https://www.tripadvisor.fr/LocationPhotoDirectLink-g187529-d574612-i349532022-Museum_of_Natural_Science_Museo_de_Ciencias_Naturales-Valencia_Province_o.html

On some recent developments in topology optimization of aerostructures {***Stiffer, Lighter, Greener*** }

Prof. Joseph Morlier

3ME Seminar at TUD

INSTITUT CLÉMENT ADER

ISAE Institut Supérieur de l'Aéronautique et de l'Espace SUPAERO

Optimisation Promo Structures Fondation Gift 83 SUPAERO ISAE Class Aero Ecodesign Topologique

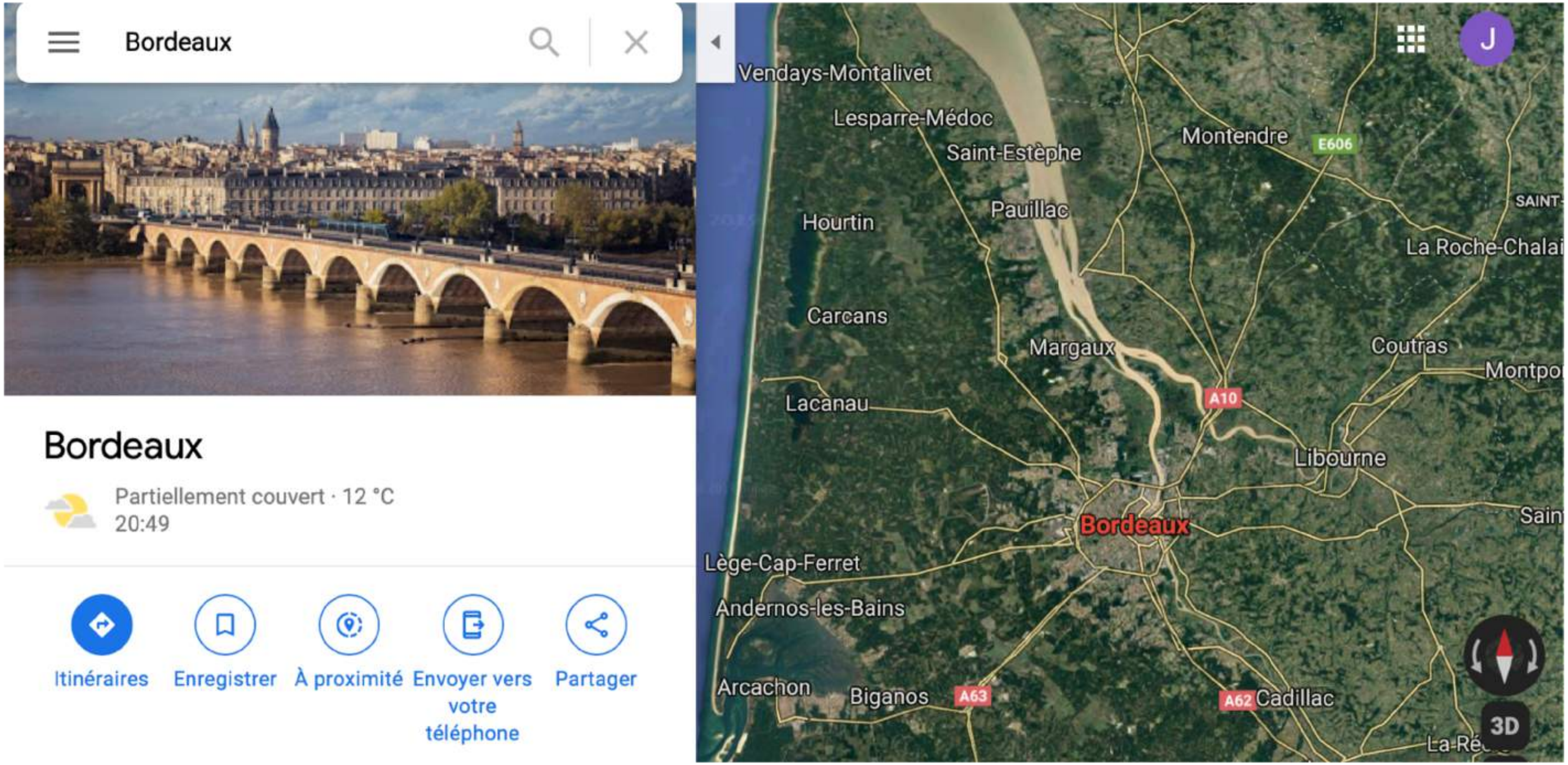
ÉCOLE POLYTECHNIQUE

IP PARIS

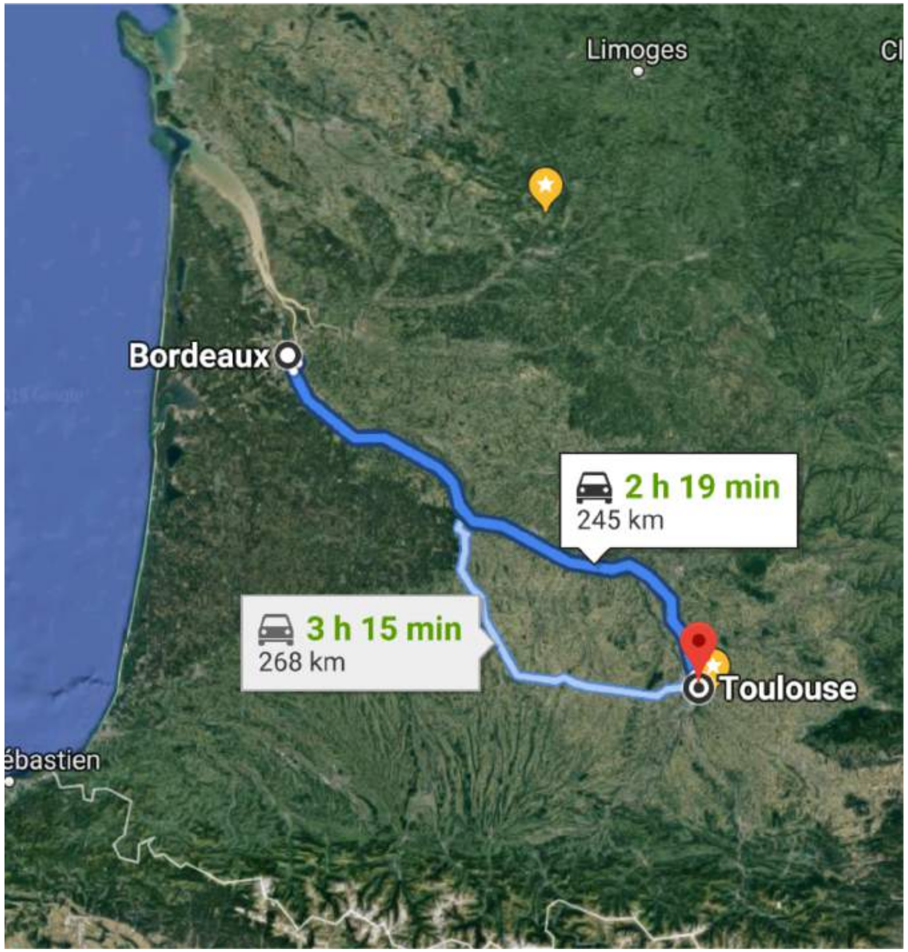
AGENCE NATIONALE DE LA RECHERCHE ANR

Fondation ISAE-SUPAERO Reconnue d'utilité publique

Who am I ?


Bordeaux
Bordeaux
Partiellement couvert · 12 °C
20:49
Itinéraires
Enregistrer
À proximité
Envoyer vers votre téléphone
Partager
Vendays-Montalivet
Lesparre-Médoc
Saint-Estèphe
Montendre
E606
Hourtin
Pauillac
La Roche-Chalai
Carcans
Margaux
Coutras
A10
Lacanau
Libourne
Bordeaux
Lège-Cap-Ferret
Andernos-les-Bains
Arcachon
Biganos
A63
A62
Cadillac
3D
J

PhD in Bordeaux then…
Toulouse



ISAE SUPAERO
Institut Supérieur de l'Aéronautique et de l'Espace

Key Figures at a Glance

1909

200
PhD students

30%
Foreign Students

60 M€
Budget

130
Professors & Researchers

1 700
Students on campus

> 130
Academic Agreements

650
students graduated a year

Thanks my Students:

Vilas Bhat, Edouard Duriez, Enrico Stragiotti, Simone Coniglio, Gabriele Capasso

Research Experiences

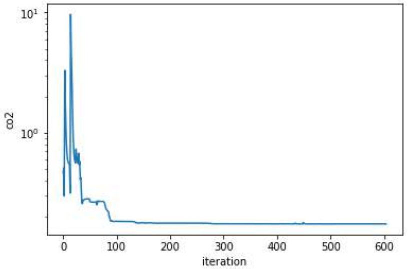
- PhD in Bordeaux SHM of civil engineering structures in 2005
- Ass. Prof in SUPAERO in 2006 SHM of composites structures
- Full Professor in Structural and Multidisciplinary Design Optimization since 2012

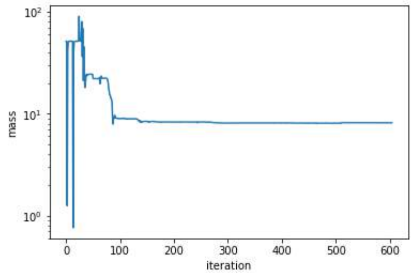
As a visiting Researcher

- in Beijing, Sino French lab on Applied Mathematics (summer 2006)
- In University of Michigan @MDOlab (summer 2017)
- **ANR Grant 2021** (French Science Foundation) →TUD in **May 2022** (and also to brainstorm regularly with **Kunal Masania since 1 year**)

?

CO_2 footprint





Vs Mass minimization

Popularization

https://www.linkedin.com/pulse/possible-build-aircraft-wing-lego-joseph-morlier/?articleId=6627240732975480832

https://www.tripadvisor.fr/LocationPhotoDirectLink-g187529-d574612-i349532022-Museum_of_Natural_Science_Museo_de_Ciencias_Naturales-Valencia_Province_o.html

Is it possible to build an aircraft wing in LEGO® ?

Publié le 17 février 2020 Modifier l'article | Voir les stats

joseph morlier
Professor in Structural and Multidisciplinary Design Optimization, ... any idea?

5 articles

Au programme

Duration	Description	Agenda
4’	Design Optimization	Stiffer
10’	GGP	Our 2016-2019 research
10’	Ecodesign	Lighter and Greener
2’	Conclusions	And future works?

Fondation ISAE - SUPAERO
Reconnue d’utilité publique

AGENCE NATIONALE DE LA RECHERCHE
ANR
PLAN D’ACTION 2021

CONSTRUCTION DE L’ESPACE EUROPEEN DE LA RECHERCHE ET ATTRACTIVITE INTERNATIONALE

Programme : « *Montage de Réseaux Scientifiques Européens ou Internationaux* »
- Edition 2021, Vague 1 -

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Au programme

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Design Optimization

On the road to design optimization

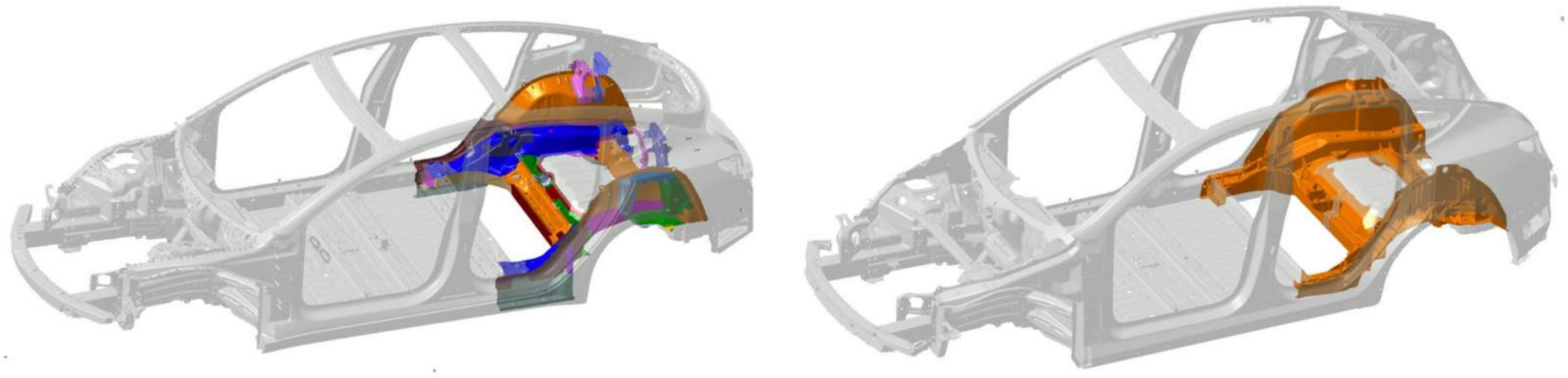
https://medium.com/daptablog/on-the-road-to-design-optimisation-a3c9867f29b6

- **optimization**
  noun [U] (UK usually **optimisation**)
  the act of making something as good as possible
  (Cambridge Dictionary)

Do Better with Less

- Design optimization is an engineering design methodology **using a mathematical formulation of a design problem** to support selection of the optimal design among many alternatives. (Wikipedia)

Think different!



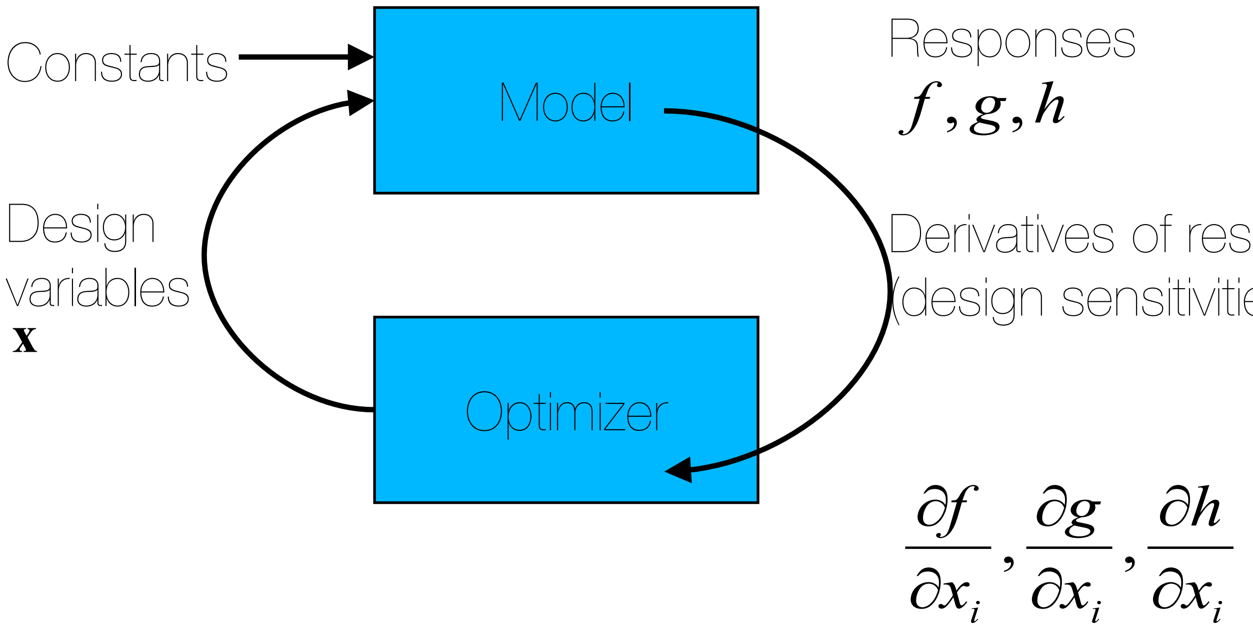
Model 3 rear underbody
70 pieces of metal

Model Y rear underbody
2 pieces of metal (eventually a single piece)

The use of 3D printing for sand casts such as that offered by voxeljet and ExOne for to enable the reduction of subassemblies (form 70 to 1) in a custom cast can bring about a significant transition even before metal AM can be used to produce such large metal parts directly. Producing a complex cast that can reduce the number of parts to this degree needs digital casting technology

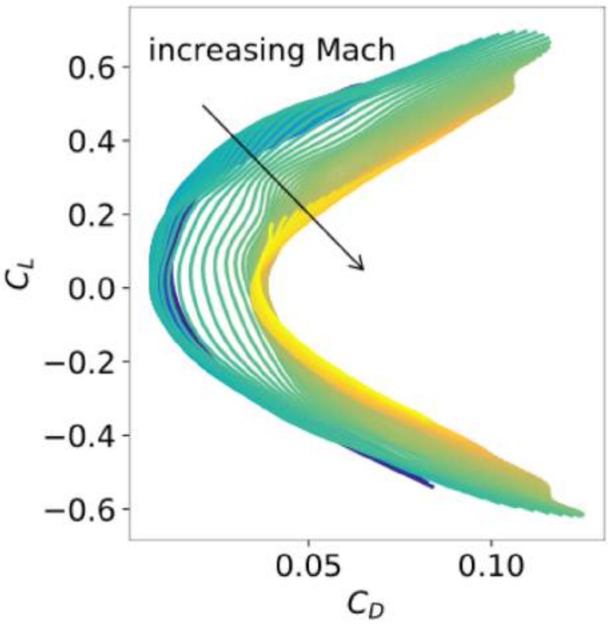
Gradient Based Optimization

- Costly if Finite Differences is used for sensitivities
- Difficult to implement Adjoint in industrial code
- Sensitive to discontinuity
- Sensitive to X_0

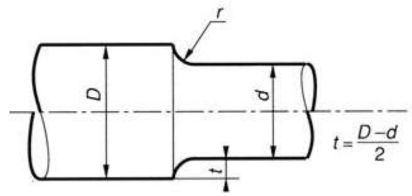


*SOL200 in MSC Nastran for example

Surrogate is the new abacus



Coefficient de concentration de contrainte : K_t .



Arbre épaulé en traction

$$\sigma_{nominale} = \frac{N}{S} \text{ d'où } \sigma_{maxi} = K_t . \sigma_{nominale}$$

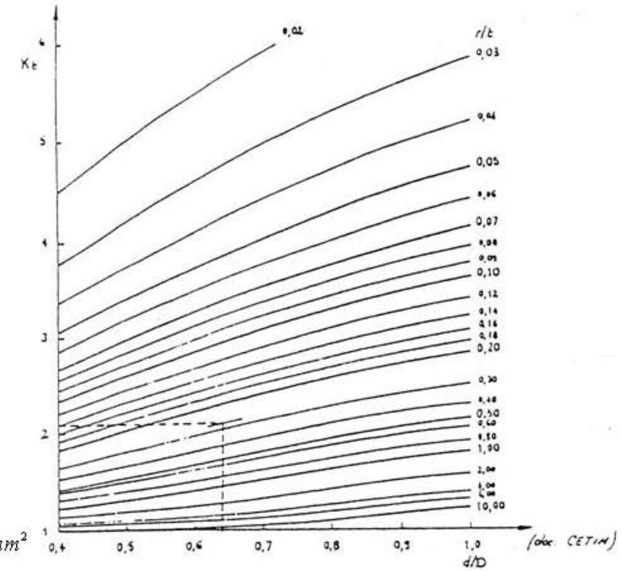
$$\text{Condition de résistance : } \sigma_{maxi} < R_{pe}$$

Exemple : D= 100, d=64, r=5
N = 5000 daN

$$\left.\begin{aligned} \frac{d}{D} &= \frac{64}{100} = 0,64 \\ \frac{r}{t} &= \frac{2.r}{D-d} = \frac{10}{100-64} = 0,278 \end{aligned}\right\} K_t = 2,1$$

$$\sigma_{nominale} = \frac{4 \times 5000}{\pi \times 64^2} = 1,55 \ daN/mm^2$$

$$\sigma_{maxi} = K_t \times \sigma_{nominale} = 2,1 \times 1,55 = 3,26 \ daN/mm^2$$



X_0

https://smt.readthedocs.io/en/latest

https://github.com/SMTorg/smt

SMT 0.8.0 documentation »

AEROSPACE ENGINEERING
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THE FRENCH AEROSPACE LAB

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Getting started

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SMT: Surrogate Modeling Toolbox

The surrogate modeling toolbox (SMT) is an open-source Python package consisting of libraries of surrogate modeling methods (e.g., radial basis functions, kriging), sampling methods, and benchmarking problems. SMT is designed to make it easy for developers to implement new surrogate models in a well-tested and well-document platform, and for users to have a library of surrogate modeling methods with which to use and compare methods.

The code is available open-source on GitHub.

Cite us

To cite SMT: M. A. Bouhlel and J. T. Hwang and N. Bartoli and R. Lafage and J. Morlier and J. R. R. A. Martins.

A Python surrogate modeling framework with derivatives. Advances in Engineering Software, 2019.

```
@article{SMT2019,
        Author = {Mohamed Amine Bouhlel and John T. Hwang and Nathalie Bartoli and Rémi Lafage
        Journal = {Advances in Engineering Software},
        Title = {A Python surrogate modeling framework with derivatives},
        pages = {102662},
        year = {2019},
        issn = {0965-9978},
        doi = {https://doi.org/10.1016/j.advengsoft.2019.03.005},
        Year = {2019}}
```

Focus on derivatives

SMT is meant to be a general library for surrogate modeling (also known as metamodeling, interpolation, and regression), but its distinguishing characteristic is its focus on derivatives, e.g., to be used for gradient-based optimization. A surrogate model can be represented mathematically as

$$y = f(\mathbf{x}, \mathbf{xt}, \mathbf{yt}),$$

Warning for this presentation

- Results restricted to 2D domain
- Tool / Results oriented instead of theory oriented*
- Lot of results limited to Compliance Optimization SAMO community testcases: L-Shape, MBB, we introduce also the Rib aerostructure

*May have a look to:

[1] Coniglio, S., Morlier, J., Gogu, C., & Amargier, R. (2019). Generalized Geometry Projection: A Unified Approach for Geometric Feature Based Topology Optimization. Archives of Computational Methods in Engineering, 1-38.

[2] Duriez, E., Morlier, J., Charlotte, M., & Azzaro-Pantel, C. (2021). A well connected, locally-oriented and efficient multi-scale topology optimization (EMTO) strategy. Structural and Multidisciplinary Optimization, 1-24.

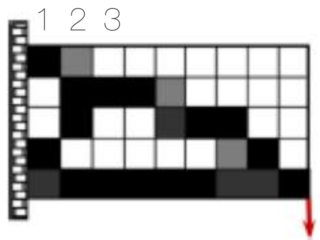
[3] Coniglio, S., Gogu, C., Amargier, R., & Morlier, J. (2019). Engine pylon topology optimization framework based on performance and stress criteria. *AIAA Journal*, *57*(12), 5514-5526.

[4] Bhat, K. V., Capasso, G., Coniglio, S., Morlier, J., & Gogu, C. (2022). On some applications of Generalized Geometric Projection to optimal 3D printing. Computers & Graphics, 199-212.

[5] Duriez, E., Morlier, J., Charlotte, M., & Azzaro-Pantel, C. (2022). Ecodesign with topology optimization. Procedia CIRP.

Intuitive Problem? Quadratic Form

$x_1 = 1$
$x_2 = 0.5$
$x_3 = 0$
$\dots$



- Objective function; Strain energy

$$\min c(\mathbf{x}) = \mathbf{U}^T\mathbf{F} = \mathbf{U}^T\mathbf{K}\mathbf{U}$$

with $x_e = \dfrac{\rho_e}{\rho_0}$ (4)

with $$\mathbf{K} = \mathbf{K}_0 \sum_{e=1}^{N} x_e^p$$ one can write:

$$\min c(\mathbf{x}) = \sum_{e=1}^{N} (x_e)^p \mathbf{u}_e^T \mathbf{k}_0 \mathbf{u}_e$$

Scalar

(5)

- Contraints: mass target

$$\frac{V(\mathbf{x})}{V_0} = f \overset{\cdot}{\underset{\cdot}{=}} const \Leftrightarrow \sum_{e=1}^{N} V_e x_e - V_0 f = 0 = h(\mathbf{x})$$

Scalar

$$0 < \rho_{\min} \le \rho_e \le 1$$

Pixels?

When the size of the FE model is increasing, the SIMP optimization problem is … increasing

Chris Columbus et al, Pixels, movie 2015

Au programme

Duration	Description	Agenda
4’	Design Optimization	Stiffer
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2’	Conclusions	And future works?

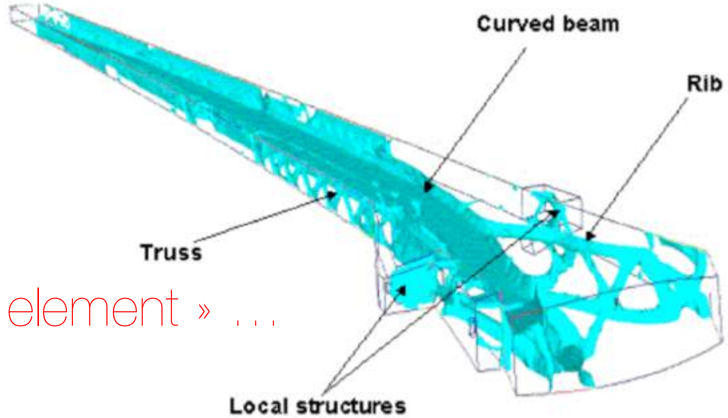
GGP

Reproducible Research

- https://www.topopt.mek.dtu.dk
- https://www.top3d.app

In 2016 I was searching to differentiate my TopOpt research

My idea was to use meshless method in TopOpt for « expolicit » structural elements, why?

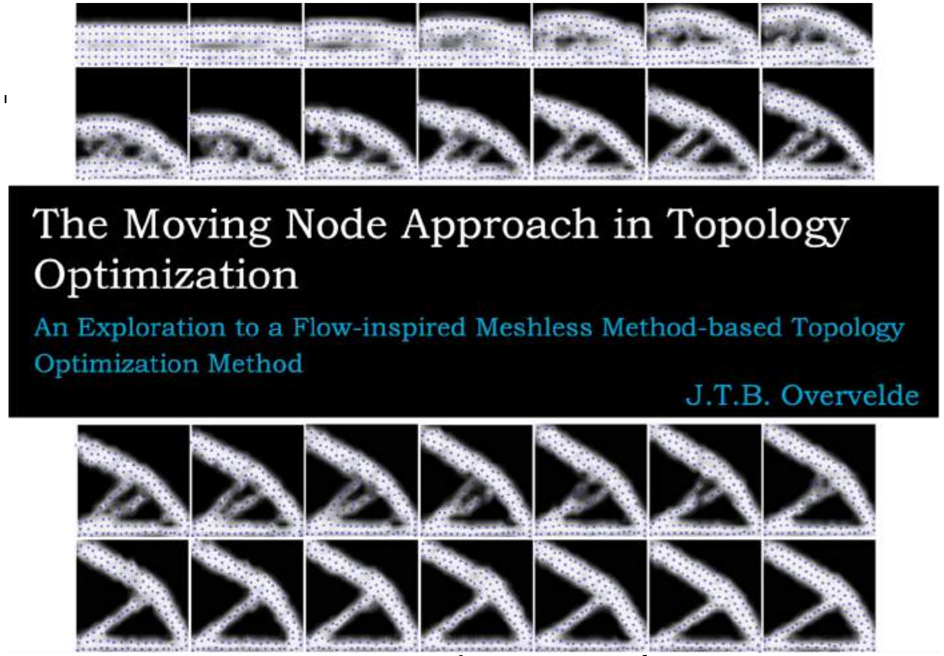


Industrial Results @ AIRBUS
see Grihon's works WSMO 2009, difficult to extract « structural element » …

But this kind of work already existed… in a TUD master thesis

Let's try to follow this paper's conclusions

- **Improve the algorithm**
  - **Convergence**
  - **Replace meshless methods with FEM**



Dr . ir . Matthijs Langelaar
Prof. dr. ir. Fred van Keulen

Johannes T. B. Overvelde

SUIVRE

Associate Professor, AMOLF & Eindhoven University of Technology
Adresse e-mail validée de amolf.nl - Page d'accueil
Soft Matter Mechanical Metamaterials Soft Robotics Computational Engineering Optimization

So we started with a SUPAERO MsC student

CSMA 2017
13ème Colloque National en Calcul des Structures
15-19 Mai 2017, Presqu'île de Giens (Var)

Optimisation topologique sans maillage
Vers la reconnaissance d'éléments structuraux

G. Raze[1], M. Charlotte [2], J. Morlier[2]

[1] *Université de Toulouse, ISAE SUPAERO, 10 avenue Edouard Belin, 31405 Toulouse, France*
[2] *Institut Clément Ader (ICA), Université de Toulouse, ISAE SUPAERO-CNRS-INSA-Mines Albi-UPS, Toulouse, France*

Résumé — Cet article présente des résultats d'une étude d'optimisation topologique utilisant une nouvelle approche par ajout de variables de localisation des nœuds. Dans cette approche, la discrétisation spatiale est découplée de la distribution matérielle. Les effets de la méthode de discrétisation, de l'optimiseur et de la fraction de volume sont étudiés. Les résultats de l'approche par ajout de variables de localisation des nœuds sont prometteurs et suggèrent que cette approche pourrait constituer une alternative aux méthodes actuellement utilisées en optimisation topologique.

Mots clés — Mécanique des structures ; Optimisation topologique ; Compliance minimale ; Méthodes sans maillage ; Approche par ajout de variables de localisation des nœuds ; Méthode des éléments finis

check some possible improvements of the method.

Ghislain Raze

PhD Student, University of Liège
Adresse e-mail validée de uliege.be

SUIVRE

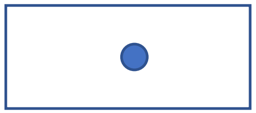
TITRE	CITÉE PAR	ANNÉE
A digital nonlinear piezoelectric tuned vibration absorber G Raze, A Jadoul, S Guichaux, V Broun, G Kerschen Smart Materials and Structures 29 (1), 015007	14	2019
Active tuned inerter-damper for smart structures and its $\mathcal{H}_\infty$ optimisation G Zhao, G Raze, A Paknejad, A Deraemaeker, G Kerschen, C Collette Mechanical Systems and Signal Processing 129, 470-478	12	2019

Moving Node Approach (MNA)
5 variables per node

Structural Members: Beam is the primitive chosen here

Optimization variables :

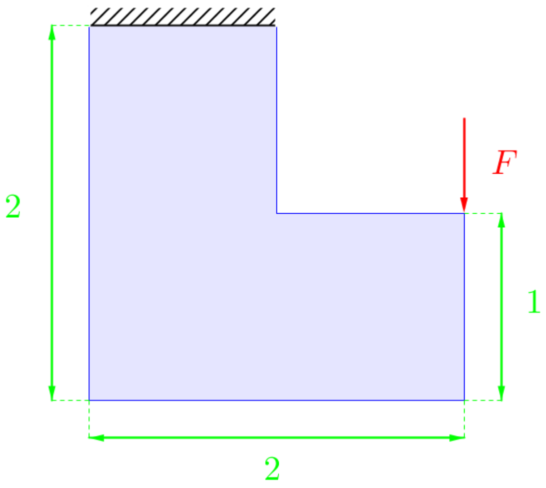
- Positions (x,y)
- Orientation (θ)
- Dimensions (Lx,Ly)

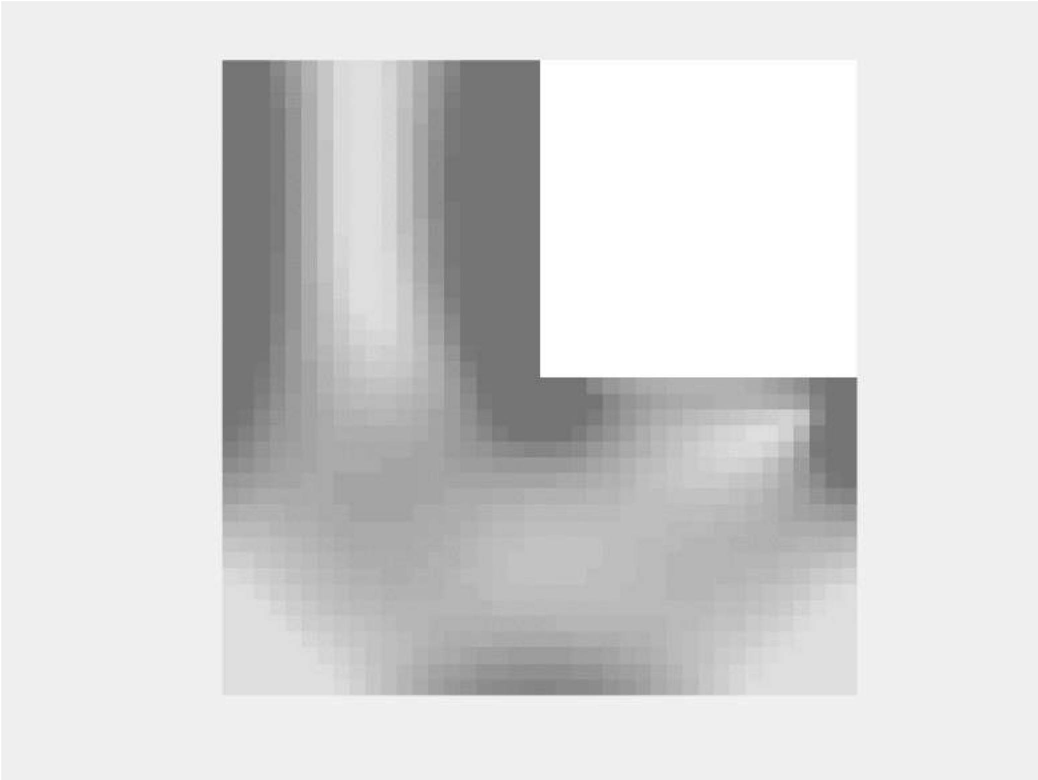


```
disp('SIMP')
top88(nelx,nely,volfrac,3,2,1)

disp('MNA')
topmna(x0,nelx,nely,volfrac,3,[ratio;aspect],tolchange);
```

Results SIMP nelx=nely=40→ 1600 design variables minC wrt Volfrac=0.25 , Ku=f



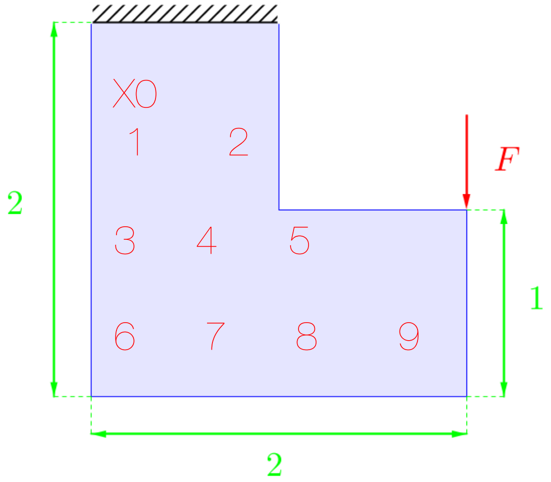


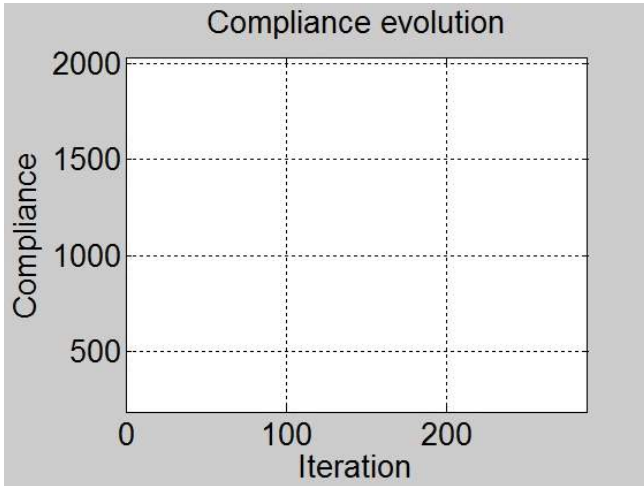
Andreassen, E., Clausen, A., Schevenels, M., Lazarov, B. S., & Sigmund, O. (2011). Efficient topology optimization in MATLAB using 88 lines of code. Structural and Multidisciplinary Optimization, 43(1), 1-16.

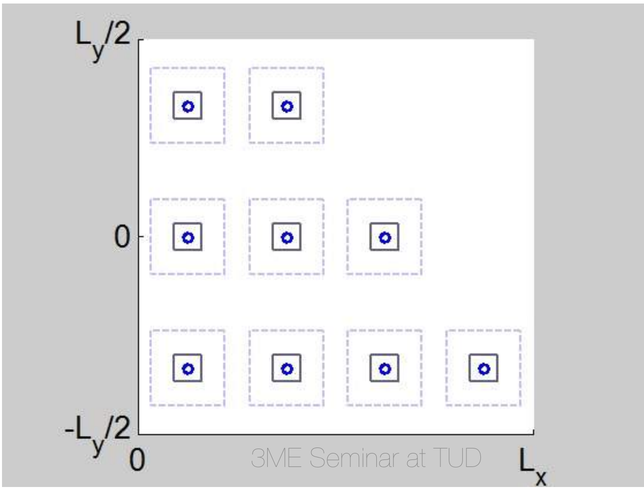
http://www.topopt.mek.dtu.dk

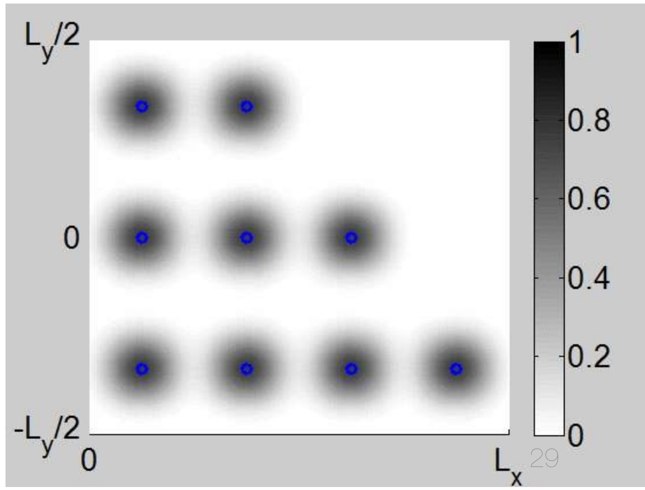
Results MNA, 9*5=45 design variables minC wrt Volfrac=0.25 , Ku=f

At the end, explicit assembly of beams i.e. Structural Layout
But sensitivity to X_0/mesh









Raze, G., & Morlier, J. (2021). Explicit topology optimization through moving node approach: beam elements recognition. arXiv preprint arXiv:2103.08347..

Then S. Coniglio 'PhD tries to unify existing methods

Design variables update

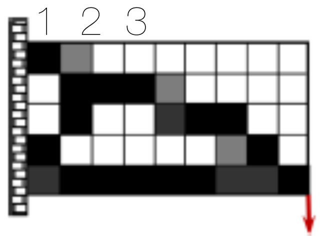
Interpretation

Model update
Density, Young modulus

Density based

variables : material density

$$x_1 = 1$$
$$x_2 = 0.5$$
$$x_3 = 0$$
$$\ldots$$

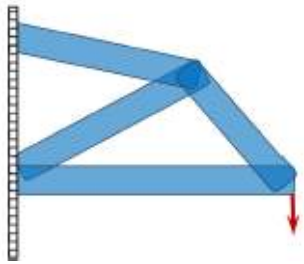


Innovative approach to help engineering solution identification : Components are placed in design space according to variables and material density are derived accordingly.

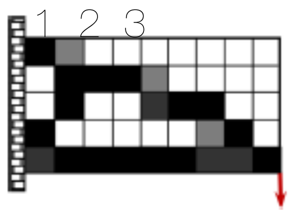
Lagrangian approaches

Variables : geometrical data

$$x_1 = Position$$
$$x_2 = Length, Height \ldots$$



Projection

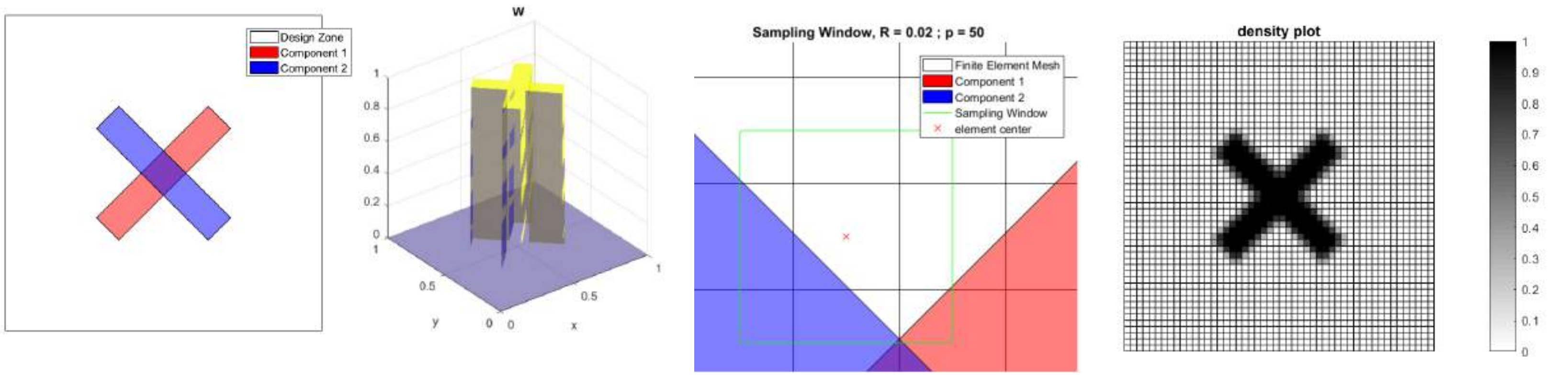


[12] Zhang, Weisheng, Jian Zhang, and Xu Guo. "Lagrangian description based topology optimization—a revival of shape optimization." Journal of Applied Mechanics 83.4 (2016): 041010.

Design is made of engineering bricks like: beam, plate, brick….

Generalized Geometric Projection

Geometric features → Characteristic functions → Generalized Geometric Projection → Fixed mesh model update



[Coniglio et al. 2019]

$$\mathbf{D}(\{X_g\}, \boxed{p, R}) = \{\{X\} \in \mathbb{R}^{d_g} \mid \| \{X\} - \{X_g\} \|_{2p} \leq R\}$$

$$\delta_i^{el}(\boxed{W_i}, p, R) = \frac{\int_{\mathbf{D}(\{X_g^{el}\}, p, R)} W_i(\{X\}, \{X_i\}, \{r\}) d\Omega}{\int_{\mathbf{D}(\{X_g^{el}\}, p, R)} d\Omega}$$

$$E^{el} = \boxed{\mathbb{M}}(\{\delta^{el}\}_c, E, E_{min}, \kappa)$$

$$\rho^{el} = \boxed{\mathbb{V}}(\{\delta^{el}\}_v, \kappa)$$

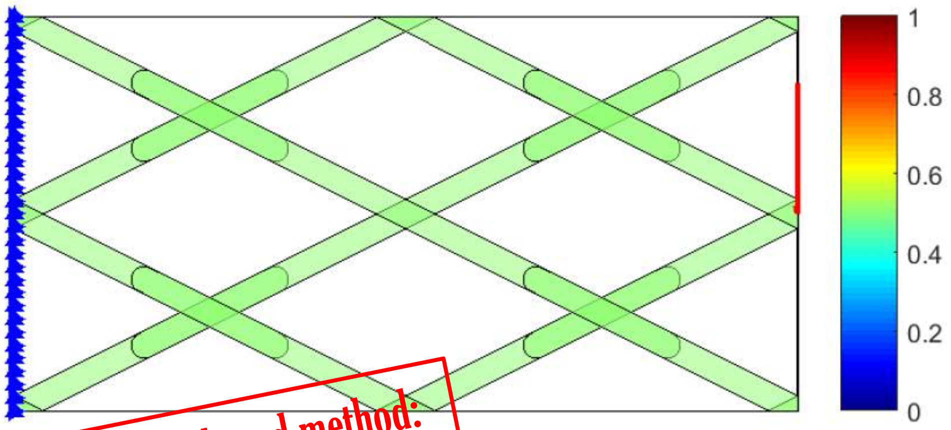
Generalized **G**eometry **P**rojection (GGP)

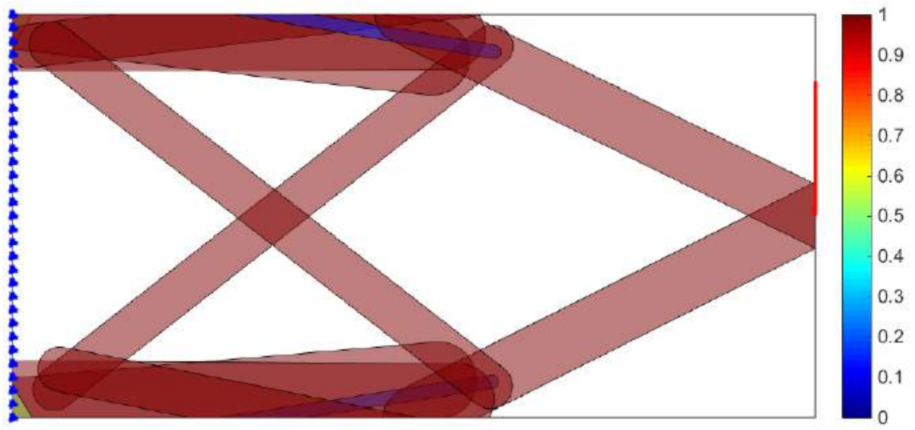
Table 1: Choice to be made to recover all other approaches using Generalized Geometric Projection

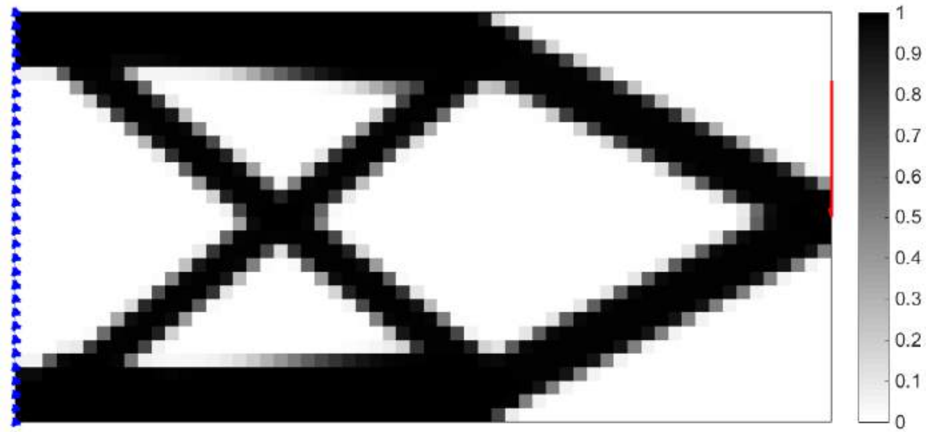
Method	MMC	GP	MNA
W^c	$H_\epsilon(\chi^{el})^q$	$\tilde{\delta}_i^{el} m_i^{\gamma_c}$	$m_i^{\gamma_c} w_i^{el}$
W^v	$H_\epsilon(\chi^{el})$	$\tilde{\delta}_i^{el} m_i^{\gamma_v}$	$m_i^{\gamma_v} w_i^{el}$
p	∞	∞	∞
R	$\frac{\sqrt{3}}{2}dx$	$\frac{1}{2}dx$	$\frac{1}{2}dx$
N_{GP}	4	1	1
$\mathbb{V}$	$\frac{\sum_{j=1}^{4} H_\epsilon(\chi_j^{el})}{4}$	$\Pi(\left\{\hat{\delta}^{el}\right\}_v, \kappa)$	$\Pi(\{\delta^{el}\}_v, \kappa)$
$\mathbb{M}$	$\frac{\sum_{j=1}^{4}(H_\epsilon(\chi_j^{el}))^q}{4}$	$\Pi(\left\{\hat{\delta}^{el}\right\}_c, \kappa)E$	$E_{min} + (E - E_{min})\Pi(\{\delta^{el}\}_c, \kappa)^{p_b}$

- All reviewed approach can be represented as a special case of Generalized Geometry Projection
- One can moreover change sampling window size (R),shape (p), Gauss Points number (N_{GP})
- Changing the number of Gauss point one can avoid optimization saddle points induced by the projection

Generalized **G**eometry **P**rojection (GGP)





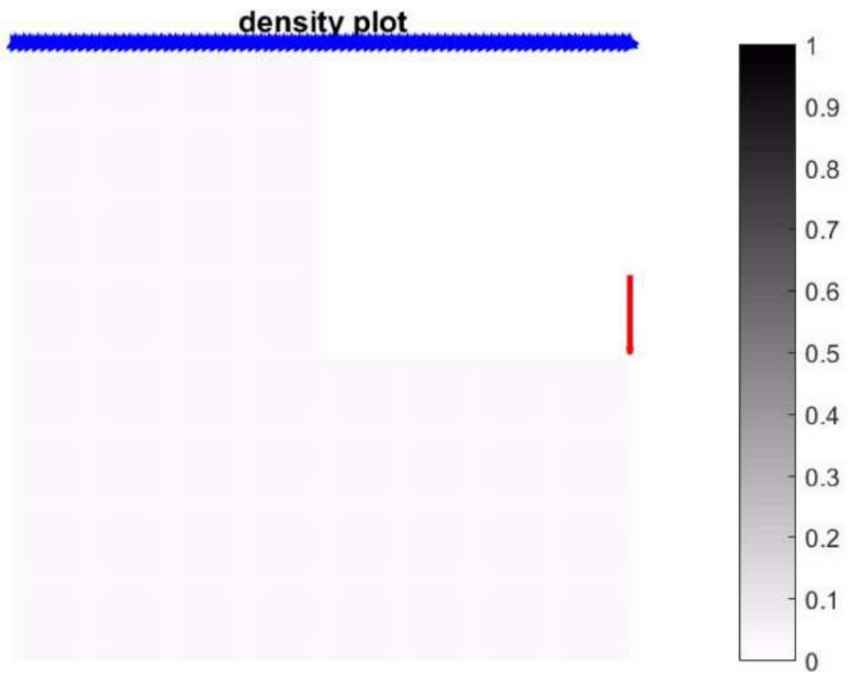


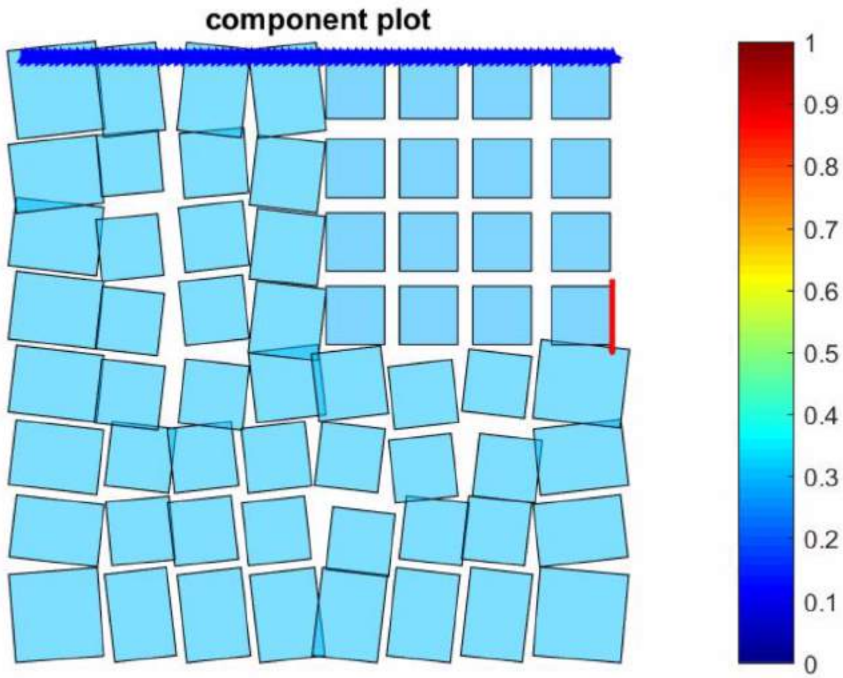
For every Gradient based method:
X0 sensitivity

$$\begin{cases} \min_{\{x\}} C = \{U\}^T\{F\} \\ s.t. \\ V = \dfrac{\sum_{el=1}^{N} \rho^{el}}{N} \leq V_0 \\ \{l_b\} \leq \{x\} \leq \{u_b\} \end{cases}$$

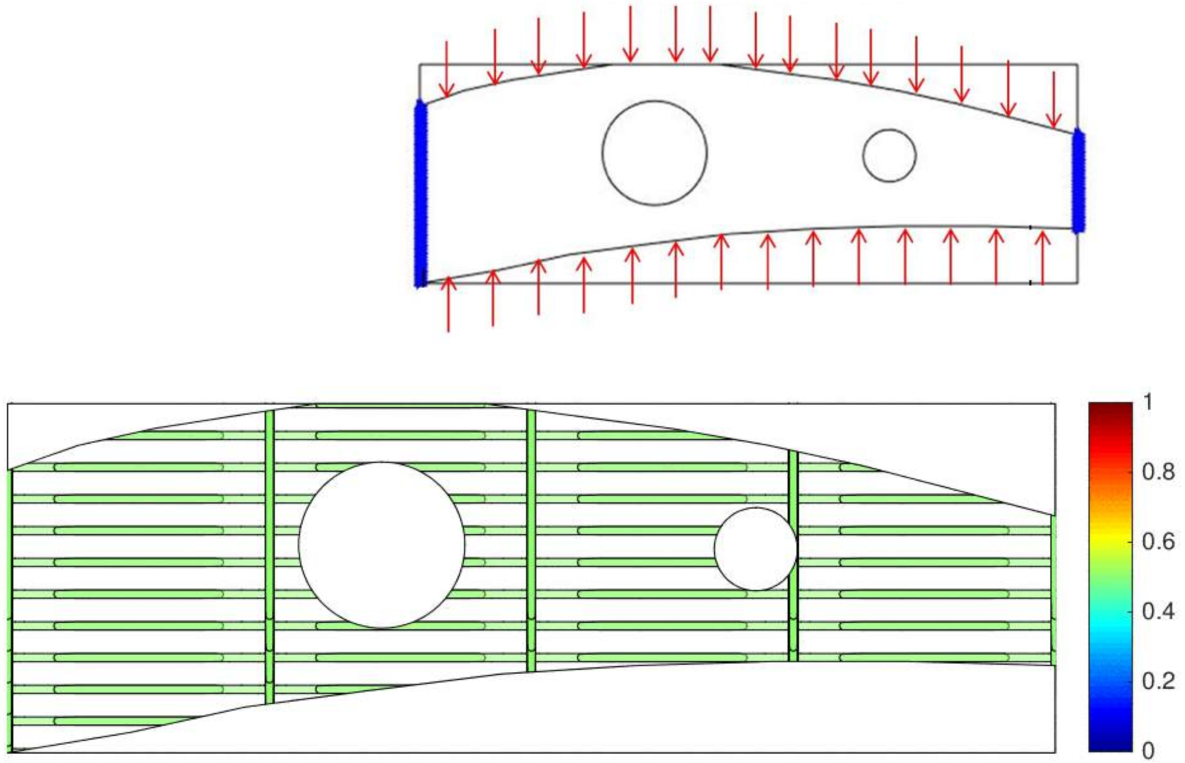
Results MNA, 8*8*6=384 design variables minC st Volfrac=0,4

At the end, explicit assembly of components!





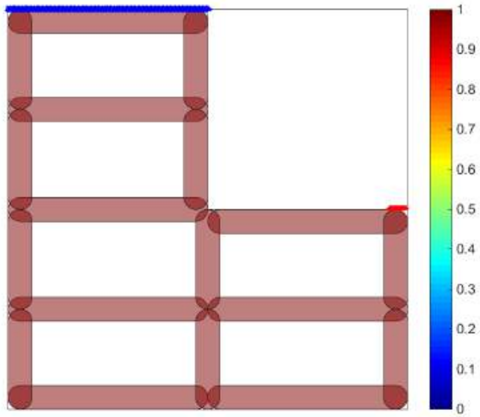
A typical Aerostructures, a « GGP » simple **design**

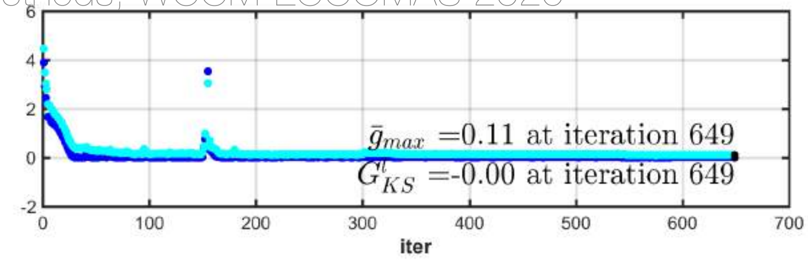


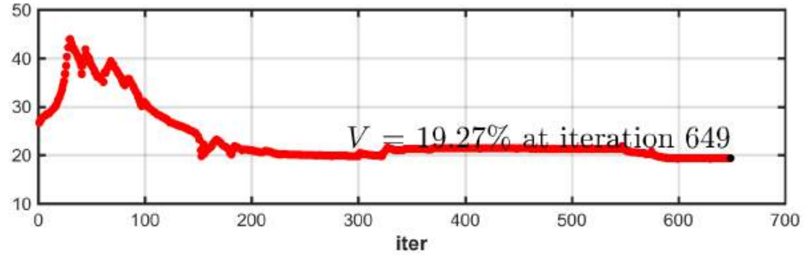
https://github.com/topggp/blog

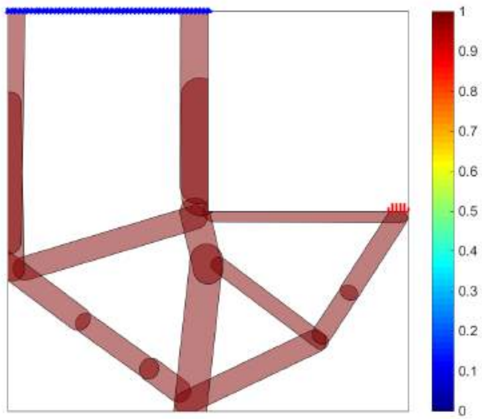
Stress based GGP…

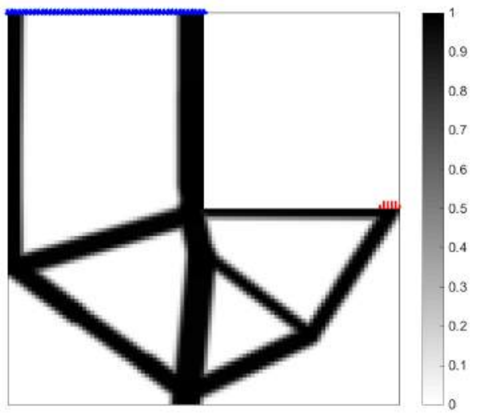
S. Coniglio, J. Morlier, C. Gogu, An introduction to Generalized Geometry Projection, a unified framework for feature-based topology optimization methods, WCCM-ECCOMAS 2020

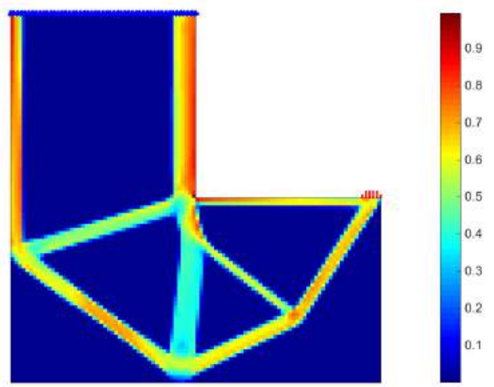




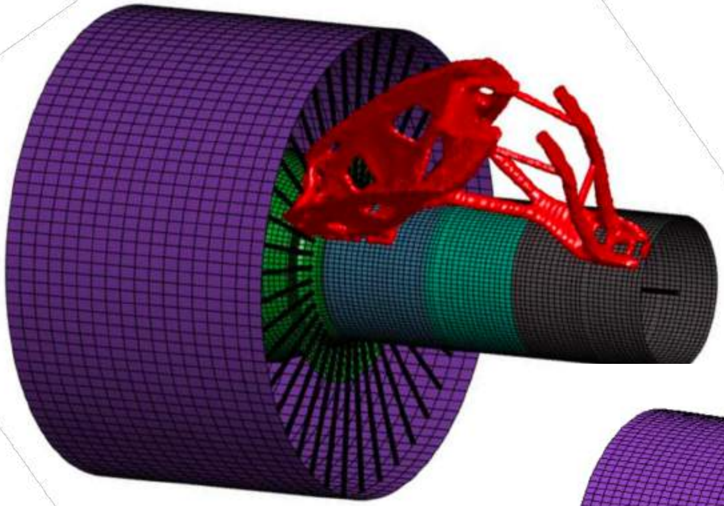






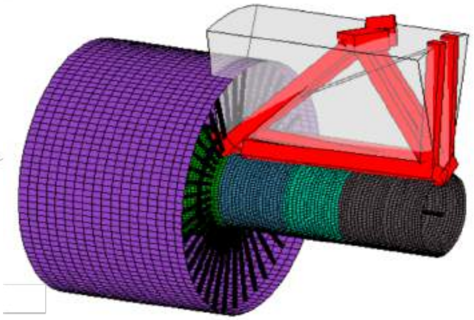


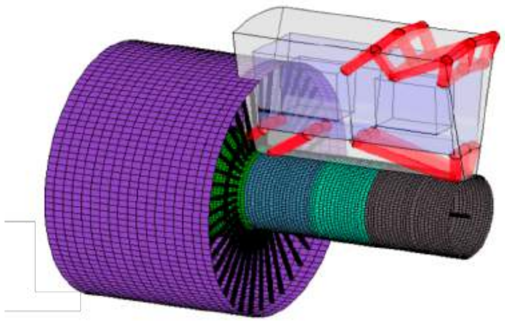
Bionic SIMP vs EXPLICIT TRUSS vs EXPLICIT BOX



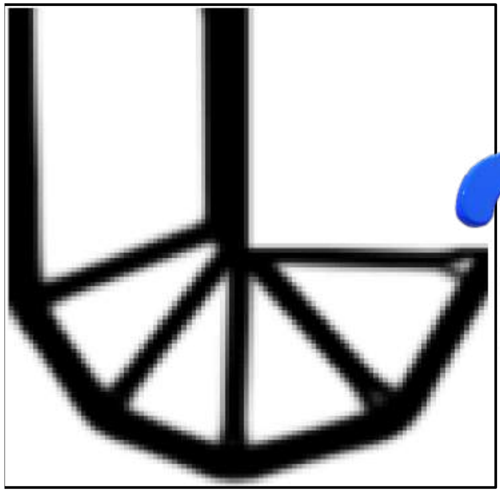
RESULTS OF SIMONE CONIGLIO PHD

TSFC + STRESS
ABAQUS REANALYSE

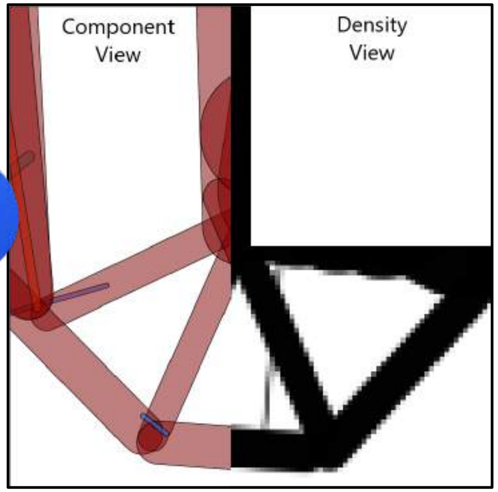




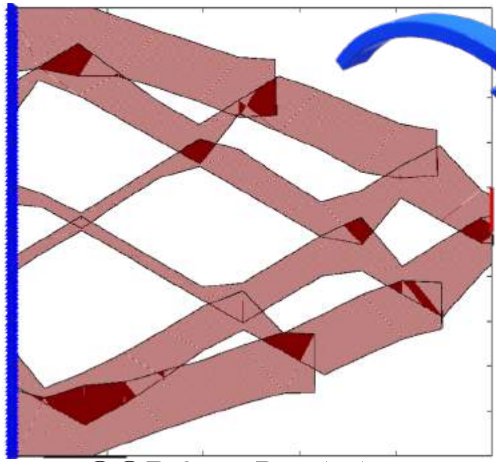
GGP For ALM?



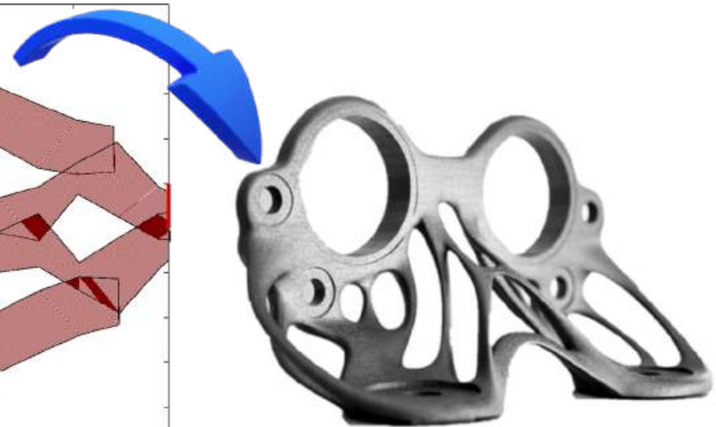
SIMP



GGP



GGP for 3D printing

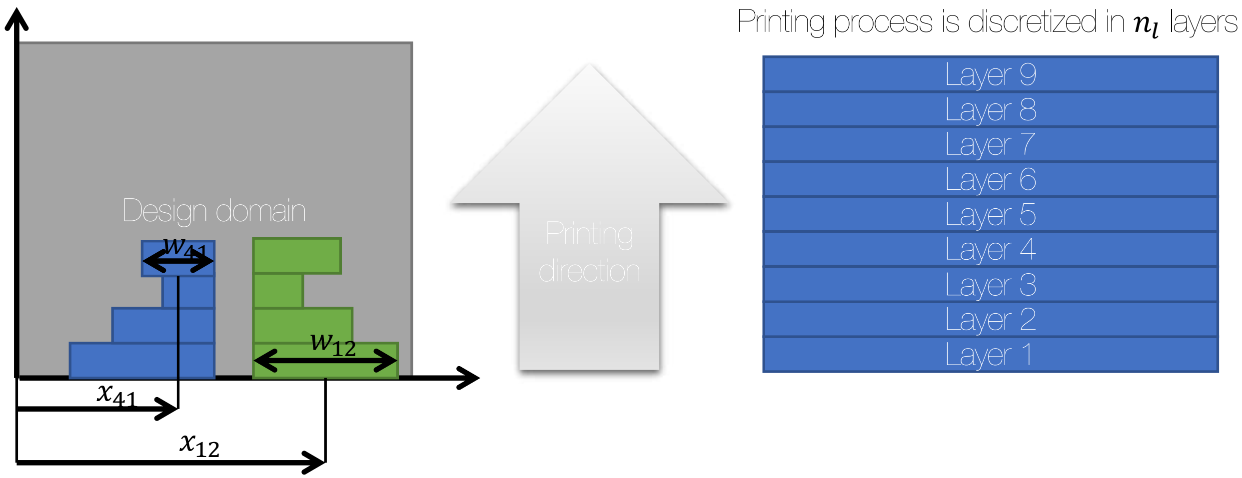


3D Printed part

First explicit topopt for overhang angle (CSMA 2017)

A solution is determined by its manufacturing process: (in this case printing path)

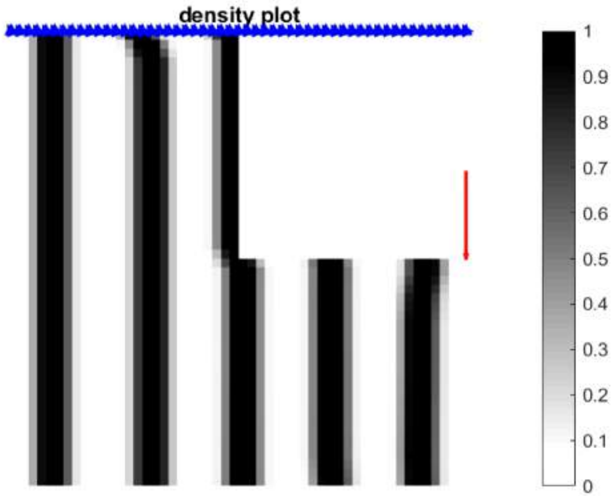
Printing process is discretized in n_l layers

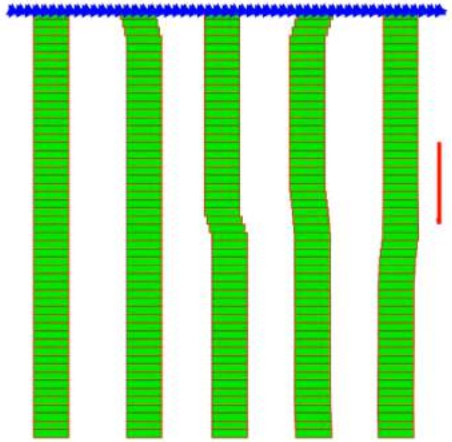


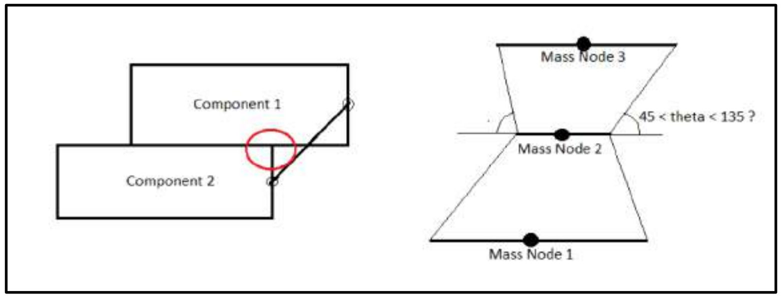
- MNA Components are replaced by printed branches
- Design variables will be printed branch position and width per layer: x_{li}, w_{li}
- For each layer a projection is made to get the solid model modulus

Results

$$\begin{cases} \min_X c = F^T \cdot U \\ s.t. \\ \sum_{i=1}^{N} \rho_i - v_f N \leq 0 \\ \theta_l \leq \theta \quad \leq \pi - \theta_l \end{cases}$$







$N_x = N_y = 52$
$v_f = 0.4$
$5\ printing\ components$
$18\ printing\ intervals$
$5 \times 18 \times 2\ design\ variables$

Comparison with ALM Filter

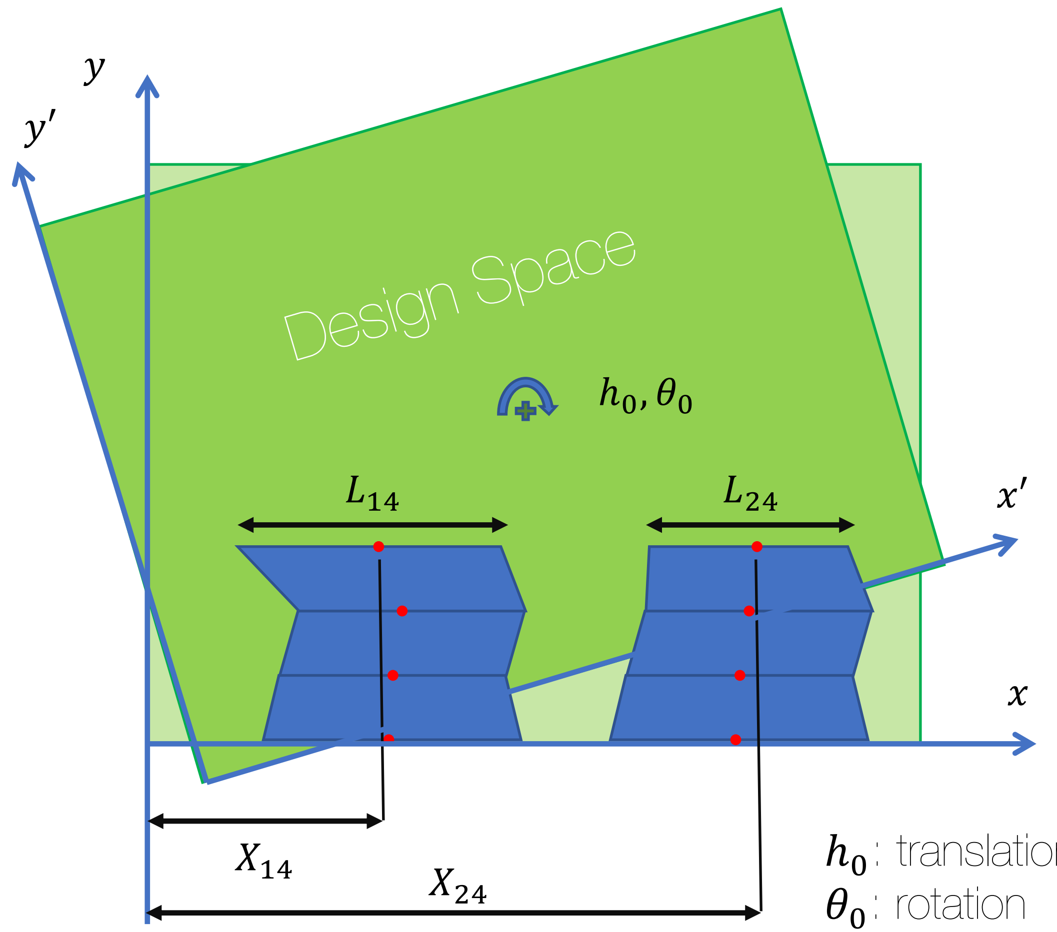
given in SAMO's paper

Problem	Method	Volume Fraction	
		0.25	0.5
Short Cantilever	1D MNA + ALM	60.62	16.86
	SIMP + ALM Filter	69.73	17.09
L – Shaped Cantilever	1D MNA + ALM	179.21	70.07
	SIMP + ALM Filter	204.98	74.42

Then new work in 2019 Adding More ALM constraints: Now clearly more references are available

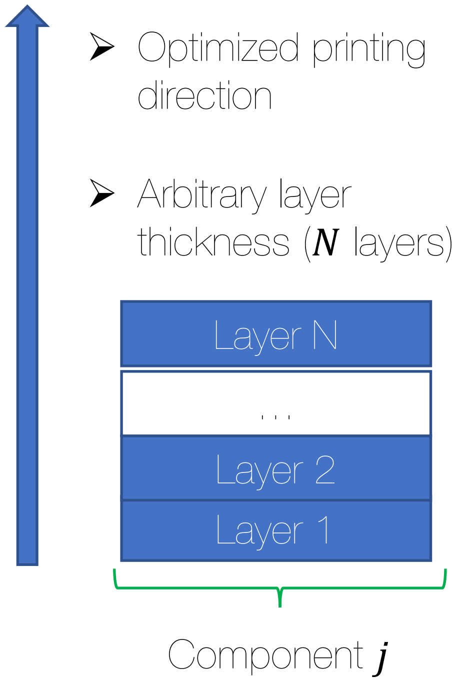
	Check on	Overhang angle	Bridge length	Optimal printing plane	Comment
SIMP [Leary et al. 2014]	Boundaries	Yes	No	No	Additional iterations
AM Filter (SIMP-based) [Langelaar 2015]	Densities	Yes	No	No	One constraint per **element**
Level-set [Allaire et al. 2017]	Boundaries	Yes	Yes	No	Implicit constraints
MMV [Guo et al. 2017]	Boundaries	Yes	No	No	
MMC [Xian et al. 2019]	Components angles	Yes	No	Yes	Difficult quality **check**

ALM based GGP



h_0: translation
θ_0: rotation

- Optimized printing direction
- Arbitrary layer thickness ($\boldsymbol{N}$ layers)



Problem Statement

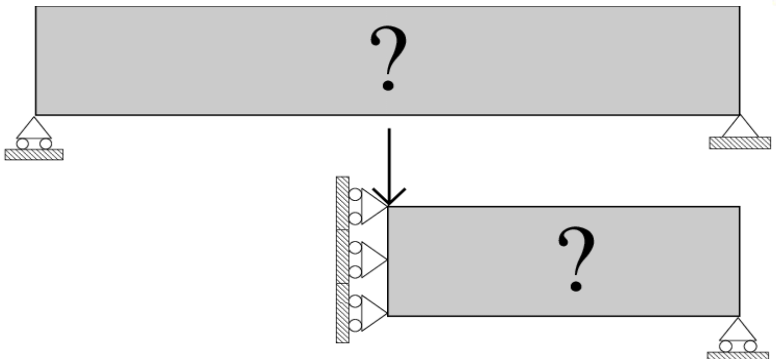
$$
\begin{cases}
min & & C(X, U_f) \\
s.t.: & & V \leq V_0 \\
& \theta_{ij} \leq \theta_{max} & \forall\, i = 1, \dots, N \quad j = 1, \dots, M \\
& BL_{ij} \leq BL_{max} & \forall\, i = 1, \dots, N \quad j = 1, \dots, M
\end{cases}
$$

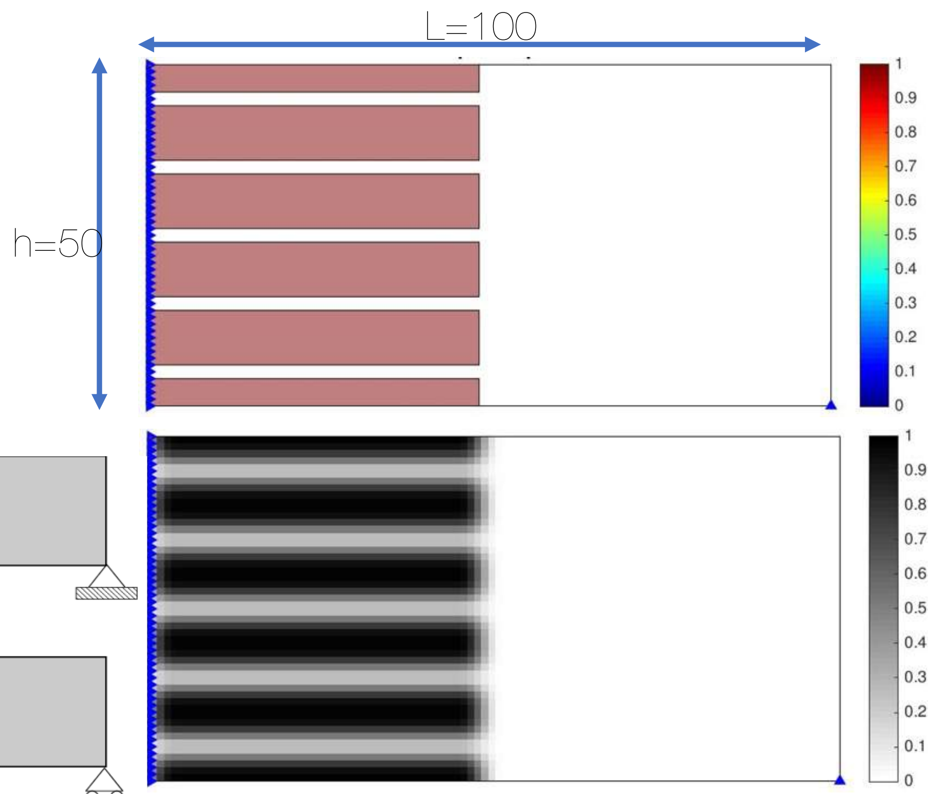
- N layers per component
- N+1 segments per component
- M components
- 2 features per segment (X_k, L_k)
- 2 features per component (h_j, m_j)
- 2 global features (h_0, θ_0)

→ $2M(N+2)+2$ design variables

MBB Results: convergence

Parameter	Quantity
Mesh	50×100
V_0	0.3
θ_{max}	45°
$BL_{max}/2$	25
N (layers)	18
M (components)	6
Design variables	242





MBB Results: convergence

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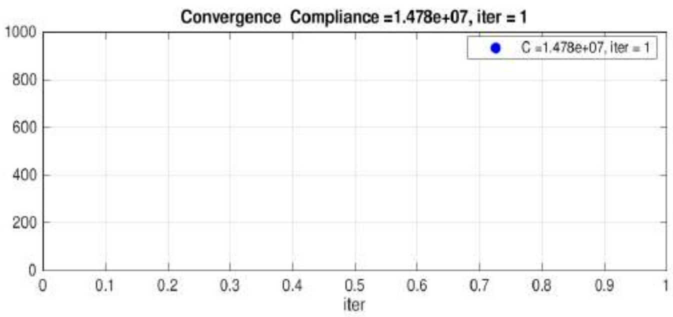
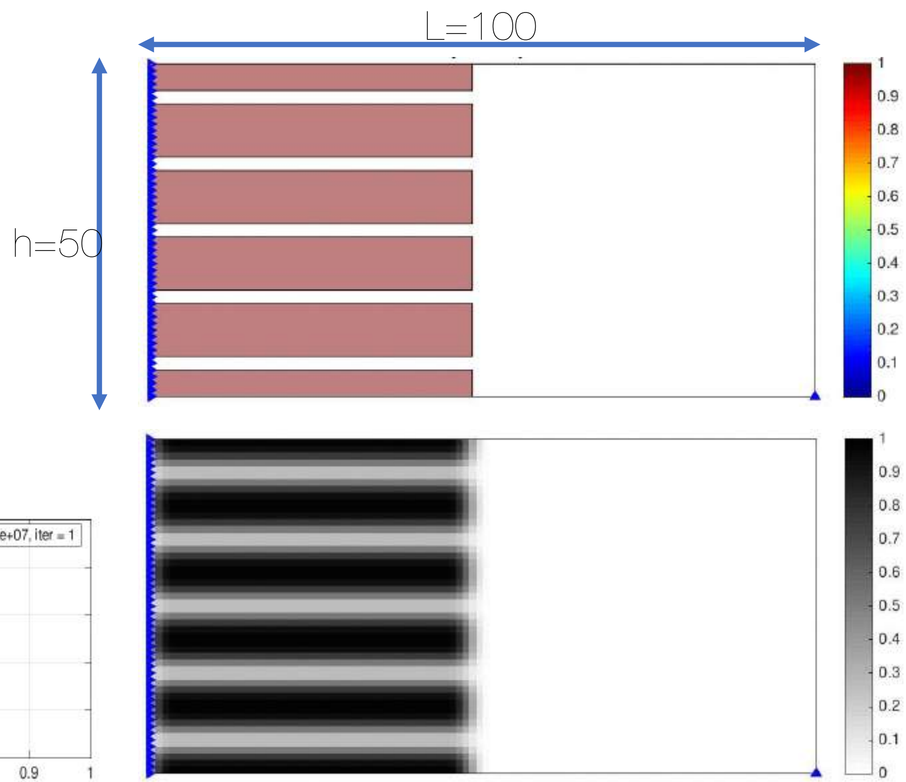
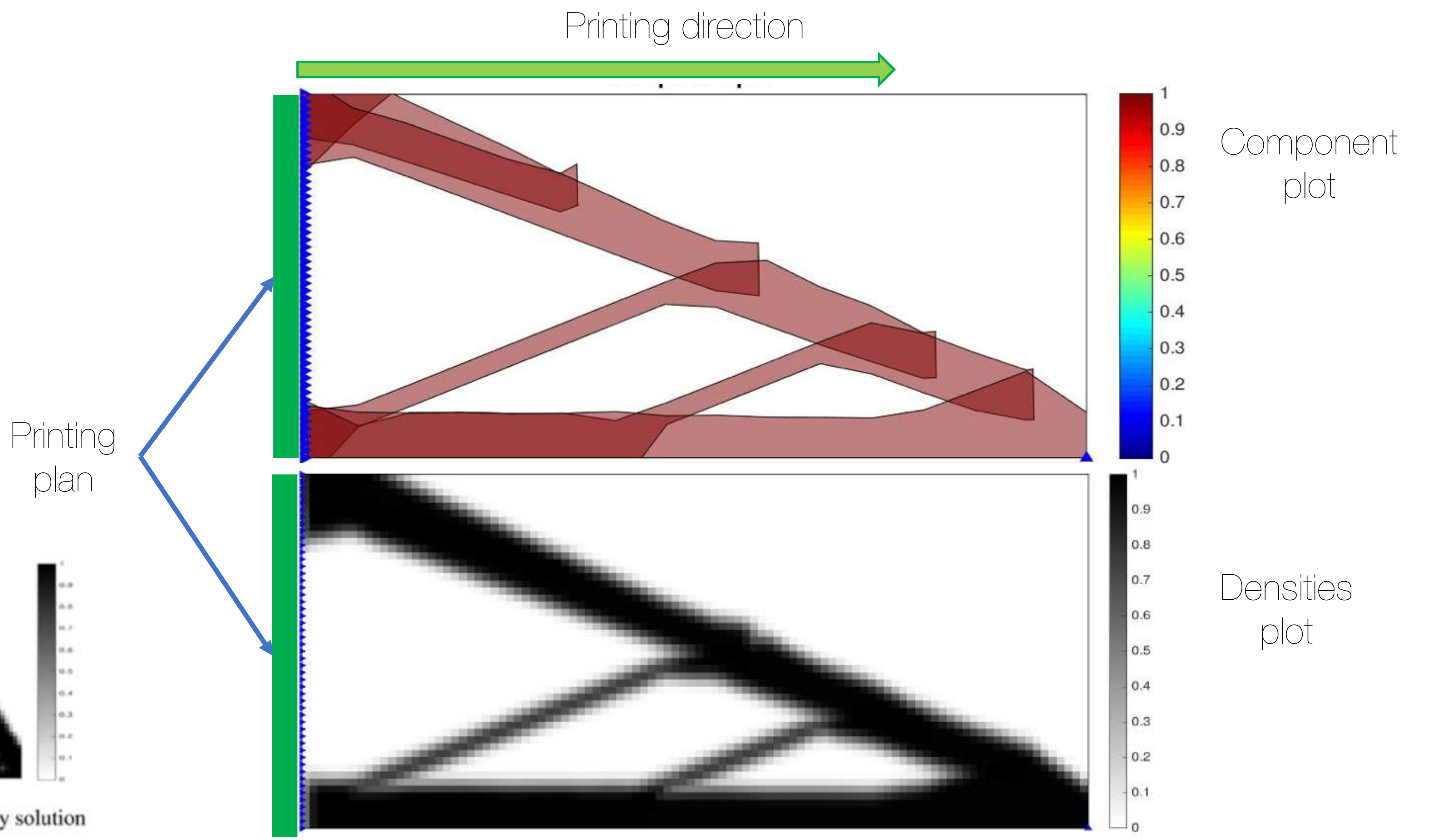




MBB Final Results



(a) SIMP + AMfilter with West baseplate density solution

Comparison

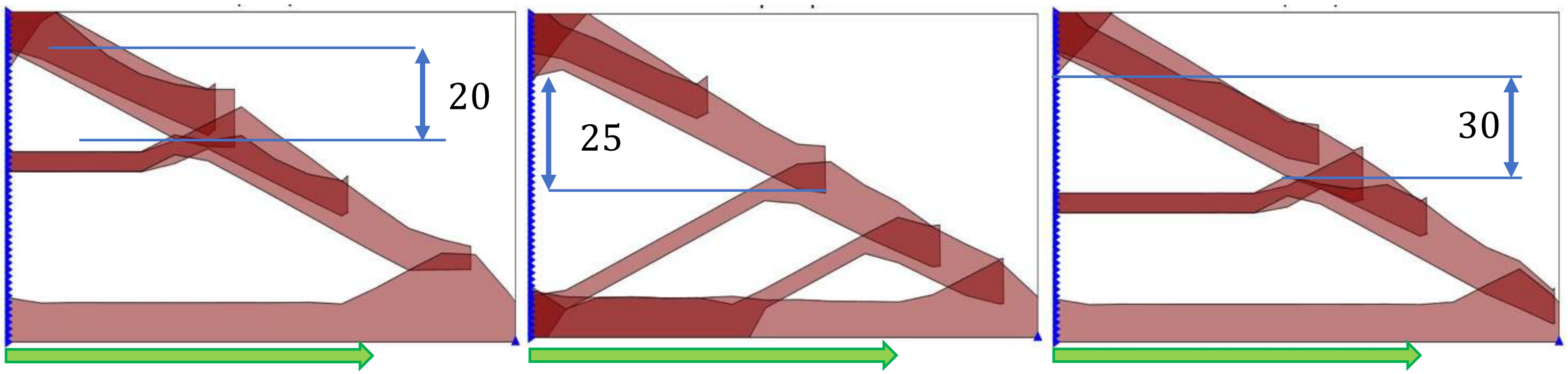
The framework seems to provide practical solutions for preliminary design. The objective values generally decrease as the BL constraint is increased due to the progressive relaxation of the component shape and position, effectively reducing the difference in optimum values, if not the final solution design.

Table 3
Compliance, Deviation and Baseplate Orientation of design solutions obtained from reference and GGP+AMNA methods.

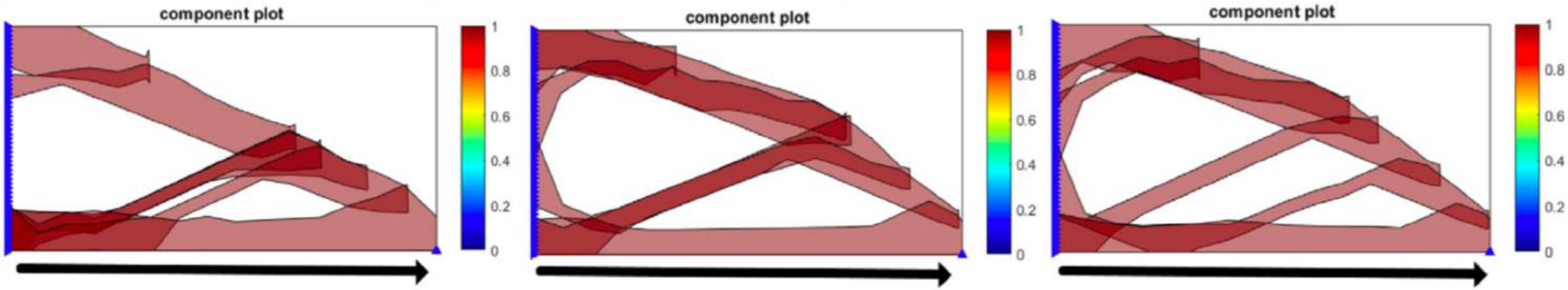
Method	ALM constraints		Compliance	Deviation	Baseplate orientation
	Overhang angle	Bridge length			
MBB Beam					
SIMP	X	X	100.82	0	X
SIMP + AMfilter	✓	X	101.59	0	W
GGP-AMNA (Original framework)	X	X	104.8	3.95%	X
GGP - AMNA (Presented framework with new geometric primitive)			104.86	3.75%	W
	✓	X	115.3	13.5%	W
	✓	20	128.3	26.3%	W
	✓	25	116.2	14.4%	W
	✓	30	117.7	15.4%	W

Bridge length variation

$BL_{max}/2 = 20$ $BL_{max}/2 = 25$ $BL_{max}/2 = 30$



and resolution effect



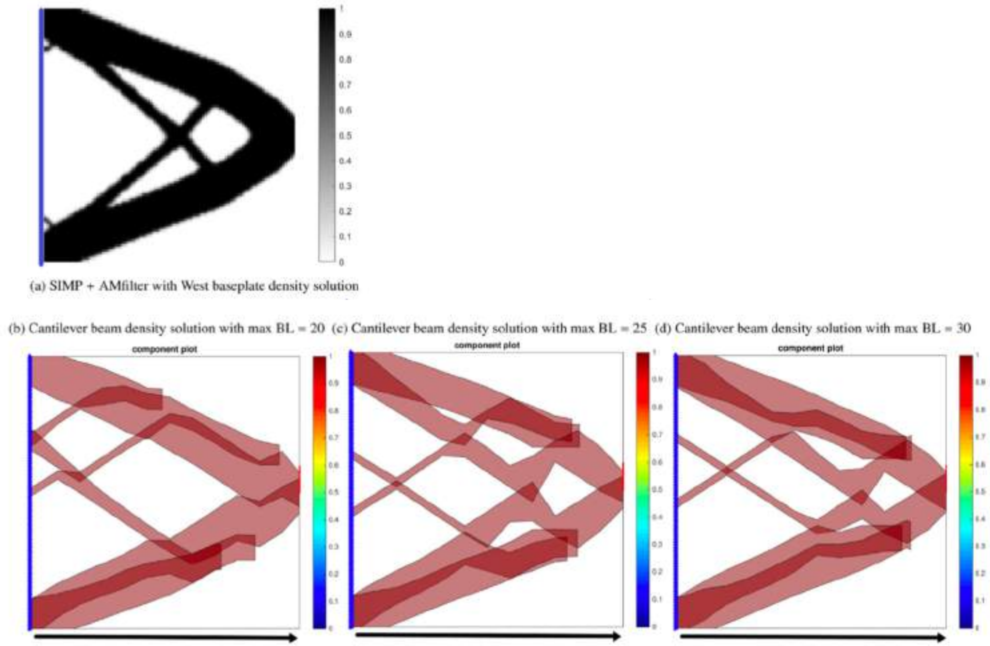
(e) MBB component solution with max BL = 20 (f) MBB component solution with max BL = 25 (g) MBB component solution with max BL = 30

SC

Short Cantilever					
SIMP	X	X	18.48	0	X
SIMP + AMfilter	✓		18.47	0	W
GGP-AMNA (Original framework)	X	X	18.35	−0.7%	X
GGP - AMNA (Presented framework with new geometric primitive)	X	X	18.48	0%	W
	✓	X	18.83	1.95%	W
	✓	20	19.09	3.36%	W
	✓	25	19.51	5.6%	W
	✓	30	19.24	4.2%	W

Higher possibility of sub-optimal minima (i.e., local minima) if the initial component distribution contains too many components, thereby introducing higher number of thin components, resulting in higher greyness in the density map of the solutions.

For the Short Cantilever case across all variations of constraints, it can be observed that the design solution is not symmetrical across the X-axis, and therefore, the compliance can be considered as a local minima.



(a) SIMP + AMfilter with West baseplate density solution

(b) Cantilever beam density solution with max BL = 20 (c) Cantilever beam density solution with max BL = 25 (d) Cantilever beam density solution with max BL = 30

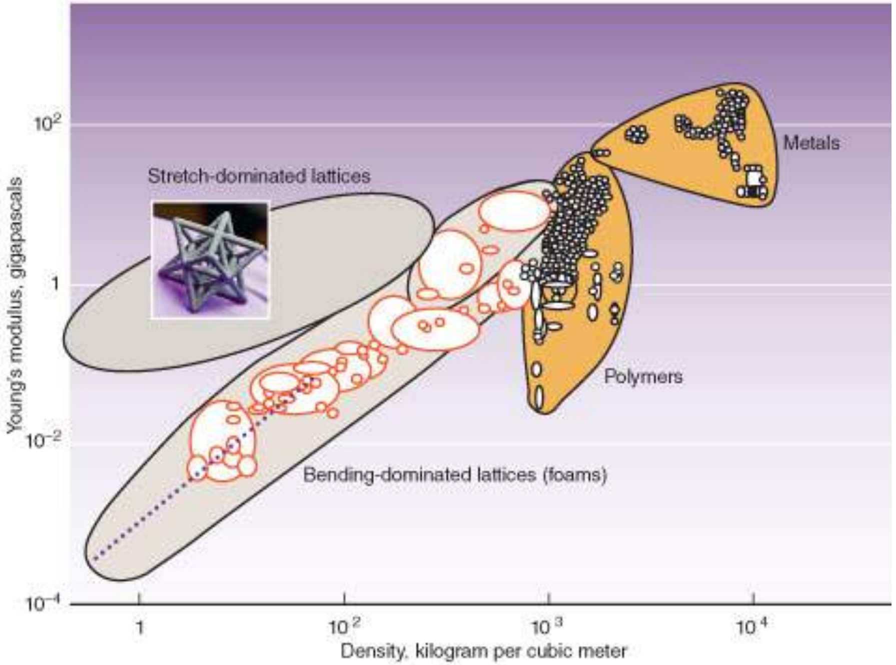
(e) Cantilever beam component solution with max BL = 20 (f) Cantilever beam component solution with max BL = 25 (g) Cantilever beam component solution with max BL = 30

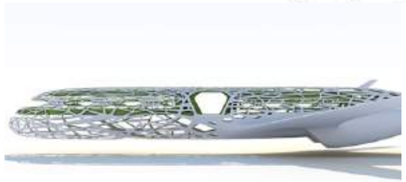
Au programme

Duration	Description	Agenda
4’	Design Optimization	Stiffer
10’	GGP	Our 2016-2019 research
10’	Ecodesign	Lighter and Greener
2’	Conclusions	And future works?

Ecodesign

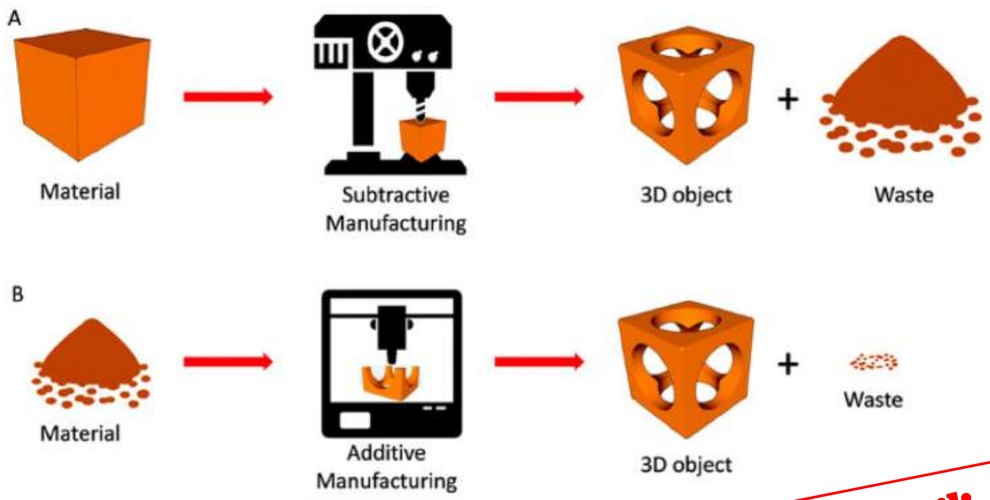
The ERA of DIGITAL MATERIALS





Chris Spadaccini (llnl,USA) "By controlling the architecture of a microstructure, we can create materials with previously unobtainable properties in the bulk form."

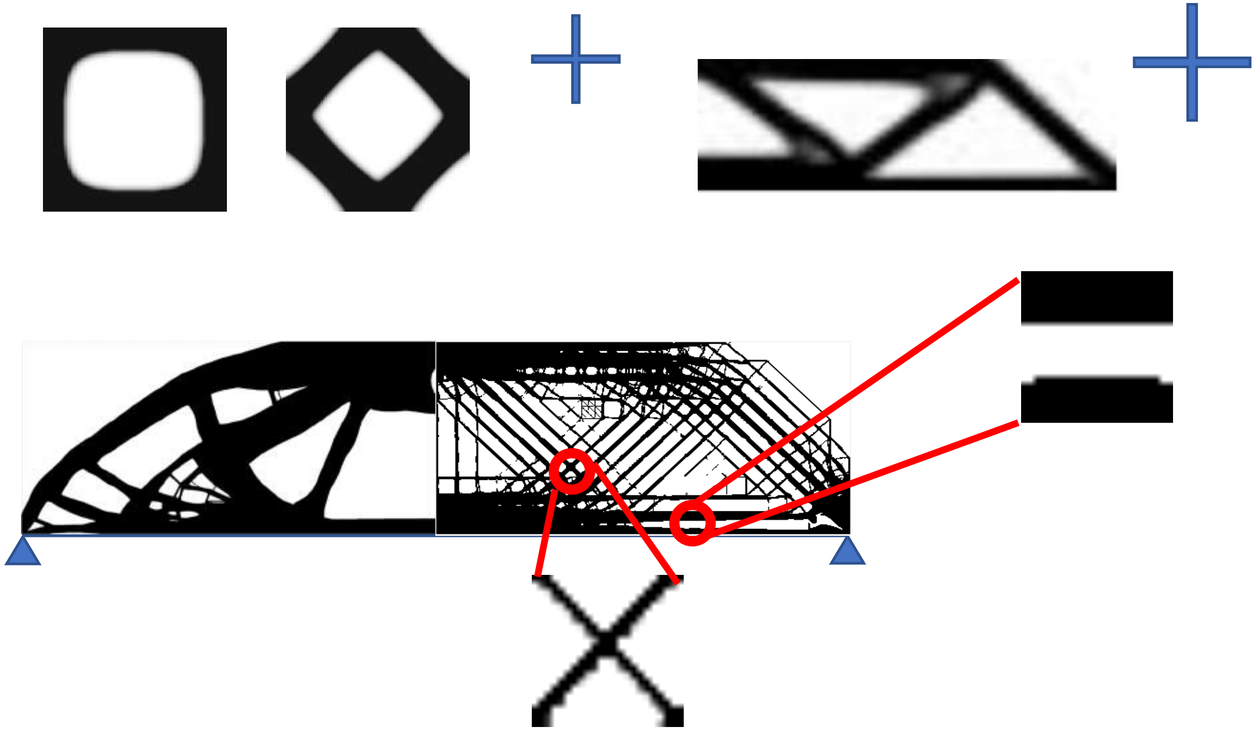
Why Metallic 3D printing?



+Near 100% material utilization
+Recyclability, Buy to fly ratio
+LCA of 3D printing machine
+Monitoring

Multi-scale TO

A two level optimization that combines Unit cell design & Topology Optimization

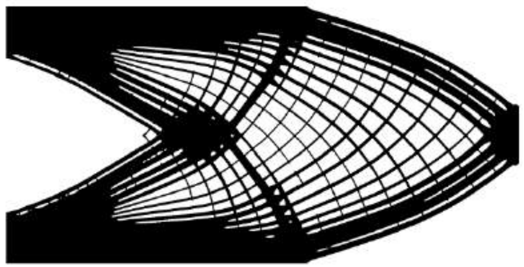


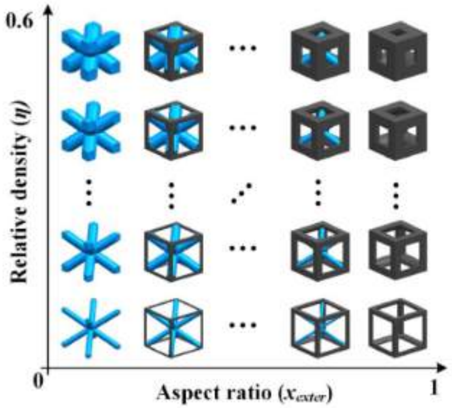
Xia L, Breitkopf P (2015) Design of materials using topology optimization and energy-based homogenization approach in Matlab. Struct Multidisc Optim 52(6):1229–1241. https://doi.org/10.1007/s00158-015-1294-0

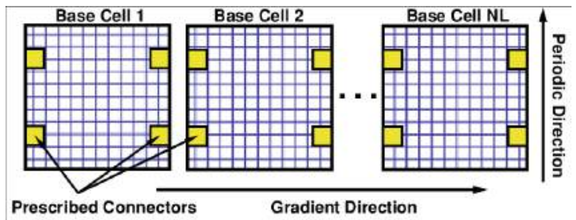
Main MTO methods

More : review [5], topwebinar :
https://topwebinar.weblog.tudelft.nl/

Approach	Examples	Connectivity	Locally adapted	Speed	Manufacturability
De-homogenization	[1],[2]				
Parametrized lattice	[3]				
Connectors	[4]				

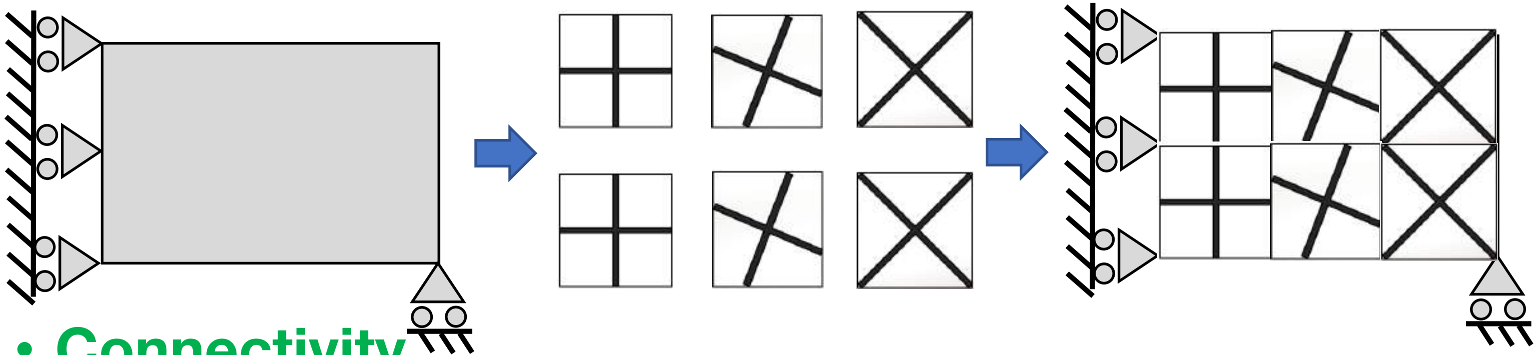




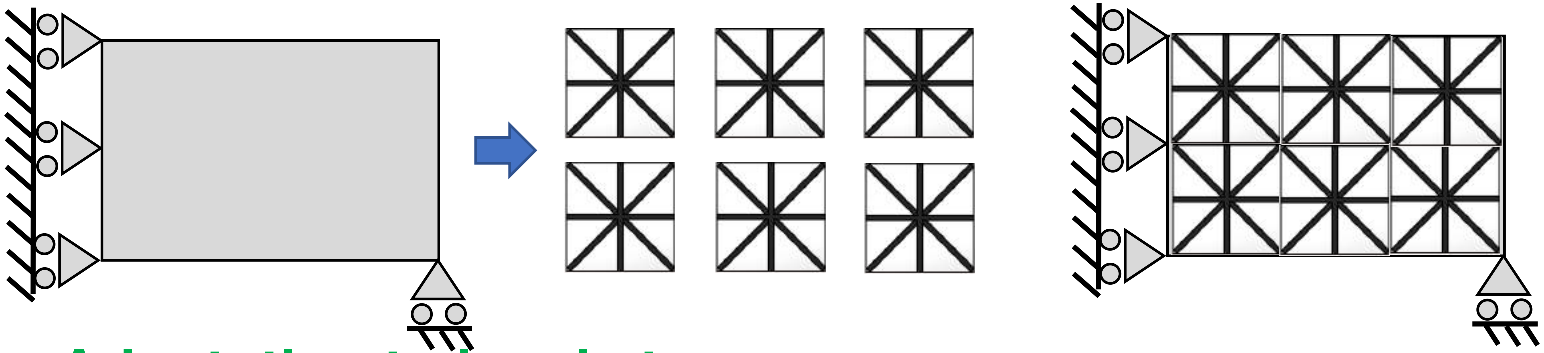


[1] Pantz, Olivier, and K. Trabelsi. “A Post-Treatment of the Homogenization Method for Shape Optimization.” *SIAM J. Control and Optimization*
[2] Groen, Jeroen P., and Ole Sigmund. “Homogenization-Based Topology Optimization for High-Resolution Manufacturable Microstructures: Homogenization-Based Topology Optimization for High-Resolution Manufacturable Microstructures.” *International Journal for Numerical Methods in Engineering*
[3] Wang, Chuang, et al. “Concurrent Design of Hierarchical Structures with Three-Dimensional Parameterized Lattice Microstructures for Additive Manufacturing.” *Structural and Multidisciplinary Optimization*
[4] Zhou S, Li Q (2008) Design of graded two-phase microstructures for tailored elasticity gradients. Journal of Materials Science
[5] Wu, Jun, et al. “Topology Optimization of Multi-Scale Structures: A Review.” *Structural and Multidisciplinary Optimization*

MTO challenges



- **Connectivity**



- **Adaptation to local stress**
- **Speed**

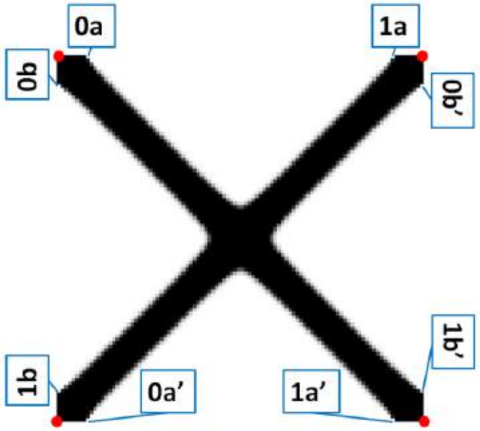
Transmission zones

- To address connectivity issue
- Impose location of strain transmission from one cell to another

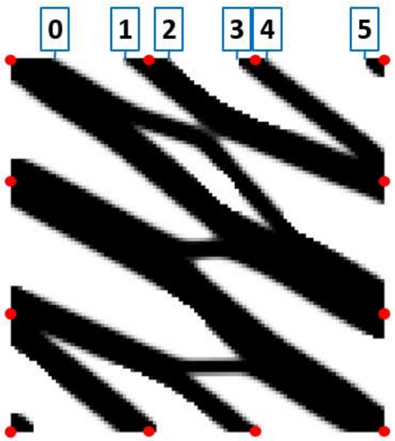
⇒ Periodic boundary conditions only in those locations

4 transmission

Zones (TZ):



12TZ:



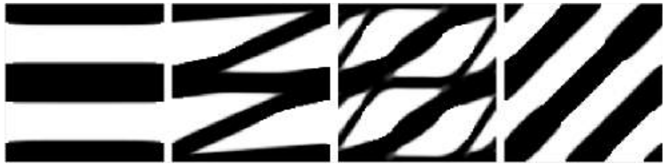
- Difference to Kinematical Connective constraints : absence of non-design zones

Zhou S, Li Q (2008) Design of graded two-phase microstructures for tailored elasticity gradients. Journal of Materials Science 43:5157–5167. https://doi.org/10.1007/s10853-008-2722-y

Scale-bridging variables

- Density

- Orientation



- Cubicity

- Micro-optimization objective function:

Rotated homogenized stiffness tensor

$$\boldsymbol{E}^{\alpha} = \boldsymbol{M}_{\alpha}^{T} * \mathbf{E} * \boldsymbol{M}_{\alpha} = (E_{klmn}^{\alpha})_{k,l,m,n\in\{1,2\}}$$

- We also add a variable defining the relative importance of the two principal directions. A value of 1 means the two principal directions are equivalent, while a value of 0 means the first principal direction alone is considered.

Off-line Microscale Problem

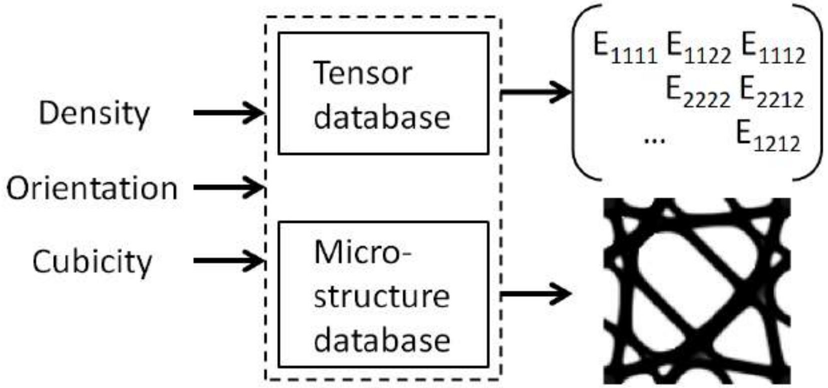
Since the objective is to create micro-structure with optimal properties towards specific directions, the objective function is a weighted function of the two components $E\alpha$ 1111 and $E\alpha$ 2222 as follow

Objective function

$$c = \left(1 - \frac{x_{cub}}{2}\right) E_{1111}^{\alpha} + \frac{x_{cub}}{2} E_{2222}^{\alpha}$$

Database and surrogate

- To address speed issue ($t_{tot} = t_{cell} * n_{cell} * n_{it};\ t_{cell} = 10'$)



- Surrogate regression to have smooth derivatives

$\Rightarrow$ Nadaraya-Watson weighted average with Gaussian kernel:

$$E_{pred}(x) = \frac{\sum_{m=1}^{k} G(x,x_m) E_{db}(x_m)}{\sum_{m=1}^{k} G(x,x_m)}\ ;\ G(x, x_m) = \exp\left(\frac{-d_{eucl}(x,x_m)^2}{2b^2}\right)$$

- t_{tot} =10'' on 200-300 macro-element design

Efficient Multiscale Topology Optimization

Macroscale Problem

$$\underset{x^i_{\text{dens}}, x^i_a, x^i_b, \dots}{\text{minimize}} \quad c = u^T K u$$

$$\text{subject } to \quad Ku = f$$

$$\sum_{i=1}^{n} \sum_{j=1}^{m} \rho_{i,j} \leq n \times m \times v_f$$

$$\epsilon < \rho_{i,j} < 1$$

$$x^i = [x^i_{\text{dens}}, x^i_{\text{or}}, x^i_{\text{cub}}]$$

Optimal

$$x^i = [x^i_{\text{dens}}, x^i_{\text{or}}, x^i_{\text{cub}}]$$

Gaussian regression in the Tensor Database

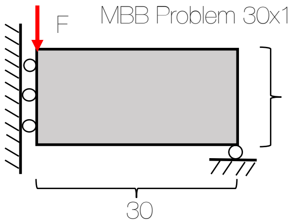
$$\mathbf{E}_{\text{pred}}(x^i) = \frac{\sum_{l=1}^{k} G(x^i, x_l)\mathbf{E}_{\text{db}}(x_l)}{\sum_{l=1}^{k} G(x^i, x_l)}$$

$$G(x^i, x_l) = \exp\left(\frac{-d_{\text{eucl}}(x^i, x_l)^2}{2b^2}\right)$$

$$x^{i\prime} = [x^i_{\text{dens}} + \Delta, x^i_{\text{or}}, x^i_{\text{cub}}] \qquad \Delta = 0.01$$

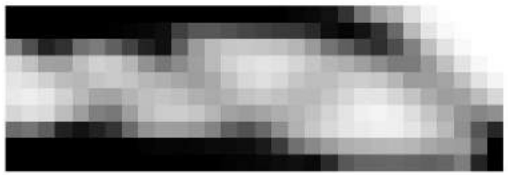
$$\frac{\partial \mathbf{E}_{\text{pred}}}{\partial x_{\text{dens}}}(x^i) \approx \frac{\mathbf{E}_{\text{pred}}(x^{i\prime}) - \mathbf{E}_{\text{pred}}(x^i)}{\Delta}$$

MBB Problem 30x10 macro elements

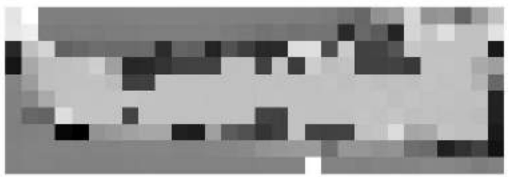


Theoretical compliance 192.7

Density of the cells



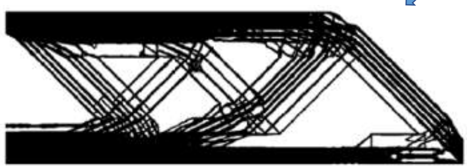
Orientation of the cells



Cubicity of the cells

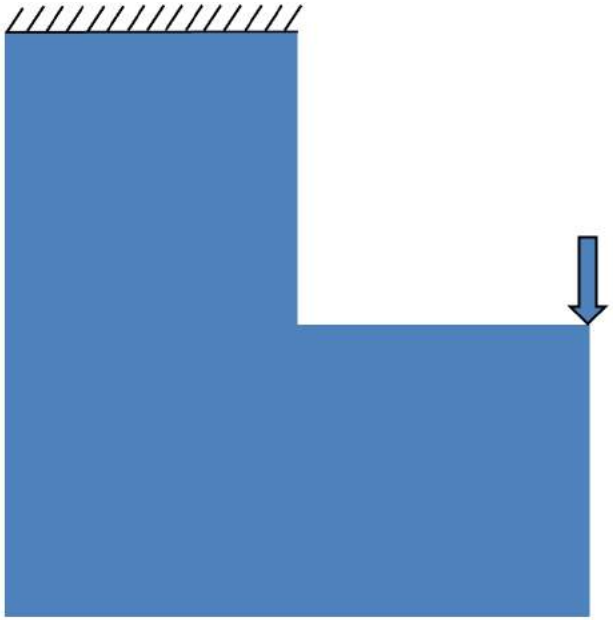
Structure Database and post-treatment

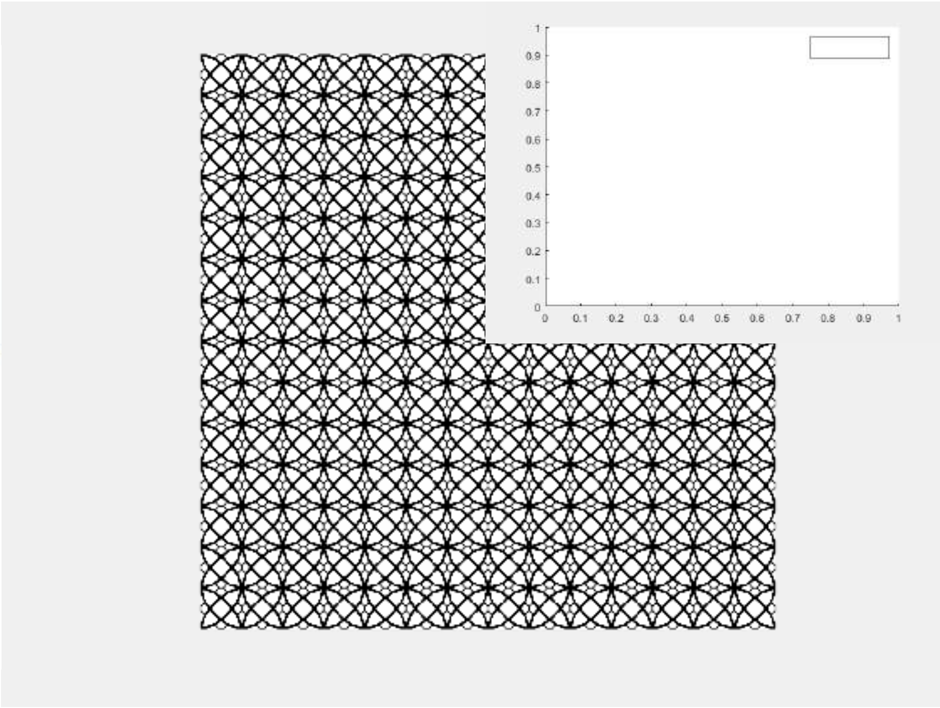
EMTO MBB solution



top88 MBB solution

EMTO on L-shape (cellular /digital materials)



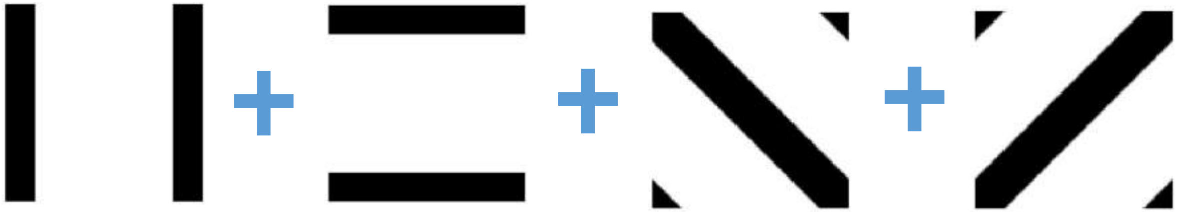


https://github.com/mid2SUPAERO/EMTO

Crystal Clear EMTO

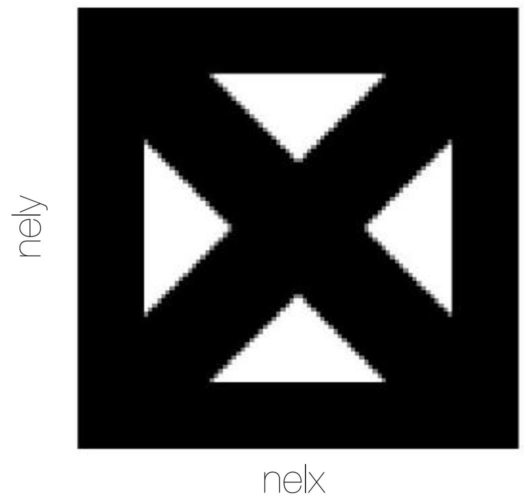
~~"Transmission Zones"~~ → Build a DATABASE of Intrinsically well connected beam-like unit cell

4 Parameters related to the thickness of the beams



Example of 2D unit Cell

```
Cell_4p(nelx,nely,[0.2,0.2,0.2,0.2)
```

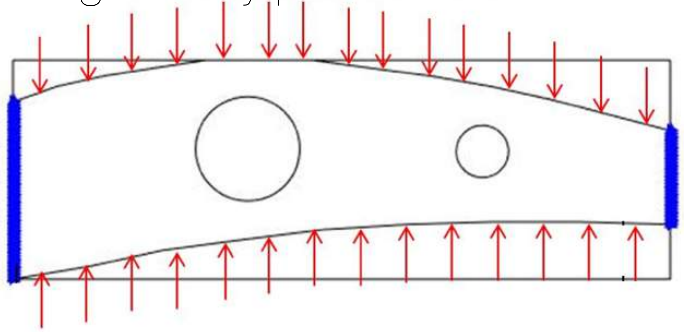


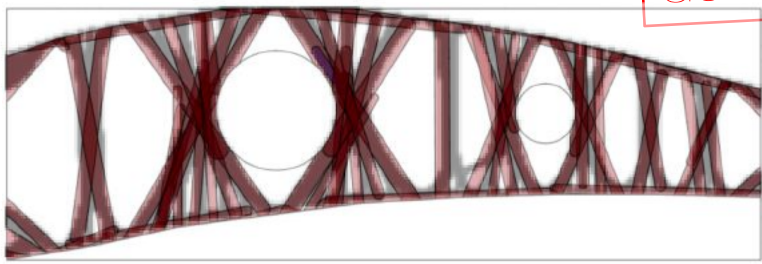
Aircraft rib design

GGP ;= EASY EXPLORATION of POTENTIAL DESIGN OF STRUCTURES

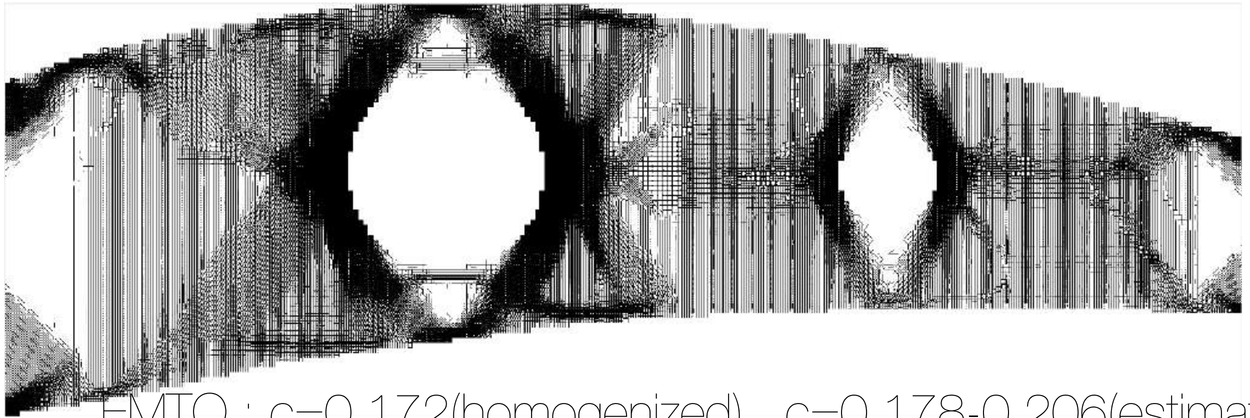
GGP-MNA: C=0.194

- Again Only pressure loads



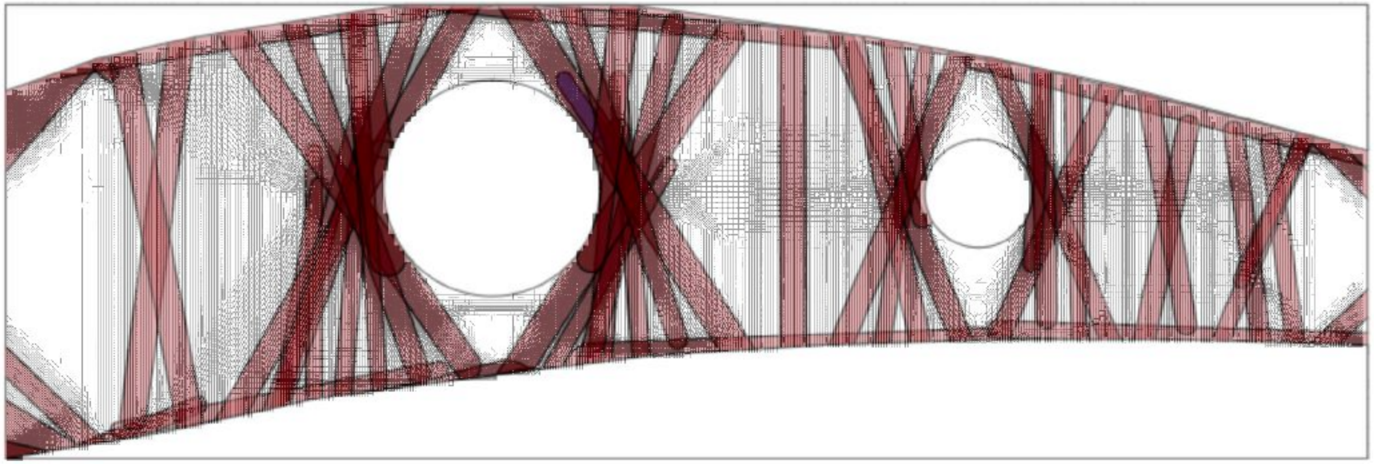


SIMP : c=0.198

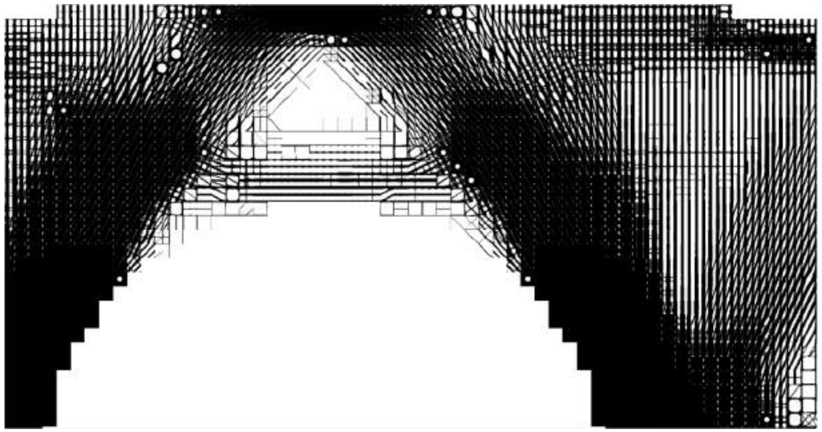


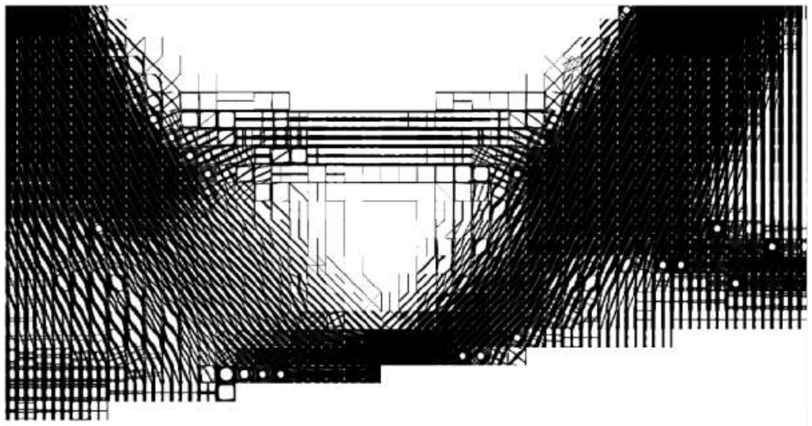
EMTO : c=0.172(homogenized) c=0.178-0.206(estimate)

EMTO vs GGP



Multiscale approach is a complete REDESIGN: Creation of multiple paths for internal forces





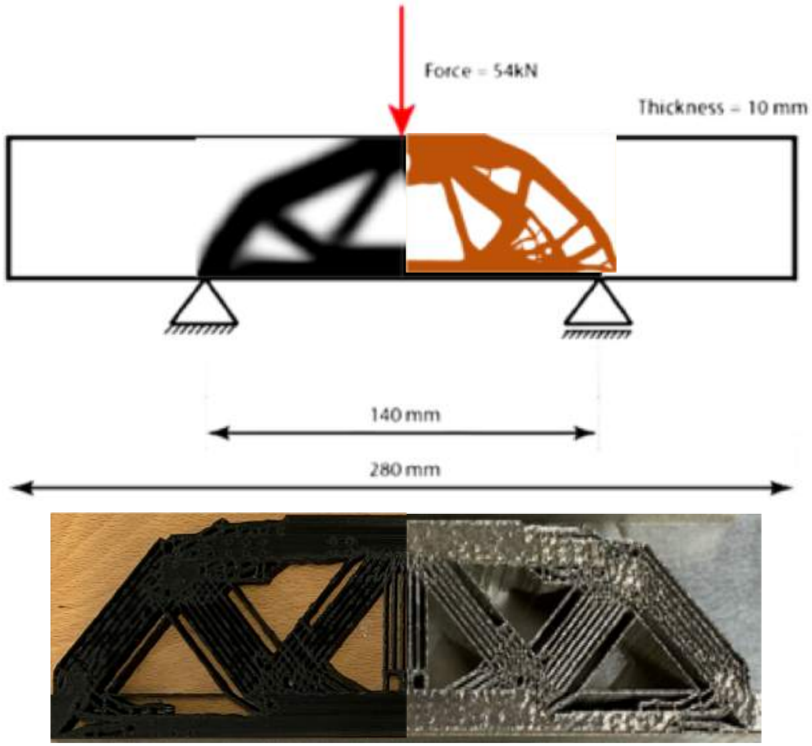
It should be manufactured by machine

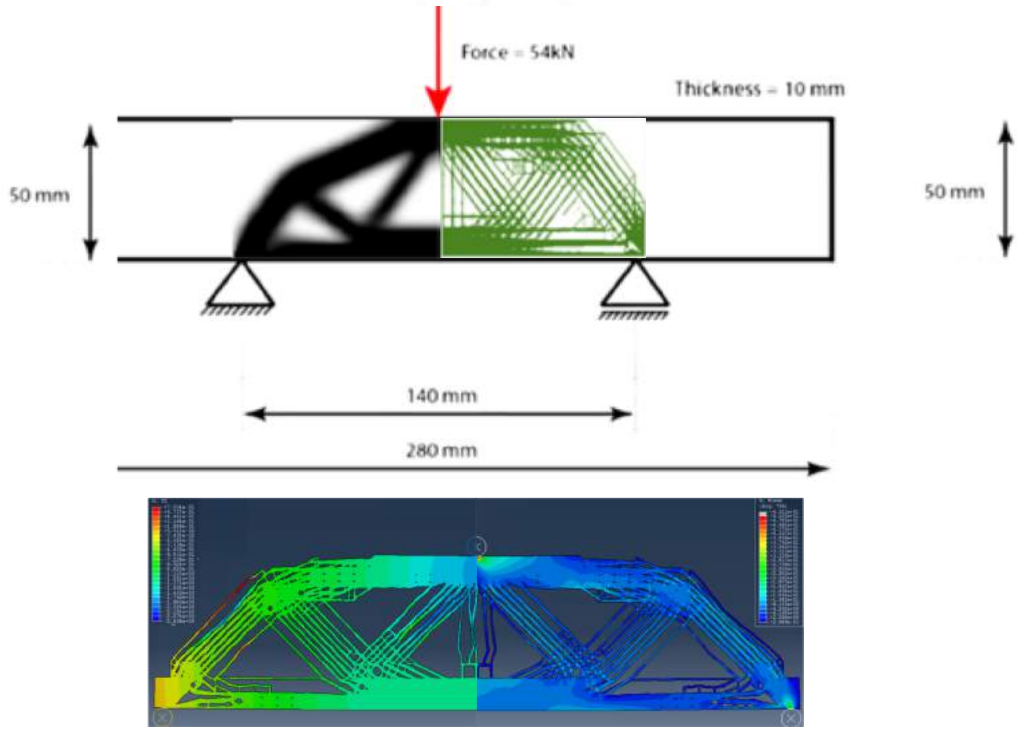
How to **ECO**design tomorrow's structures?

Prof. Joseph Morlier, Edouard Duriez, Miguel Charlotte, Catherine Azzaro-Pantel

Print it , Test it

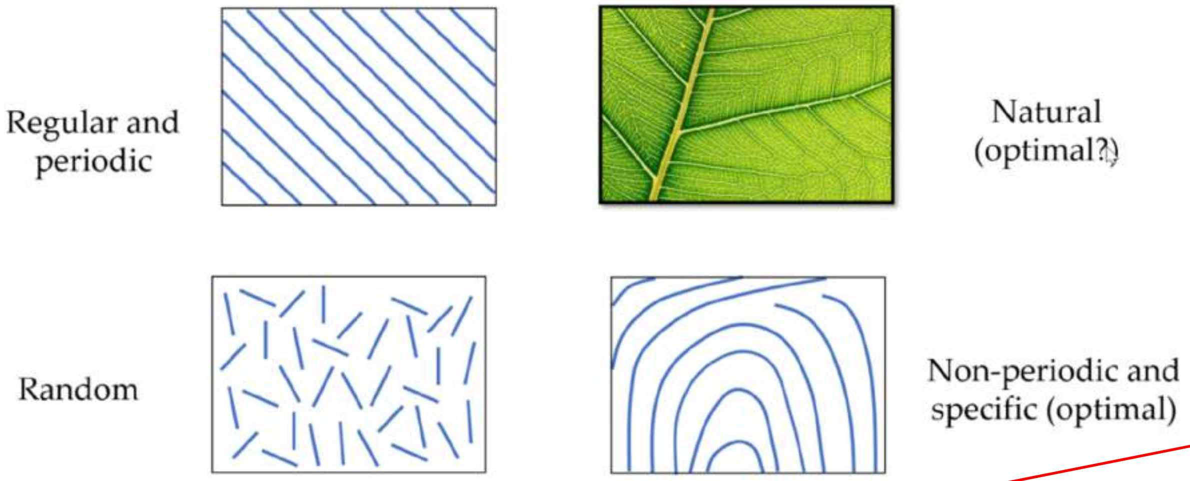
EXP +ABAQUS
REANALYSE





PLA or Selective Laser Melting (**SLM**)

Why Composites 3D printing?

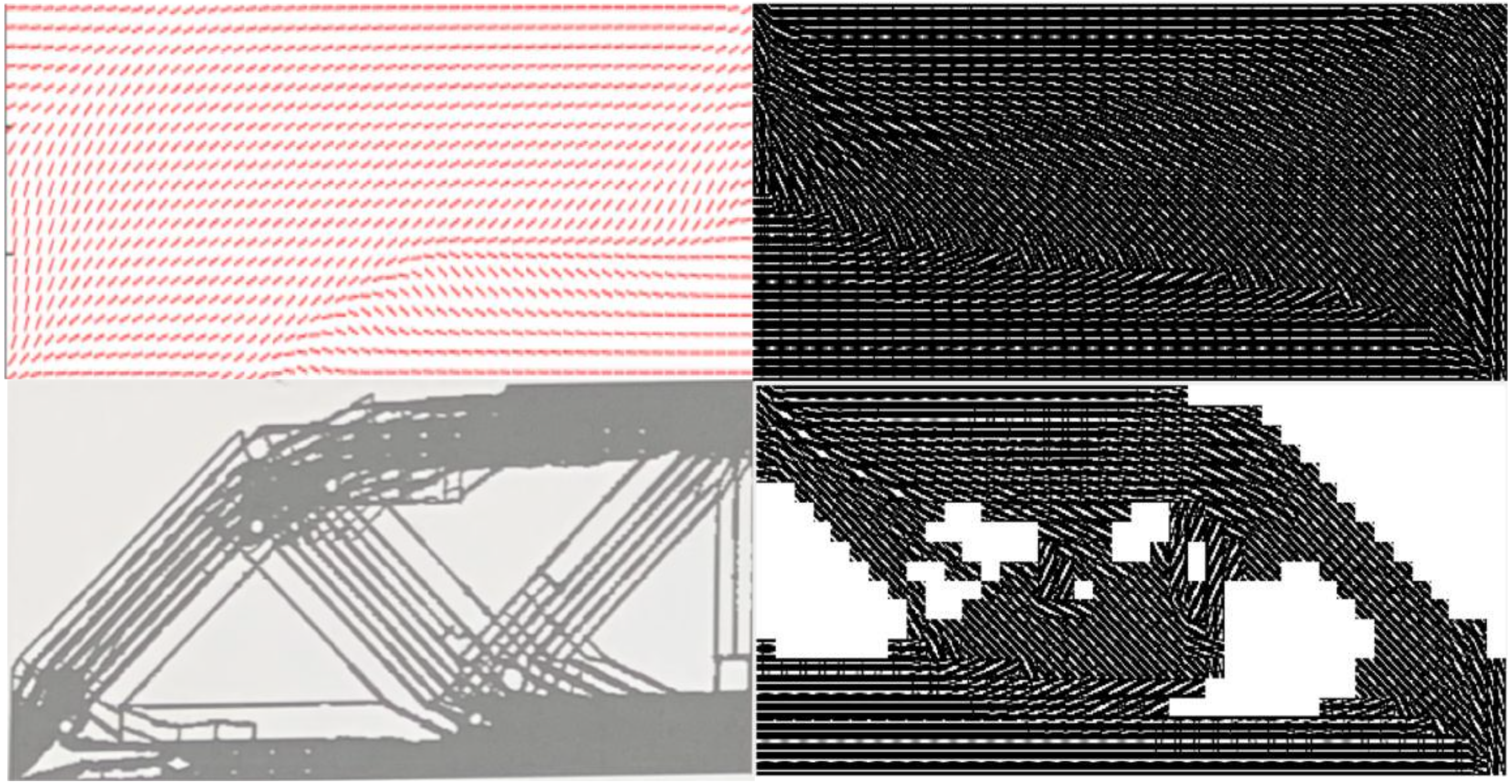


+ Automatic Fiber Placement + eco-fiber/resin selection +Monitoring

Restrict “EMTO” for Fiber Placement (cubicity=0)

Stegmann and Lund (2005) Discrete Material Optimization (DMO)

EMTO

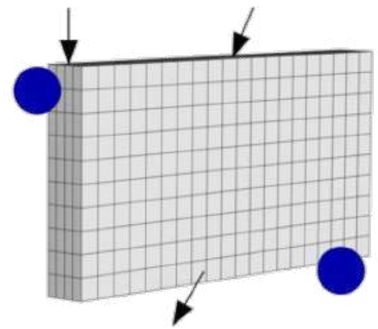


EMTO_FP volfrac=1

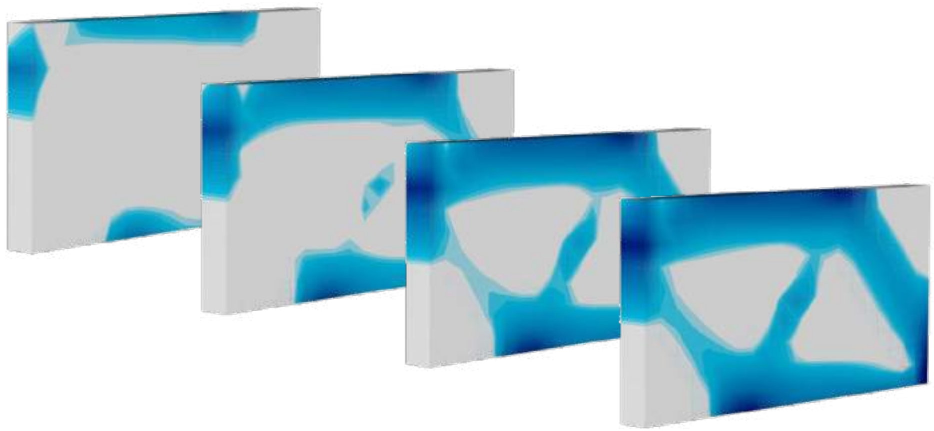
EMTO volfrac=0.5

A simple way to do Ecodesign with Topology Optimization?

Start with Topology Optimization



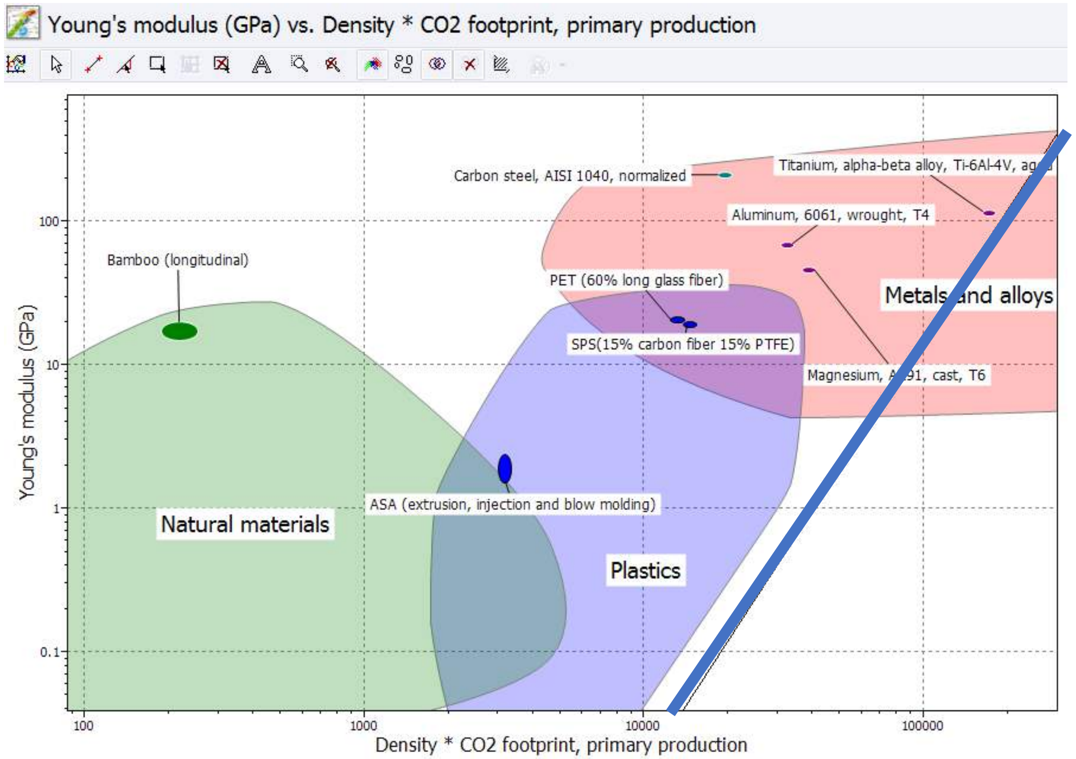
Inputs: Material, BCs and Loading



Outputs: design of a „stiff" bicycle frame

CO2 footprint minimization (Ashby's method)

Inputs: Type of Structures, default materials



Outputs: Optimal material (bamboo) with optimal Design

MDO

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ScienceDirect

Procedia CIRP 00 (2021) 000–000

www.elsevier.com/locate/procedia

32nd CIRP Design Conference

Ecodesign with topology optimization

Edouard Duriez*[a], Joseph Morlier[a], Catherine Azzaro-Pantel[b], Miguel Charlotte[a]

#Generalized Ashby's theory compatible with TopOpt
#All In One problem is a MDO problem !!!

$$
\begin{aligned}
\underset{mat,\mathcal{D},t}{\arg\min} \quad & CO_2^{tot}(mat,\mathcal{D},t) \\
s.t. \quad & \delta \leq \delta_{max} \\
& mat = \{E, \rho, CO_{2mat}^{i}\} \in \Phi \\
& 0 < v_f(\mathcal{D}) \leq 1
\end{aligned}
$$

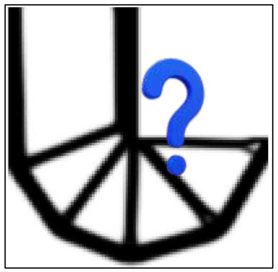
Time to conclude

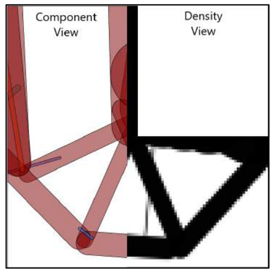
Duration	Description	Agenda
4’	Design Optimization	Stiffer
10’	GGP	Our 2016-2019 research
10’	Ecodesign	Lighter and Greener
2’	Conclusions	And future works?

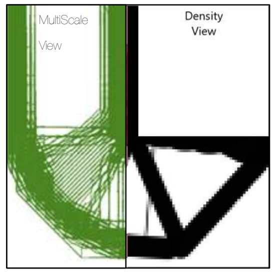
Researcher view (Reproducible Research)

- https://www.topopt.mek.dtu.dk
- https://www.top3d.app
- AM FILTER

- https://github.com/topggp/blog
- Crystal clear and preliminary ALM
- https://github.com/mid2SUPAERO/EMTO
- Redesign for ALM
- https://smt.readthedocs.io/en/latest/
- Design Acceleration



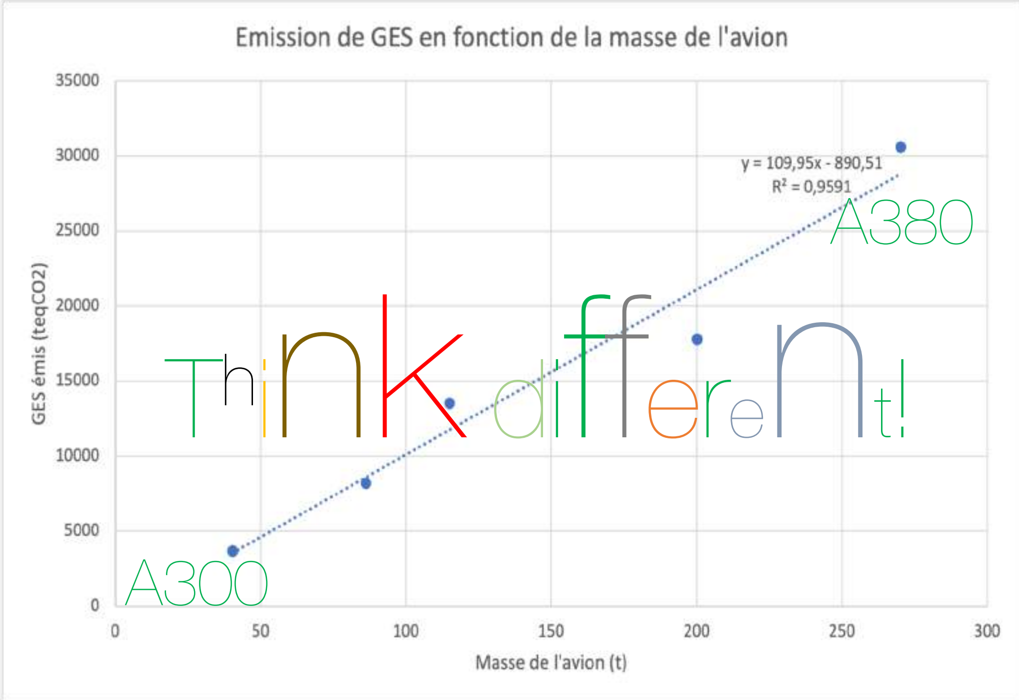




Rank1 on actual aircraft

At the first order

min {mass} is proportional to min {CO2}



Stiffer, Lighter, Greener =

TOPOLOGY OPTIMIZATION + ARCHITECTED MATERIALS + DIGITAL FABRICATION + ECODESIGN

Perspectives

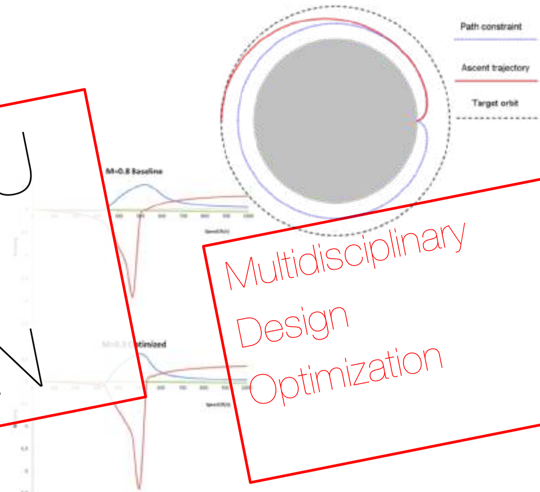
→ Multiobjective formulation CO_2 versus Cost
→ MDO for ALM
→ Natural Fiber / Resin Eco-selection

https://ica.cnrs.fr/author/jmorlier/

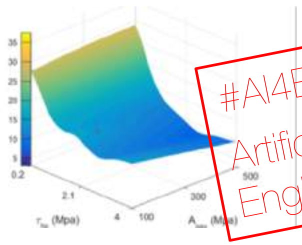
INSTITUT CLÉMENT ADER

Structural Optimization & Ecodesign

THANK YOU for Your ATTENTION

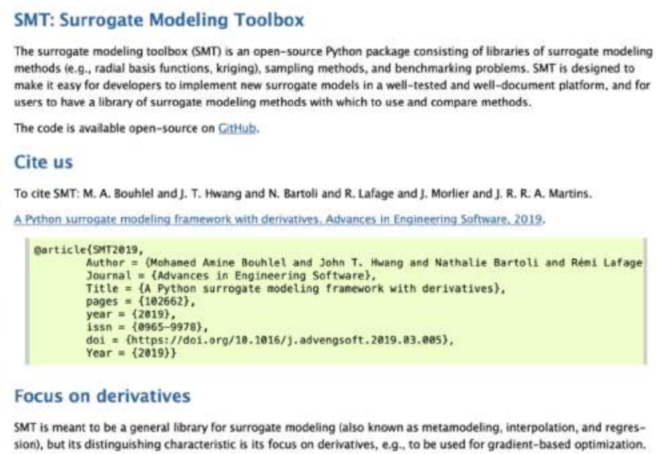


Multidisciplinary Design Optimization



#AI4E Artificial Intelligence For Engineers

https://github.com/SMTorg/smt



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Getting started

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SMT: Surrogate Modeling Toolbox

The surrogate modeling toolbox (SMT) is an open-source Python package consisting of libraries of surrogate modeling methods (e.g., radial basis functions, kriging), sampling methods, and benchmarking problems. SMT is designed to make it easy for developers to implement new surrogate models in a well-tested and well-document platform, and for users to have a library of surrogate modeling methods with which to use and compare methods.

The code is available open-source on GitHub.

Cite us

To cite SMT: M. A. Bouhlel and J. T. Hwang and N. Bartoli and R. Lafage and J. Morlier and J. R. R. A. Martins.

A Python surrogate modeling framework with derivatives. Advances in Engineering Software, 2019.

```
@article{SMT2019,
        Author = {Mohamed Amine Bouhlel and John T. Hwang and Nathalie Bartoli and Rémi Lafage
        Journal = {Advances in Engineering Software},
        Title = {A Python surrogate modeling framework with derivatives},
        pages = {102662},
        year = {2019},
        issn = {0965-9978},
        doi = {https://doi.org/10.1016/j.advengsoft.2019.03.005},
        Year = {2019}}
```

Focus on derivatives

SMT is meant to be a general library for surrogate modeling (also known as metamodeling, interpolation, and regression), but its distinguishing characteristic is its focus on derivatives, e.g., to be used for gradient-based optimization.