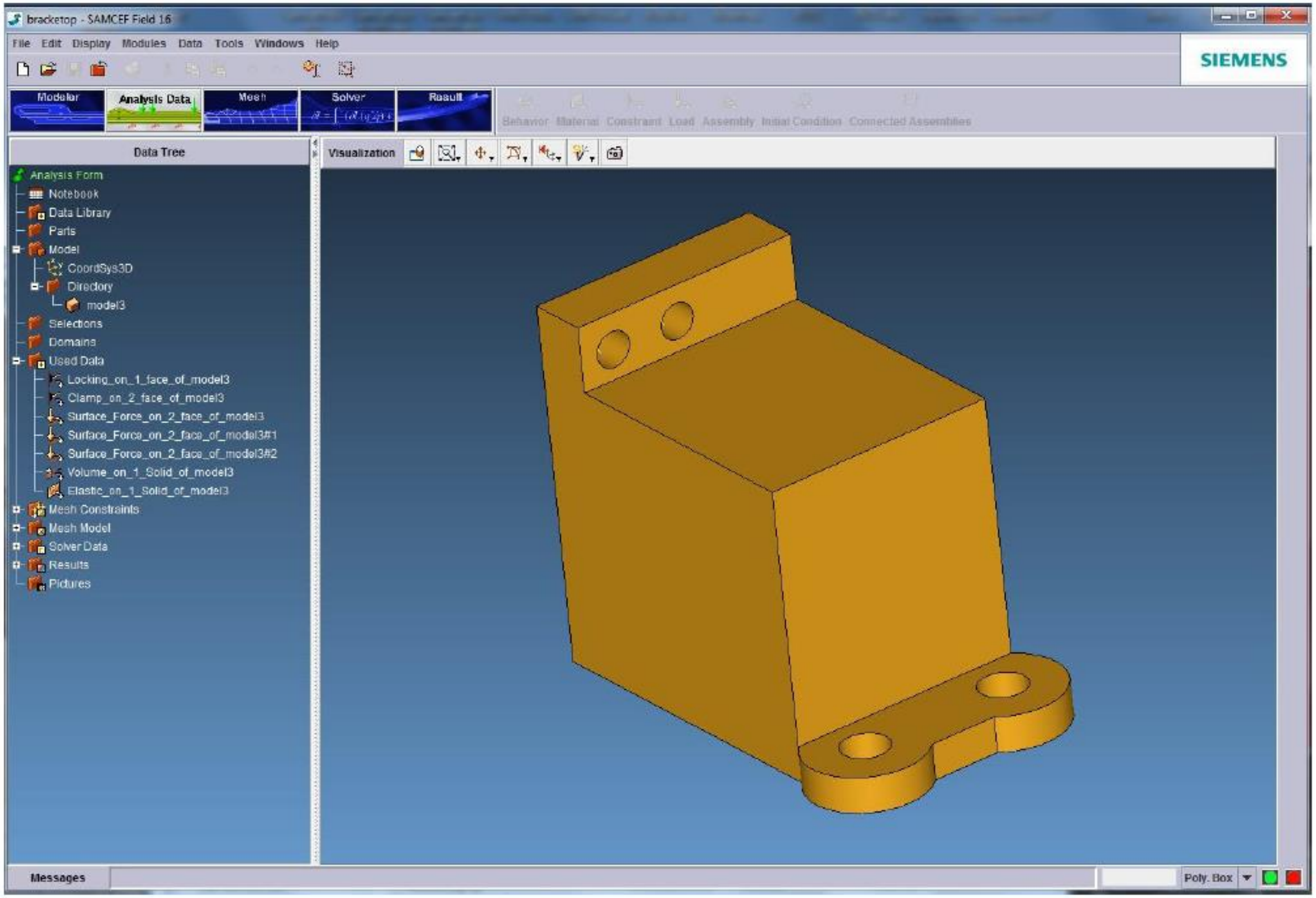
METHODOLOGY

- 1/ Choice of the design domain
  - Can be used to prescribe overall design constraints (packaging, system integration)
  - Be careful with infinite boundary conditions: avoid interaction of the optimized material distribution with the design domain boundaries
  - Be able to account for the fixations, loads, etc.
  - Take benefit of symmetry conditions, repeated patterns, etc.



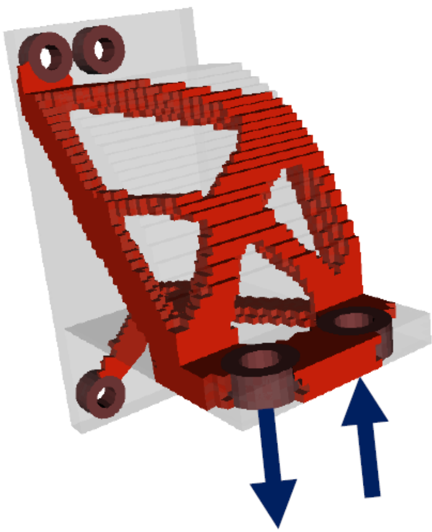
METHODOLOGY

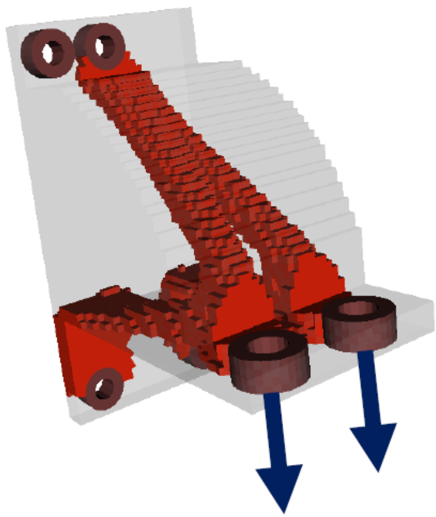
- Choice of the design domain

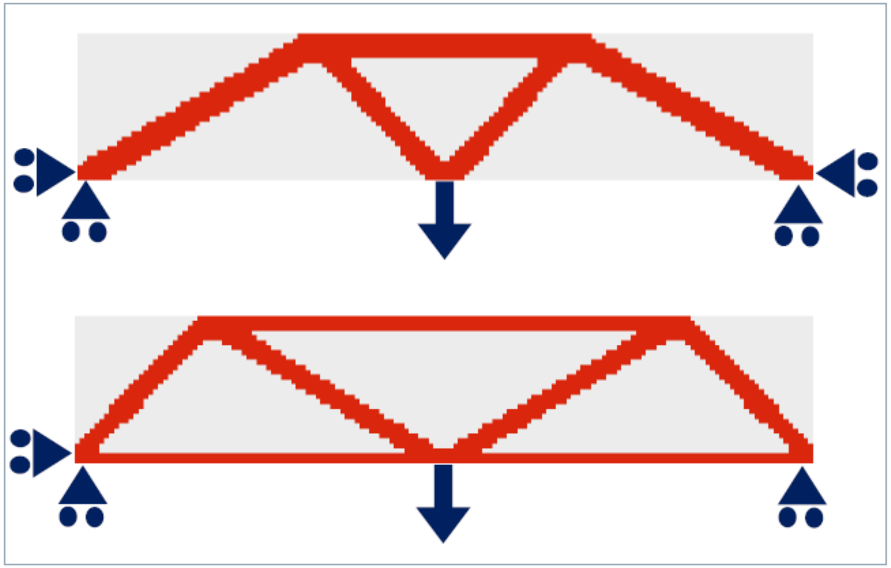


METHODOLOGY

- Choosing the appropriated loads and boundary condition is essential!

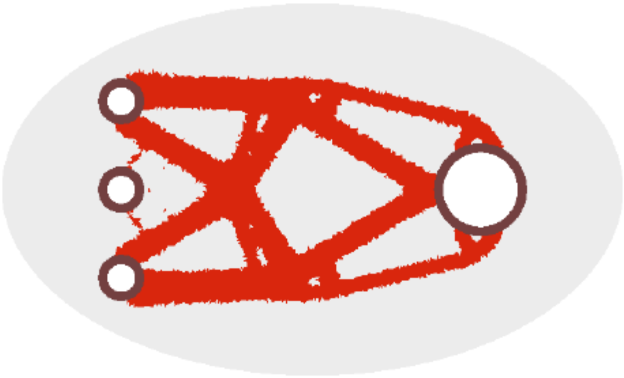




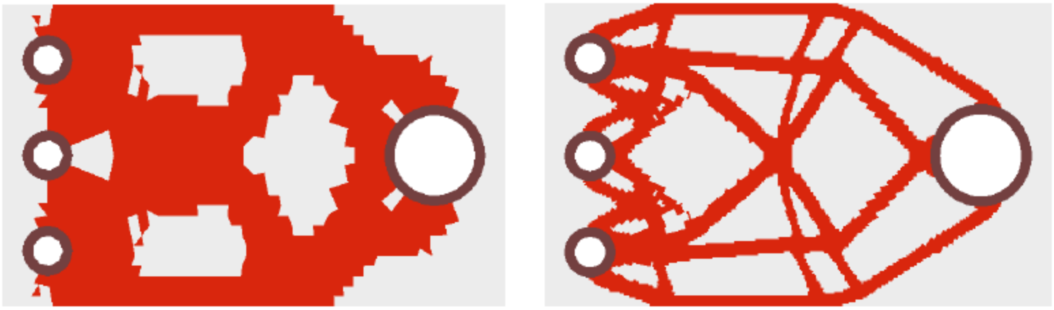


METHODOLOGY

- Large design domain gives full freedom to the designer

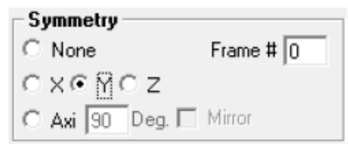


- Design domain can restrain the optimized distribution

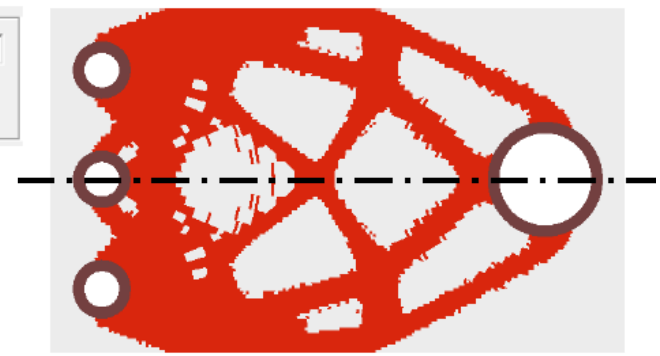


METHODOLOGY

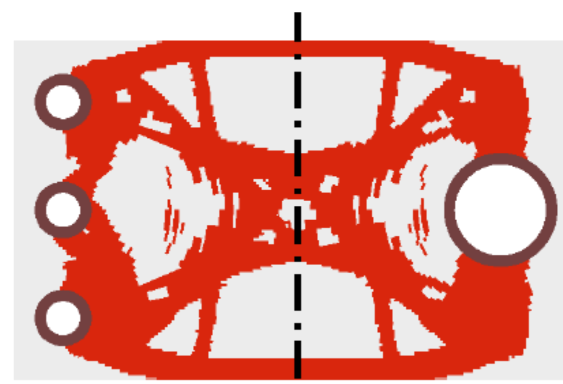
- No symmetry
  - No geometrical symmetry
  - No loading symmetry



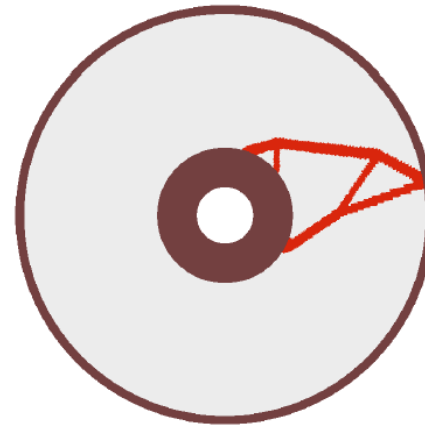
- Symmetry about y-axis
  - Use structural frame (.FRAME)
  - Applicable on non symmetric meshes
  - Applied only on optimizable design elements



- Symmetry about x-axis



METHODOLOGY



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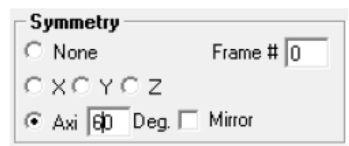
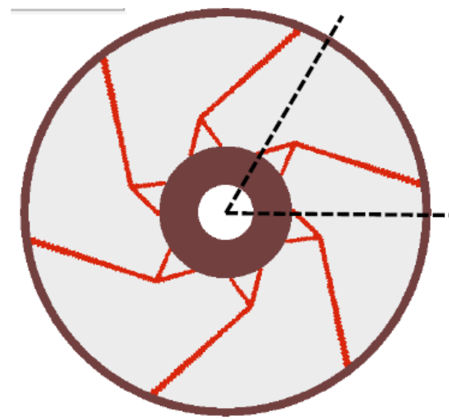
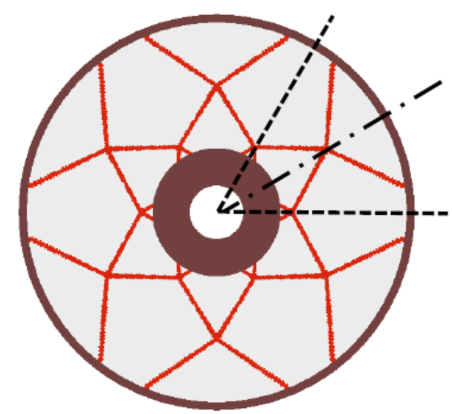




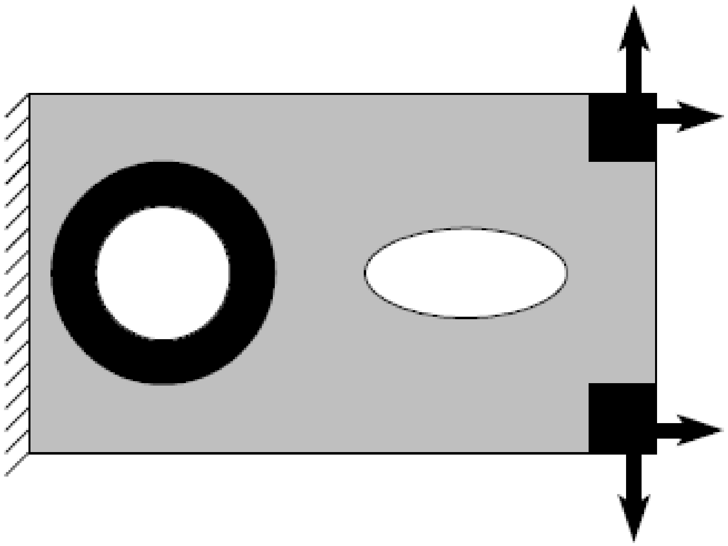
- With 60° cyclic symmetry



- With mirror symmetry inside sector

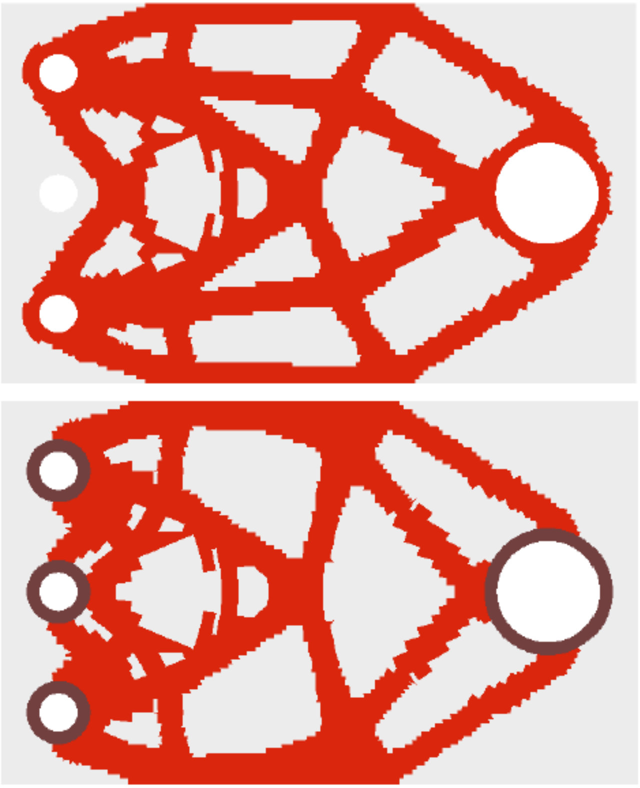
METHODOLOGY

- 2/ Identification of design variables
  - Non design parts
    - Part with full density material (mandatory presence of material)
      - Loads application points
      - Supports
      - Functional surfaces for connections
    - Parts with zero density ➔ holes or other components



METHODOLOGY

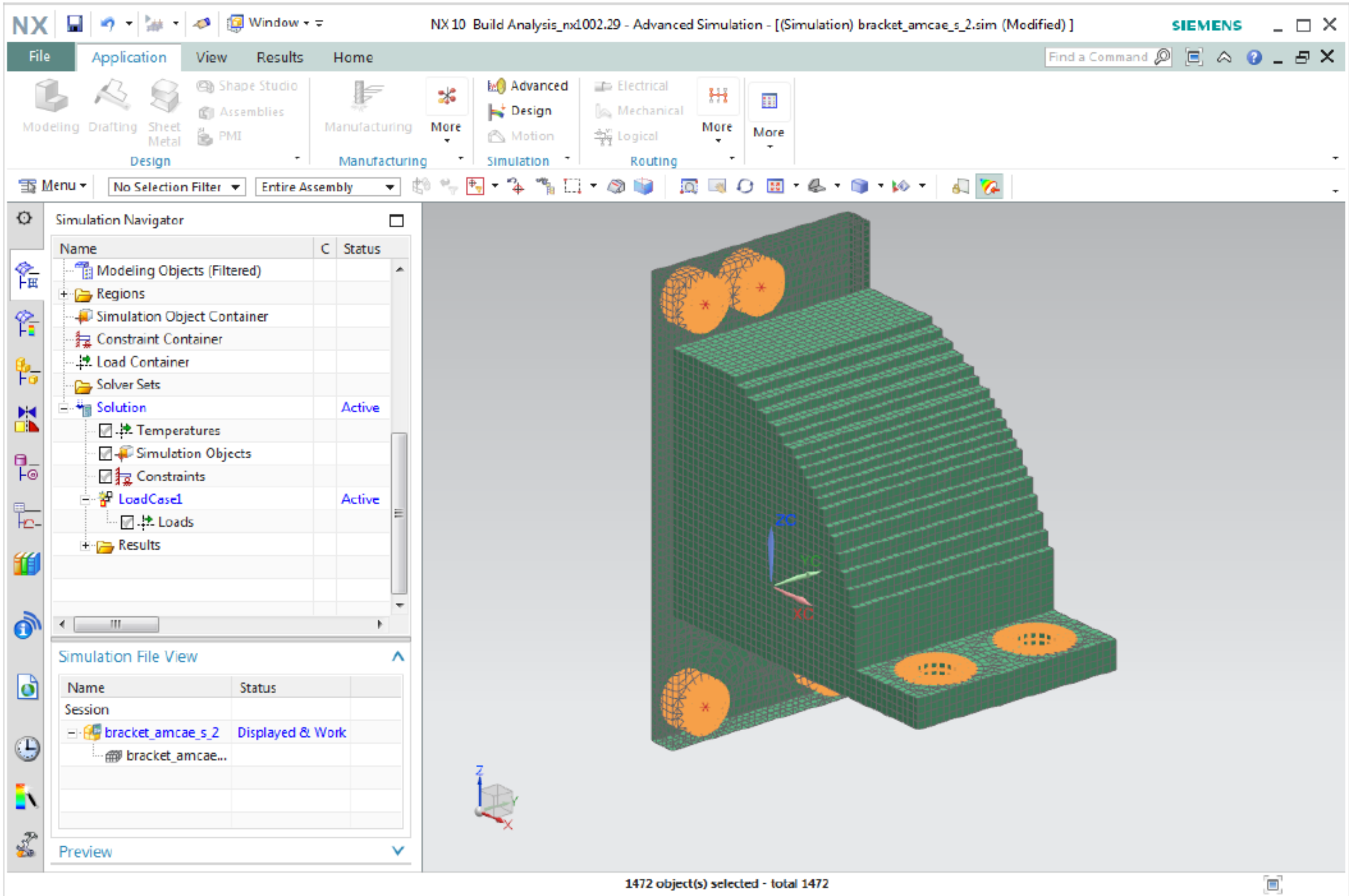
- Select groups of elements
- TOPOLVAR ➔ optimizable elements
- TOPOLFIX ➔ fixed density element = removed from optimization
- But default: all elements are optimized



Define the cylinders holes as non design

METHODOLOGY

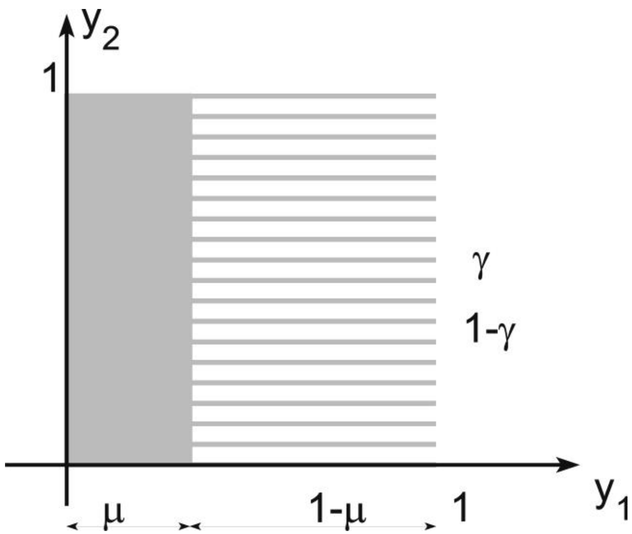
- Non design regions

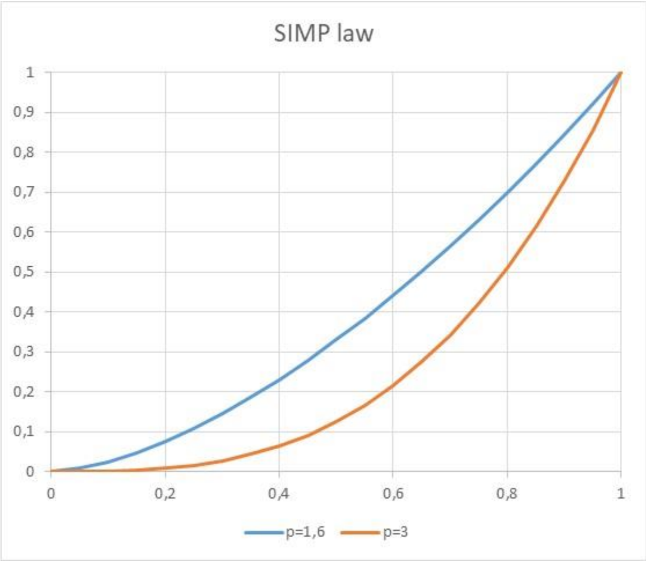


METHODOLOGY

- 3/ Choice of a material interpolation law / composite microstructure

- Interpolation is necessary to relax the 0/1 optimization problem → continuous variable optimization
- Penalization: reduce intermediate density regions
- Optimal microstructures like rank-N materials → full mathematical relaxation
- Other microstructures or mathematical interpolation laws: Uncomplete relaxation





METHODOLOGY

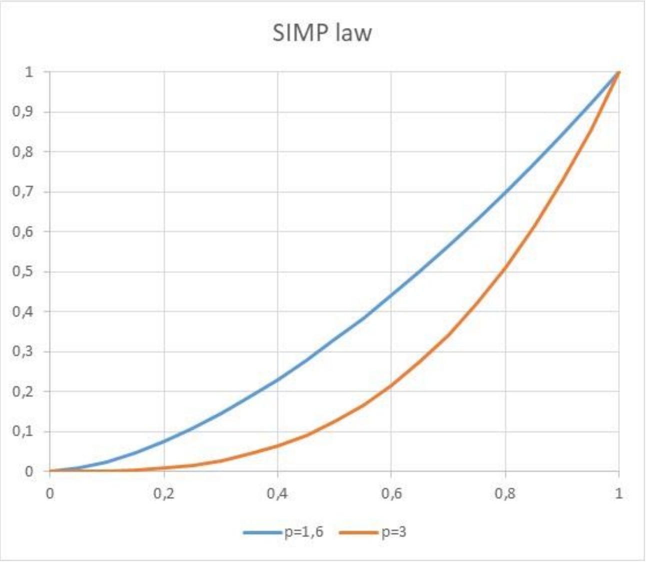
- 3/ Choice of a material interpolation law / composite microstructure
- SIMP (Simply Isotropic Material with Penalization) :

$$E(x) = x^p \, E^0 \quad p > 1$$

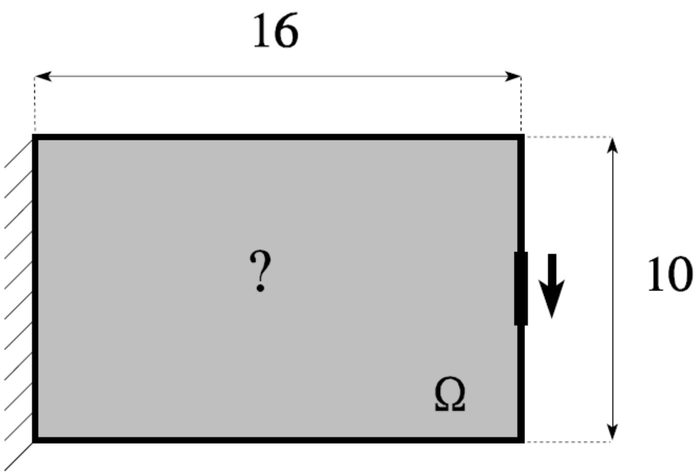
- Modified SIMP should be preferred to avoid singularities

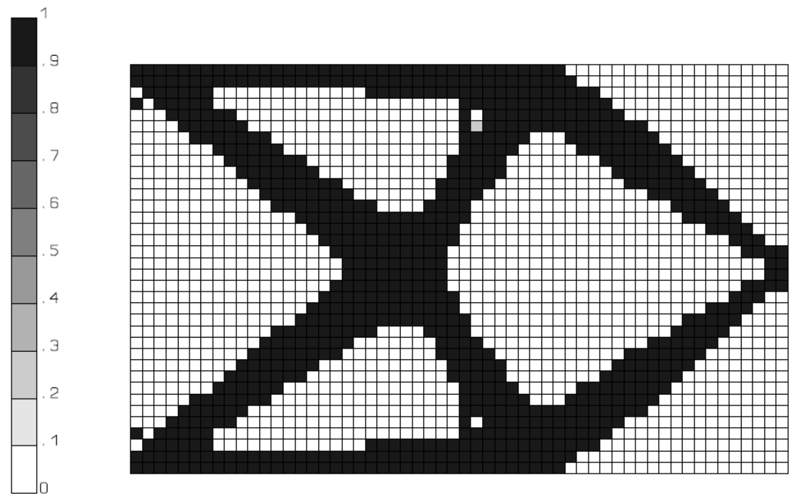
$$E(x) = E_{min} + x^p (E^0 - E_{min})$$

- Choice of parameter p
  - Classic choice p= 3!
  - Low penalization (very stable convergence) p=1.6
  - High penalization (but many local optima!) p= 4 or more…

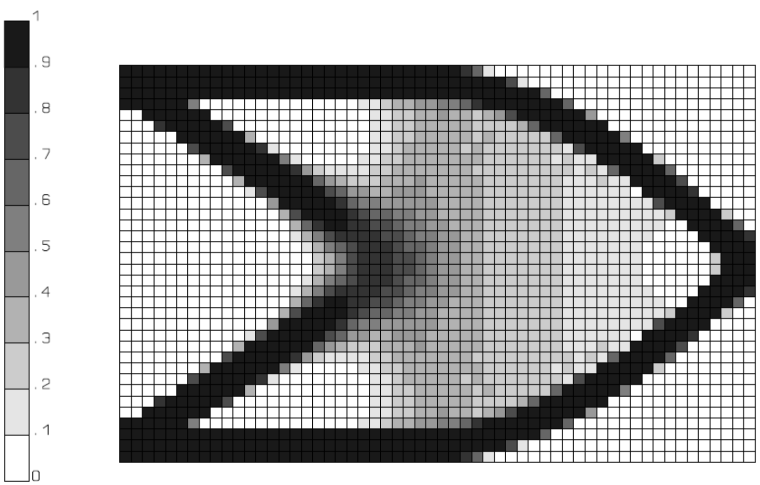


METHODOLOGY

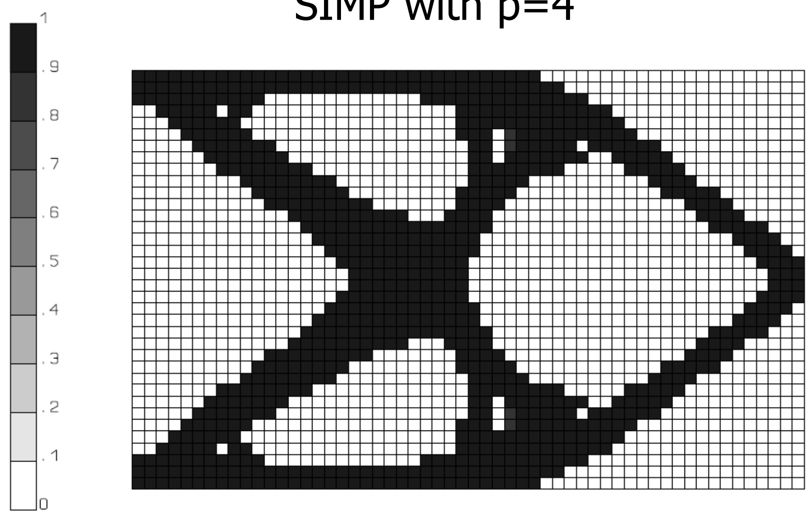




SIMP with p=4



SIMP with p=2



SIMP with p=3

METHODOLOGY

- 3/ Choice of a material interpolation law / composite microstructure
- Alternatively RAMP parameterization (Stolpe & Svanberg, 2001) enables controlling the slope at zero density

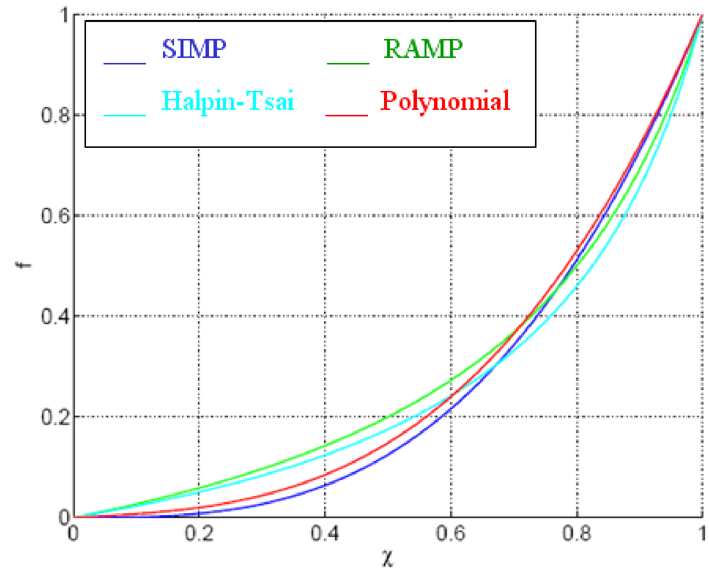
$$E(x) = \frac{x}{1+p(1-x)}\,E^0$$

- Halpin Tsai (1969)

$$E(x) = \frac{r\,x}{(1+r)-x}\,E^0$$

- Polynomial penalization (Zhu, 2009):

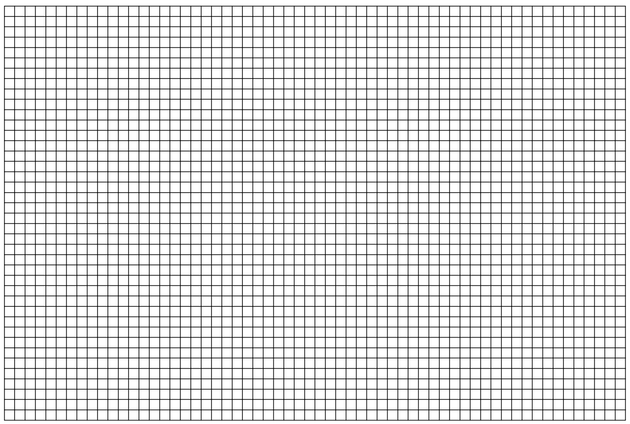
$$E(x) = \left(\frac{\alpha-1}{\alpha}x^p + \frac{1}{\alpha}x\right)\,E^0$$

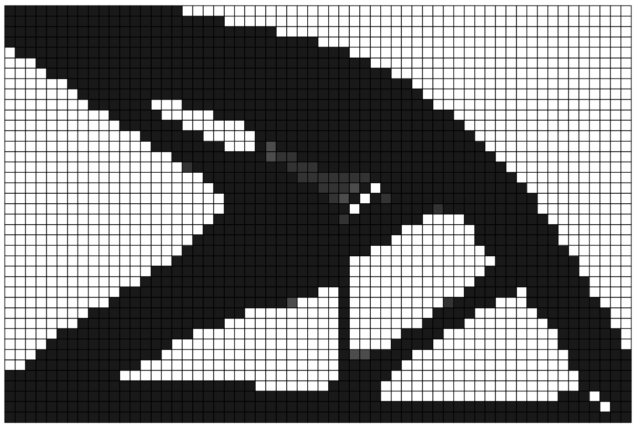


- Necessary for problems like self-weight, eigenvalue problems (vibration, stability)!

METHODOLOGY

- 4/ Finite element model
  - Mesh with appropriate density
    - Free mesh is possible
    - Mesh regularity: quadrangular finite element should be preferred





METHODOLOGY

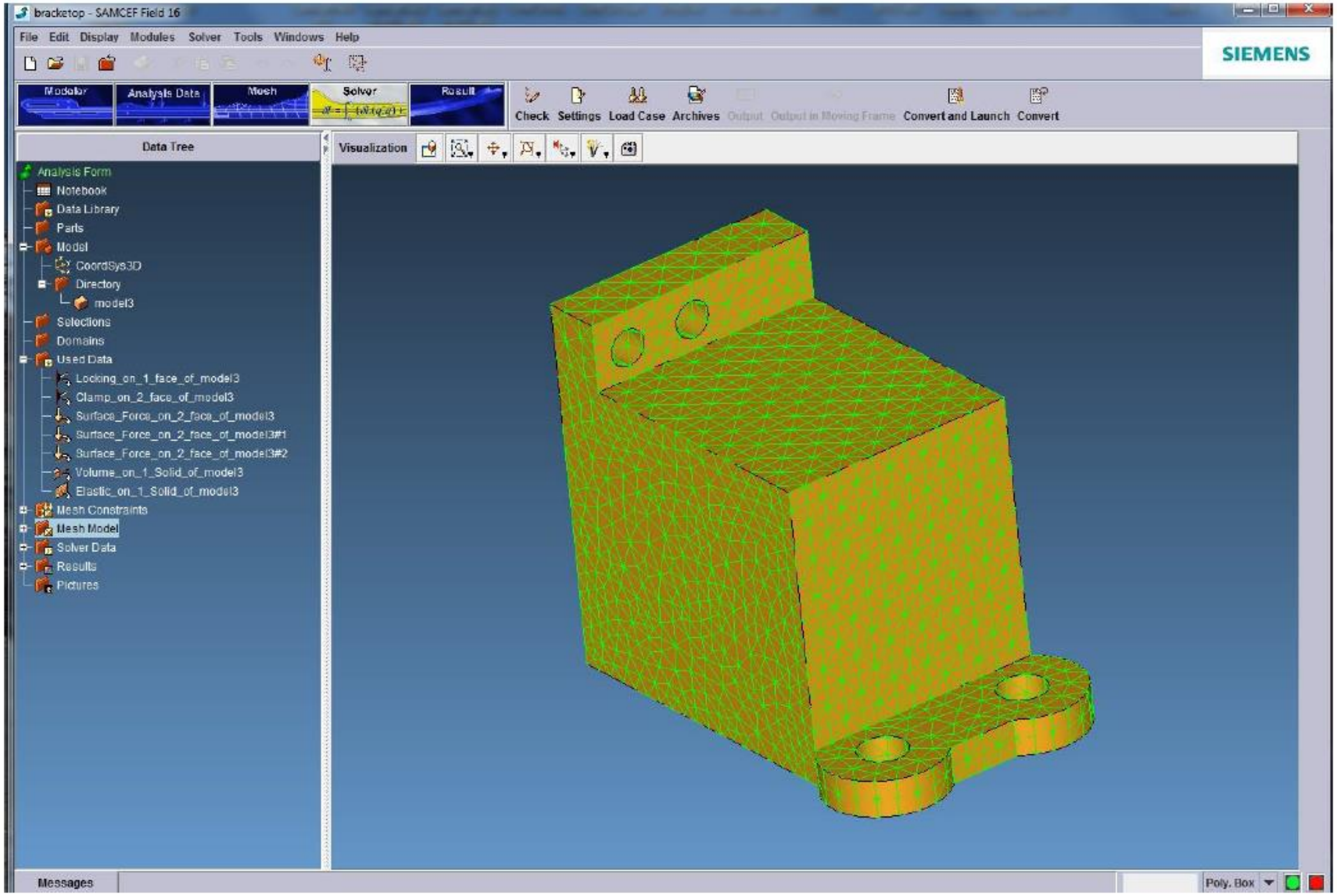
- 4/ Finite element model
  - Finite element type and approximation
    - Assumption : plate elements, volume elements, bending elements
    - Approximation degree: degree 2 is better for checkerboard alleviation and stress estimation but the CPU cost is very expensive
    - Degree 1 is possible but should completed by density filter or perimeter constraint
  - Discretization of the density field
    - Most usual discretization: constant density per finite element (centroid density)
    - Node discretization and linear interpolation function is possible
    - Level set discretization or phase field are alternative options

METHODOLOGY

- 4/ Finite element model
  - Initial density distribution
    - Uniform average density
    - Random density distribution with average satisfying volume constraint
    - Full material density

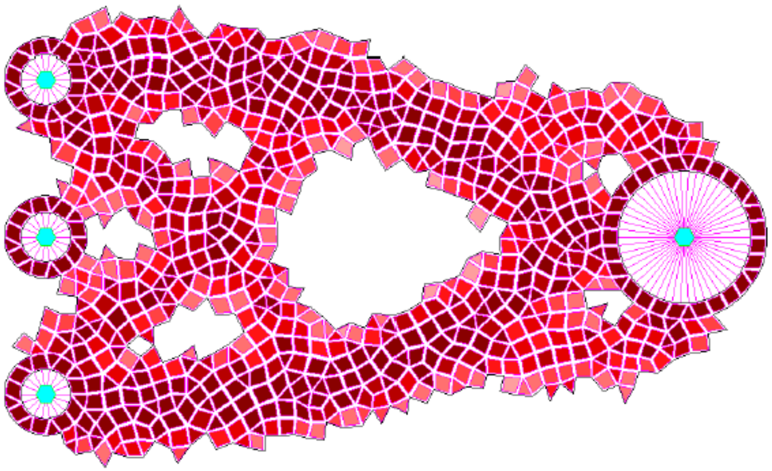
METHODOLOGY

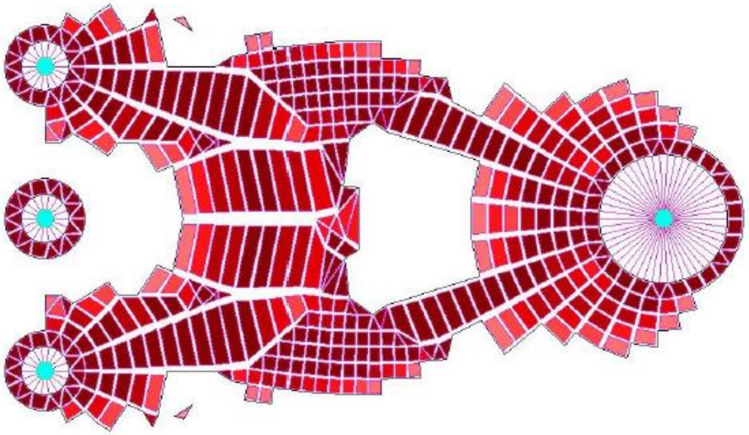
- Meshing the design domain



METHODOLOGY

- Irregular meshes give poor results





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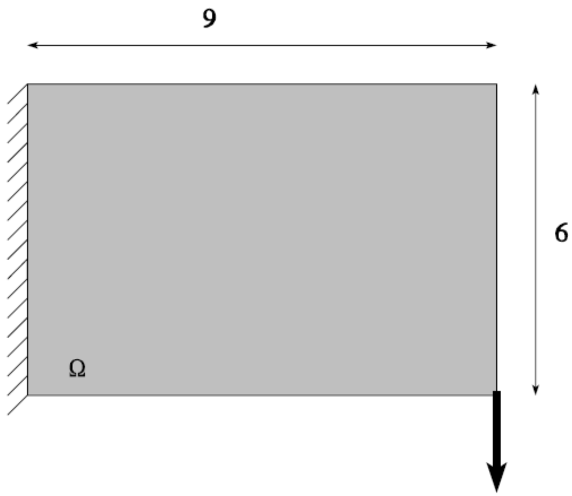
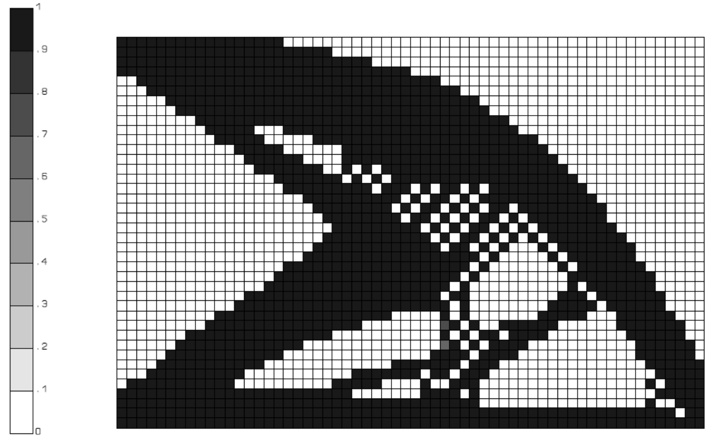
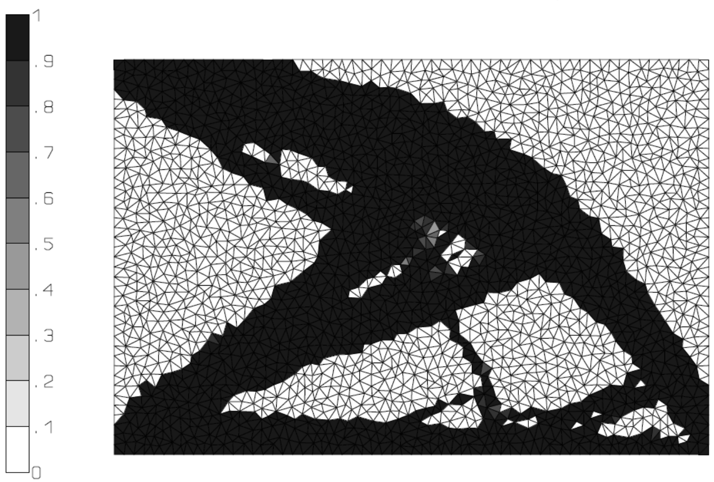
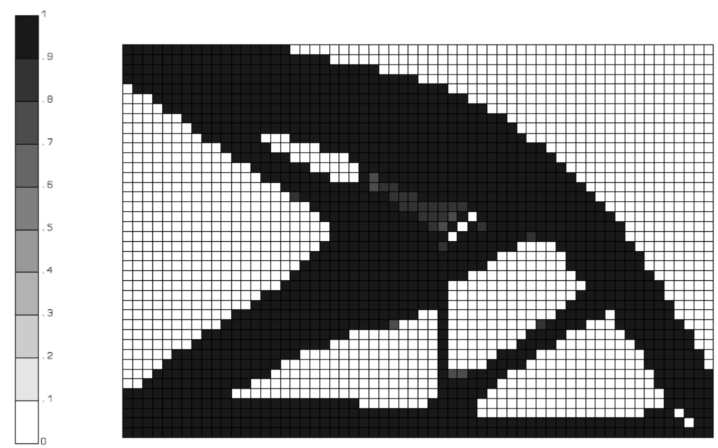




FE Degree 1



FE triangular Degree 2



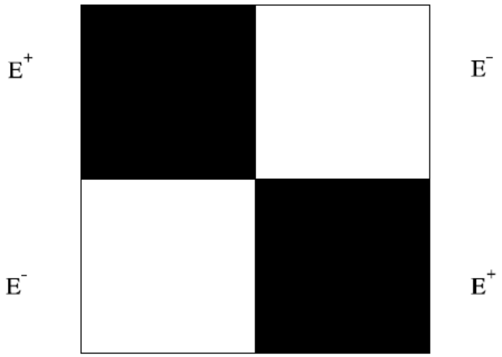
FE Degree 2

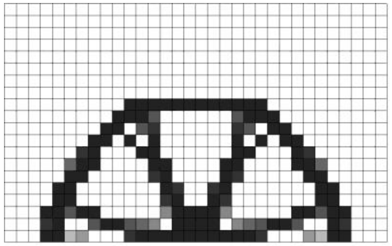
METHODOLOGY

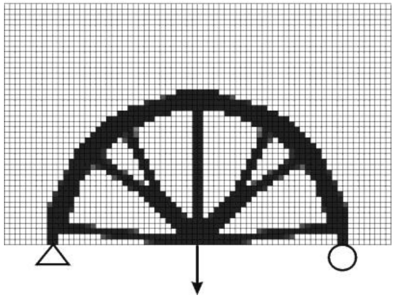
- 5/ Regularization strategy
  - Mesh independency
  - Checkerboard alleviation
  - Minimum size
  - Perimeter method: not popular anymore
  - Three field method
    - Density filtering
    - Heaviside filtering

Two numerical difficulties

- Checkerboard patterns: numerical instabilities related to the inconsistency between the displacement and density fields.
  - Appearance of alternate black-white patterns
  - Checkerboard patterns replaces intermediate densities



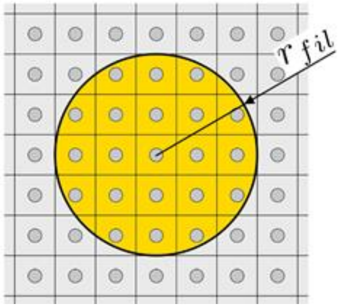




- Mesh dependency: the solution depends on the computing mesh.
  - New members appears when refining the mesh
  - Number of holes and structural features is modified when changing the mesh.
  - Stability (and meaning) of solutions?

THE THREE FIELD APPROACH

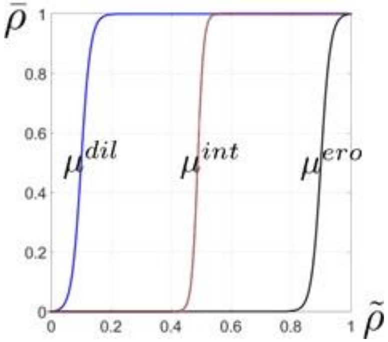
- Three field topology optimization scheme proposed by Wang et al. (2011),
  - Density filtering



$$\tilde{x}_e = \frac{\sum_{i \in N_e} w_i(X)\, v_i\, x_i}{\sum_i w_i(X_i)\, v_i}$$

  - Heaviside filter
    - Thresholding
    - Erode / delate geometry

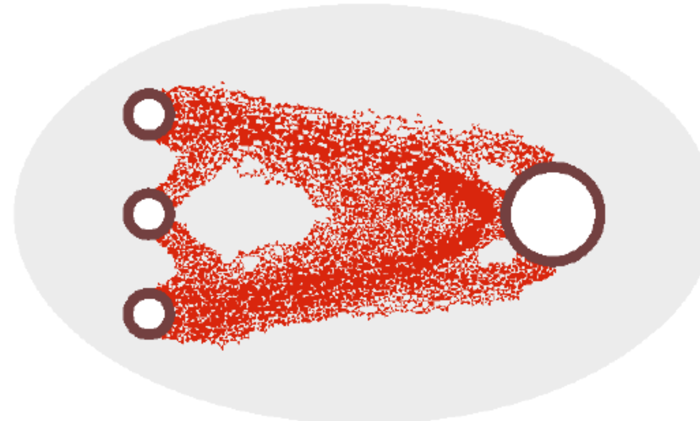
$$\hat{x}_e = \frac{\tanh(\beta\,\mu) + \tanh(\beta\,(\tilde{x}_e - \mu))}{\tanh(\beta\,\mu) + \tanh(\beta\,(1.0 - \mu))}$$

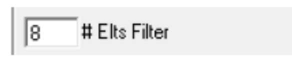


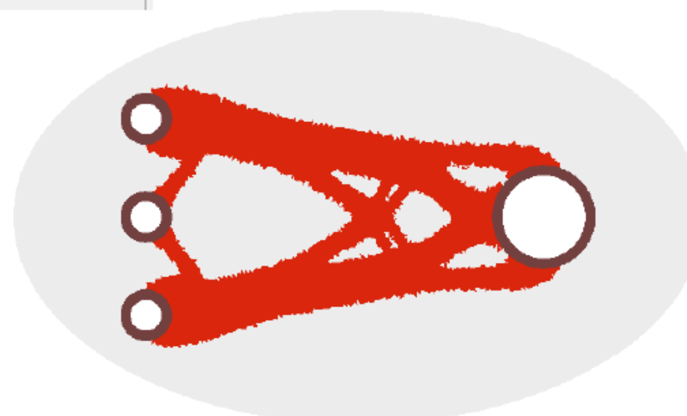
METHODOLOGY

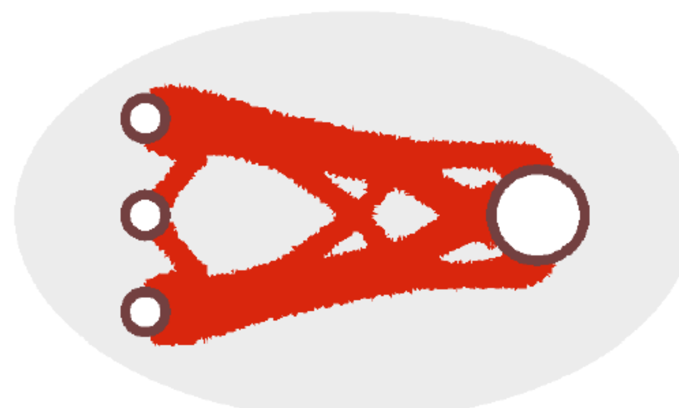
- Filter size must be:
  - Sufficiently large
  - Independent of the mesh size (absolute dimension)

- In NX, standard size of the filter
  - 2D ➔ 8 elements
  - 3D ➔ 16 elements



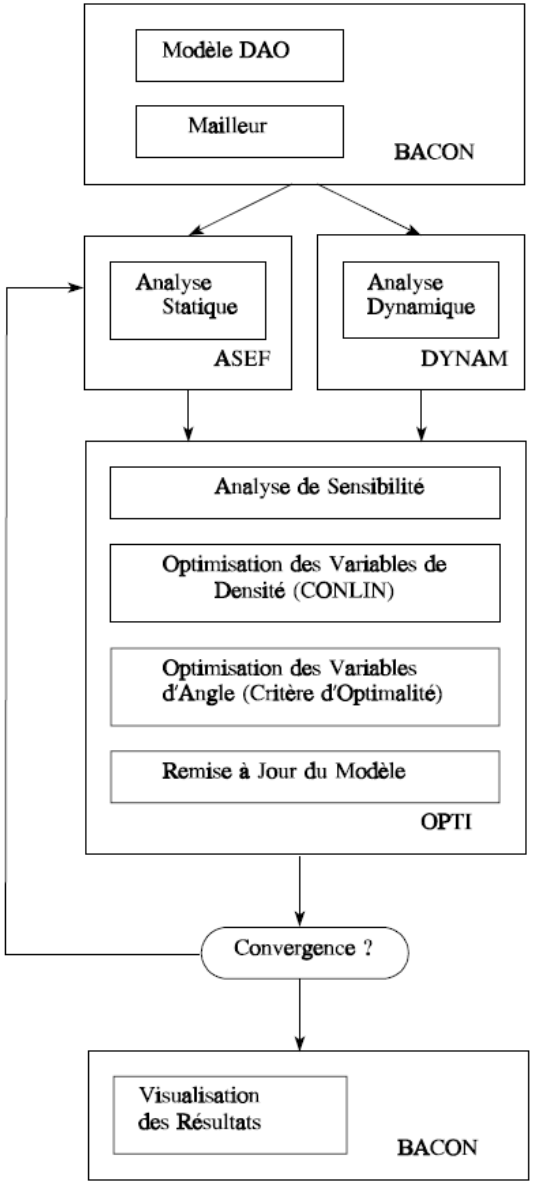






METHODOLOGY

- 7/ Optimization of the density distribution
  - One iteration includes:
    - One FE analysis
    - Sensitivity analysis
    - Optimization using CONLIN or MMA
    - Update the density field
  - Define the problem characteristics
    - Add/edit specific data
      - Formulation:
      - Optimization control
      - Topology optimization control:
    - Manage execution
    - Drive post-processing action



METHODOLOGY

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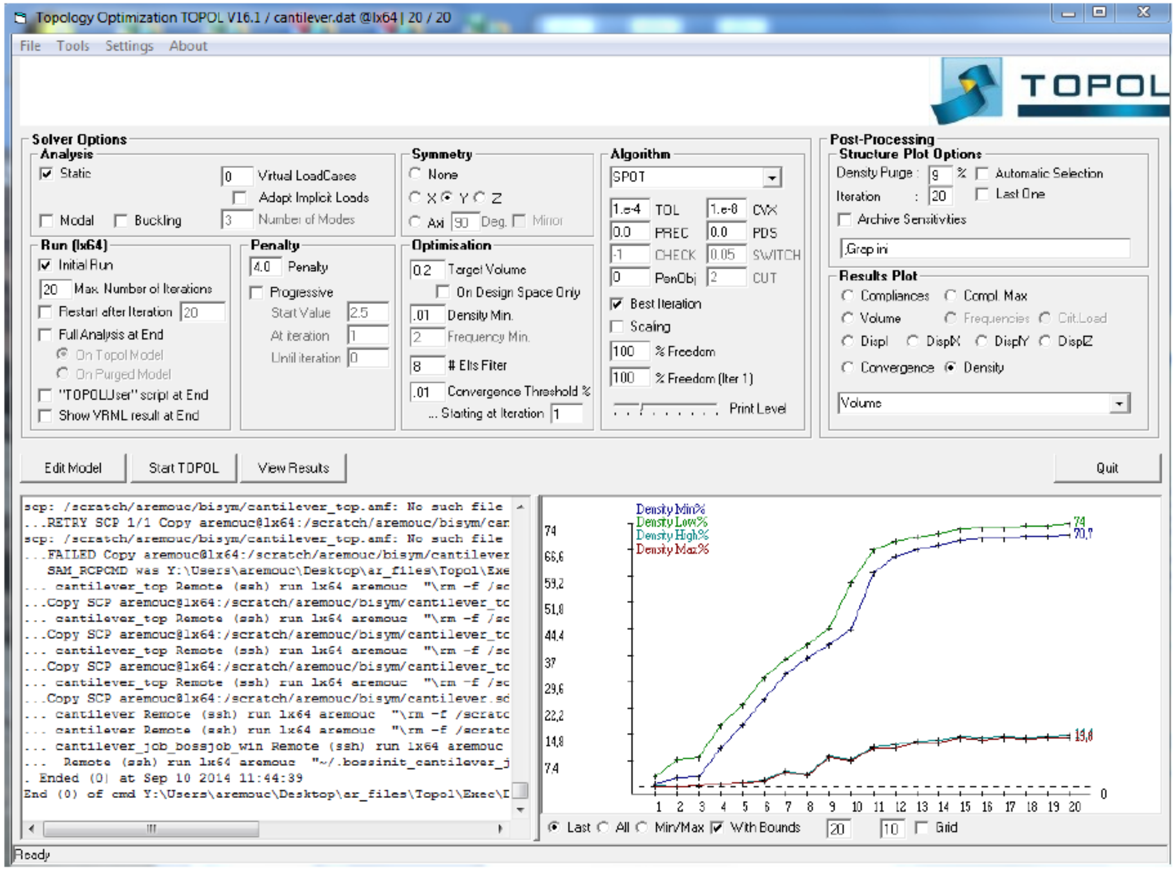


METHODOLOGY

- Minimize compliance

s.t.

- Given volume
- (bounded perimeter)
- (other constraints)

- Maximize eigenfrequenclies

s.r.

- Given volume
- (bounded perimeter)
- (other constraints)

- Minimize the maximum of the local failure criteria

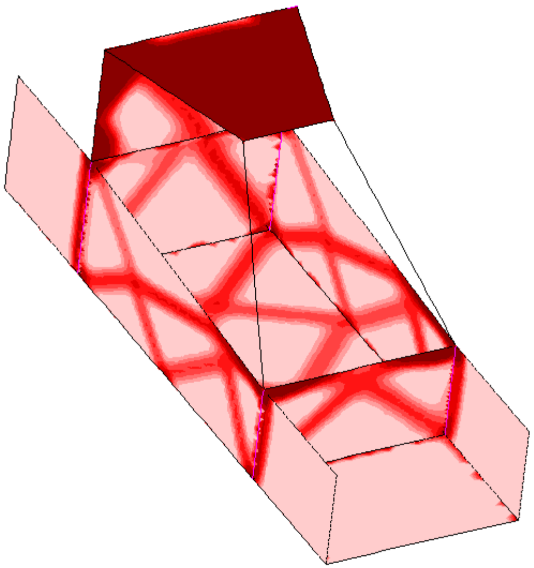
s.t.

- Given volume
- (bounded perimeter)
- (other constraints)

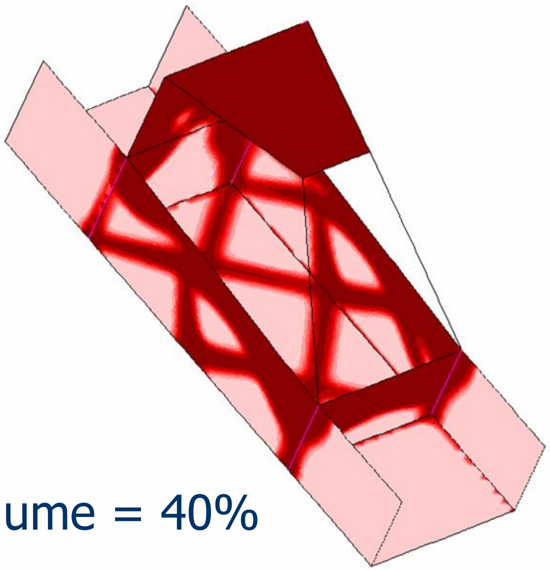
METHODOLOGY

- Volume constraint:
  - Typically between 20 to 80 → average value: 50%
  - If mass constraint is given: naturally prescribed!
  - If no mass constraint: volume is a design parameter
    - In the mean range [30%; 70%], it has not generally a major influence on final topology but more a sizing influence.
  - Convergence becomes very delicate for very low density constraint i.e. Vmax < 15% design domain volume

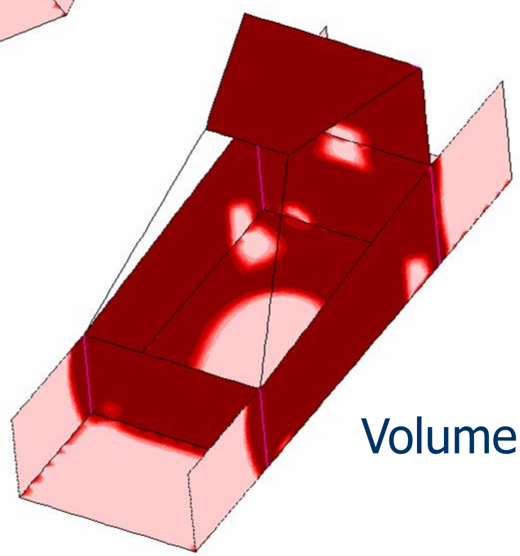
METHODOLOGY



Volume = 20%



Volume = 40%



Volume = 60%

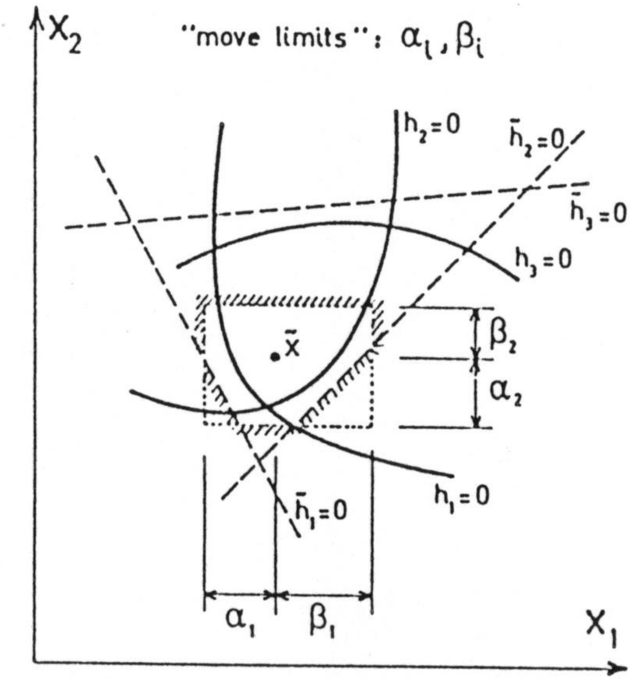
METHODOLOGY

- Optimization algorithm
  - Best algorithms used dual maximization and convex approximations
    - CONLIN → SPOT
    - MMA
    - GCMMA in case of non monotonic responses (e.g. self weight)
  - Convergence must be understood in terms of design variable stationarity NOT in terms of objective function!
    - Stopping criteria is the modification of the design variables
    - Not picture nice looking stopping criteria
  - Topology optimization convergence requires at least 100 iterations but more generally 250 iterations

METHODOLOGY

- Optimization algorithm
  - If starting from infeasible design, the first iterations are devoted to find a first feasible design point (generally satisfying the volume constraint)
  - When convergence is unstable, resort to tight move-limits

$$\hat{x}_i - \alpha_i \leq x_i \leq \hat{x}_i + \beta_i$$



  - Typically

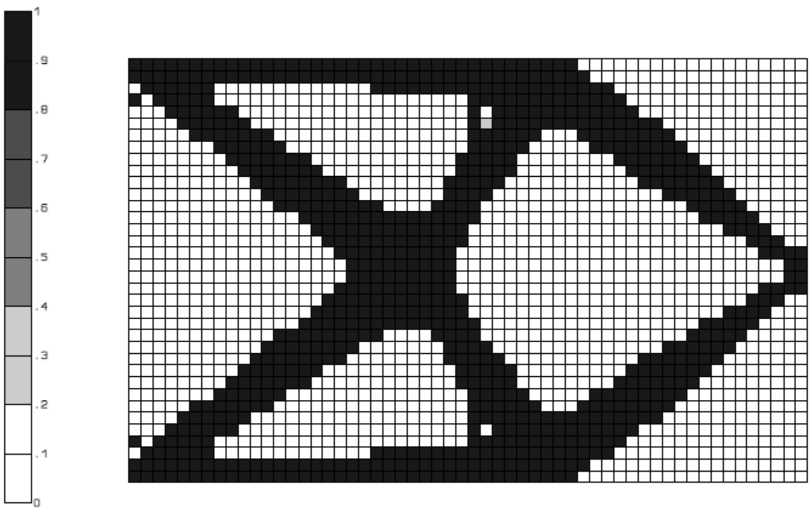
$$\alpha_i = \beta_i = \Delta x_i = 0,3$$

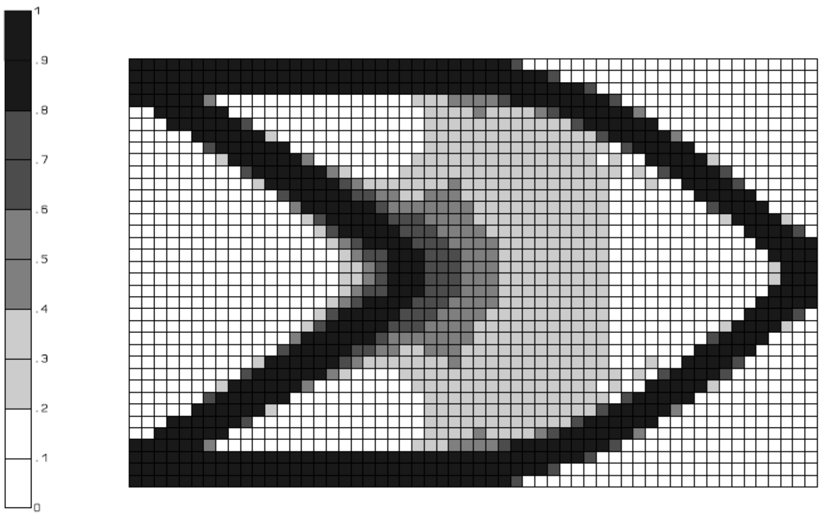
METHODOLOGY

- 8/ Visualization and interpretation of optimized density map
  - Visualization of density maps
  - Interpret optimized density
  - Construct a smooth Computer Aided Design (CAD) model
    - Introduce aesthetic or manufacturing constraints if necessary

METHODOLOGY

- Interpret the optimized topology

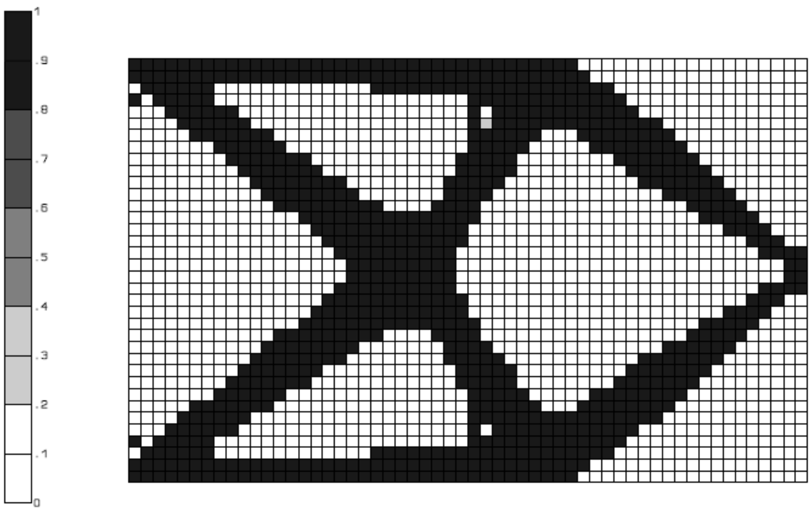


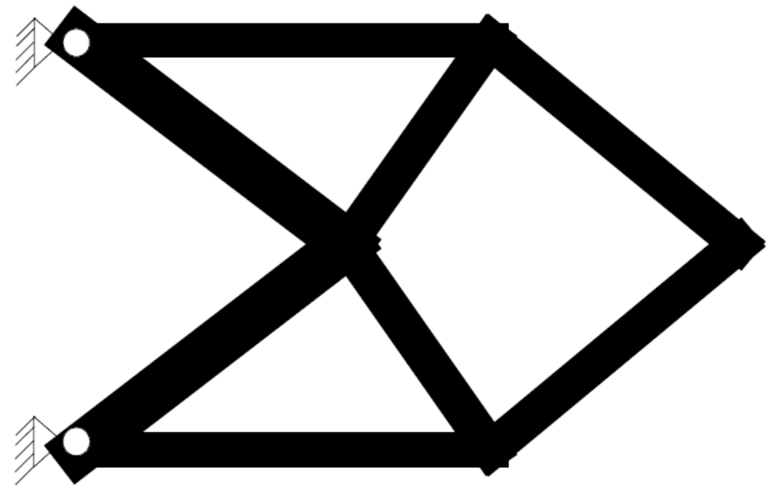


- Define the nature of structural members:
  - Beams
  - Plates
  - Volume

METHODOLOGY

- Interpret the optimized topology

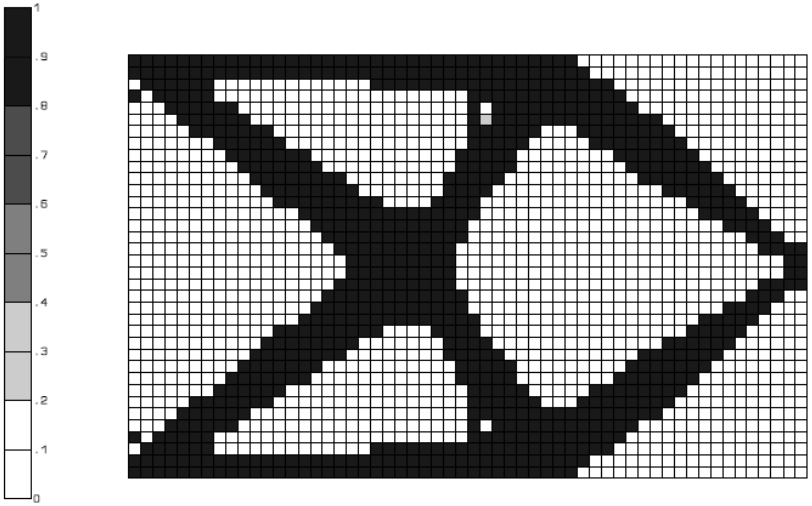


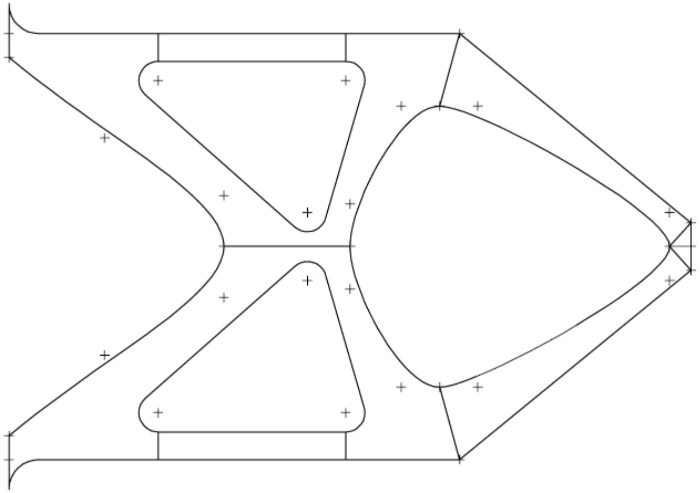


- Define the nature of structural members:
  - Beams
  - Plates
  - Volume

METHODOLOGY

- Interpret the optimized topology

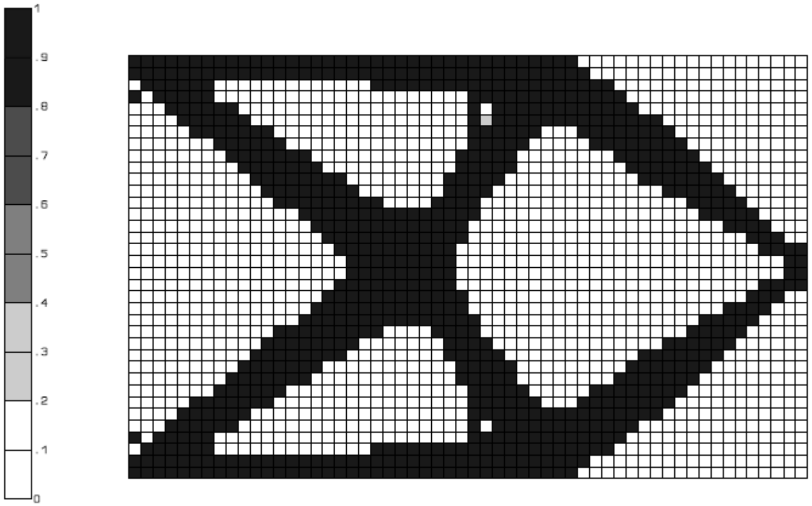




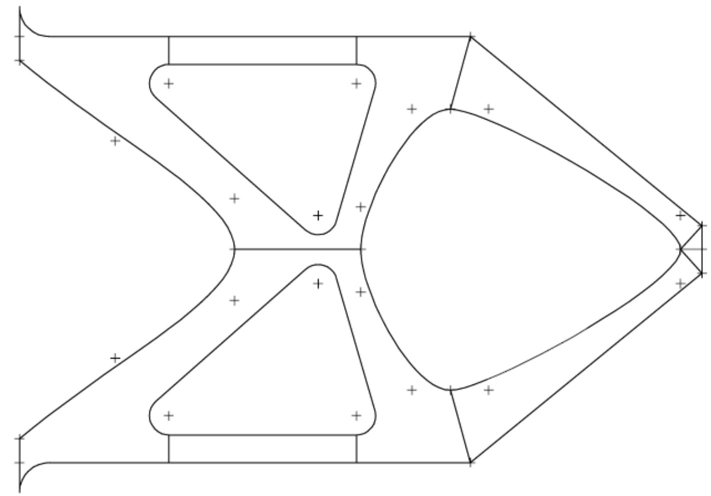
- Define the nature of structural members:
  - Beams
  - Plates
  - Volume

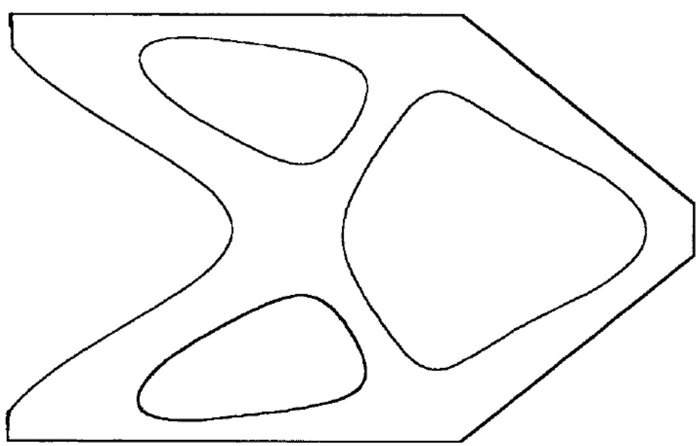
METHODOLOGY

- 2D CAD model reconstruction

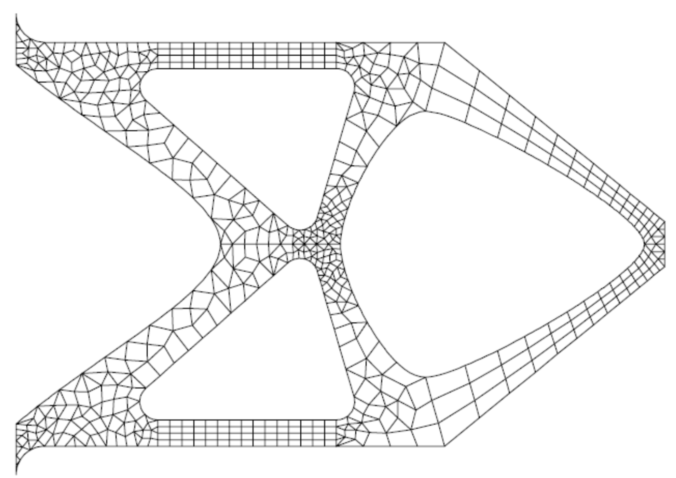


Manual reconstruction



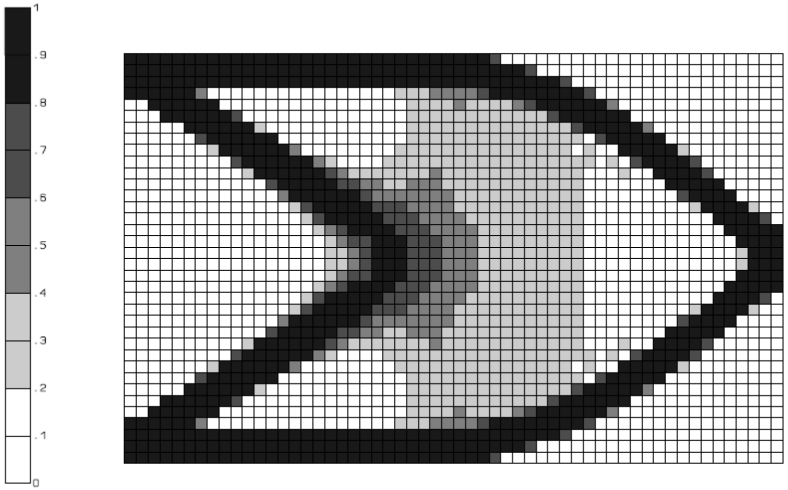


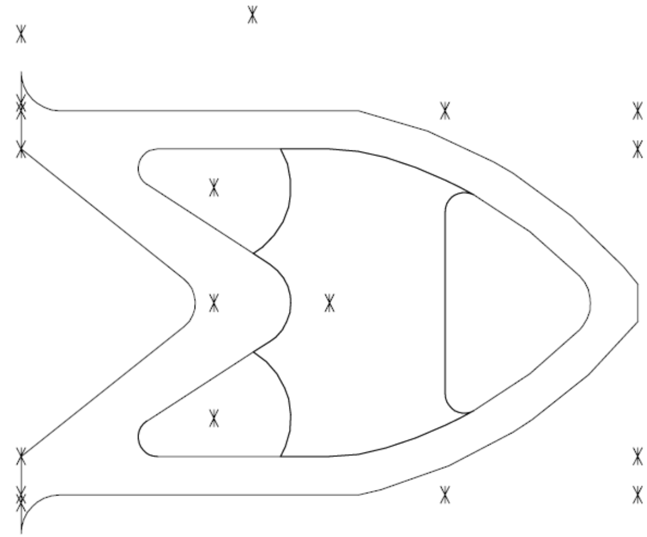
Automatic curve fitting

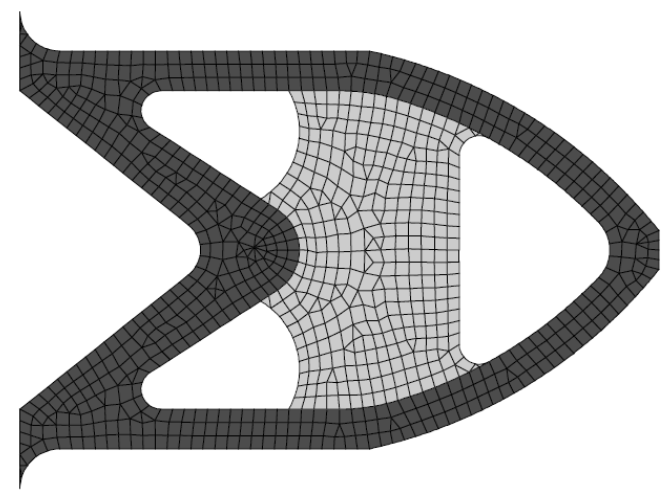


METHODOLOGY

- 2D CAD model reconstruction



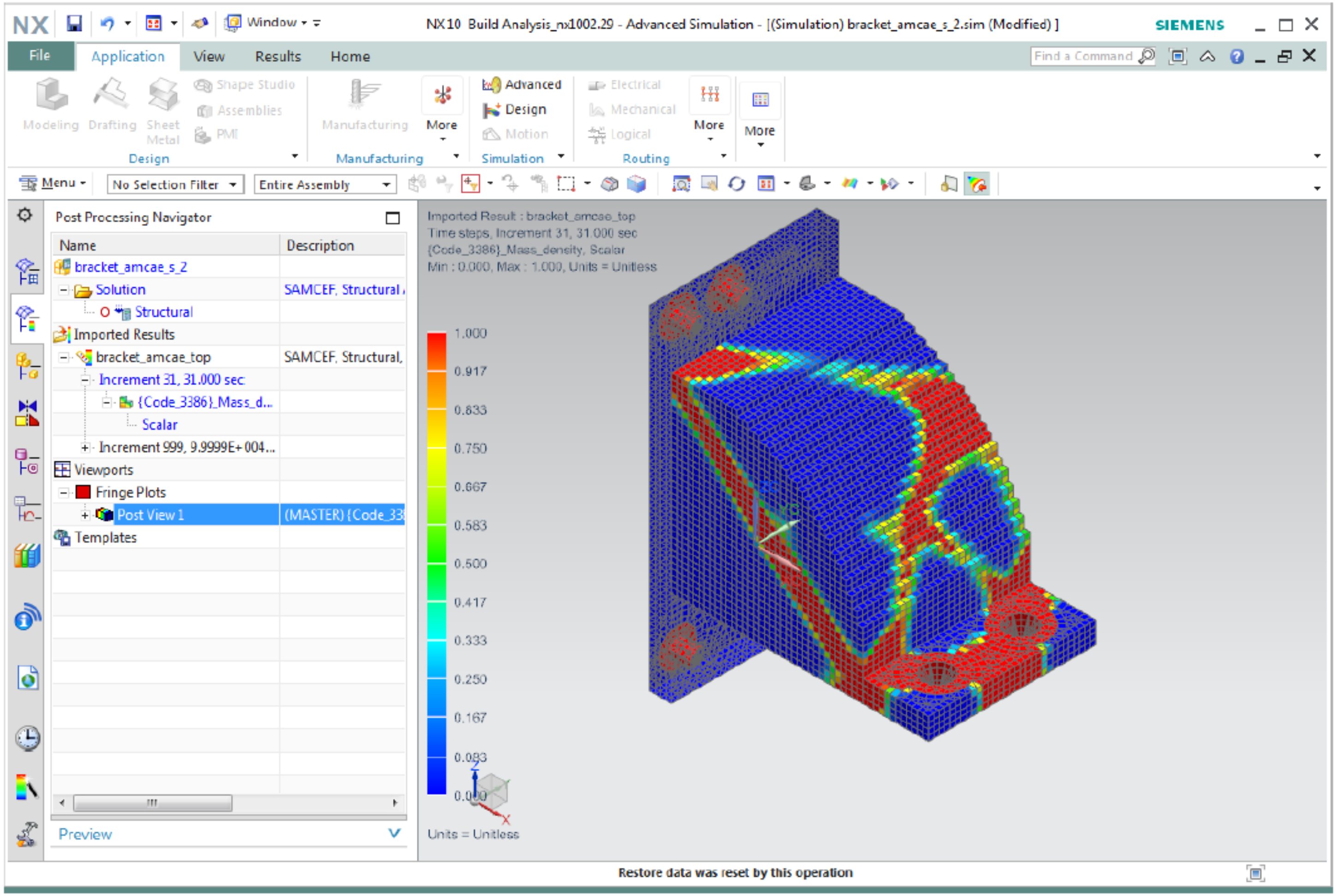




- Two zones:
  - Frame structure
  - Shear panel

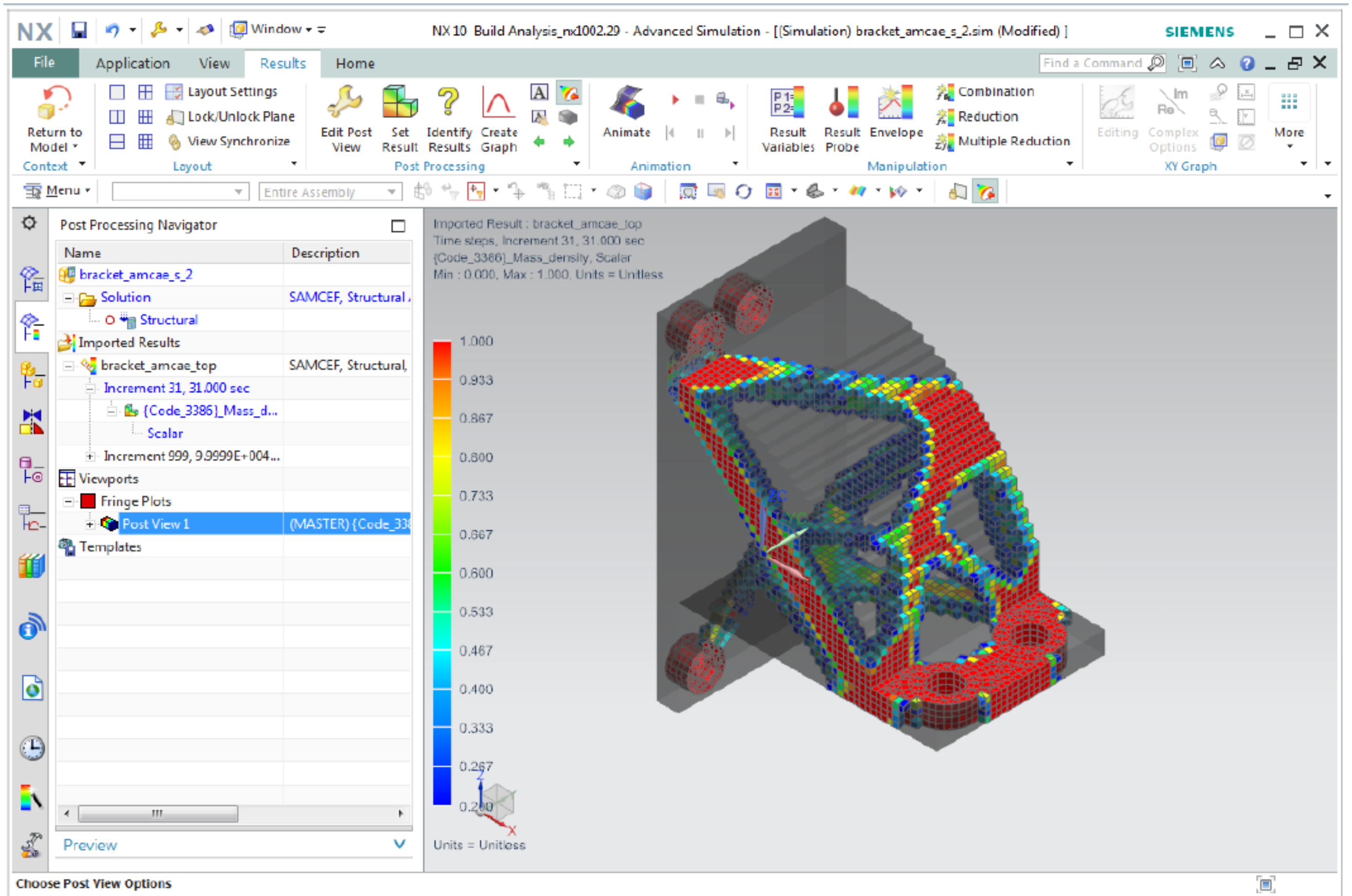
METHODOLOGY

- Interpreting the optimized density distribution



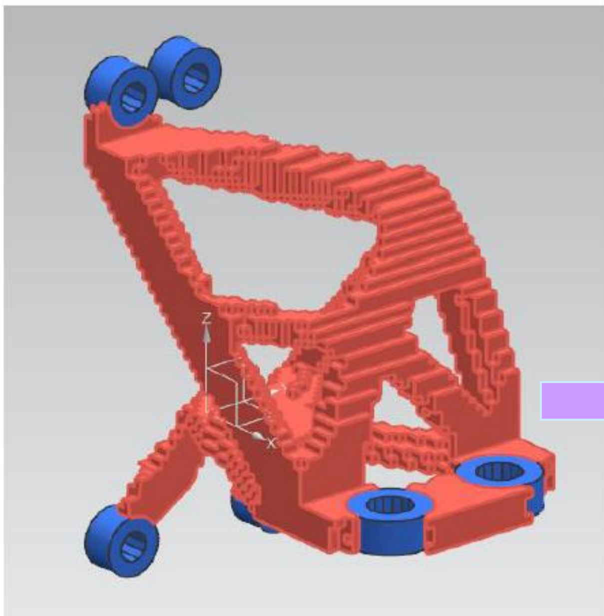
METHODOLOGY

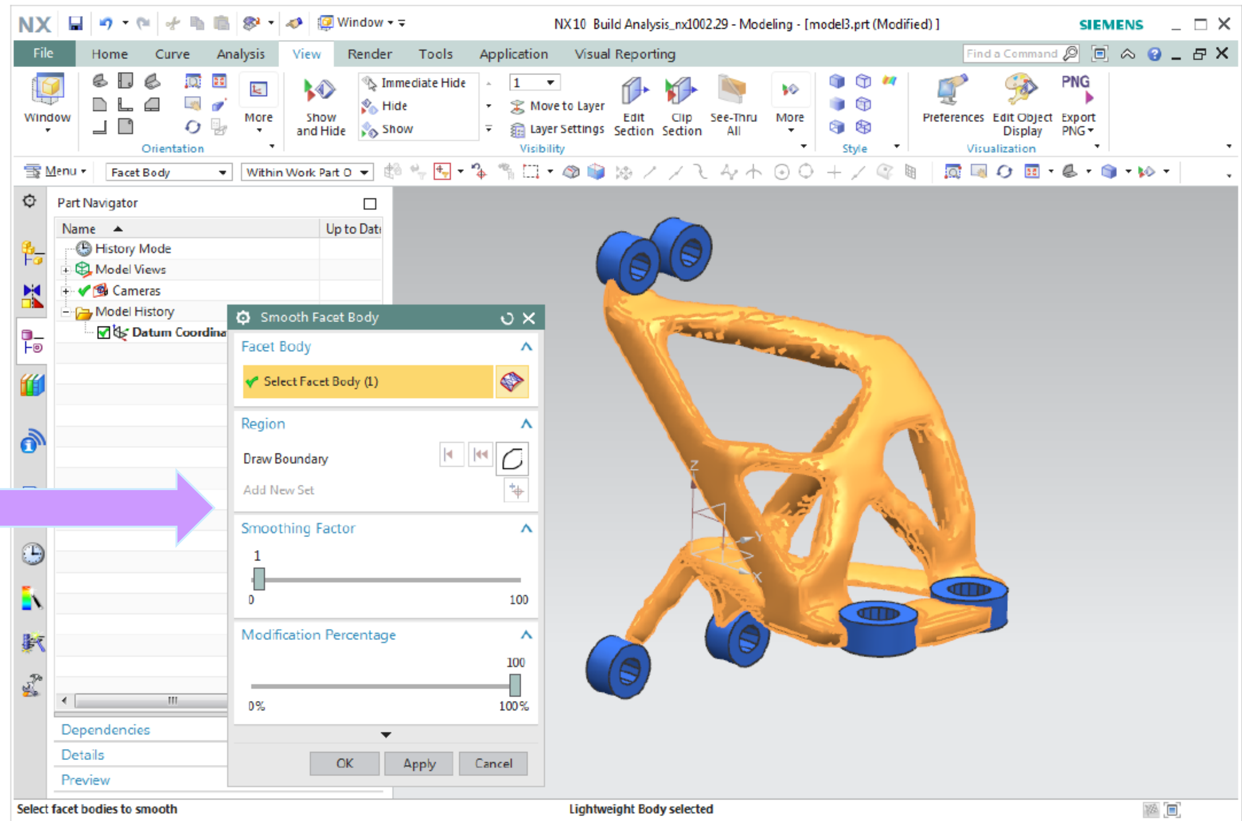
- Interpreting the optimized density distribution



METHODOLOGY

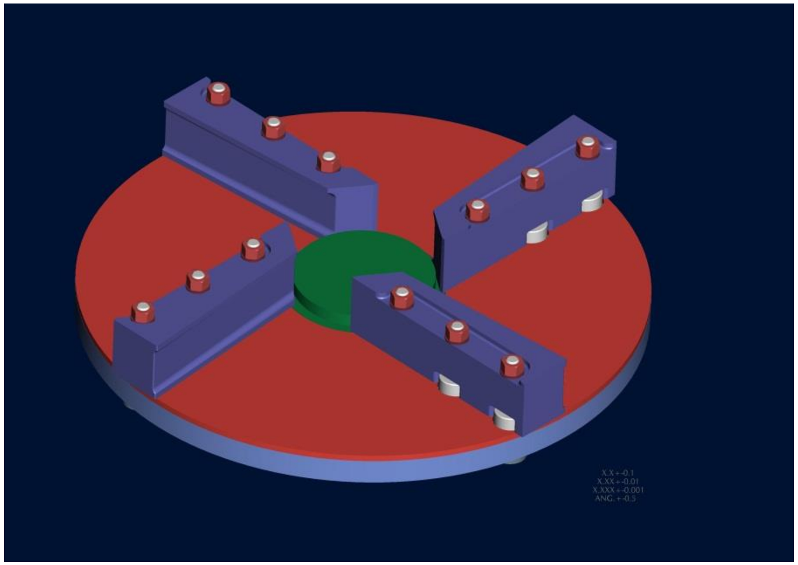
- Smoothing density distribution with NX10

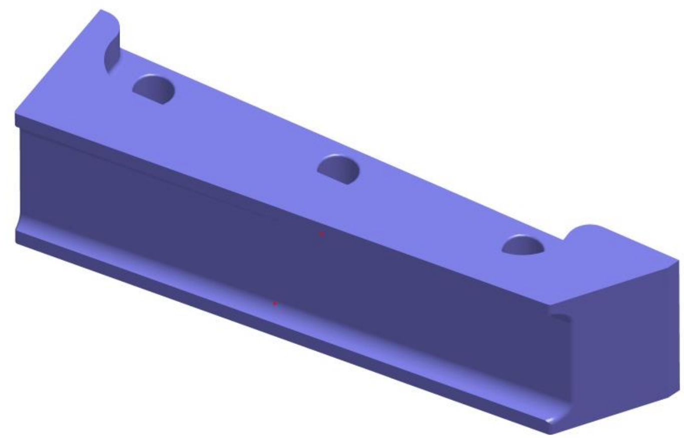


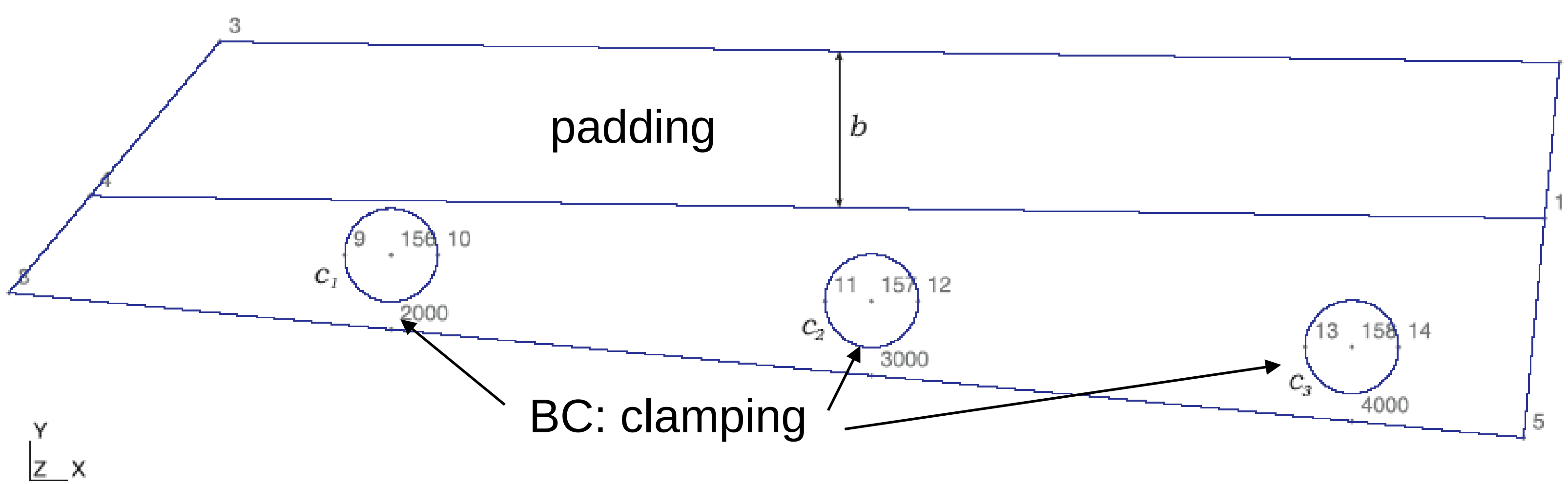


NUMERICAL APPLICATIONS

SHAPE & TOPOLOGY OPTIMIZATION OF MAG'IMPACT EJECTOR

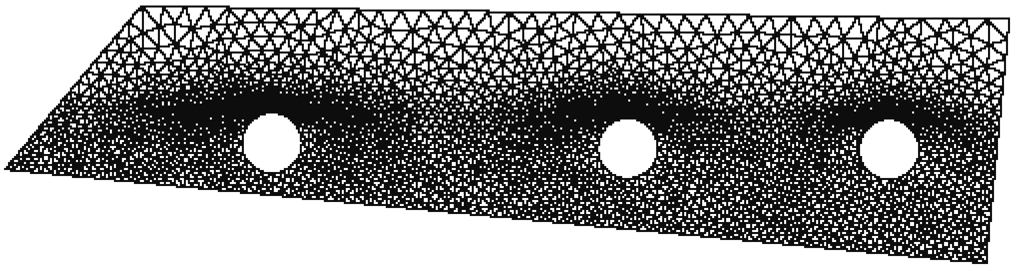






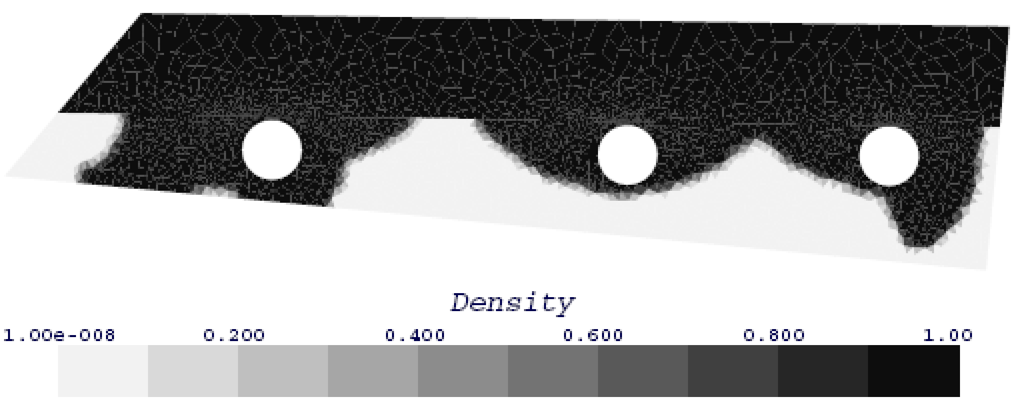
TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization with optimized bolt positions
  - Mesh and design domain



5627 FE
3524 density var.

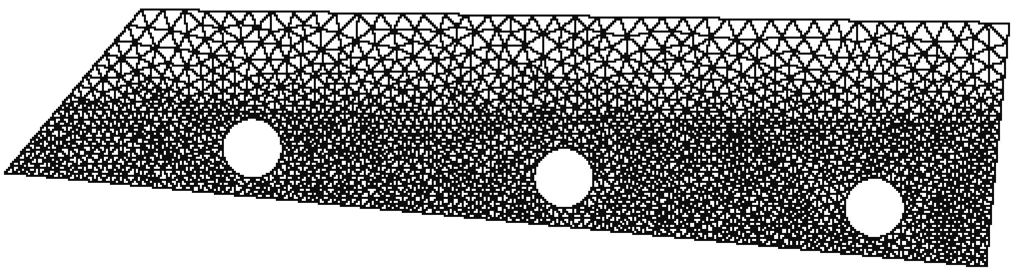
  - Material distribution field



Mass=49,7 kg
(-27%)
Compliance: 0,35J
(-50%)

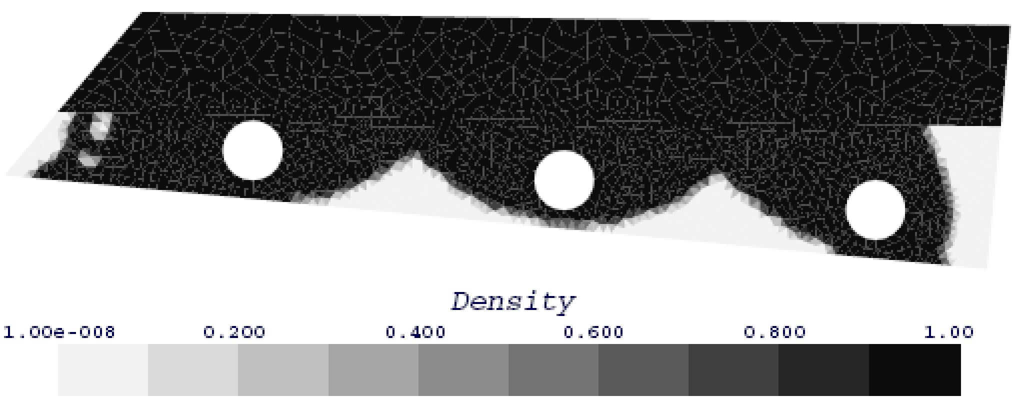
TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization of reference configuration
  - Mesh and design domain



3655 FE
2578 density var.

  - Material distribution field

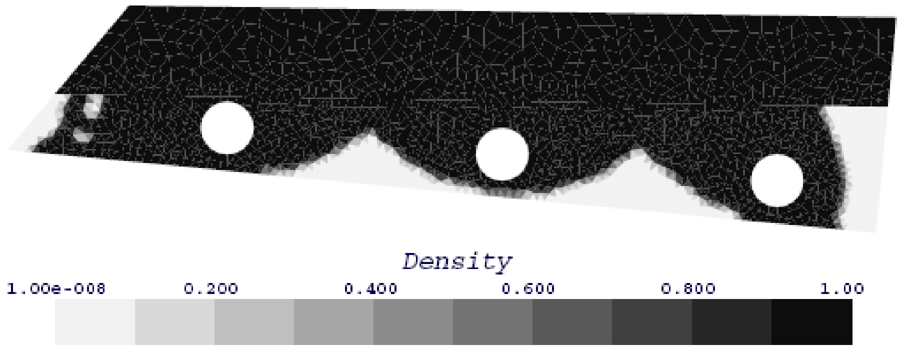


Mass=59,3 kg

Compliance: -9%

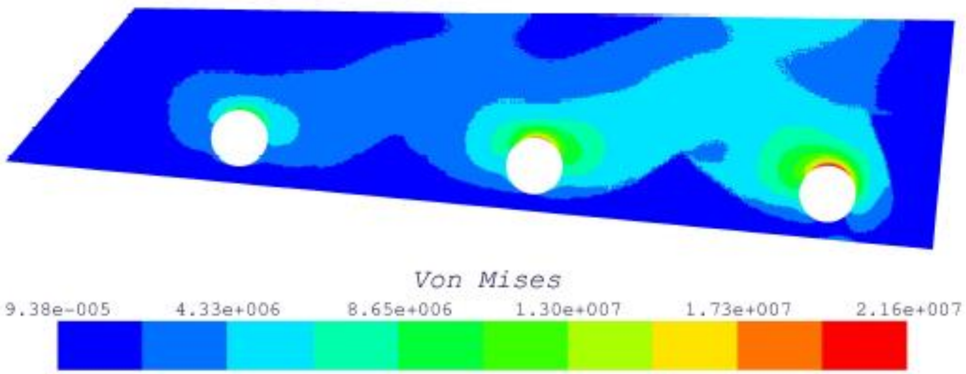
TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization of reference configuration
  - Material distribution field



Mass=59,3 kg

  - Stress field

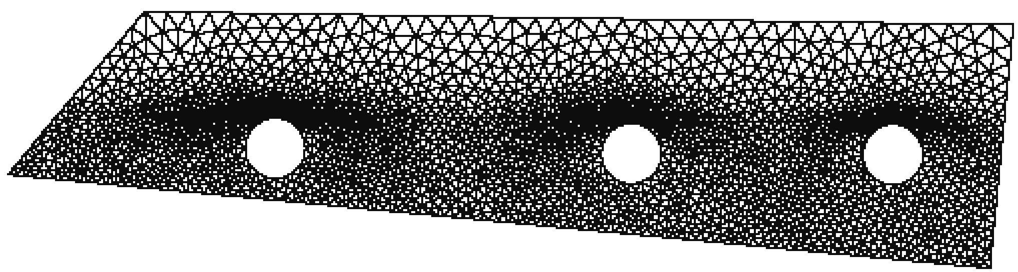


σ_{max}=21.6 MPa

TOPOLOGY OPTIMIZATION OF EJECTOR

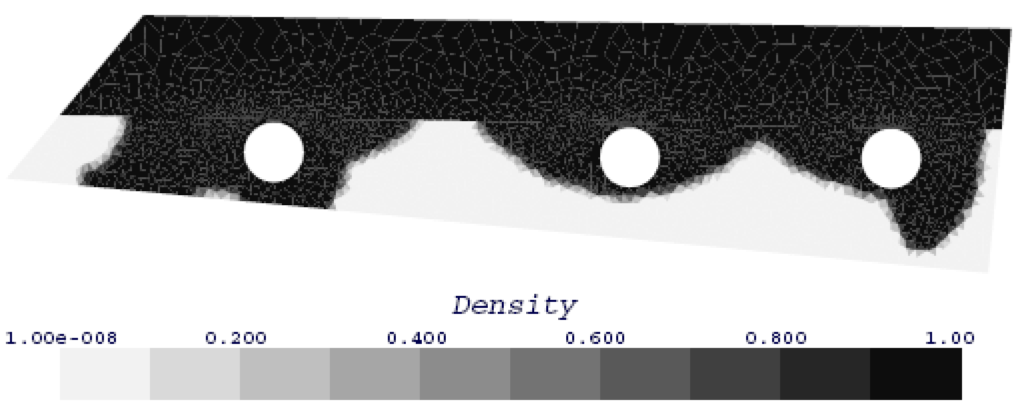
- Topology optimization with optimized bolt positions
  - Mesh and design domain

5627 FE
3524 density var.



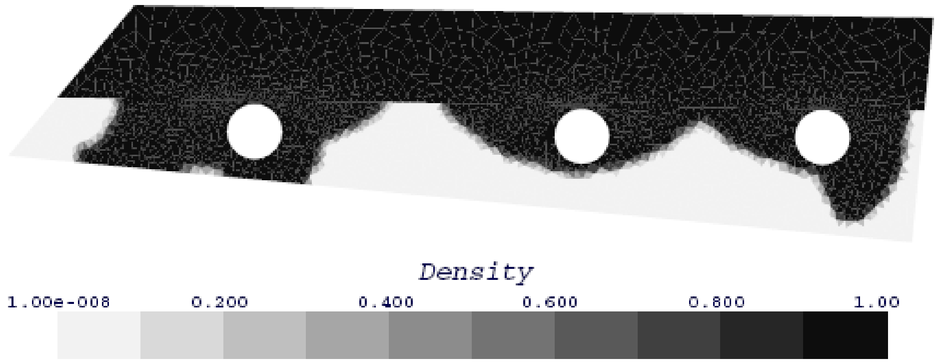
  - Material distribution field

Mass=49,7 kg
(-27%)
Compliance: 0,35J
(-50%)



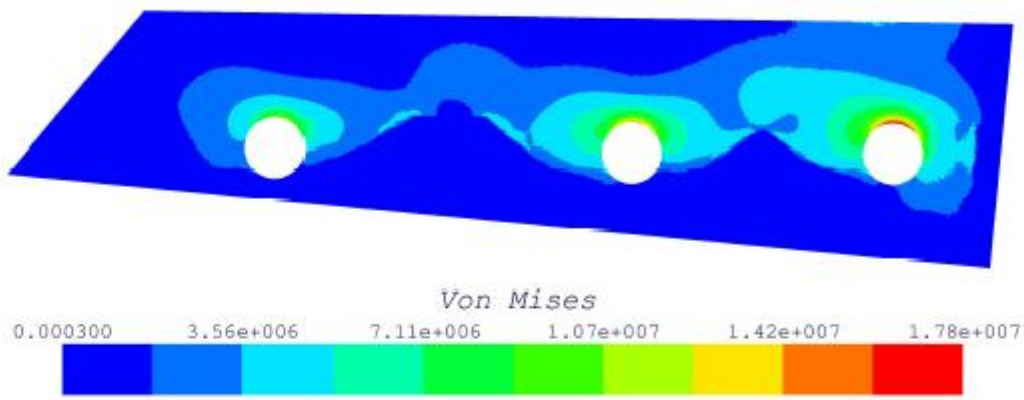
TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization of reference configuration
  - Material distribution field



Mass=49,7 kg

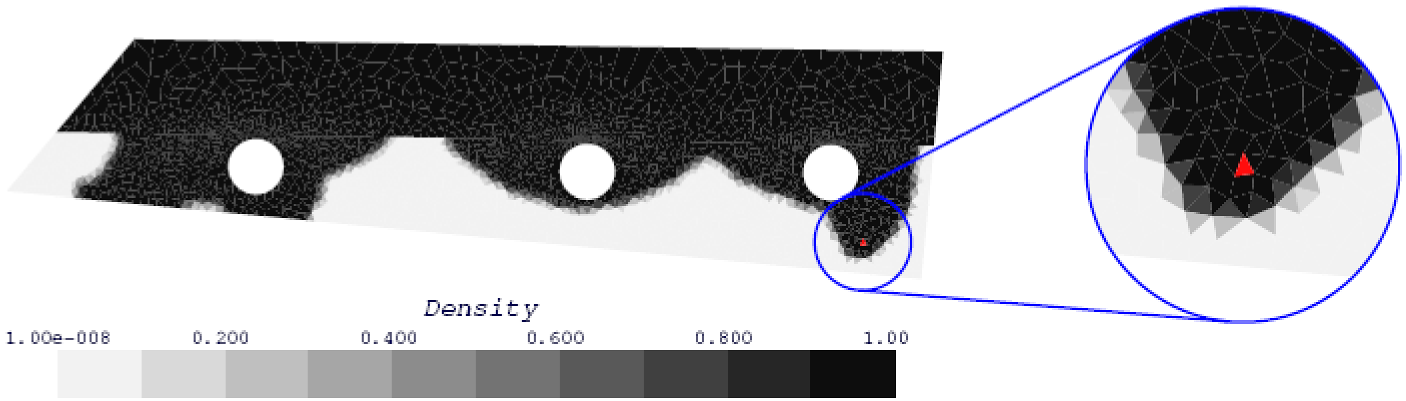
  - Stress field



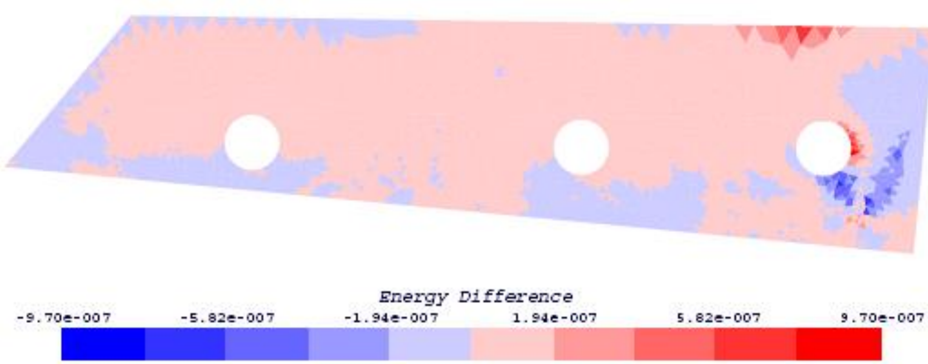
σ_{max}=17,8 MPa

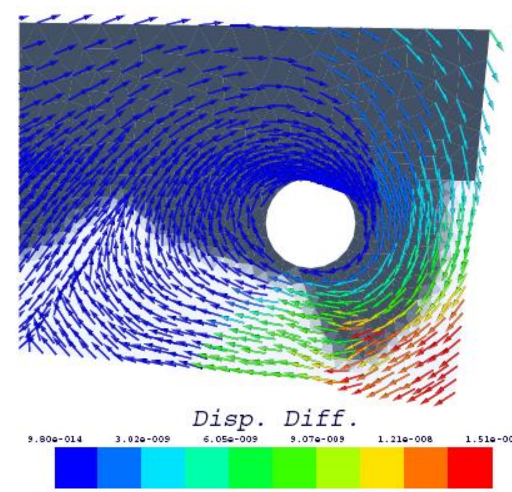
TOPOLOGY OPTIMIZATION OF EJECTOR

- Effect of counter-weight design?



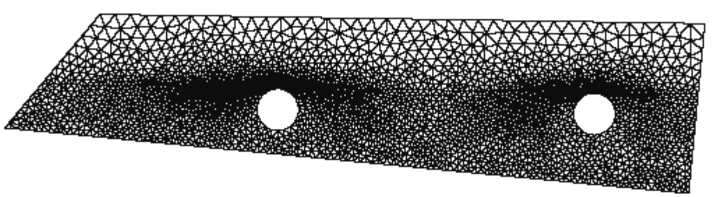
- Sensitivity of compliance (finite difference)

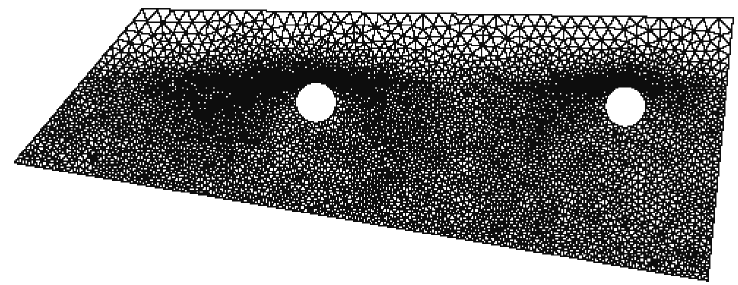




TOPOLOGY OPTIMIZATION OF EJECTOR

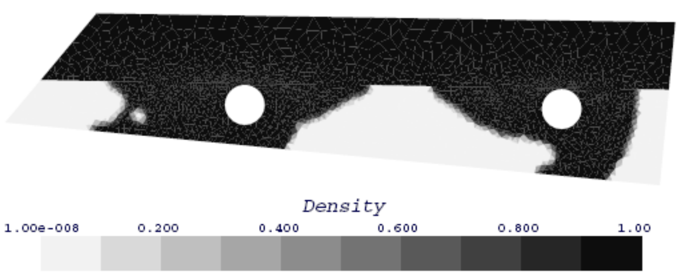
- Topology optimization with optimized 2 bolt positions

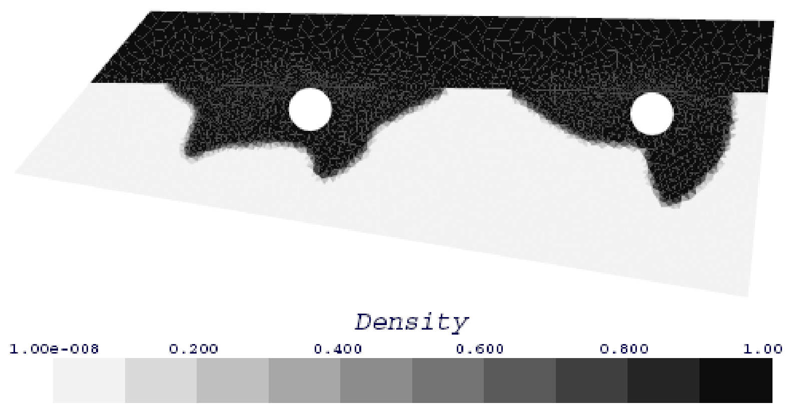




6007 FE - 3886 density var.

  – Material distribution field (it=200)





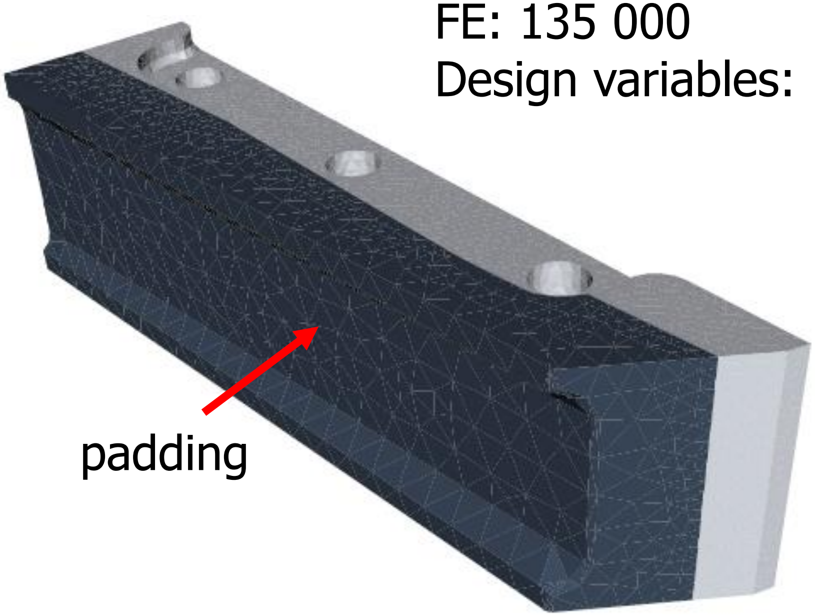
Compliance= 0,47J - Mass= 51,5 kg

σ_{max}=25,5 MPa

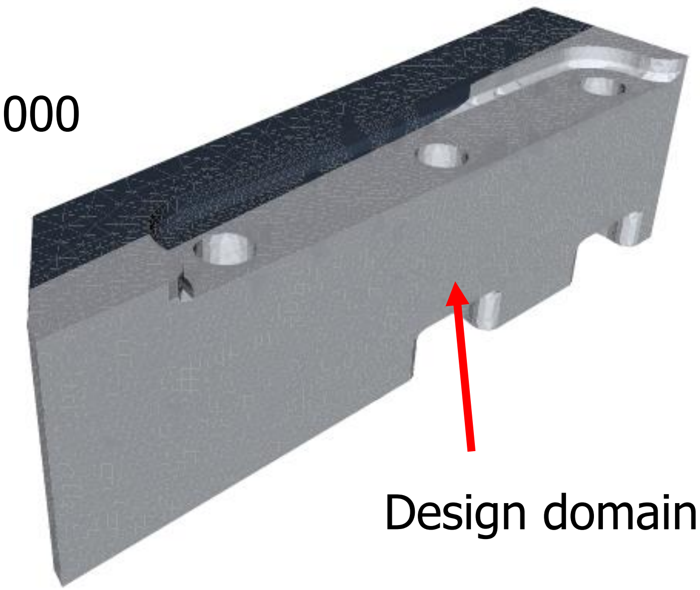
3D TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization: 3D model

FE: 135 000
Design variables: 107 000



Mass: 58,7 kg
Compliance: 1,35J



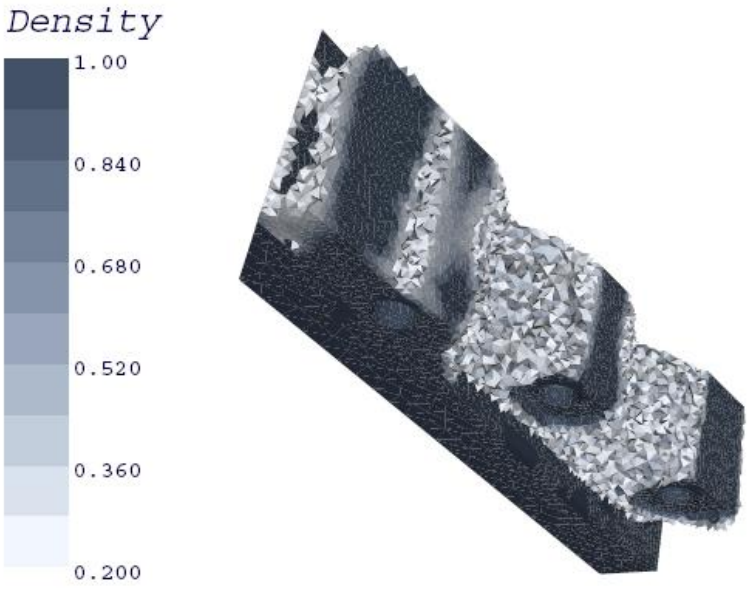
- Boundary conditions:
  – 1/ bolt holes clamped
  – 2/ bold hole 1 clamped and wall boxes of holes 2 and 3 clamped

3D TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization using BC1

Topology similar to 2 results

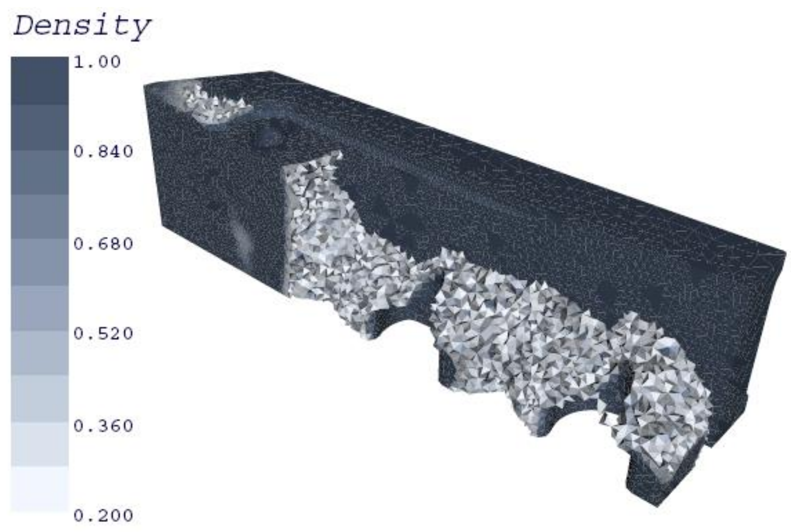
Mass=47,7kg
Compliance = 0,52J (-62%)



Wall box have disappeared

TOPOLOGY OPTIMIZATION OF EJECTOR

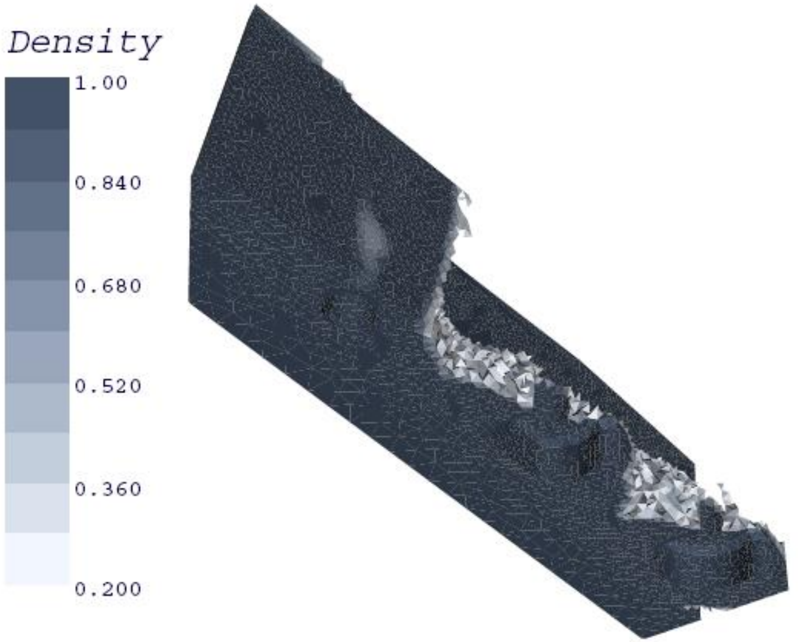
- Mostly 2D problem here: geometry remains nearly extruded from 2D
- Other boundary conditions can modify the geometry
- Worn geometry is not a critical load case



3D TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization using set of BC 2

Topologies of wall box and
bolt bores are different

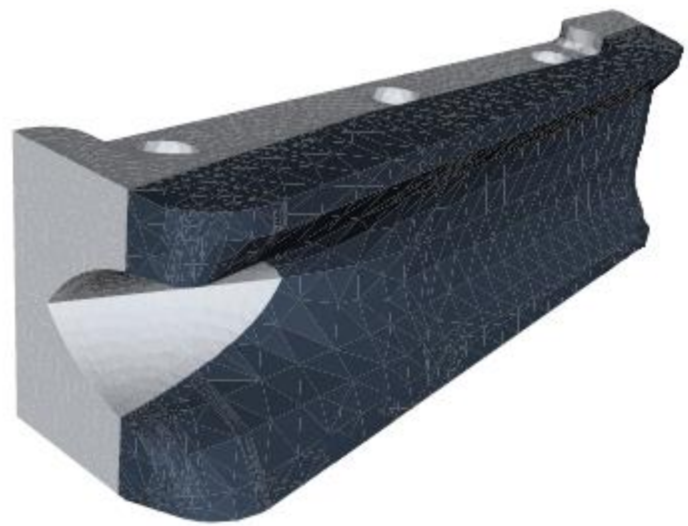


Mass=43kg
Compliance = 0,62J (-55%)

3D TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization based on used geometry

FE: 135 000
Design variables: 73 131



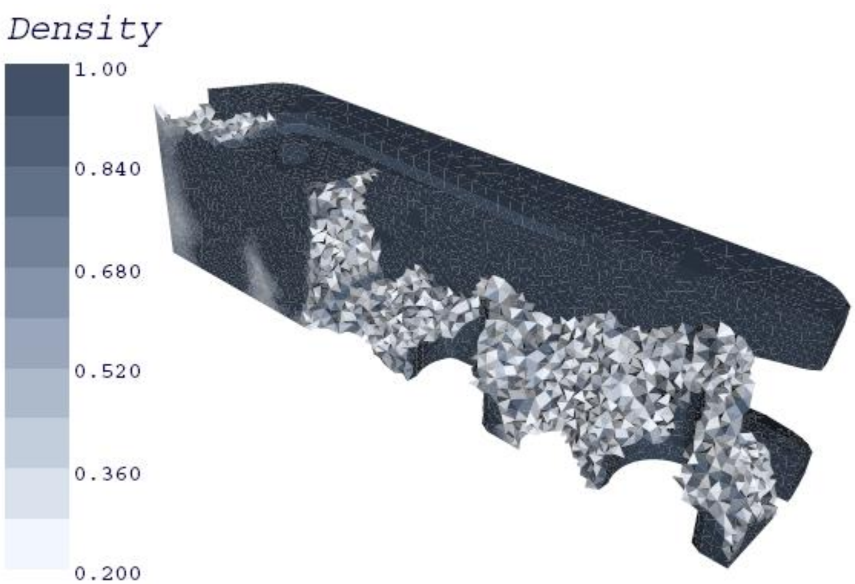
- Set of BC 2 only

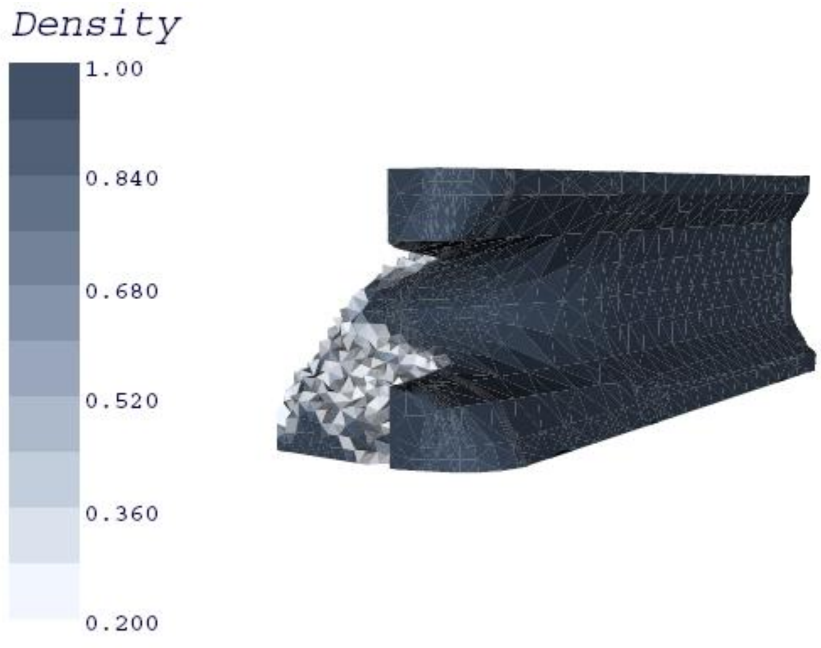
Mass: 49 kg
Compliance: 0,85J

3D TOPOLOGY OPTIMIZATION OF EJECTOR

- Topology optimization using used geometry

Topologies of wall box and bolt bores are different





Mass=32,4kg
Compliance = 0,33J (-55%)

INTERPRETATION OF OPTIMIZED EJECTOR

- Shape description using Level Sets