INdAM
Workshop
10-12 Feb, 2021

Different ways to impose **3D Printing overhang restrictions** in Topology Optimization

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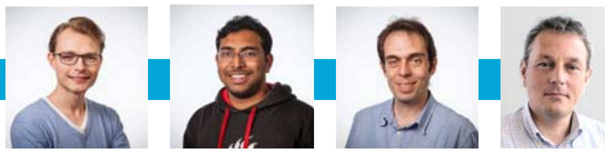

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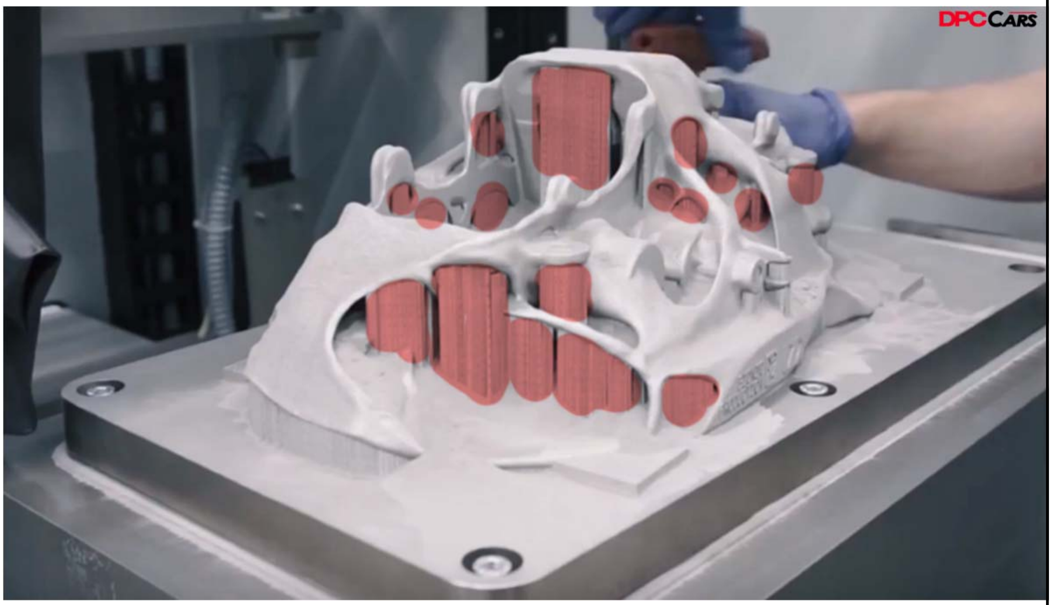

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Outline

- Topology optimization (TO)
- Additive manufacturing (AM)
- Overhang
- Approaches to control overhang in TO
    1. Geometrical, regular meshes
    2. Geometrical, unstructured meshes
    3. Thermal
- Concluding remarks

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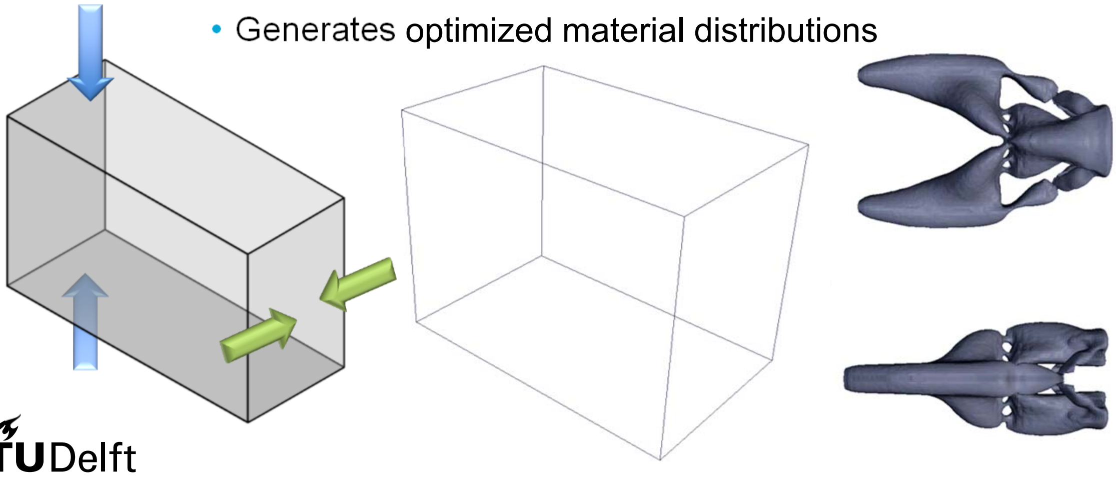
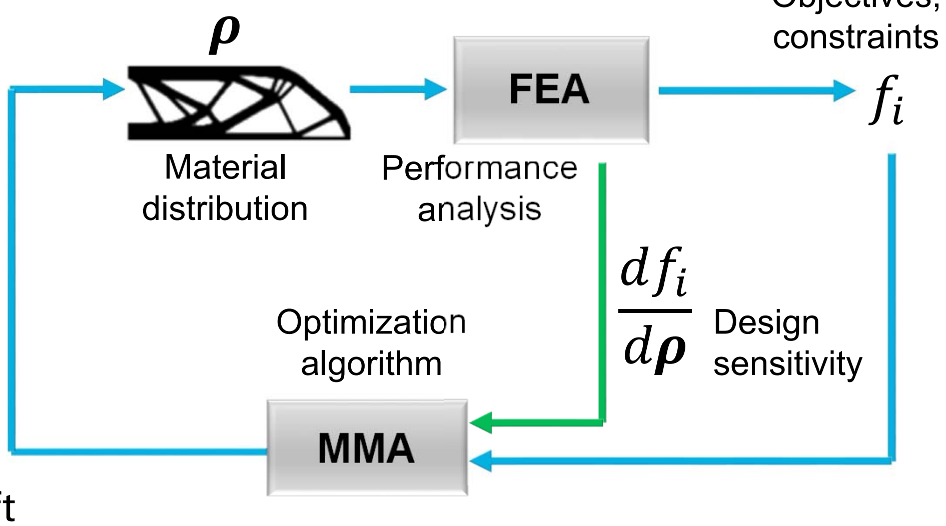
Topology optimization (TO)

- Computational design technique
- Generates optimized material distributions

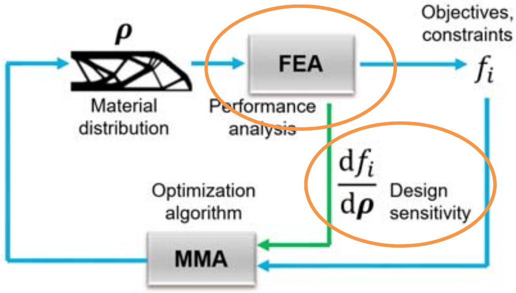


Conventional TO process



Computational TO characteristics

- Iterative process: many evaluations
- Main computational cost: FEA, sensitivity



- Sensitivity computation crucial:
  - Gradient-based optimization
  - Complexity depends on response and analysis type
  - Models must be differentiable!

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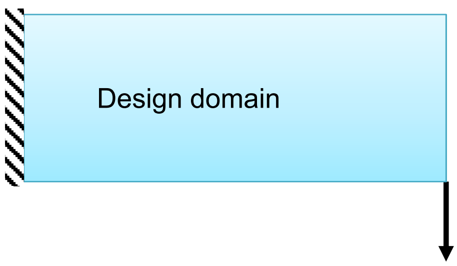
Compliance minimization

Frequently used TO problem:



$$\min_{\boldsymbol{\rho}} \quad C = \boldsymbol{f}^T \boldsymbol{u}(\boldsymbol{\rho})$$ Compliance

$$\text{s.t.} \quad V(\boldsymbol{\rho}) \leq V_{\max}$$ Volume constraint

$$\boldsymbol{K}(\boldsymbol{\rho})\boldsymbol{u} = \boldsymbol{f}$$ Finite element analysis

$$0 \leq \rho_i \leq 1$$

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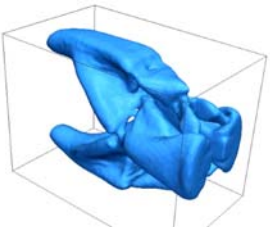
AM and TO



AM: ideal technology to realize TO designs

TO: ideal method to exploit AM design freedom

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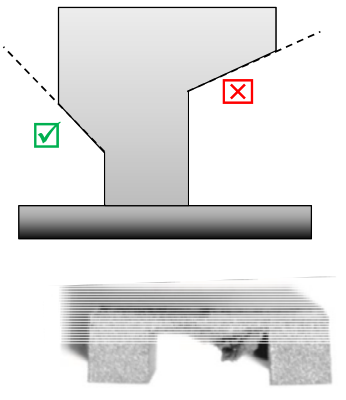
Overhang restriction



Clijsters et al, 2012

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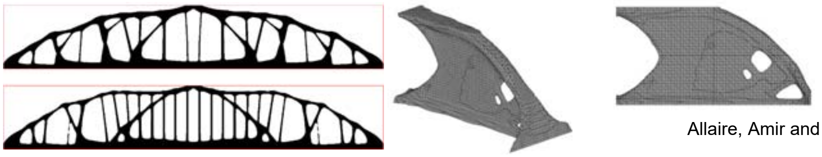
Overhang restriction in TO

Various approaches:

- E.g. directly constraining boundary angles/normals
- Or using a simplified, *geometry-based* process simulation
- Or introducing *physics-based* constraints (gravity load):



Allaire, Amir and others

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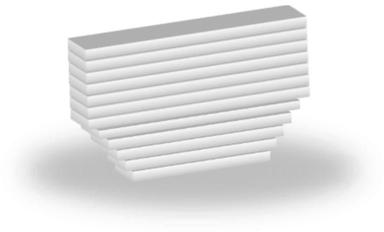
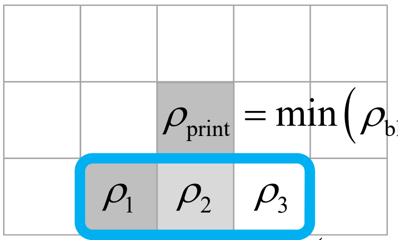
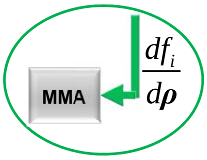
Simplified AM process model





$$\rho_{\text{print}} = \min\left(\rho_{\text{blueprint}}, \rho_{\text{support}}\right)$$

$$\rho_{\text{support}} = \max\left(\rho_1, \rho_2, \rho_3\right)$$



Differentiable
min/max operators: $\max\left(\rho_1, \rho_2, \rho_3\right) \approx \left(\sum_{i=1}^{3} \rho_i^P\right)^{1/P}$

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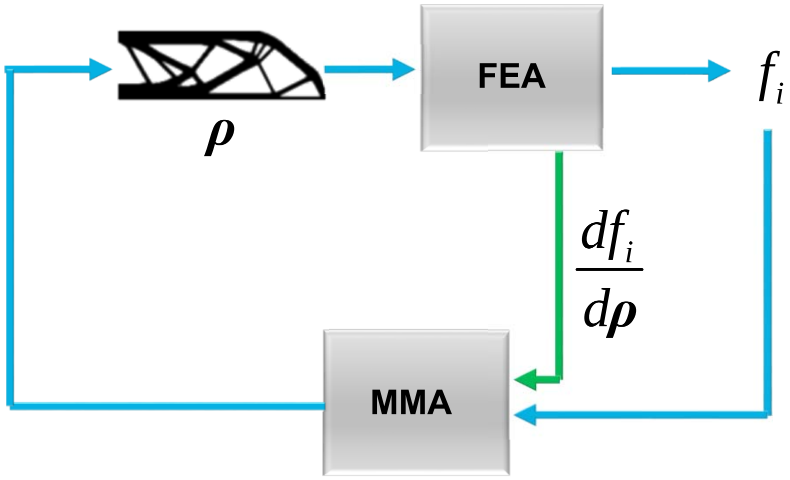
Standard TO process



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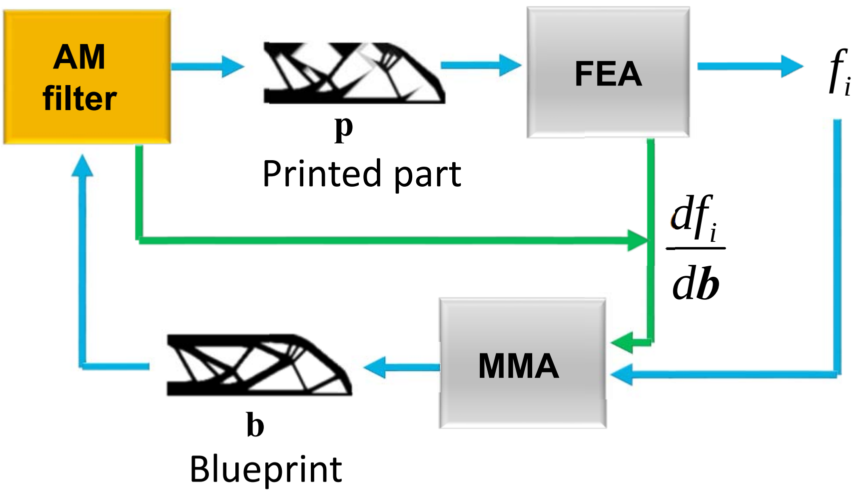
AM-based TO process



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Result: full overhang control

Code: https://dx.doi.org/10.1007/s00158-016-1522-2

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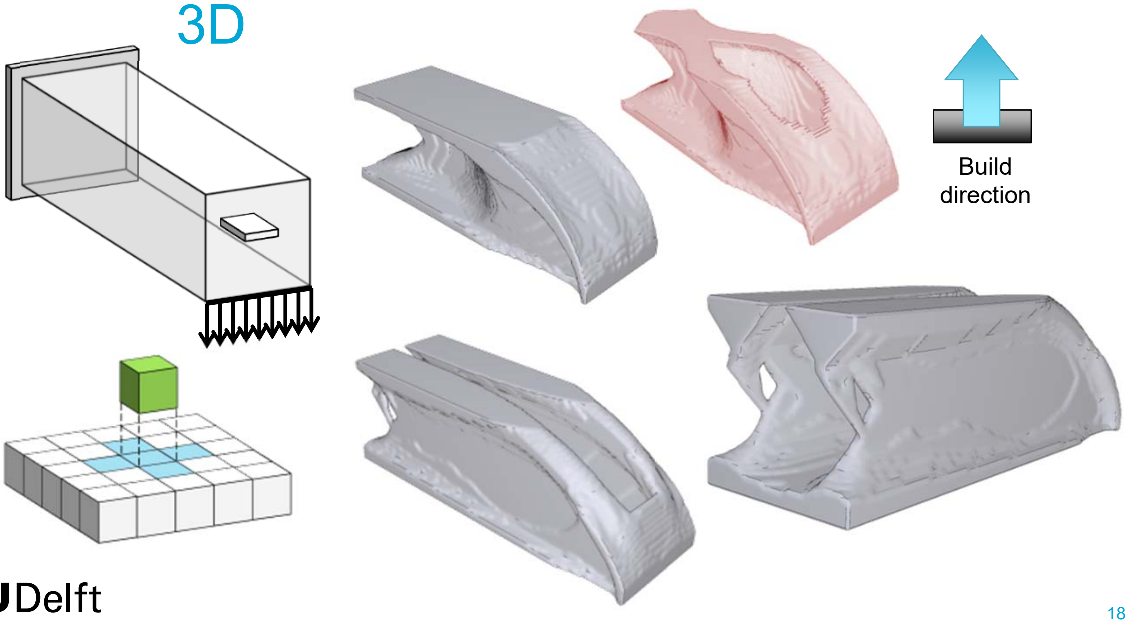
3D



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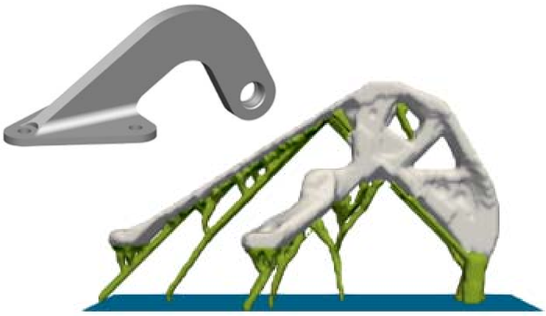
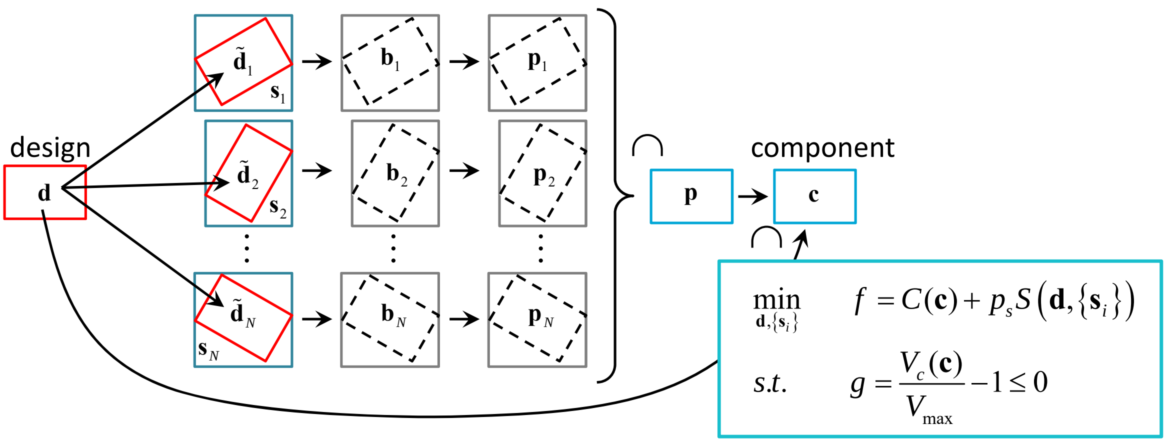
Extensions

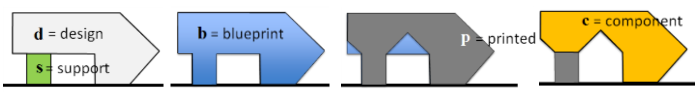


Part & support optimization

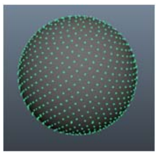
Part, support & orientation optimization

Bonus: orientation co-optimization

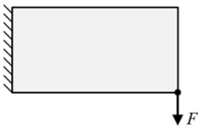


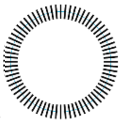


An example

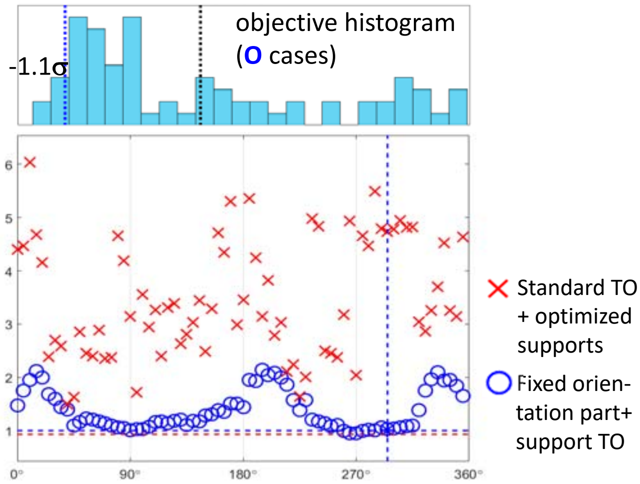


3D?





combined: 295°



combined case runtime: **2.4%**

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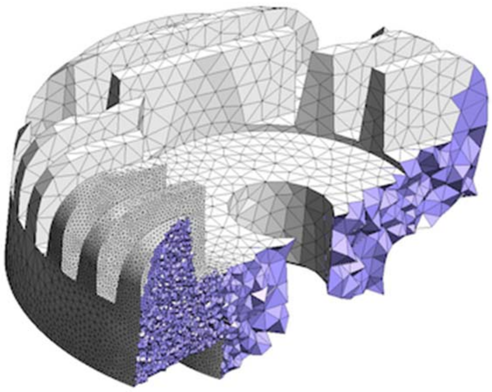
Unstructured meshes



- Common in engineering practice
- Overhang control:
  - Use mesh mapping to regular mesh
  - Develop approach for abribrary mesh

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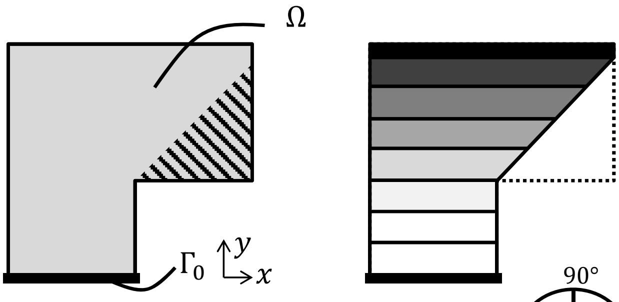
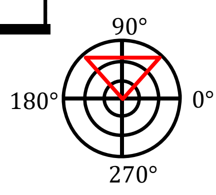
Concept: front propagation

- Propagating from Γ_0: $\|\nabla T\| = \dfrac{1}{v(\boldsymbol{x},\theta)}, \quad \boldsymbol{x} \in \Omega$



Anisotropic propagation speed:



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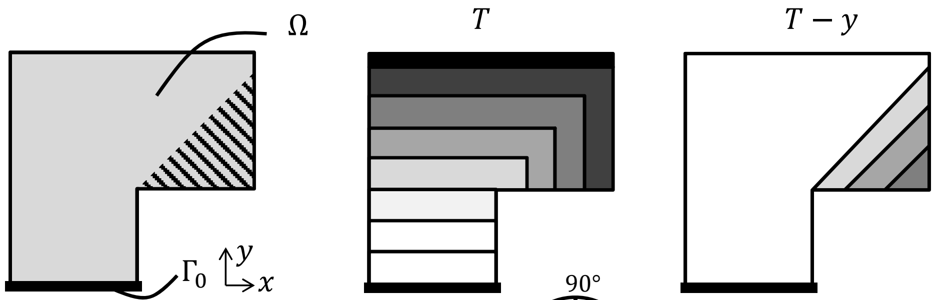
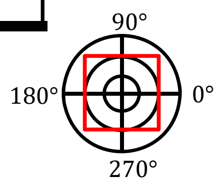
Concept: front propagation

- Propagating from Γ_0: $\|\nabla T\| = \frac{1}{v(\boldsymbol{x},\theta)}, \quad \boldsymbol{x} \in \Omega$



Anisotropic propagation speed:



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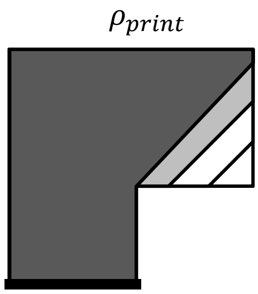
Implementation in TO

- Propagation using Ordered Upwind Method [Sethian & Vladimirsky, 2003]
- Front should only propagate through solid regions: speed scaled with local density

$$v(\boldsymbol{x},\theta) = \rho(\boldsymbol{x})V(\boldsymbol{x},\theta)$$

$$\rho_{print} = \rho e^{-\alpha(T-y)}$$



- Obtain printable part: reduce density strongly in overhanging regions

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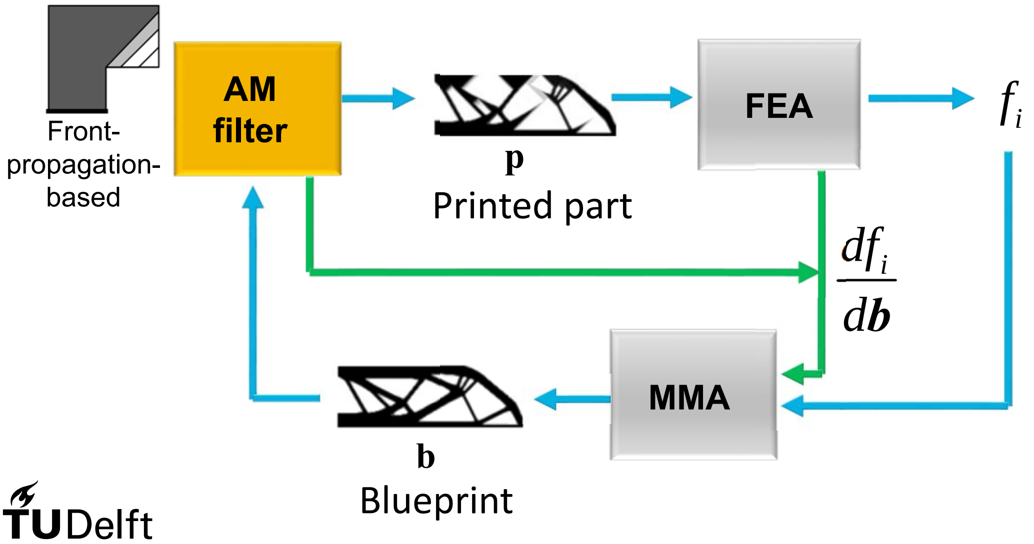
AM-based TO process



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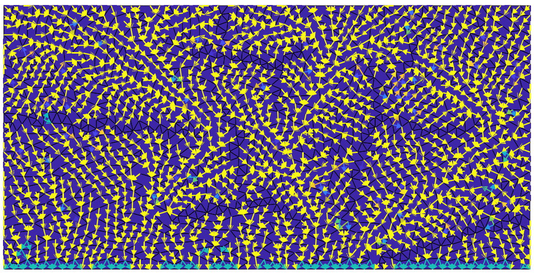
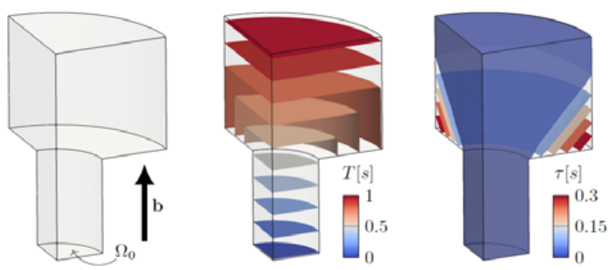
Implementation aspects

- Design gradient calculation for front propagation process: efficient since dependencies are known





- Parallel implementation for efficient 3D TO

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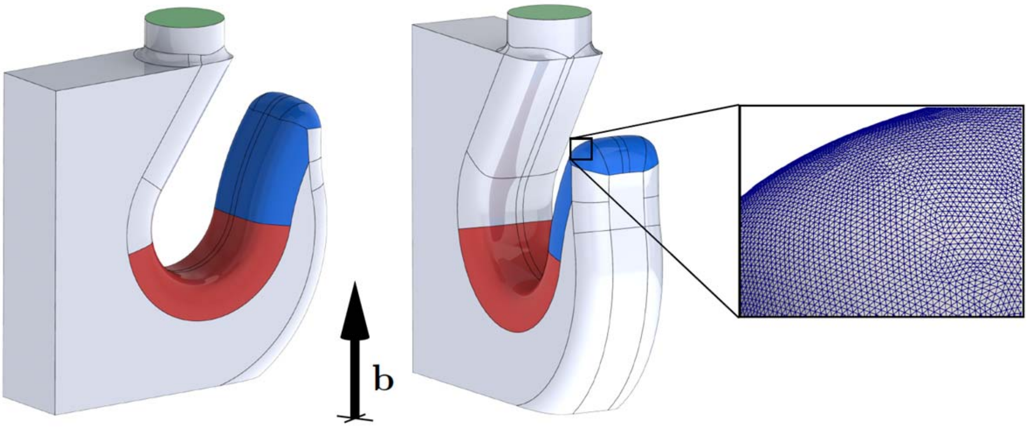
Example



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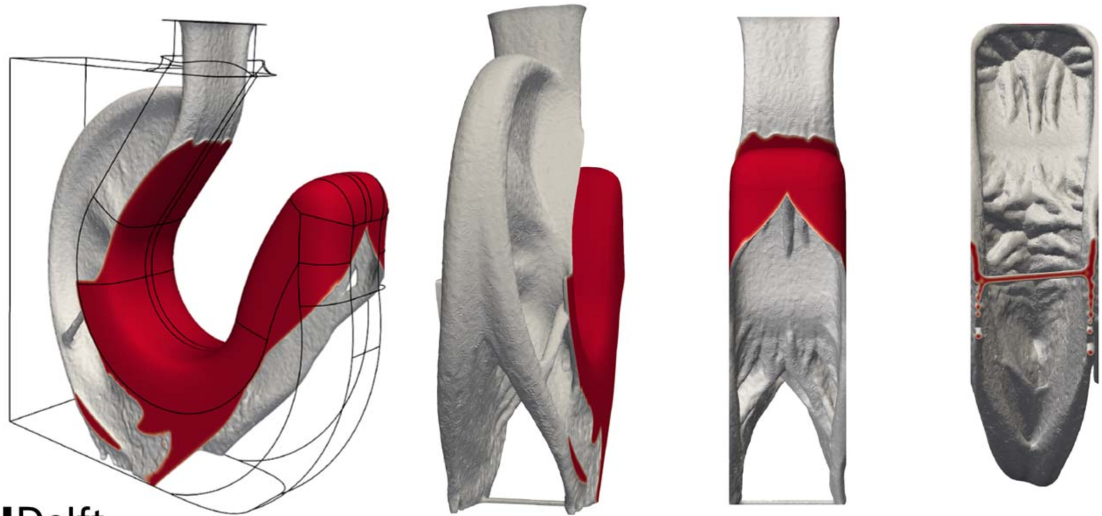
Example



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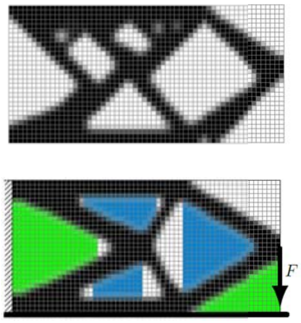
Extensions



Considering support access

Applications

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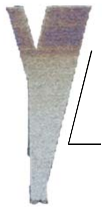
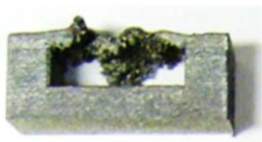
Overhangs are linked to overheating

- Local temperatures during printing process depend on local geometry
- Overhanging regions have reduced heat conduction and can be prone to *overheating*
- Overheating causes defects and inferior material quality



[Adam et al, 2014]



[Clijsters et al, 2012]

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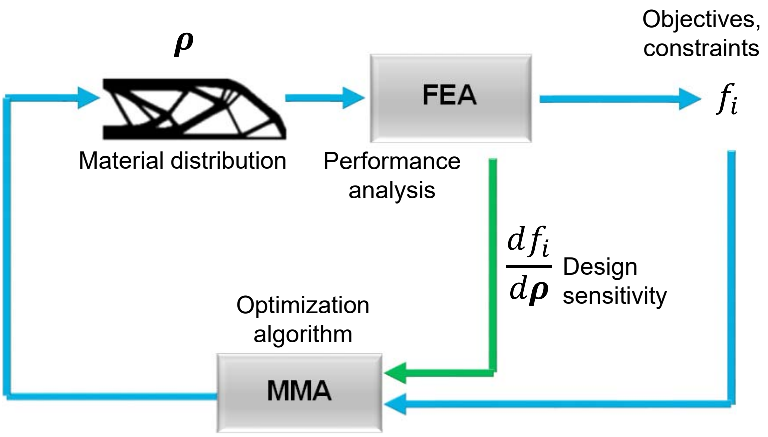
Conventional TO



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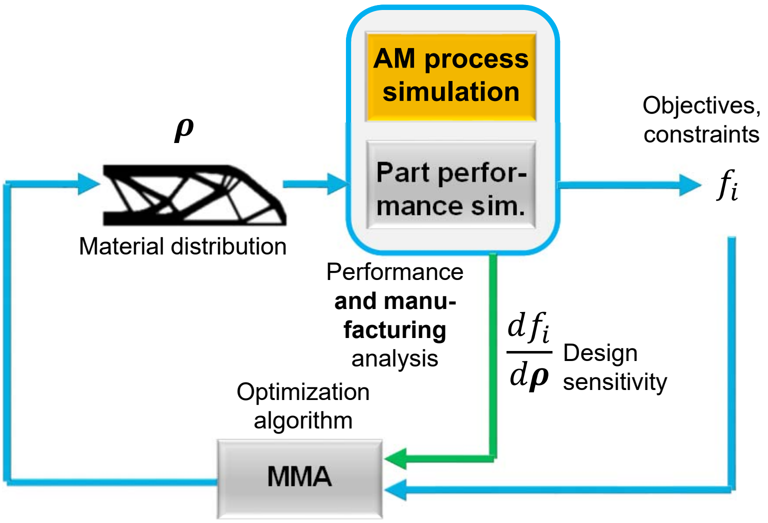
TO considering AM process physics



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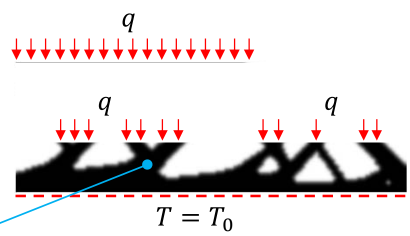
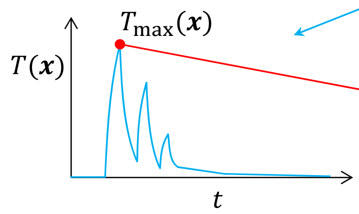
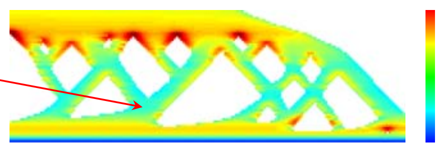
AM process simulation

Thermal process simulation

- Initial simplifications:
  - Layer-by-layer approach
  - Conduction only
  - Constant material properties
  - No phase transformation







'Hotspot map'

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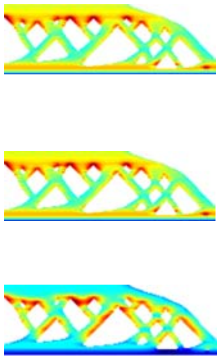
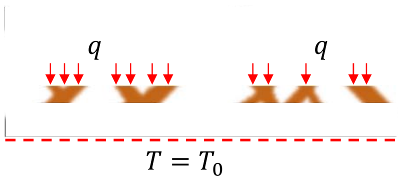
AM process simulation

Further simplifications



1. Cooling time between layers sufficiently long:
   - Decoupling of layers
   - Only consider heating phase
2. Length scale of heated region:
   - Only consider 'slab'



3. Replace transient simulation by steady-state analysis:
   - Measure of local conductance
   - Qualitative hotspot indicator

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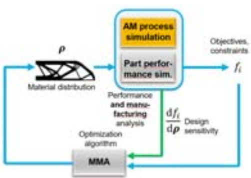
TO with overheating control



- Problem formulation:

$$\min_{\boldsymbol{\rho}} \ C = \boldsymbol{f}^T \boldsymbol{u} \qquad \text{Compliance}$$

$$\text{s.t.} \ T_{\max}(\text{part}) \le \hat{T} \qquad \text{Limit peak temperature}$$

$$V \le V_{\max} \qquad \text{Volume constraint}$$

$$0 \le \rho_i \le 1 \qquad E(\rho), K(\rho), q(\rho)$$

$$T_{\max} \approx \left(\sum_{i=1}^{n} T_i^P \right)^{1/P}$$

- Computational advantages:
  - Small decoupled steady state problems
  - Sensitivity analysis relatively straightforward

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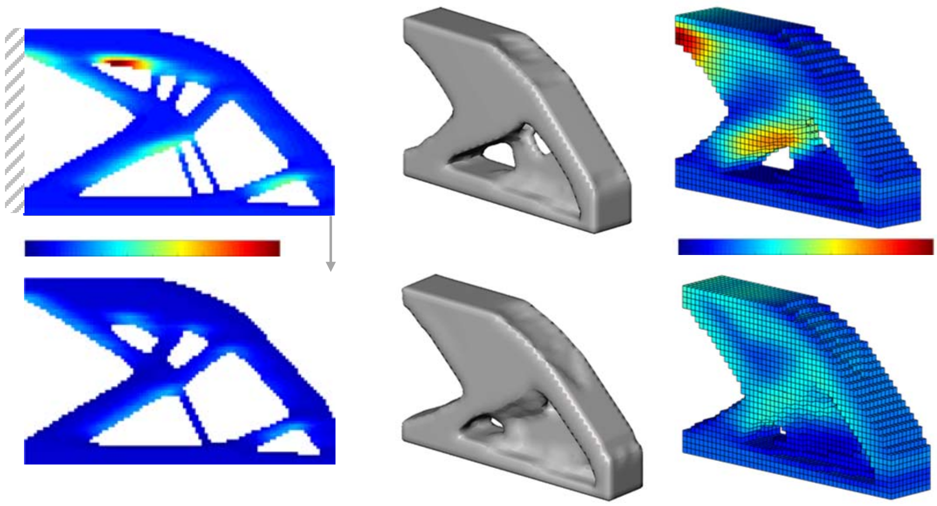
Test problems

Without hotspot constraint

With hotspot constraint



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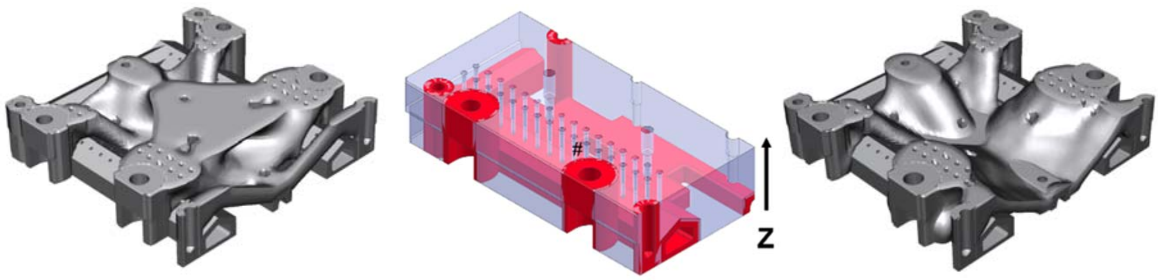
Industrial case: mold insert



Standard TO

Quarter mold insert 100x50x25 mm

TO with hotspot constraint

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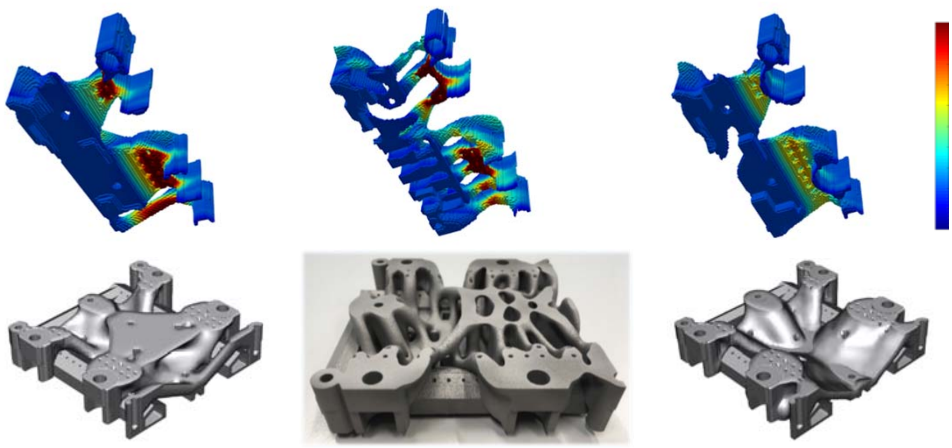
Sinico et al, SFF 2019

Mold insert: hotspot evaluation



Standard TO Overhang constraint Hotspot constraint

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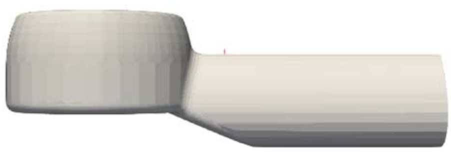
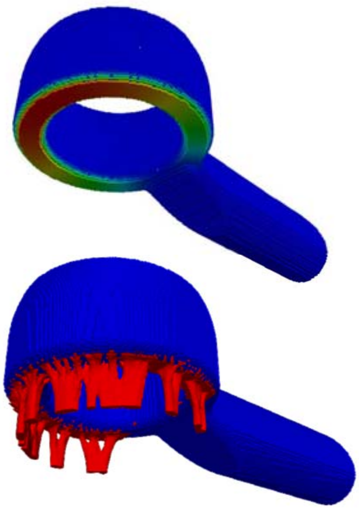
Extension





Thermal support optimization

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Concluding remarks

- **Topology Optimization: versatile method for both part and support optimization for Additive Manufacturing**

- **Overhang control**: different approaches possible
  - Fast geometric approach for regular meshes
  - Generic geometric approach using front propagation
  - Physics-based approach using local heat transfer analysis
  - And various others!

- Equally important: determining **best build orientation**

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References

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