University of Liège
Applied Science faculty
Mechanical & Aerospatiale Department

Deterministic Manufacturing constraints for Optimal Distribution in the Case of Additive Manufacturing

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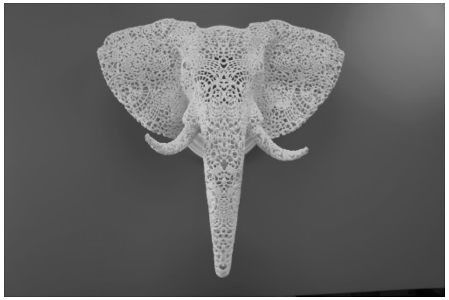
Introduction

Increasing interest in additive manufacturing

- Solution to economical and ecological constraints
- Production time is reduced (idea➔fabrication)
- Customization of the product (medical usefulness)
- Geometrical flexibility
- Material flexibility
- Optimization of the functions of the product

https://www.luxexcel.com/3d-printing/medical-3d-printing/



https://www.luxexcel.com/3d-printing/medical-3d-printing/

http://www.eos.info/eos_airbusgroupinnovationteam_aerospace_sustainability_study

Reminder

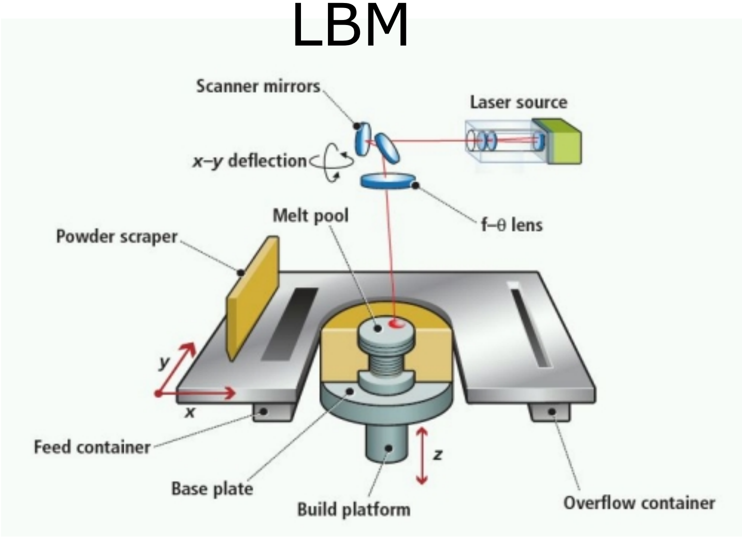
Metallic additive manufacturing technologies

Two studied technologies:

- Laser Beam Melting (LBM) and Electron Beam Melting (EBM)

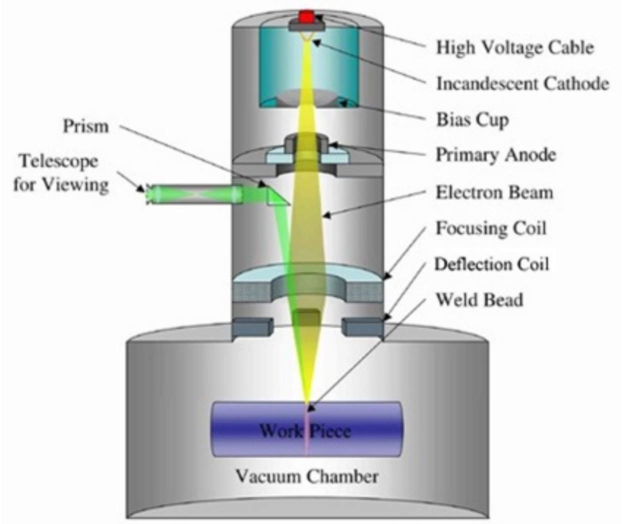
  Advantages:
  - Large choice of materials (Steel, Aluminum, Titanium…)
  - Various widths of layer deposition (20-100μm)
  - Good precision
  - High geometry complexities achievable

LBM



http://www.popular3dprinters.com/selective-laser-melting-slm/

EBM

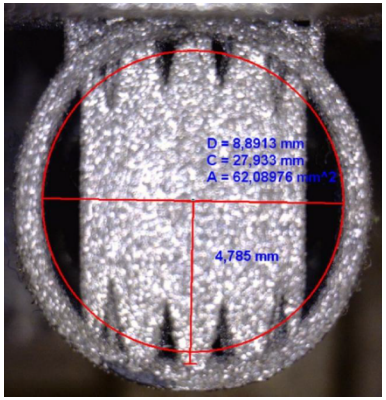


http://www.popular3dprinters.com/electron-beam-melting-ebm/

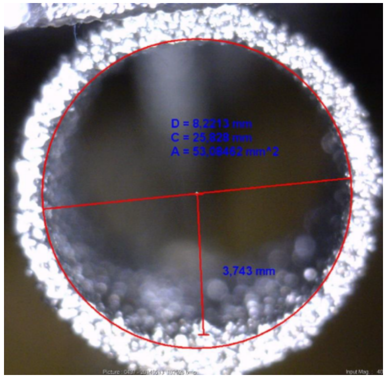
Manufacturing Constraints in ADM

Manufacturing Constraints in ADM

- Constraints caused by metallic additive manufacturing (LBM, EBM):
  - Minimum and maximum width of walls
  - Surface state
  - Post machining of working surfaces and screw thread
  - Overhanging angle
  - Part orientation
  - Dimensions precision
  - Minimum size of canals (powder evacuation)
  - No closed cavities
  - Thermal constraints
  - Support structure needed and removed



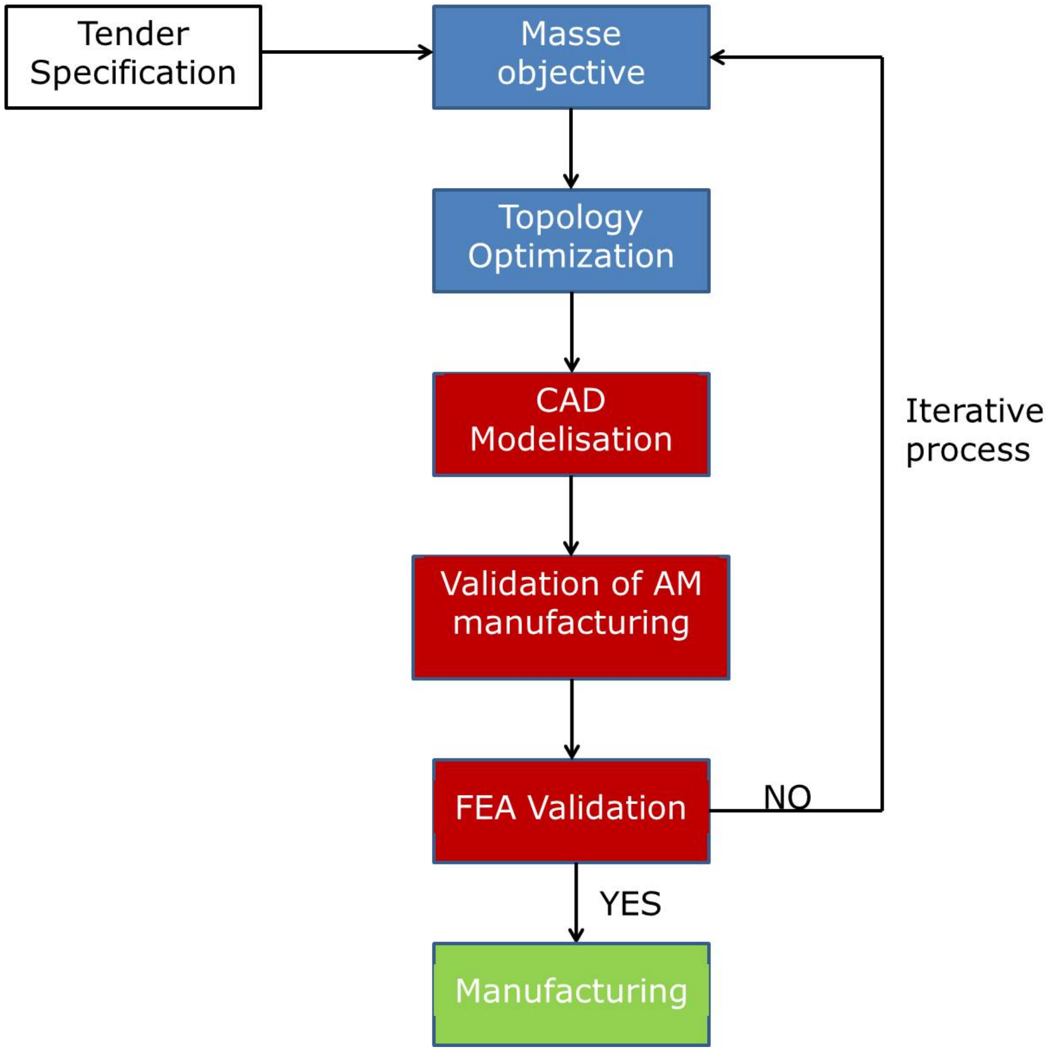
Re: Meunier



Ref: Meunier

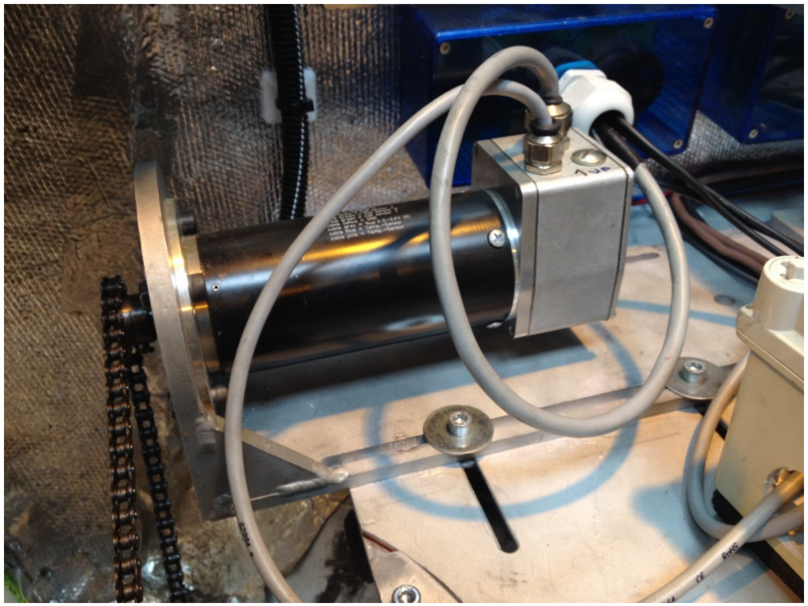
Manufacturing Constraints in ADM

Design process ➔ too much manual work versus automation process



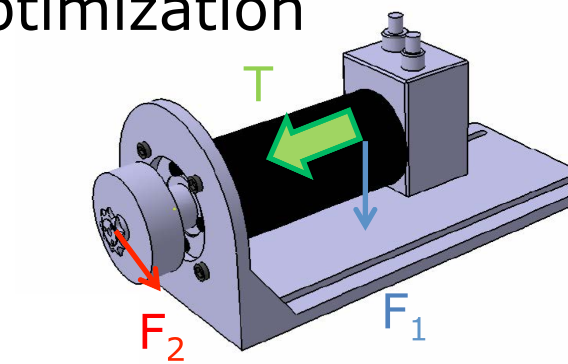
Ulg Eco-Shell motor support example

Design process on Ulg Eco-Shell motor support optimization (Ref: Cid)



Ref: Cid

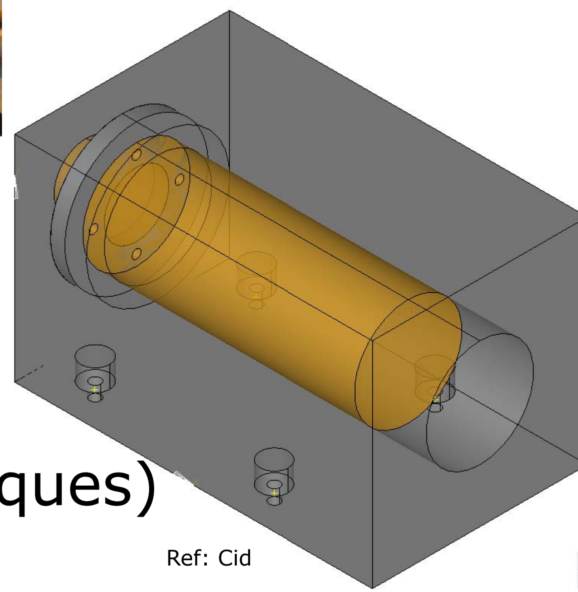
- Too massive
- Too heavy
- Room for optimization



Ref: Cid

Definition of:

- The usable volume
- Non optimizable parts
- Boundary conditions
- Applied load (forces, torques)



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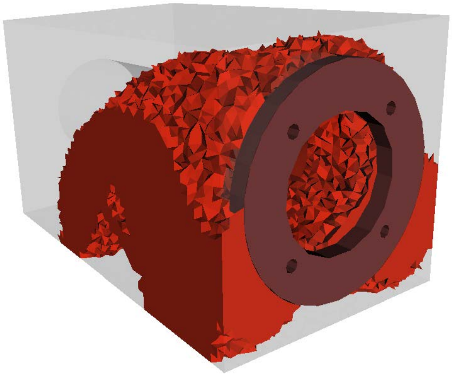
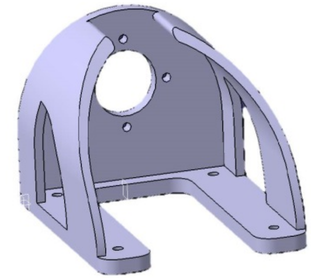
Ulg Eco-Shell motor support example



Ref: Cid

Result of optimization with industrial software

Medialization of optimized solution



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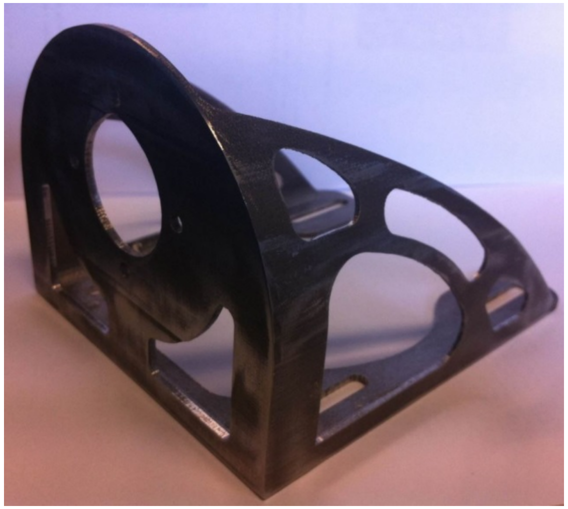
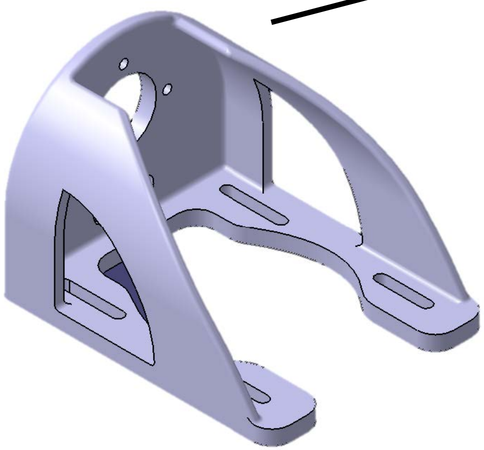
FEA + Re-optimization



Validation + Manufacturing



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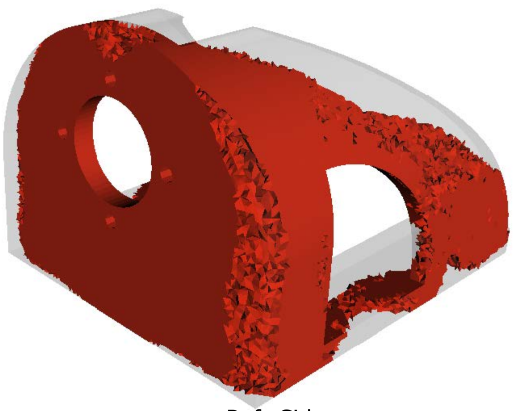

Ref: Cid

Medialization of new solution

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Existing solutions and investigation using 88line Matlab code of topology optimization

Reminder Topology Optimization Problem:

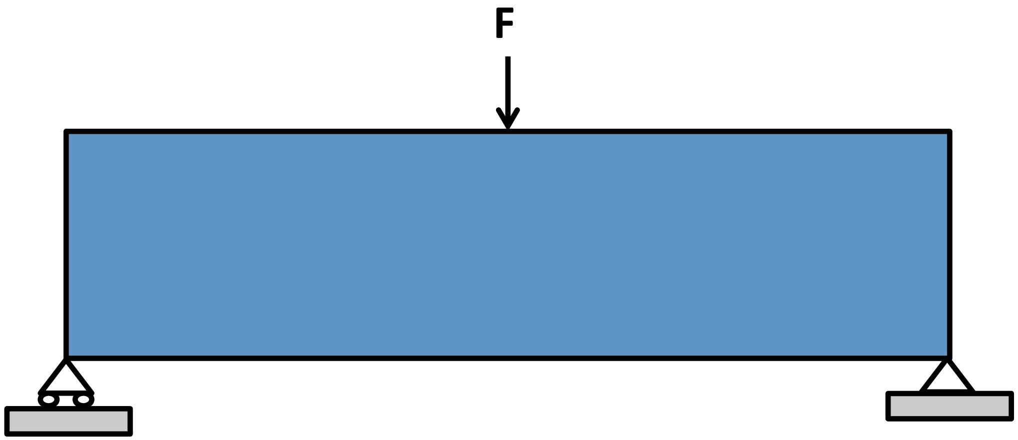
$$\begin{aligned}
\min_{\boldsymbol{\rho}} \quad &: \quad \Phi(\boldsymbol{\rho}, \boldsymbol{U}) \\
s.t. \quad &: \quad V(\boldsymbol{\rho}) \leq V^* \\
&: \quad g_i(\boldsymbol{\rho}, \boldsymbol{U}) \leq g_i^* \; i = 1, ..., M \\
&: \quad \boldsymbol{\rho}_{min} \leq \boldsymbol{\rho} \leq \boldsymbol{\rho}_{max}
\end{aligned}$$

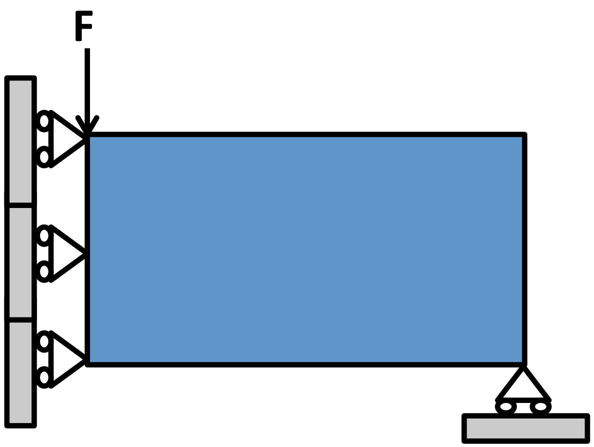
$$K(\boldsymbol{\rho})\boldsymbol{U} = F$$

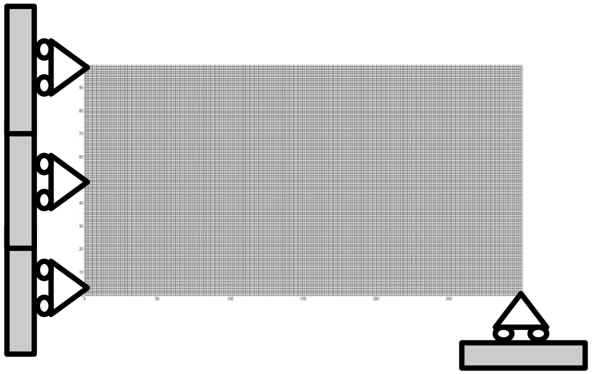
Compliance problem:

$$\Phi(\boldsymbol{\rho}, \boldsymbol{U}(\boldsymbol{\rho})) = F^T \boldsymbol{U}$$

Test on MBB-beam exemple







Number of elements
300*100

Minimum width of walls:

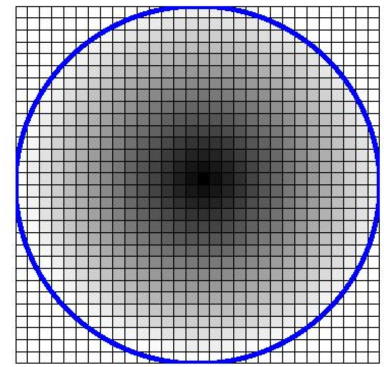
- " Achieving minimum length scale in topology optimization using nodal design variables and projection functions ", J.K. Guest, J.H. Prévost, T. Belitschko, Int. J. Numer. Meth. Engng 2004

$$\rho^e = \frac{\sum_{j \epsilon S_e} \rho_j \omega(x_j - \overline{x}^e)}{\sum_{j \epsilon S_e} \omega(x_j - \overline{x}^e)}$$

$$\omega(x_j - \overline{x}^e) = \begin{cases} \frac{r_{min} - r}{r_{min}} & \text{if} \quad x \,\epsilon\, \Omega^e_\omega \\ 0 & \text{else} \end{cases}$$

$$x \,\epsilon\, \Omega^e_\omega \text{ if } r \equiv ||x - x^e|| \leq r_{min}$$

$$\rho^d_e = 1 - e^{-\beta \widetilde{\rho_e}} + \widetilde{\rho}_e e^{-\beta}$$



Rmin=1 it=790

Rmin=2 it=1000

Rmin=8 it=3000

Maximum width control:

- "A Penalty for Enforcing Maximum Length Scale Criterion in Topology Optimization ", J.K. Guest, J.H. Prévost, Mult. Anal. and Optimization Conference 2006
- " Imposing maximum length scale in topology optimization ", J.K. Guest, Struct Multidisc Optim 2009 37:463-473

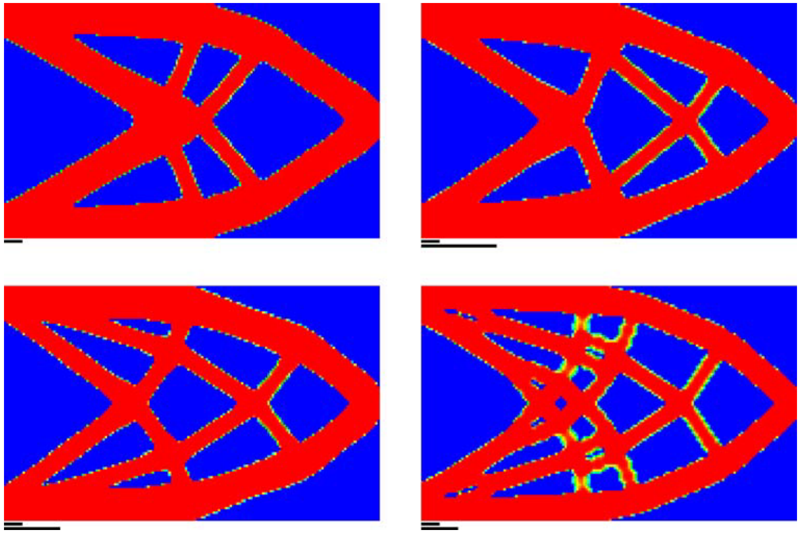
$$V_v^e(\rho^e) \geq V_{min}^e$$

$$V_v^e(\rho^e) = \sum_{i \epsilon R^e} v^i (1 - \rho^i + \rho_{min}^e)^\eta$$

$$V_{min}^e = \psi \sum_{i \epsilon R^e} v^i$$

$$S_{rx} = ((1 + cv_{min} - \alpha_1) * (1 - cv^e(\rho)))^{\alpha_2}$$

$$f_{obj} = Compliance + S_{rx}$$



Existing solutions

Surface state:

- " Manufacturing tolerant topology optimization », Ole Sigmund", Acta Mech Sin 2009
- " Robust topology optimization accounting for spatially varying manufacturing errors", M. Schevenels, B.S. Lazarov, O. Sigmund, Comput. Methods Appl. Mech. Engrg. 200 (2011)

Uniform under- and over-etching performed with morphology-based filter

Filter Radius :

$$N_e = \{i \,|\, ||x_i - x_e|| \leq R\}$$

Density Filtering:

$$\widetilde{\rho_e} = \frac{\sum_{i \epsilon N_e} \omega(x_i) v_i \rho_i}{\sum_{i \epsilon N_e} \omega(x_i) v_i}$$

Delate:

$$\rho_e^d = 1 - e^{-\beta \widetilde{\rho_e}} + \widetilde{\rho}_e e^{-\beta}$$

Erode:

$$\rho_e^e = e^{-\beta(1-\widetilde{\rho_e})} - (1 - \widetilde{\rho}_e) e^{-\beta}$$

Implementation of the uniform uncertainties by Sigmund

R=1

Dilate

Erode

$$\rho_e^d = 1 - e^{-\beta\widetilde{\rho_e}} + \widetilde{\rho}_e e^{-\beta}$$

$$\rho_e^e = e^{-\beta(1-\widetilde{\rho_e})} - (1 - \widetilde{\rho}_e)e^{-\beta}$$

Implementation of the uniform uncertainties by Sigmund

Rmin=2 it=465

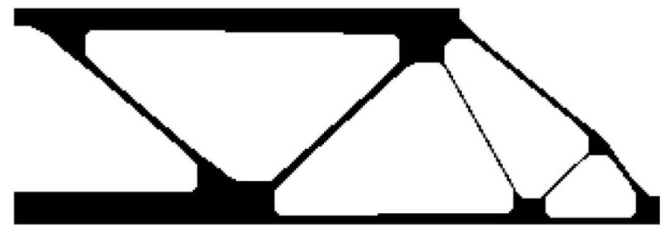
Normal

Erode

Dilate

Rmin=4 it=840

Normal



Erode

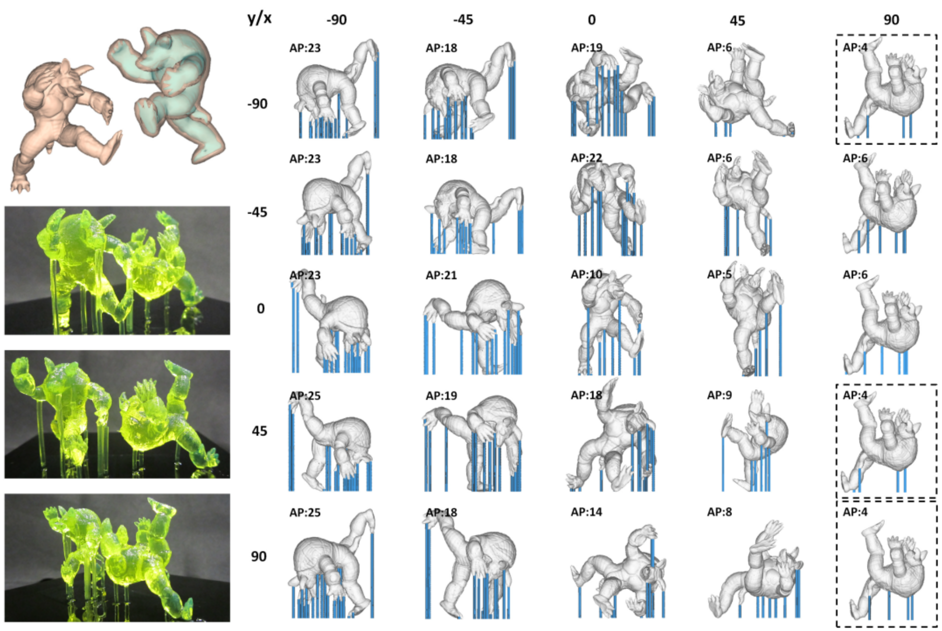
Dilate

Existing solutions

Part orientation and structure support:

- “Support slimming for single material based additive manufacturing”, K. Hu, S. Jin, C.C.L. Wang, Computer-Aided Design 65 (2015) 1-10

Propose a solution to form optimization issues with support structure and part orientation



Downsizing:

- Not suited for topology optimization
- Thermal issues not taken into account

Existing solutions

No closed cavities:

- "Morphology-based black and white filters for topology optimization", O. Sigmund, Struct Multidisc Optim (2007) 33:401-421

Interesting filtering method could solve metallic additive manufacturing constraints. Further investigation must be done in this direction

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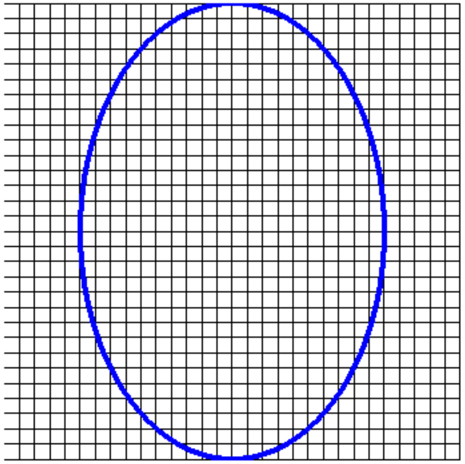
Variation of Rmin solution of Guest with ellipse function

$$\rho^e = \frac{\sum_{j\epsilon S_e} \rho_j \omega(x_j - \overline{x}^e)}{\sum_{j\epsilon S_e} \omega(x_j - \overline{x}^e)}$$

$$\omega(x_j - \overline{x}^e) = \begin{cases} 1 - ((\frac{|(x_{jx} - \overline{x}_{ex})|}{a})^2 + (\frac{|(x_{jy} - \overline{x}_{ey})|}{b})^2 & \text{if} \quad x \ \epsilon \ \Omega_\omega^e \\ 0 & \text{else} \end{cases}$$

Parameters a,b to change the geometry

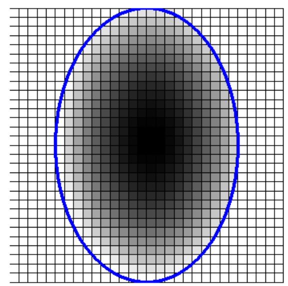


Test in Matlab code of topology optimization

Variation of Rmin solution of Guest with ellipse function

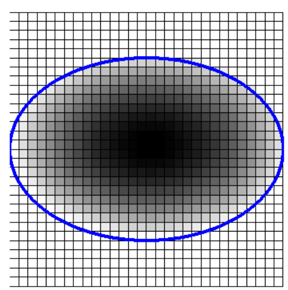
Rmin=2 it=1000

a=1 b=4



a=2 b=4

a=4 b=1



a=4 b=2

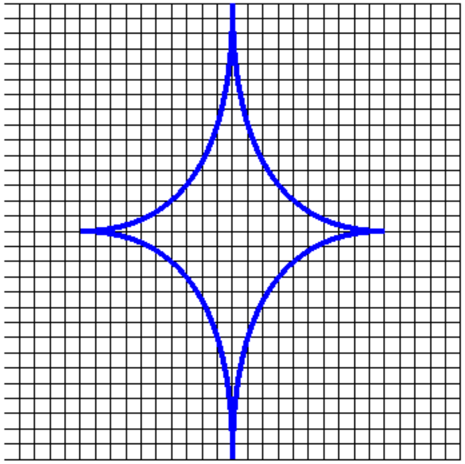
Test in Matlab code of topology optimization

Variation of Rmin solution of Guest with super-ellipse function

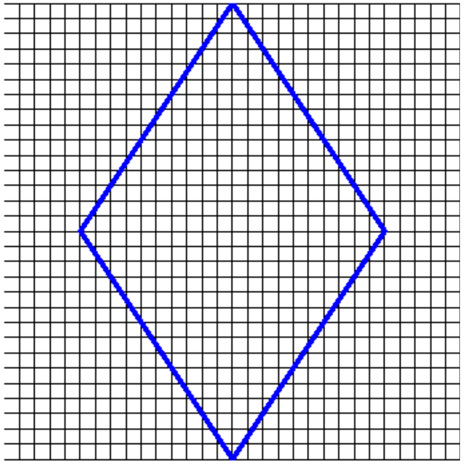
$$\rho^e = \frac{\sum_{j \epsilon S_e} \rho_j \omega(x_j - \overline{x}^e)}{\sum_{j \epsilon S_e} \omega(x_j - \overline{x}^e)}$$

$$\omega(x_j - \overline{x}^e) = \begin{cases} 1 - \left(\left(\frac{|(x_{jx} - \overline{x}_{ex})|}{a}\right)^n + \left(\frac{|(x_{jy} - \overline{x}_{ey})|}{b}\right)^m \right. & \text{if} \quad x \epsilon \Omega^e_\omega \\ 0 & \text{else} \end{cases}$$

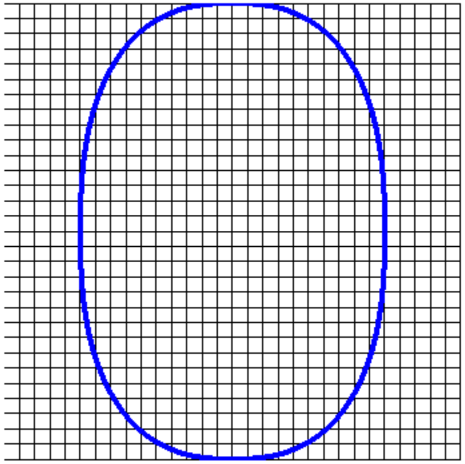
Parameters a,b,n,m to change the geometry



n=m=0.5



n=m=1



n=m=2.5

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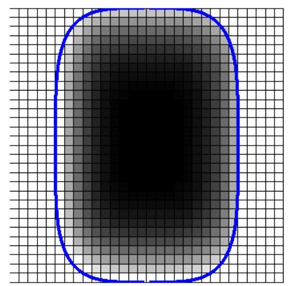
Test in Matlab code of topology optimization

Variation of Rmin solution of Guest with super-ellipse function

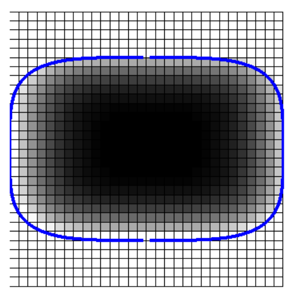
Rmin=2 it=1000

a=1,b=4,n=m=4



a=2,b=4,n=m=4

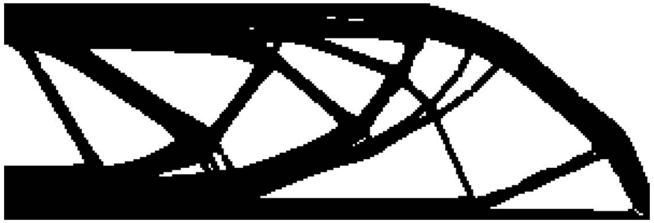
a=4,b=1,n=m=4



a=4,b=2,n=m=4

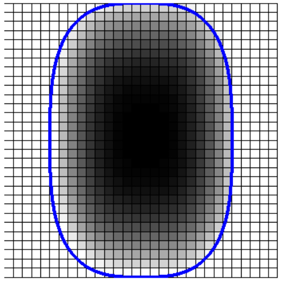
Test in Matlab code of topology optimization

Variation of Rmin solution of Guest with super-ellipse function



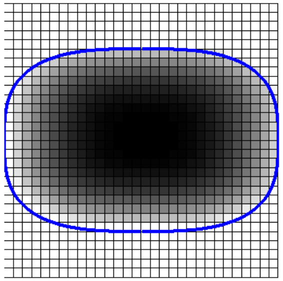
Rmin=2 it=1000

a=1,b=4,n=m=3



a=2,b=4,n=m=3

a=4,b=1,n=m=3



a=4,b=2,n=m=3

Perspectives and Conclusions

Perspectives and Conclusions

- Minimum width constraints ➔ Guest solution ✔
- Maximum width constraints ➔ Guest solution must be implemented ✔
- Overhanging angle ➔ Modified Guest ✔
- Surface state ➔ Dilate and erode solution of Sigmund but non uniform approach characterized to metallic additive manufacturing should be find and implemented ✔

Perspectives and Conclusions

Still lots of issues to be solved:

- Post machining of working surfaces and screw thread ✗
- Overhanging angle ✓ Improvement ✗
- Part orientation ✗
- Dimensions precision ✗
- Minimum size of canals (powder evacuation) ✗
- No closed cavities ✗
- Thermal constraints ✗
- Support structure needed and removed ✗
- Optimum member of thermal supports ✗

Although thanks to this work hints of solutions can be insight

Acknowledgements

I would like to acknowledge Xavier Cid and Bertrand Meunier for their work during their master thesis

Thank you for your attention

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Question ?