Topological Optimization for AM

Contribution to design of support structures

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EUSPEN, Special Interest Group Meeting: Advancing Precision in Additive Manufacturing, Nantes, 17/09/2019

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Topological Optimization

Principles

- Part of the design process of a shape
- Find a shape Ω which minimizes an objective F with respect to the constraints G_i

$$\begin{cases} \min\limits_{\Omega \subset D} F(\Omega) \\ \forall i, G_i(\Omega) \leq G_{max}^i \end{cases}$$

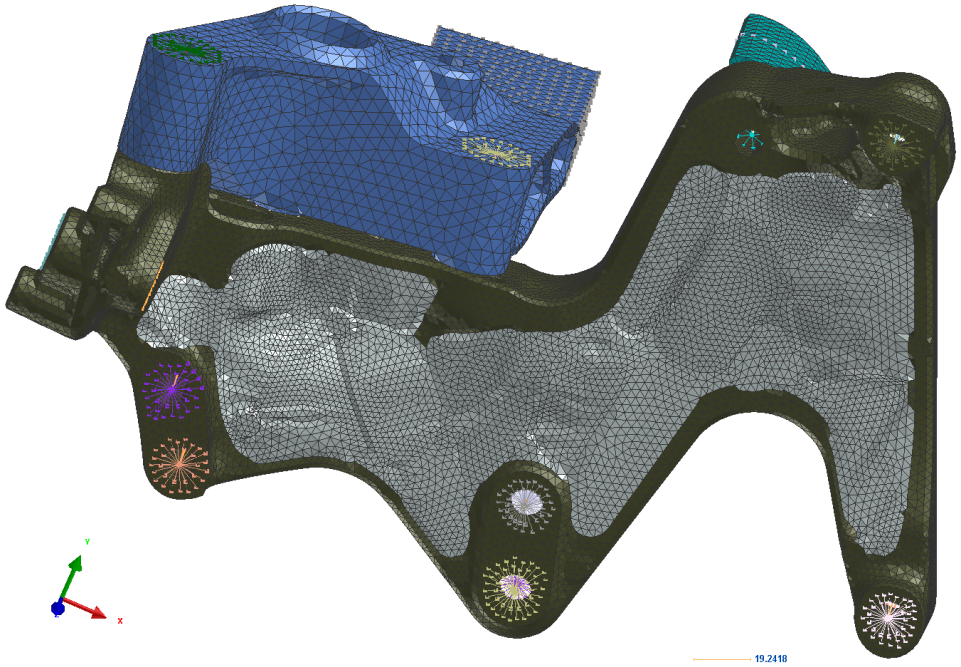
  - Examples of objective: volume, mass
  - Examples of constraint: eigenfrequencies, displacement of a node, thermal flux

- Iterative method: we start from an initial shape Ω_0 that we improve step-by-step

Topological Optimization

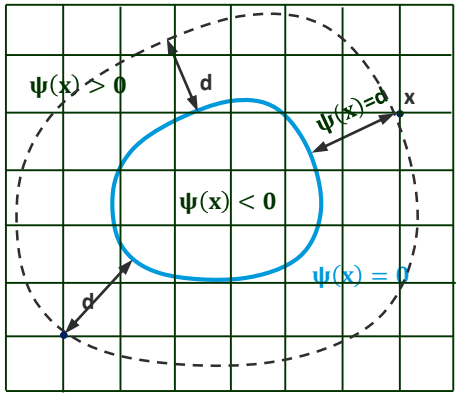
Shape representation on fixed mesh

- Design Space is meshed once and never modified during optimization

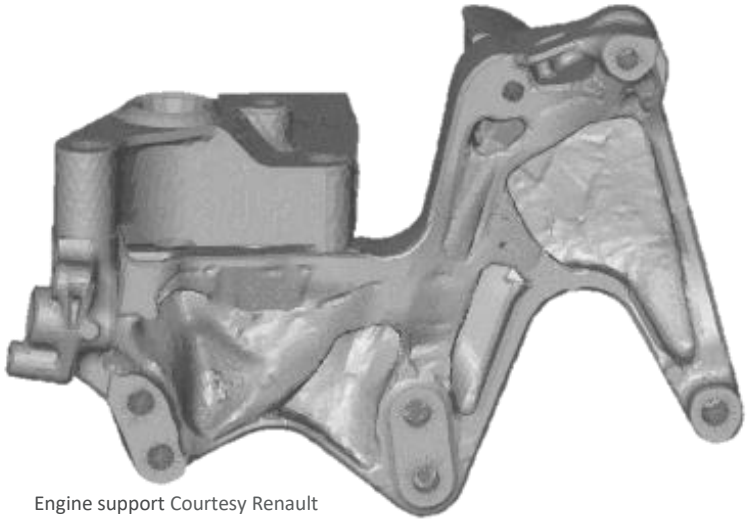


- Shape represented with a Level-Set, the signed distance to boundary
  - $\psi(x) < 0$ if inside the shape
  - $\psi(x) > 0$ if outside the shape

  $\Rightarrow \psi(x) = 0$ the boundary of the shape



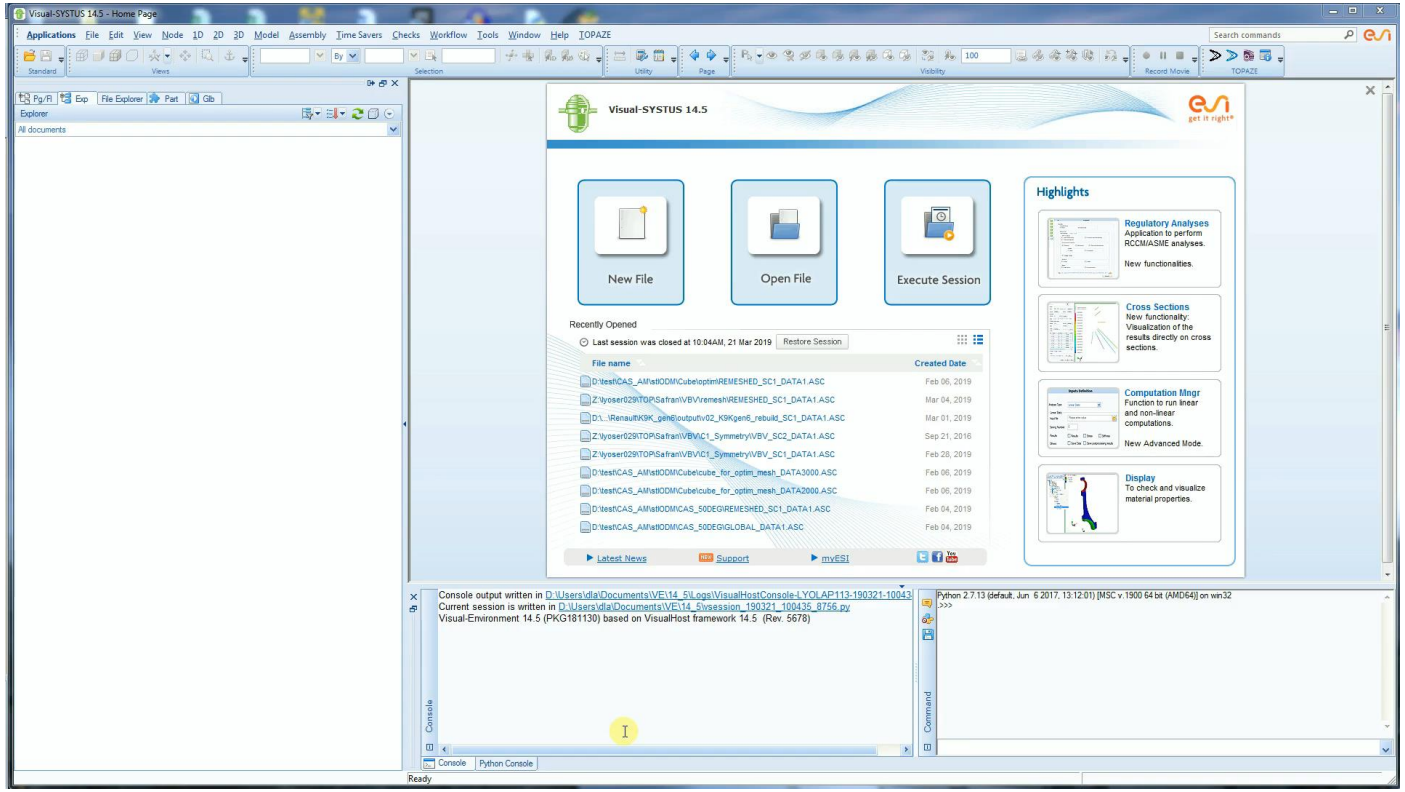
- Precise knowledge of the location of the boundary on a non-fitting mesh



Engine support Courtesy Renault

Topological Optimization

Key features of TOPAZE

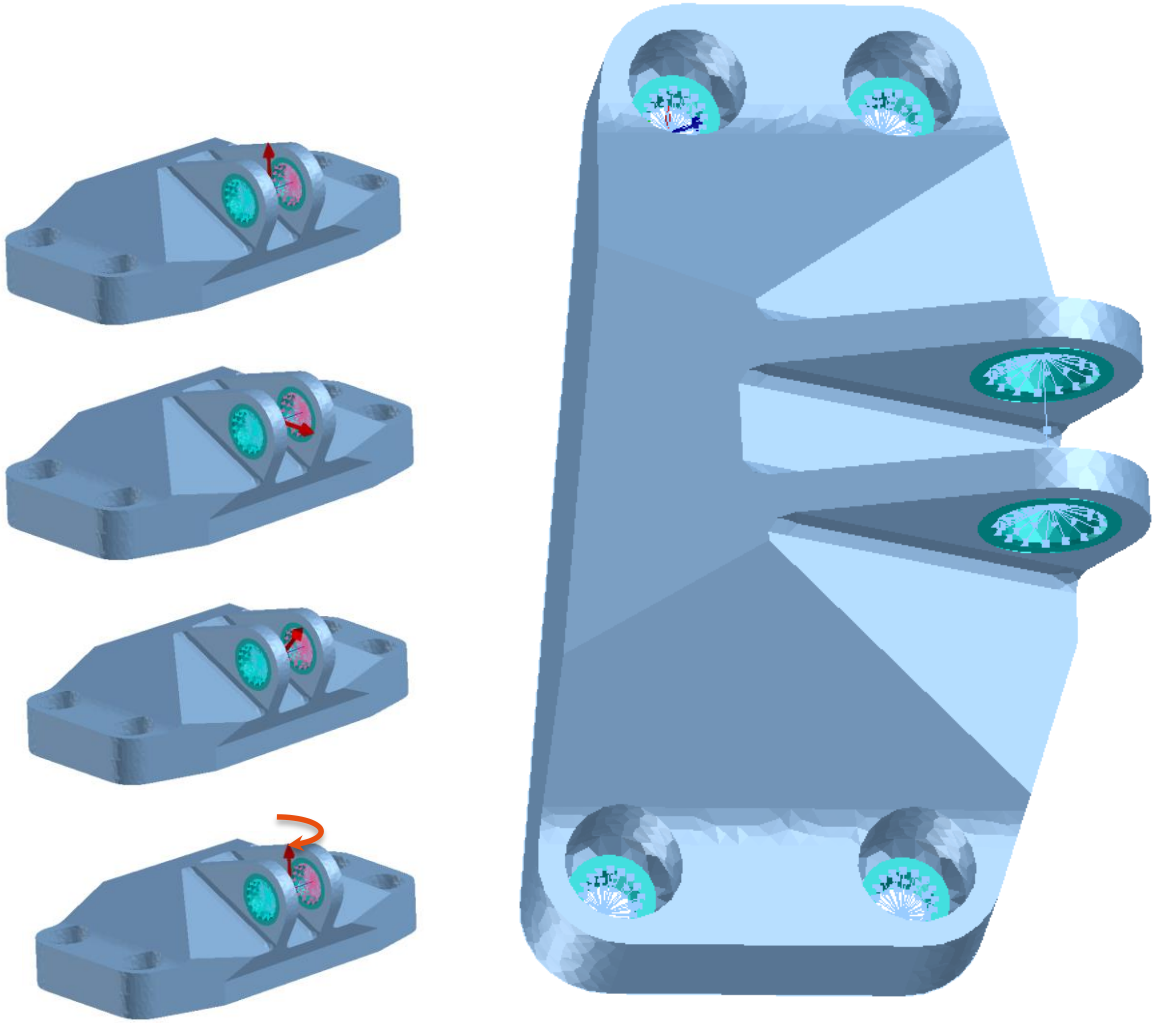


- Physic engines
  - Static (linear or non-linear)
  - Eigenmode computation
  - Harmonic response (direct or modal)
  - Thermal
- Criteria
  - Volume, surface, perimeter
  - Mass, thickness
  - Molding, symmetry
  - Displacement, velocity, acceleration, temperature
  - Stress, strain, heat flux
- Fully integrated Into Visual-Environment
  - More info https://myesi.esi-group.com/products/multiphysics

Example: Engine Bracket

Geometry and mechanics

- System units: mm, t, sec, K
- Material: Titan alloy Ti-6Al-4V
  - Young's Modulus = 114000 MPa
  - Poisson's ratio = 0,342
  - Density = 4.2e-9 t/mm3
  - Thermal conductivity 7,2 W/m/K
- 3 subcases
  - Static Mechanical analysis
    - 4 load cases
  - Eigen Frequency
    - Free-free 10 modes
  - Static Thermal analysis
    - 1 load case



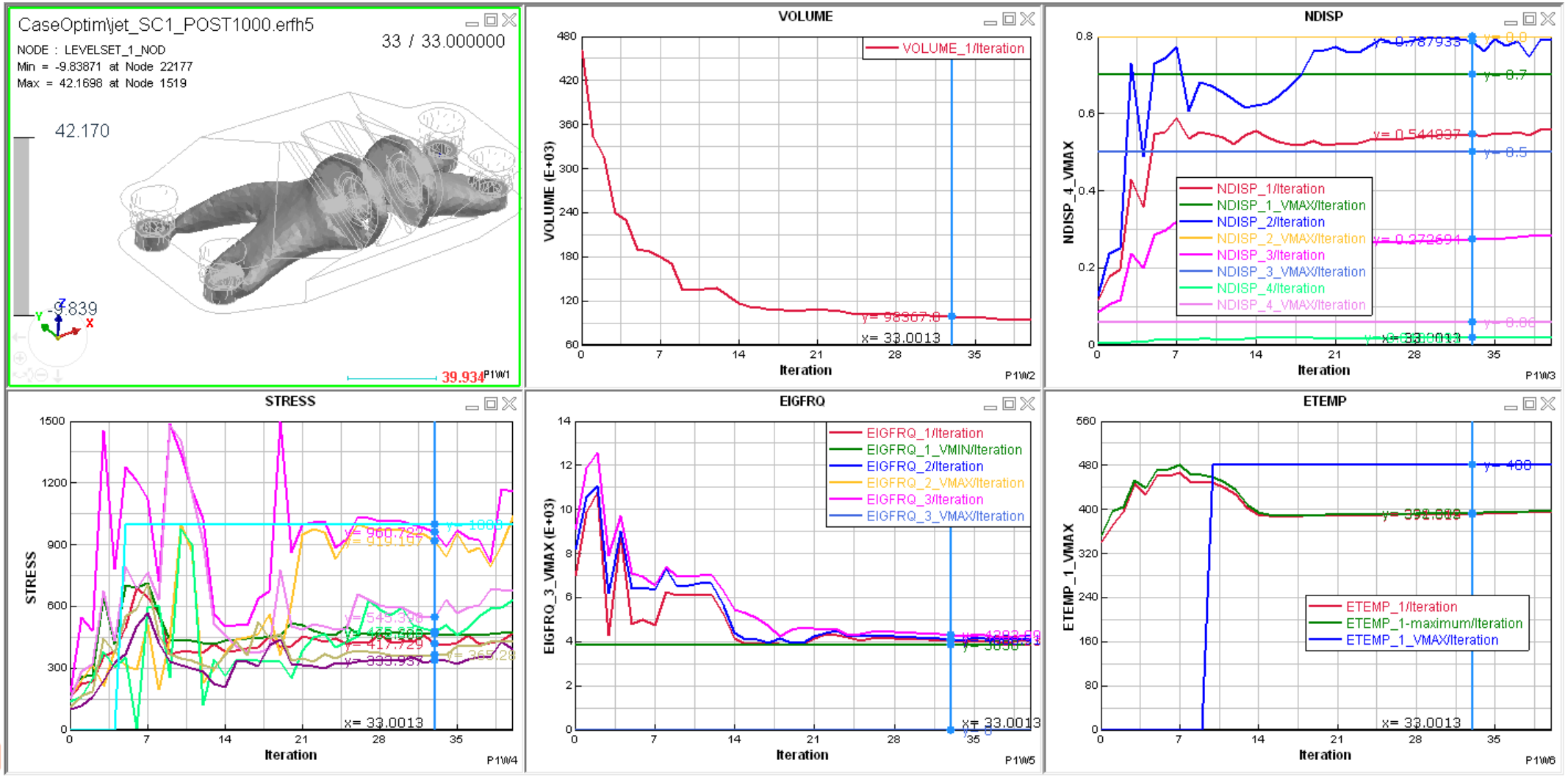
Example: Engine Bracket

Performance specifications

- On subcase 1:
  - Volume reduction
  - Displacement norm Node 22746 LC1 < 0,7 mm
  - Displacement norm Node 22746 LC2 < 0,8 mm
  - Displacement norm Node 22746 LC3 < 0,5 mm
  - Displacement norm Node 22747 LC4 < 0,06 mm
  - Max across E_OPTIMIZED of Von Mises Stress LC1 - LC4 < 1000 MPa
- On subcase 2:
  - First physical Eigenfrequency (MODE 7) > 3850 Hz
- On subcase 3:
  - Max across CONTROL_AREA of Temperature < 480°K

Example: Engine Bracket

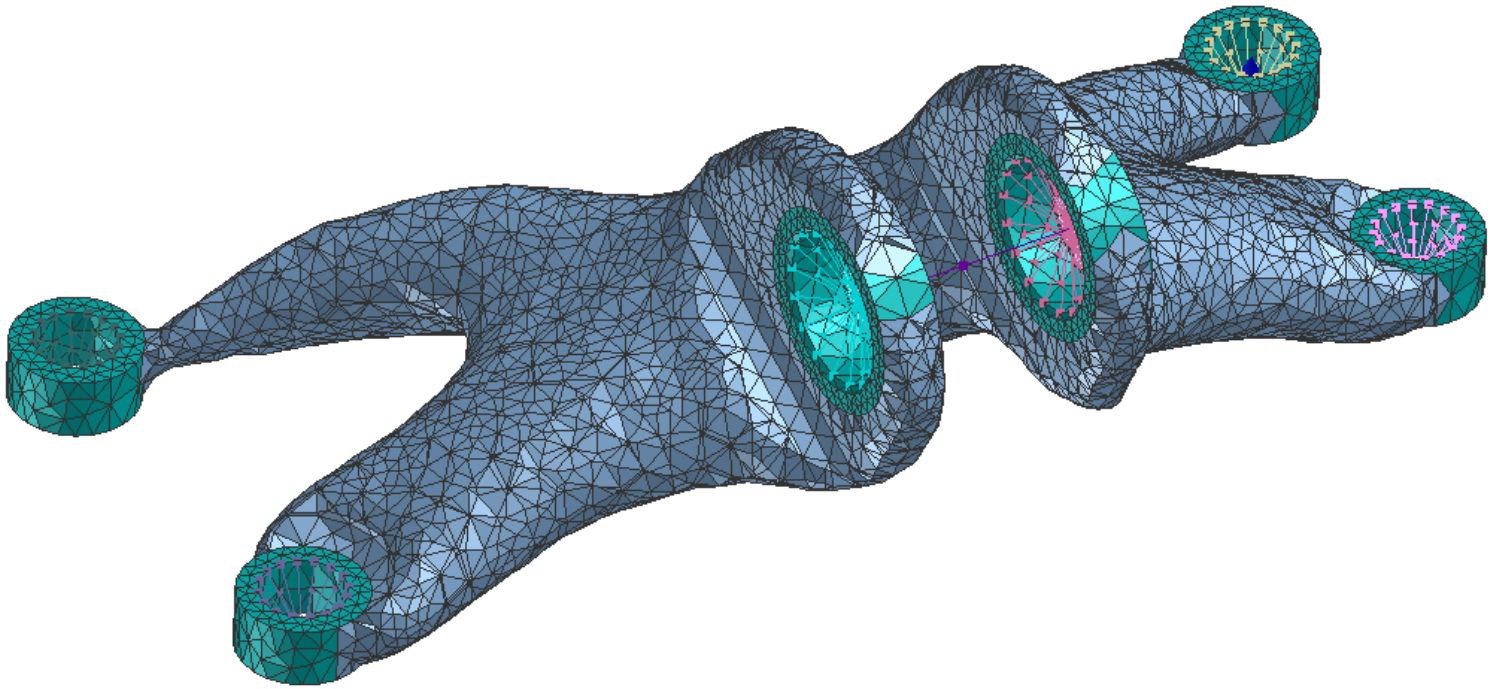
Results



Example: Engine Bracket

The remeshed optimal shape

- At the end of an optimization, TOPAZE remeshes the optimal shape



Application to Additive Manufacturing

Support structures

- The aim is to minimize the thermo-mechanical effects of overhangs

- Collaboration with Grégoire Allaire and Beniamin Bogosel, CMAP, Polytechnique School
    - *"Optimizing supports for additive manufacturing", Allaire, G. & Bogosel, B. Struct Multidisc Optim (2018) 58: 2493. https://doi.org/10.1007/s00158-018-2125-x*

    - *Support optimization in additive manufacturing for geometric and thermo-mechanical constraints", Allaire G, Bihr M, and Bogosel, B, to be submitted*

- Part of SOFIA project (SOlution pour la Fabrication Industrielle Additive métallique), https://www.sofia-3d.fr/

SOFIA

Application to Additive Manufacturing

Support structures: Mechanical

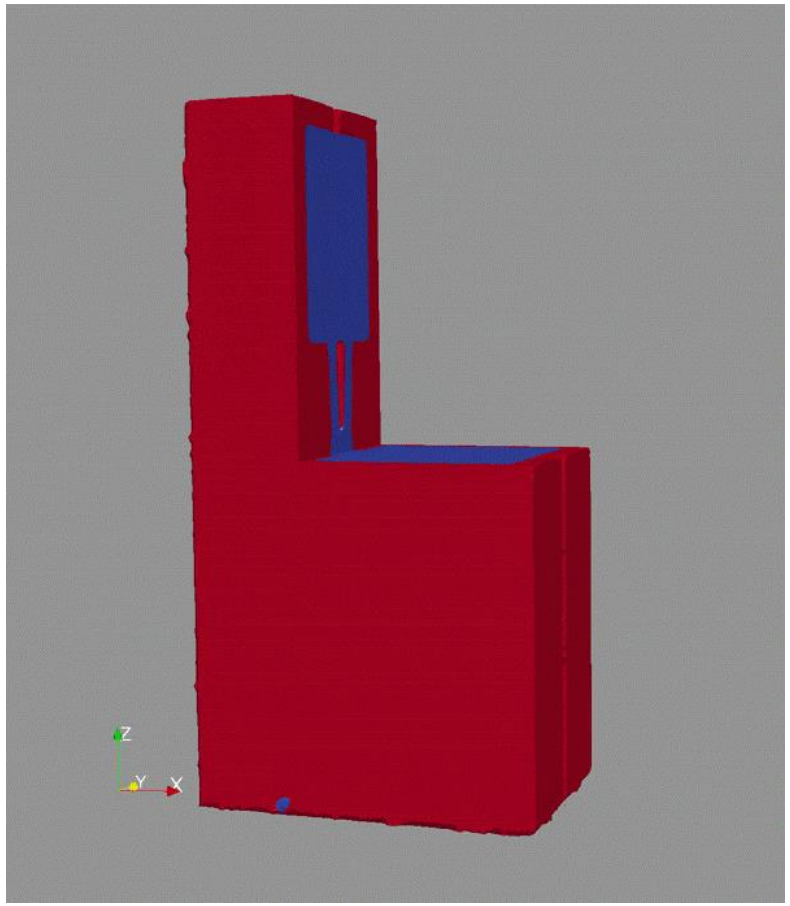
- First step is minimizing the mechanical effects of overhangs, without taking into account a thermal model
  - Thermo-mechanical is a bit more complex

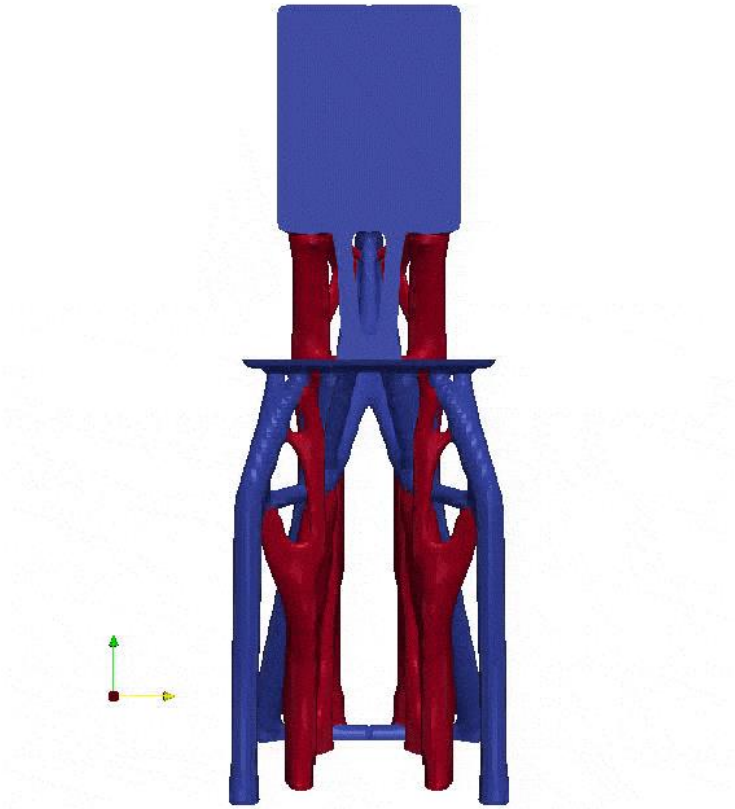
- We suppose that the shape is already designed

- We only optimize the supports
  - The model is submitted to the gravity
  - Objective: minimize volume of the supports
  - Constraint: compliance of the (shape+supports) has a maximum

Application to Additive Manufacturing

Support structures: examples

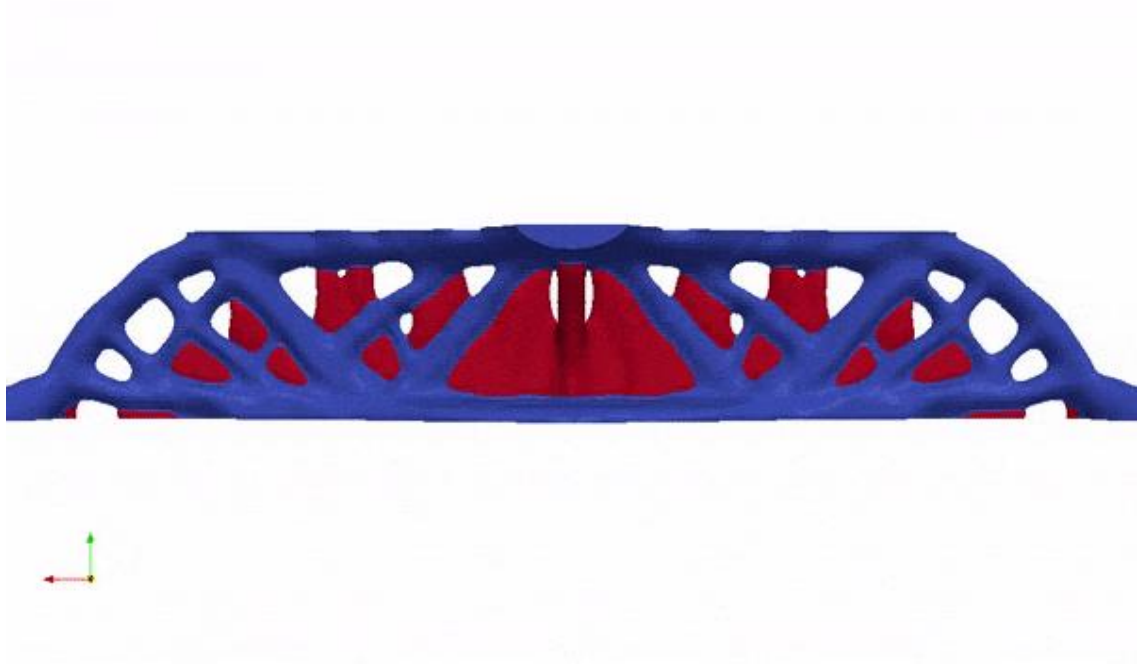


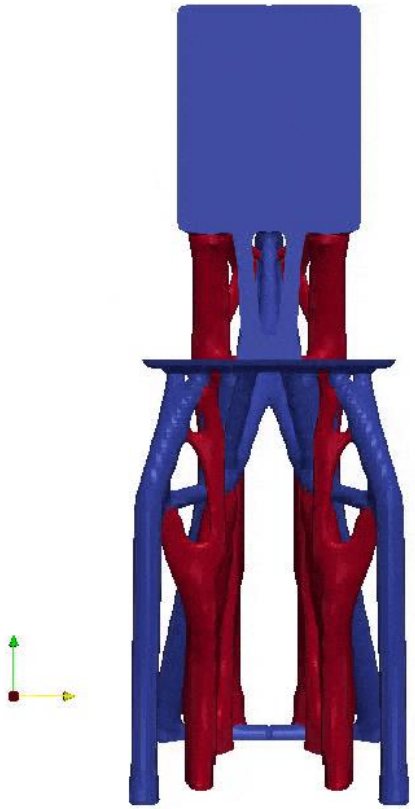


Pictures courtesy of Beniamin Bogosel, CMAP, Polytechnique School

Application to Additive Manufacturing

Support structures: examples





Pictures courtesy of Beniamin Bogosel, CMAP, Polytechnique School

Application to Additive Manufacturing

Support structures: Thermal evacuation

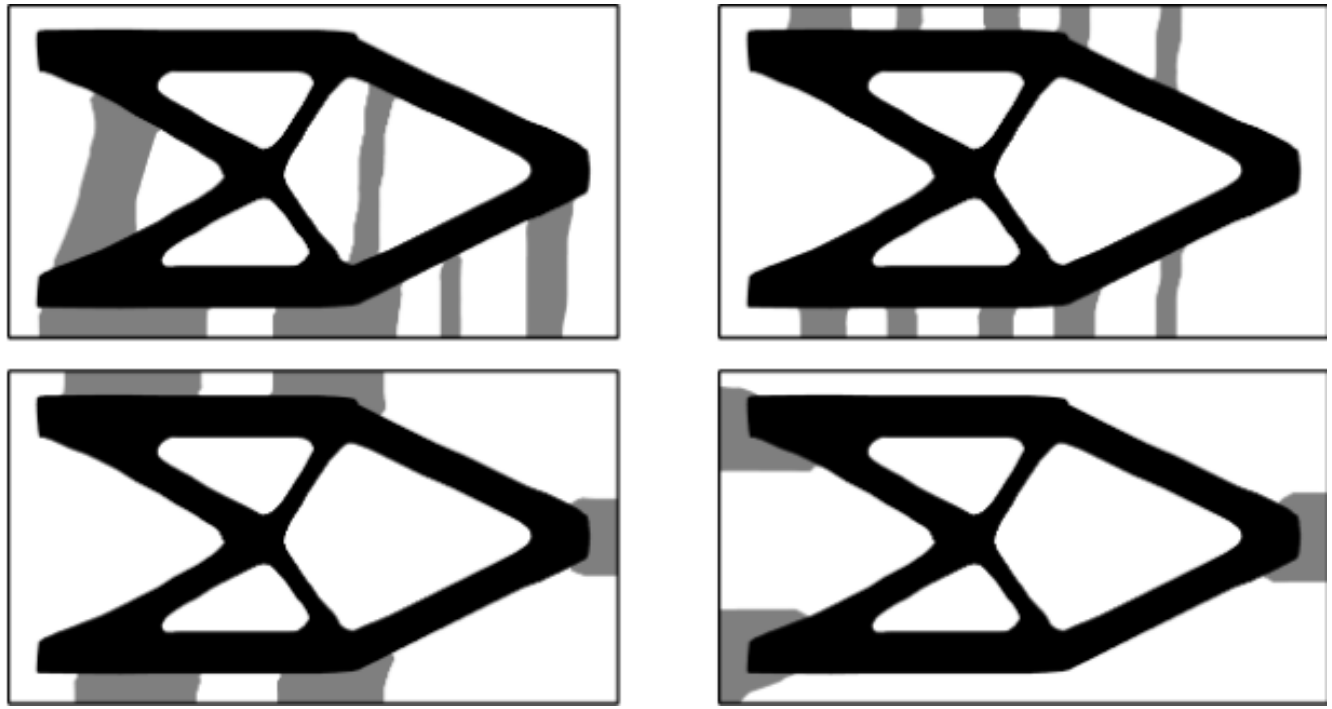
- We suppose that the shape is already designed

- We optimize the supports to maximize the thermal evacuation:

  - The model is submitted to a constant thermal source in the shape
  - One of the side of the model is “cold” (T=0)
  - Objective: minimize thermal compliance of (shape + supports)
  - Constraint: volume of supports is bounded

Application to Additive Manufacturing

Support structures: examples



Pictures courtesy of Beniamin Bogosel, CMAP, Polytechnique School

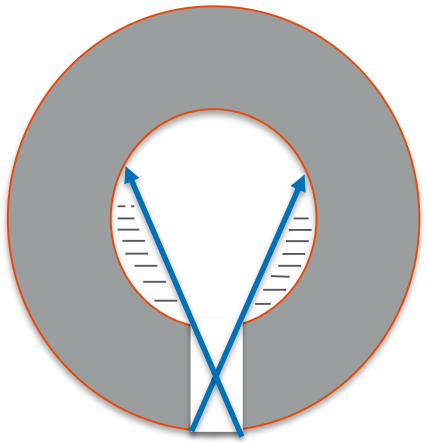
Application to Additive Manufacturing

Support structures with forbidden areas

- We suppose that the shape is already designed.

- We optimize the support structures (for thermic or static problem), but they can't lean on unattainable areas
  - Geometrical criterion:
    - We compute the "access range" of each areas
    - Penalization of the volume of support outside these "access ranges"

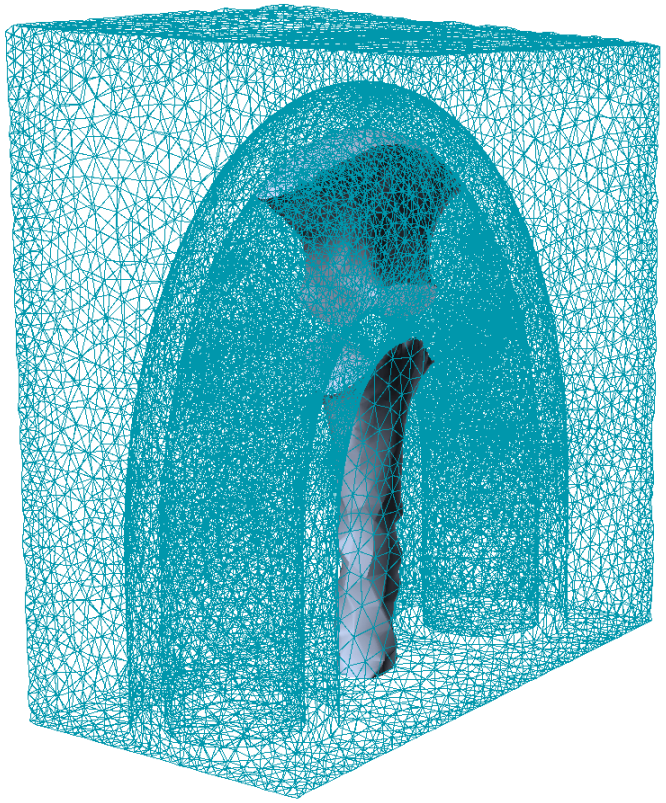
  - Special treatment of the level-set on these areas



Application to Additive Manufacturing

Support structures: example

U-shaped Tube without forbidden areas

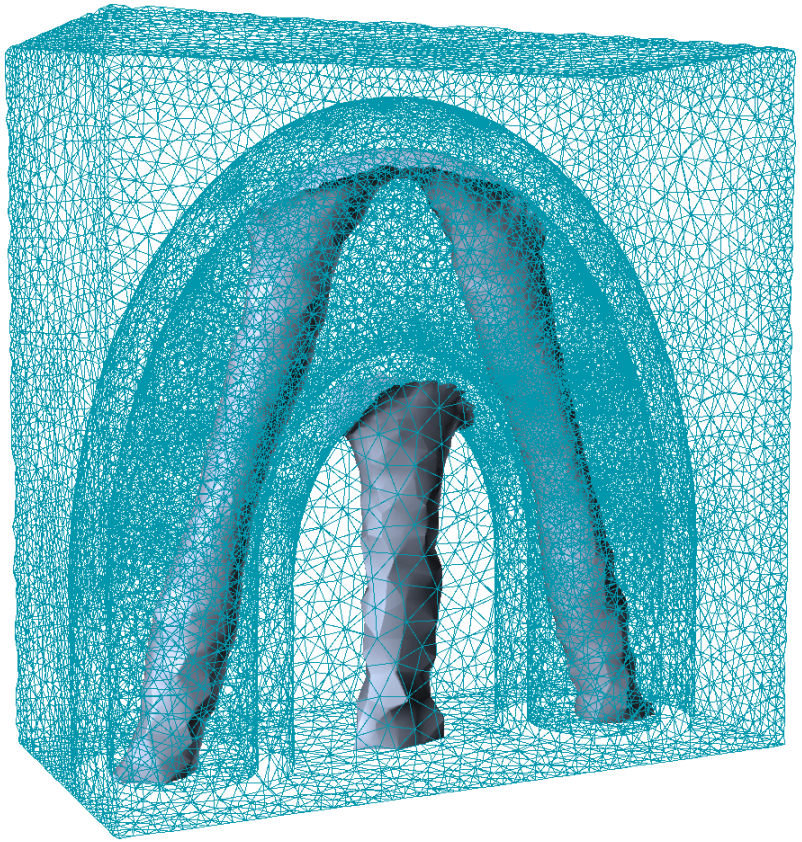


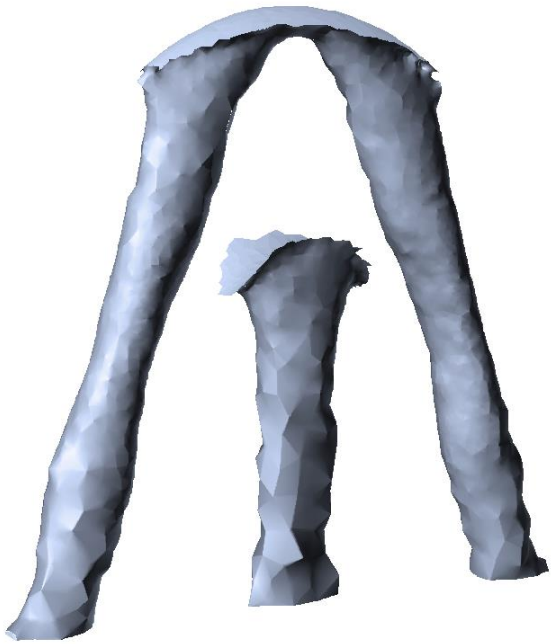
Pictures courtesy of Beniamin Bogosel, CMAP, Polytechnique School

Application to Additive Manufacturing

Support structures: example

U-shaped Tube with forbidden areas





Pictures courtesy of Beniamin Bogosel, CMAP, Polytechnique School

Conclusions

- TOPAZE allows users to solve problems of topological optimization
- It is based on the Level-Set technology, which guaranties an exact definition of the optimal shape

- For the 2020 version, as part of the SOFIA project, we plan to integrate tools for supports
  - Mechanical optimization
  - Thermal optimization
  - Forbid some areas

- More developments are in progress
  - Full thermo-mechanical optimizations
  - Optimization of the supports taking into account the slice-by-slice process of AM
  - Synergy ESI-AM, our solutions for Metal Additive Manufacturing

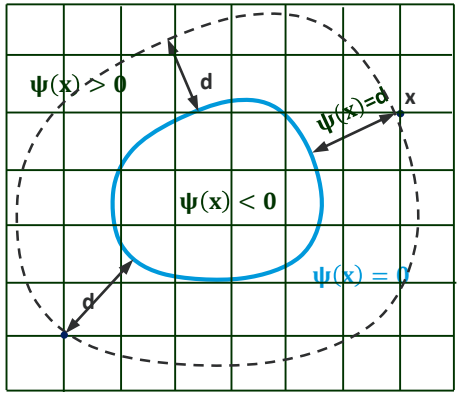
Thank you

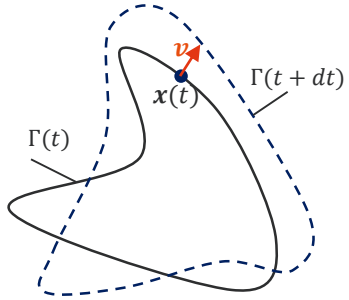
Topological Optimization

Shape representation with a Level-Set

- Simple scalar function ψ to define the shape

- Conventionally: the signed distance to boundary
  - $\psi(x) < 0$ if inside the shape
  - $\psi(x) > 0$ if outside the shape
  - $\Rightarrow \psi(x) = 0$ the boundary of the shape





- Precise knowledge of the location of the boundary on a non-fitting mesh

- Evolution of the shape using a descent direction v, computed from objective and constraints.
  - Hamilton-Jacobi equation $\frac{\partial \psi}{\partial t} + v\|\nabla \psi\| = 0$

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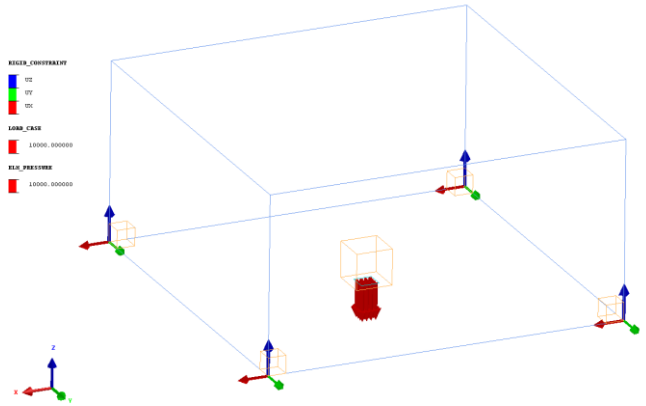
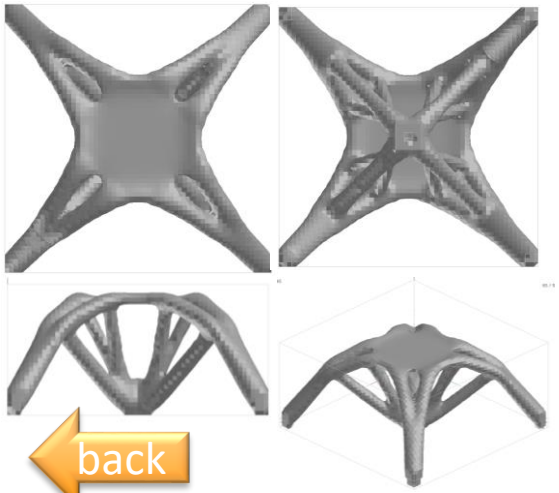
Geometrical Constraints

Maximum Thickness

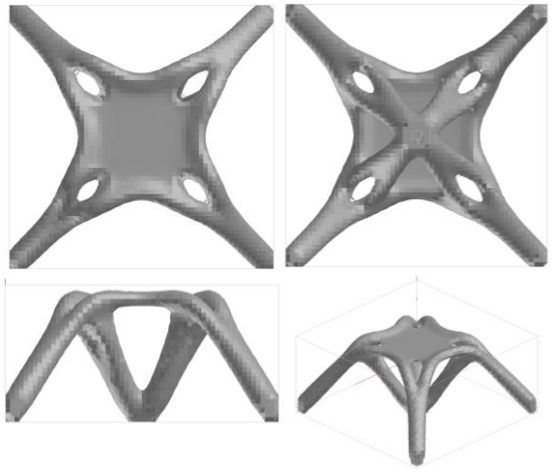
- Criterion that leads to topological changes depending on the threshold
- The optimizer changes the number of bars to fit the constraint



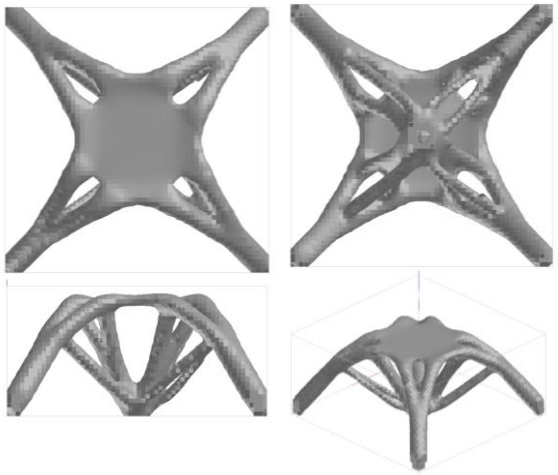
No e



e = 0.4



e = 0.2



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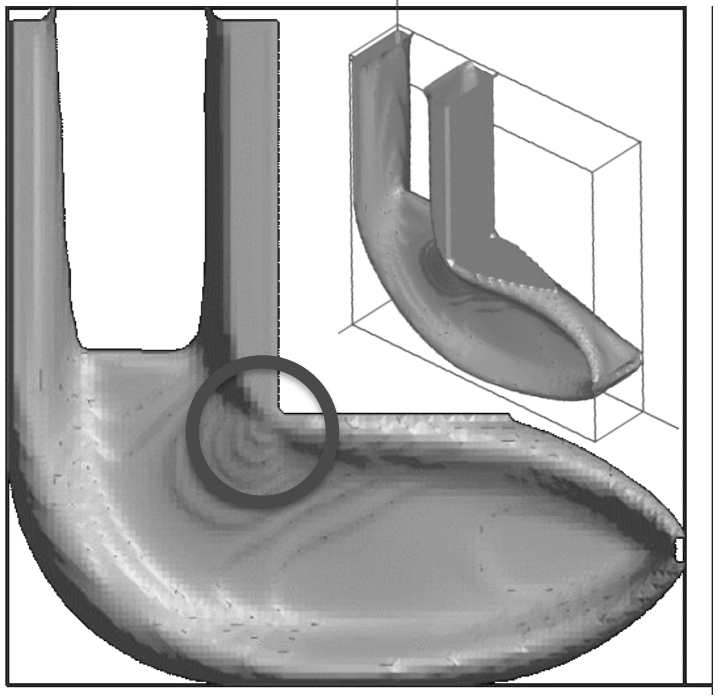
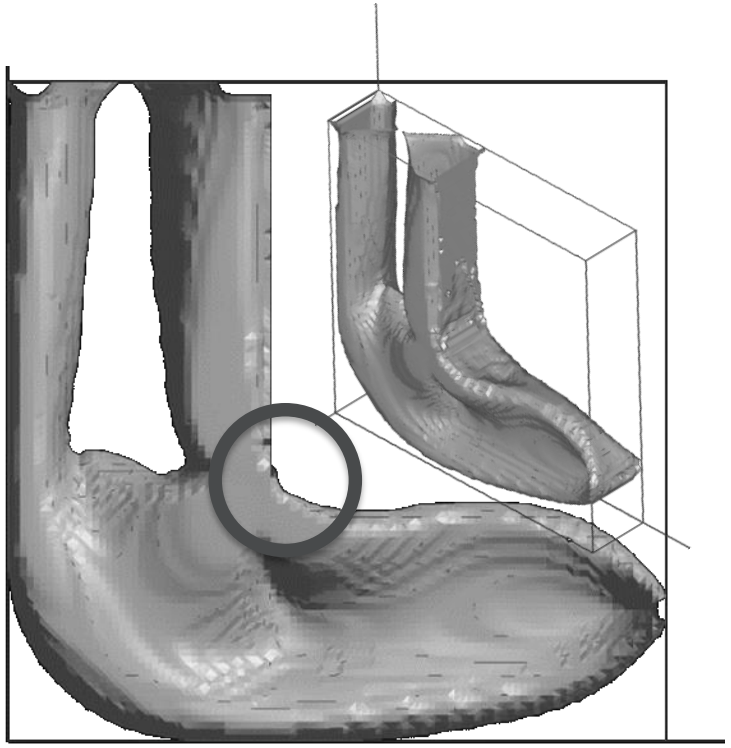
Semi Infinite Constraints

Maximum Von Mises example

- L-shape optimization
  - A fillet is needed to reduce stress



Without Von Mises constraint



With Von Mises constraint

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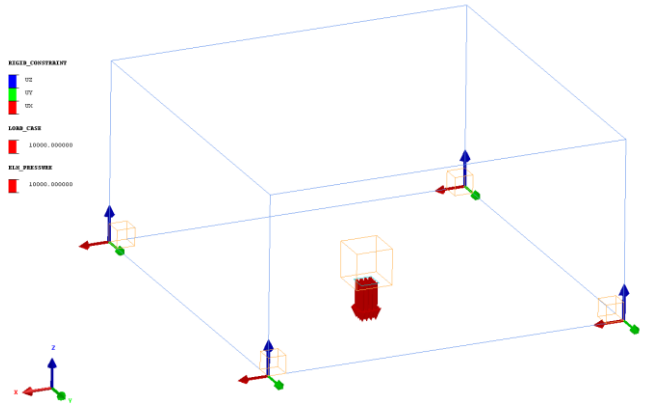
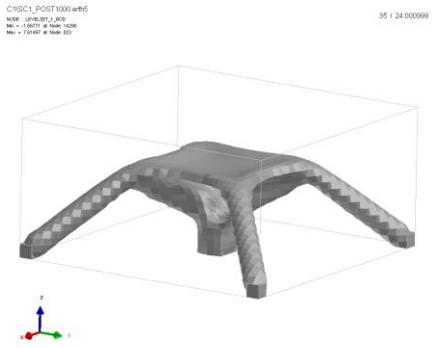
Manufacturing Constraints

Molding

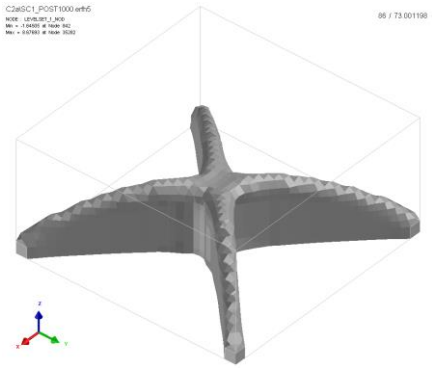
- Criterion that leads to topological changes depending on the molding direction and parting surface definition
- The parting surface can also be unknown



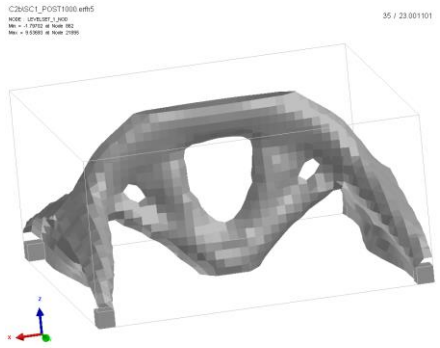
No molding



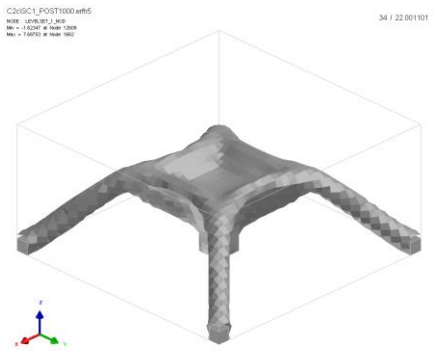
Molding in Z direction with parting surface Z=0



Molding in Y direction with parting surface Y=0.5



Molding in Z direction without parting surface



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