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

Concevoir une {aéro}structure en LEGO

Prof. Joseph Morlier *et al*

Concevoir une {aéro}structure en LEGO

Prof. Joseph Morlier *et al*

et al is important

Why ?

Student's Research projects @SUPAERO

Giving Back with SUPAERO's students

Prof's Impact increases, Students are becoming Phds, or R&T engineers (these new researches feed the courses&RP)

Students produce research papers and obtain new skills !

At master Level: Prof teaches elective courses+ Research Projects with students

Students are PhD Ready in CSM/MDO

Popularization

décembre 5, 2017

Construire une aile d'avion en Lego c'est possible

Joseph Morlier, *ISAE-SUPAERO*

Les recherches d'optimisation permettent de créer de nouvelles structures plus légères et plus résistantes. Idéales pour les avions !

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

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

Warning

- Restricted in this presentation to 2D domain
- Lot of results limited to Compliance Optimization (classical benchmark)
- SAMO community testcases: L-Shape, MBB, we introduce the Rib. aerostructure

Agenda for today

- Part1 Introduction 4'
- Part2 Topology Optimization & Opensource software 4'
- Part3 GGP for aerostructures 5'
- Part4 Ecoptimization & Computational Fabrication 5'

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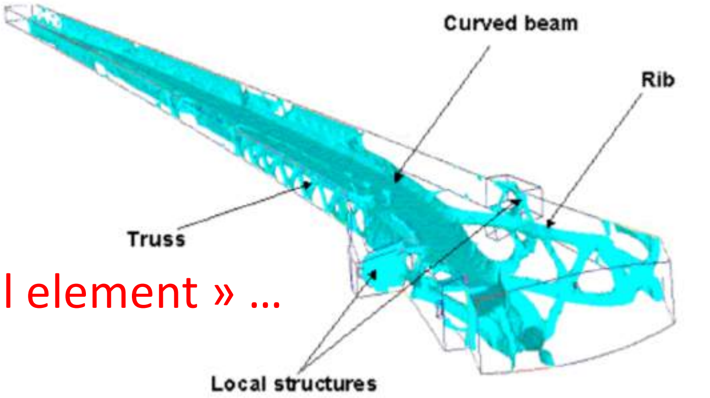
In 2016 I was searching to differentiate my TopOpt research

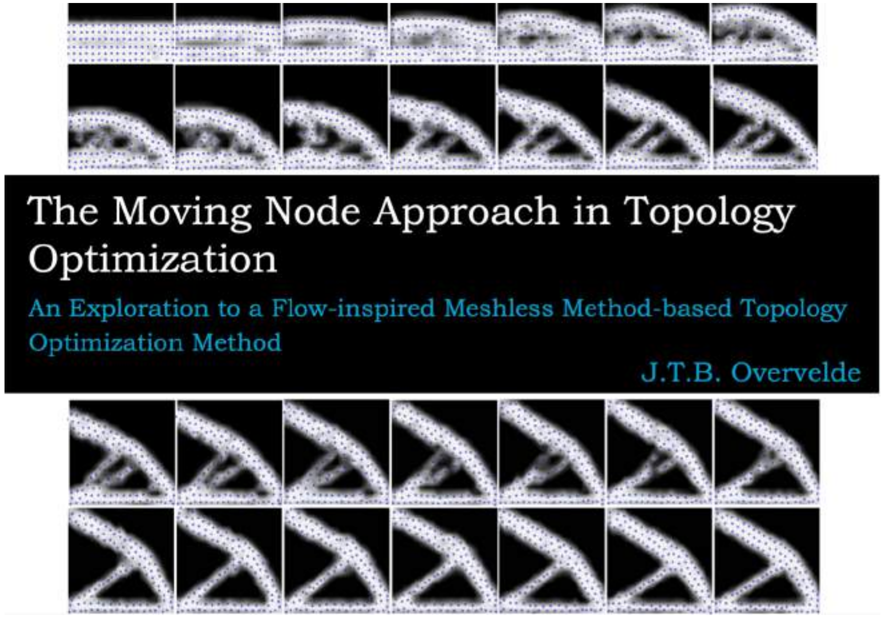
My idea was to use meshless method in TopOpt for « expolicit » structural elements, why?



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

But this work already existed…
in a master thesis

Let's try to follow this paper's conclusions



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

Johannes T. B. Overvelde

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

SUIVRE

So we started with a SUPAERO's student project

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

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 $\mathscr{H}_\infty$ optimisation G Zhao, G Raze, A Paknejad, A Deraemaeker, G Kerschen, C Collette Mechanical Systems and Signal Processing 129, 470-478	12	2019

According to Bendsøe (1989), Topology optimization:
"… should consist of a determination for every point in space whether there is material in that point or not."

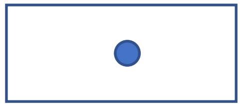
Moving Node Approach (MNA)

5 variables per node

Structural Members: Beam is the primitive chosen here

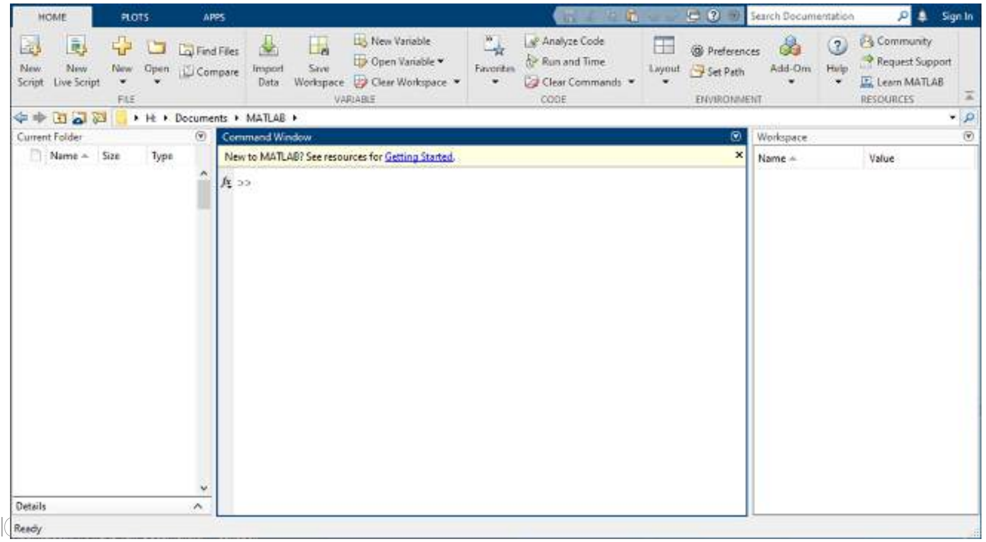
Optimization variables :

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

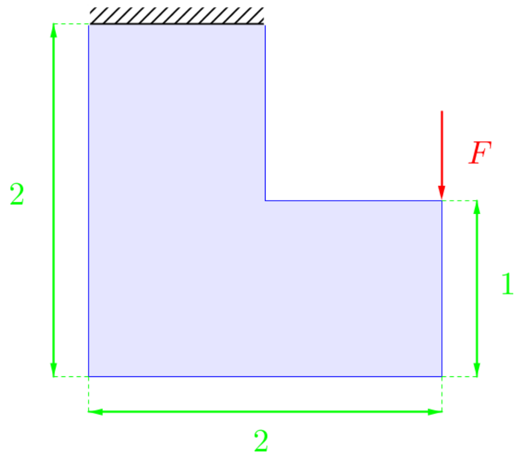


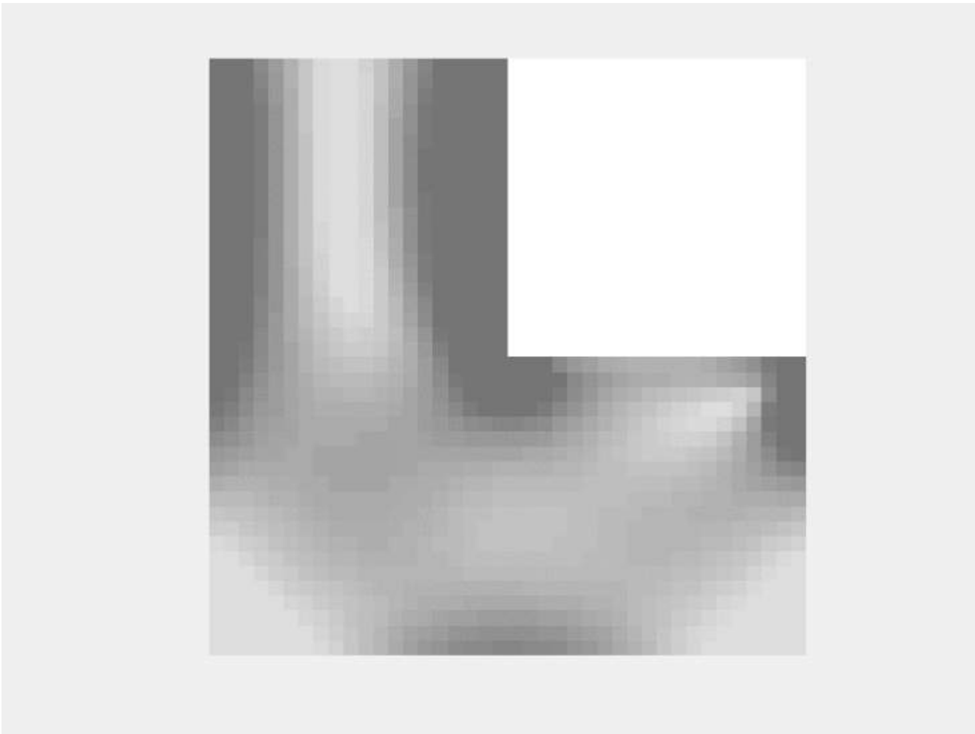
```
disp('SIMP')
top88(nelx,nely,volfrac,3,2,1)

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.

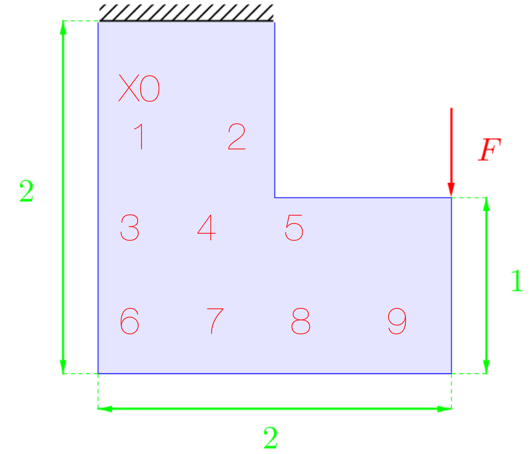
http://www.topopt.mek.dtu.dk

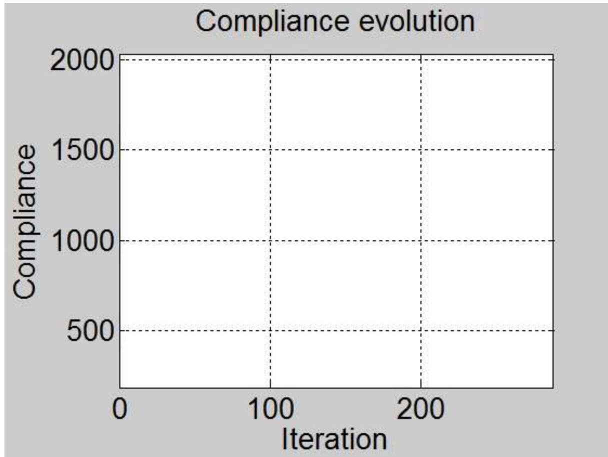
Results MNA, 9*5=45 design variables minC wrt Volfrac=0.25 , Ku=f

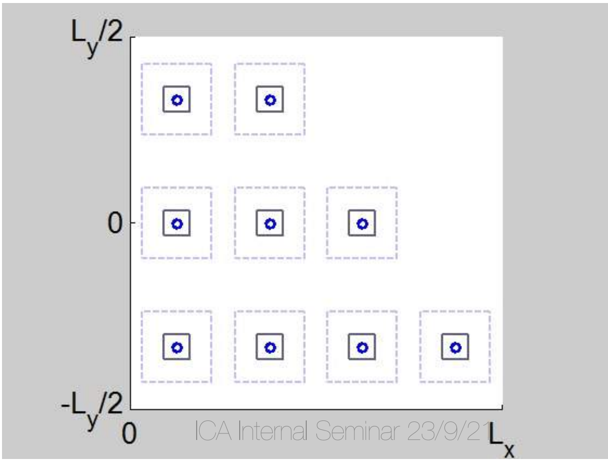
At the end, explicit assembly of beams i.e. Structural Layout

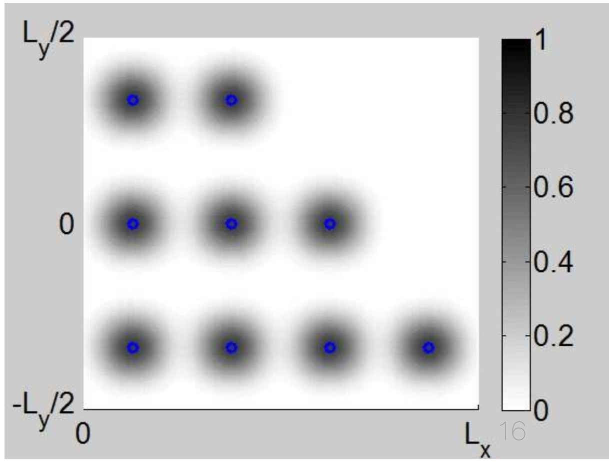
But sensitivity to X_0/mesh

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









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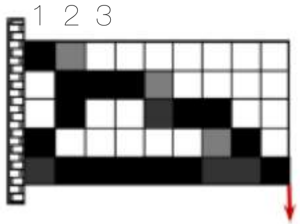
Intuitive Problem? Quadratic Form

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



- Objective function; Strain energy

$$\min c(\mathbf{x}) = \mathbf{U}^T\mathbf{F} = \mathbf{U}^T\mathbf{K}\mathbf{U} \qquad \text{with} \quad x_e = \frac{\rho_e}{\rho_0} \tag{4}$$

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

$$\min c(\mathbf{x}) = \sum_{e=1}^{N} (x_e)^p \mathbf{u}_e^T \mathbf{k}_0 \mathbf{u}_e \tag{5}$$

Scalar

- Contraints: mass target

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

Scalar

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

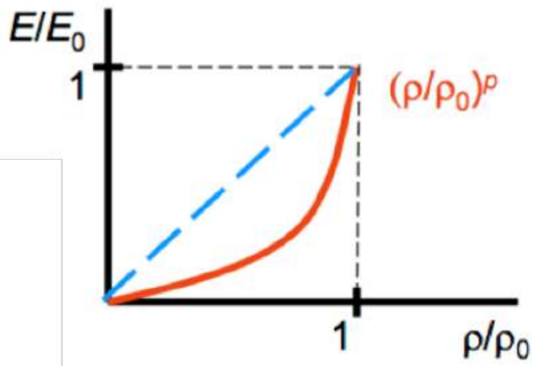
Avoid intermediate densities !

Solid Isotropic Material with Penalization (SIMP)

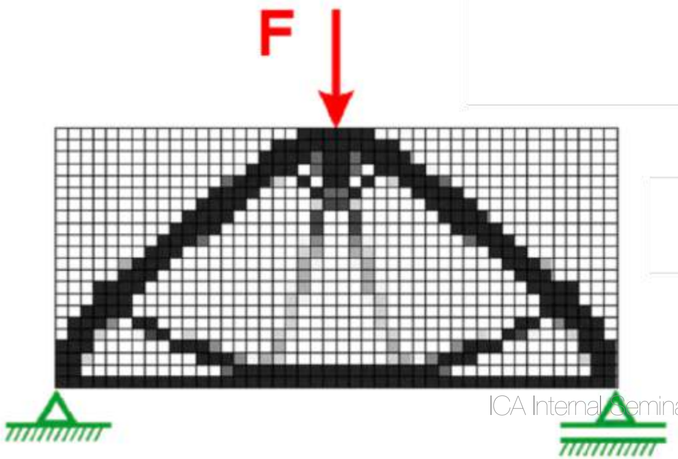
$$E(x) = E_{min} + (E_0 - E_{min})x^p$$

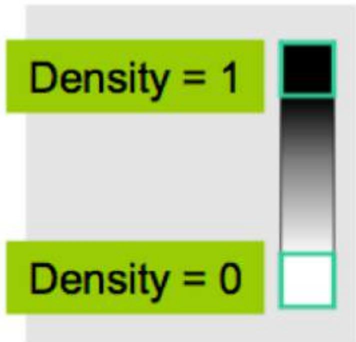
p is the penalty parameter to push densities to black (1) and white (0).

E_{min} is a small value that avoid stiffness matrix singularity



Penalization for altering stiffness localy



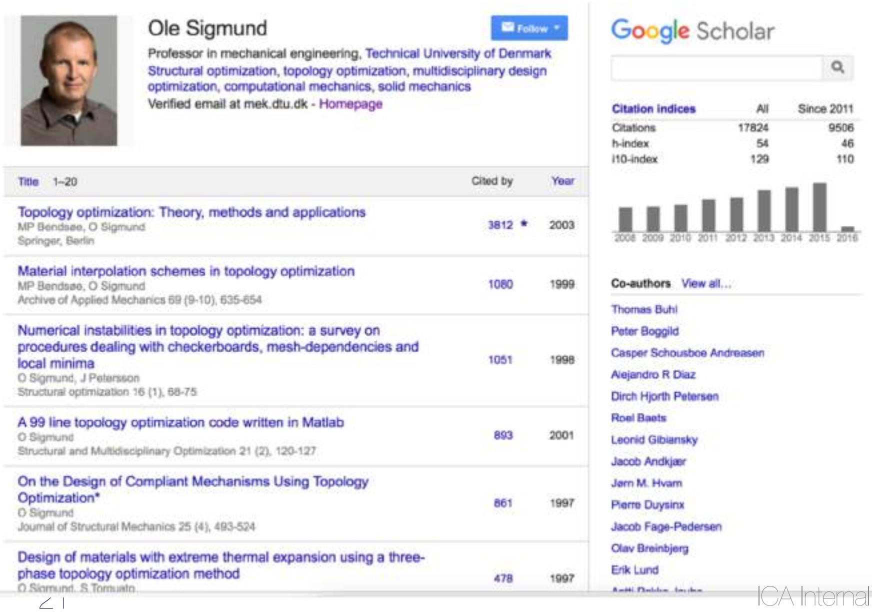


BUT ...IN PRACTICE?

Educational article:

O. Sigmund , A 99 line topology optimization code written in Matlab Struct Multidisc Optim 21, 120–127 Springer-Verlag 2001

Heuristic formulation (intuitiive method of optimisation, but with no convergency proofs) to update xe by bi-section algorithm



1. Transform discrete variables continuously (TO USE gradient-based algorithms)
2. Find an objective function with "cheap" derivatives

Cheap derivative (1)

Compliance Sensitivity

Compliance

$$C = \mathbf{F}^T \mathbf{U}$$

$$\frac{\partial C}{\partial x_i^l} = \frac{\partial \mathbf{F}}{\partial x_i^l}^T \mathbf{U} + \mathbf{F}^T \frac{\partial \mathbf{U}}{\partial x_i^l}$$

No body forces, no accelerations:

$$\frac{\partial \mathbf{F}}{\partial x_i^l} = 0$$

Cheap derivative (2)

Compliance Sensitivity

Discrete equilibrium equation

$$\mathbf{K}\mathbf{U} = \mathbf{F}$$

$$\frac{\partial \mathbf{K}}{\partial x_i^l}\mathbf{U} + \mathbf{K}\frac{\partial \mathbf{U}}{\partial x_i^l} = \frac{\partial \mathbf{F}}{\partial x_i^l} = 0$$

Hence

$$\frac{\partial \mathbf{U}}{\partial x_i^l} = -\mathbf{K}^{-1}\frac{\partial \mathbf{K}}{\partial x_i^l}\mathbf{U}$$

$$\boxed{\frac{\partial C}{\partial x_i^l} = \mathbf{F}^T\frac{\partial \mathbf{U}}{\partial x_i^l} = -\mathbf{U}^T\mathbf{K}^T\mathbf{K}^{-1}\frac{\partial \mathbf{K}}{\partial x_i^l}\mathbf{U} = -\mathbf{U}^T\frac{\partial \mathbf{K}}{\partial x_i^l}\mathbf{U}}$$

Knowing displacements
you also know gradients

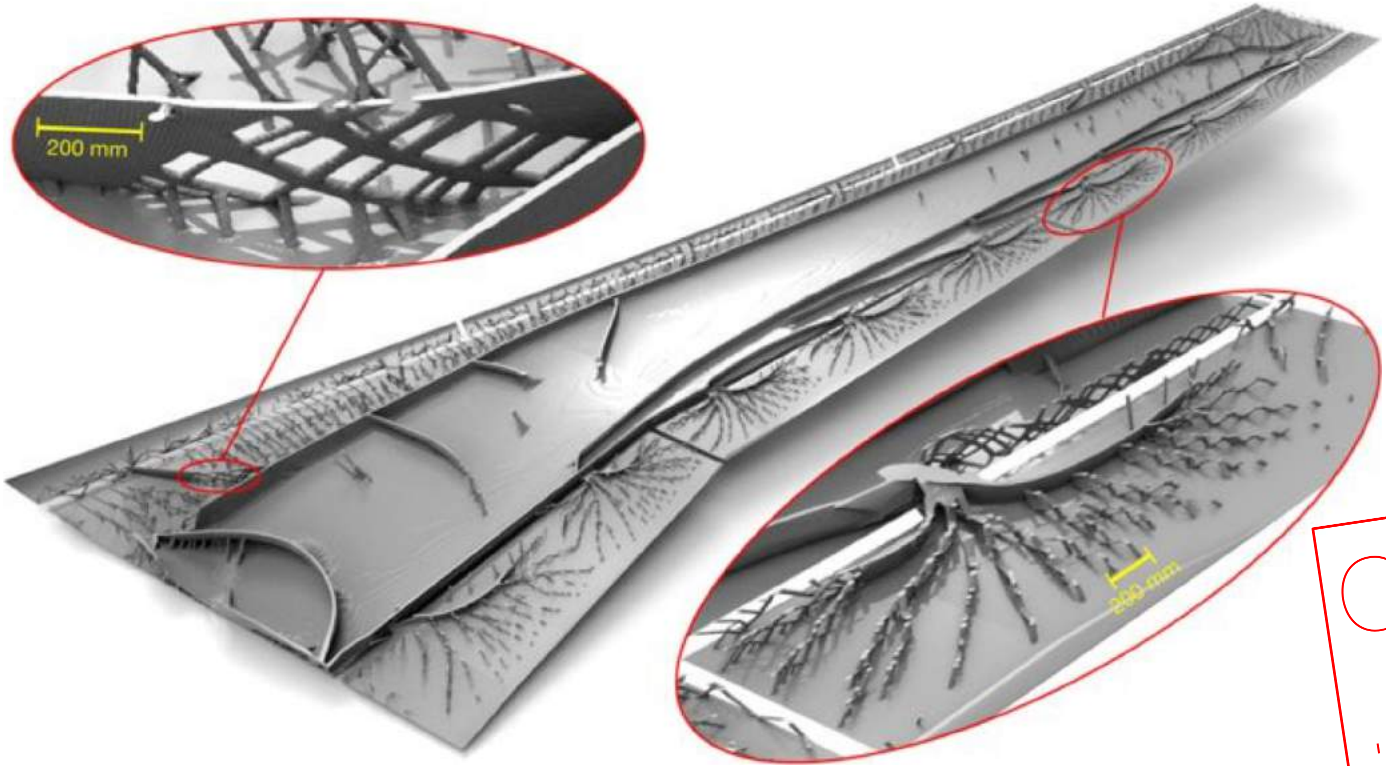
Pixels?

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

Chris Columbus et al, Pixels, movie 2015

Use HPC and lot of time

Niels Aage, Erik Andreassen, Boyan S Lazarov, and Ole Sigmund. Giga-voxel computational morphogenesis for structural design. Nature, 550(7674):84, 2017.



Or

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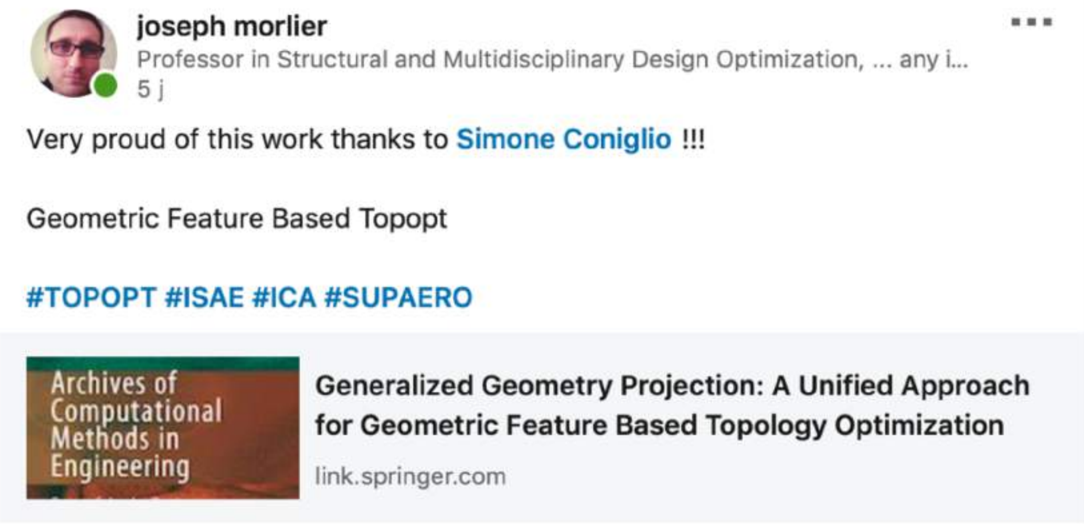
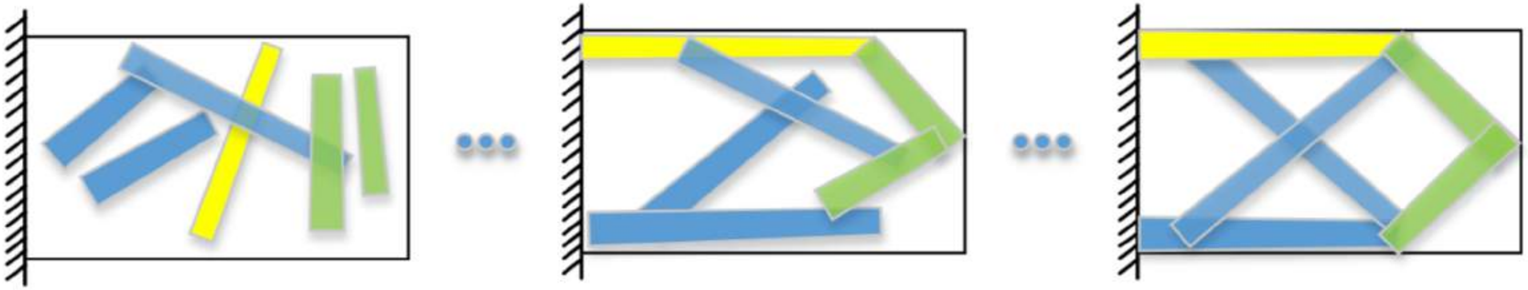
Explicit TopOpt



https://github.com/topggp/blog



Eulerian VS Lagrangian

Design variables update

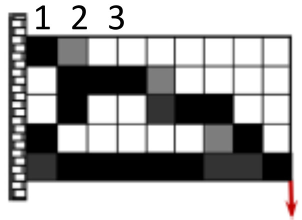
Interpretation

Model update
Density, Young modulus

Density based

variables : material density

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

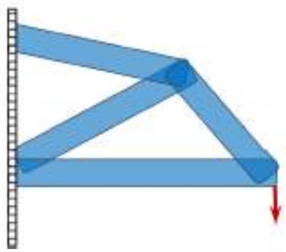


Innovative approach to help engineering solution identification : Components are placed in design space according to variables and material density are derived accordingly.

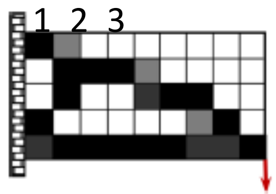
Lagrangian approaches

Variables : geometrical data

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



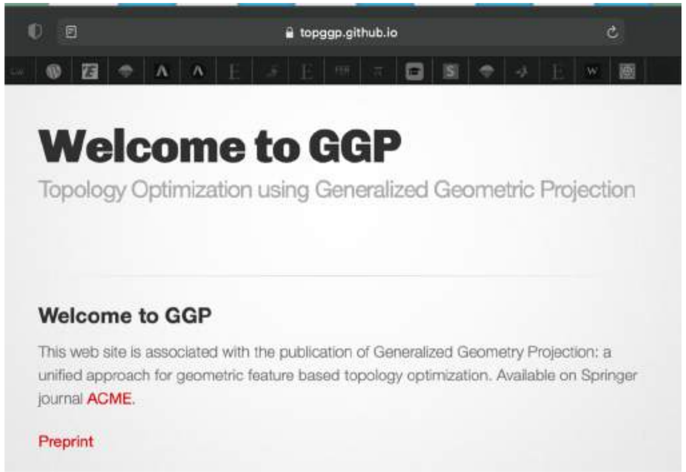
Projection



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

[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.

Different Programing language &app



Matlab (historic top88)
code by S. CONIGLIO: [Matlab's topggp]
Python
code by J. CRUZ-FERREIRA-MATOS: [Python's topggp]
Julia (differential programing)
code by R. GRAPIN & J. MORLIER: [Julia's topggp]
Applications for Aerospace
Tutorials available by V. BHAT and J. MORLIER
[Aerospace's topggp]
Applications for ALM
Tutorials available by G. CAPASSO, V. BHAT S. CONIGLIO, C. GOGU and J. MORLIER
[ALM's topggp]

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
$\mathbb{V}$	$\frac{\sum_{j=1}^{4} H_\epsilon(\chi_j^{el})}{4}$	$\Pi(\left\{\hat{\delta}^{el}\right\}_v, \kappa)$	$\Pi(\left\{\delta^{el}\right\}_v, \kappa)$
$\mathbb{M}$	$\frac{\sum_{j=1}^{4} (H_\epsilon(\chi_j^{el}))^q}{4}$	$\Pi(\left\{\hat{\delta}^{el}\right\}_c, \kappa)E$	$E_{min} + (E - E_{min})\Pi(\left\{\delta^{el}\right\}_c, \kappa)^{p_b}$

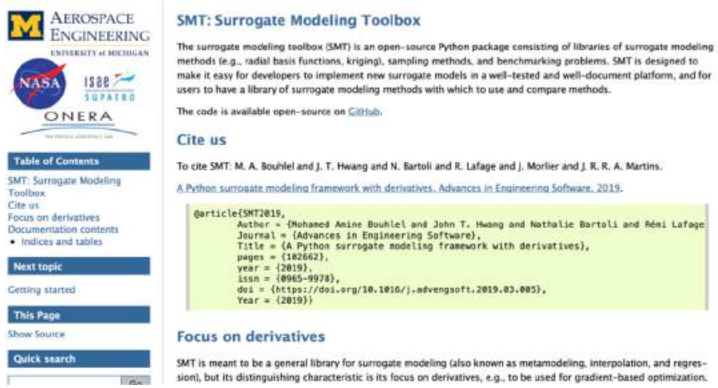
- All reviewed approach can be represented as a special case of Generalized Geometry Projection
- One can moreover change sampling window size (R),shape (p), Gauss Points number (N_{GP})
- Changing the number of Gauss point one can avoid optimization saddle points induced by the projection

Researcher view (Reproducible Research)

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

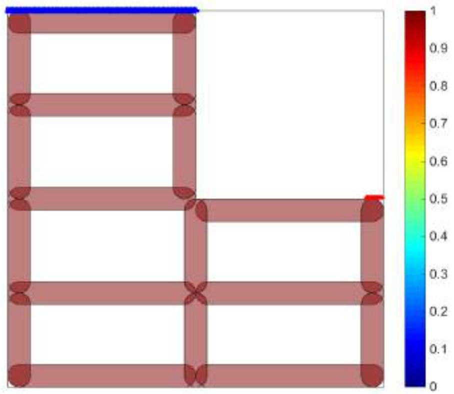
- https://github.com/topggp/blog
- https://github.com/mid2SUPAERO/EMTO

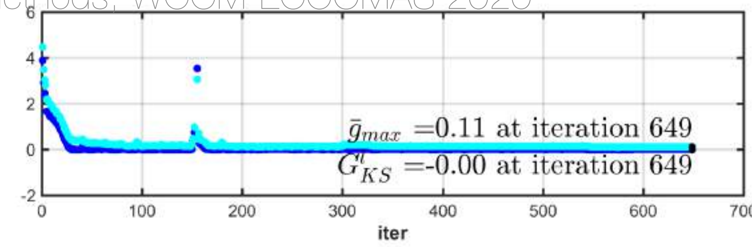
- https://smt.readthedocs.io/en/latest/

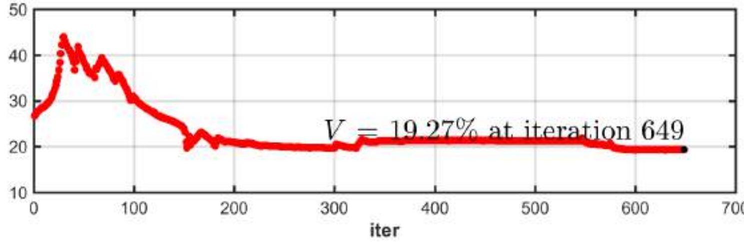


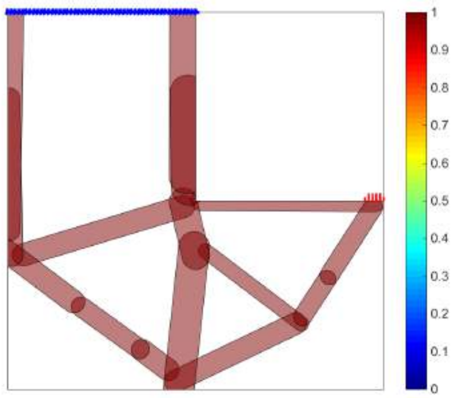
Remind my warning…

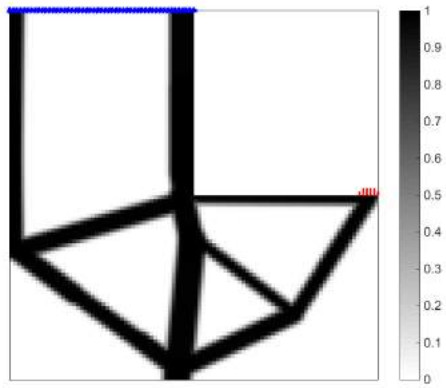
S. Coniglio, J. Morlier, C. Gogu, An introduction to Generalized Geometry Projection, a unified framework for feature-based topology optimization methods, WCCM-ECCOMAS 2020

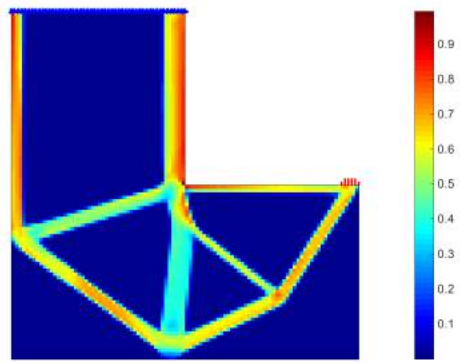








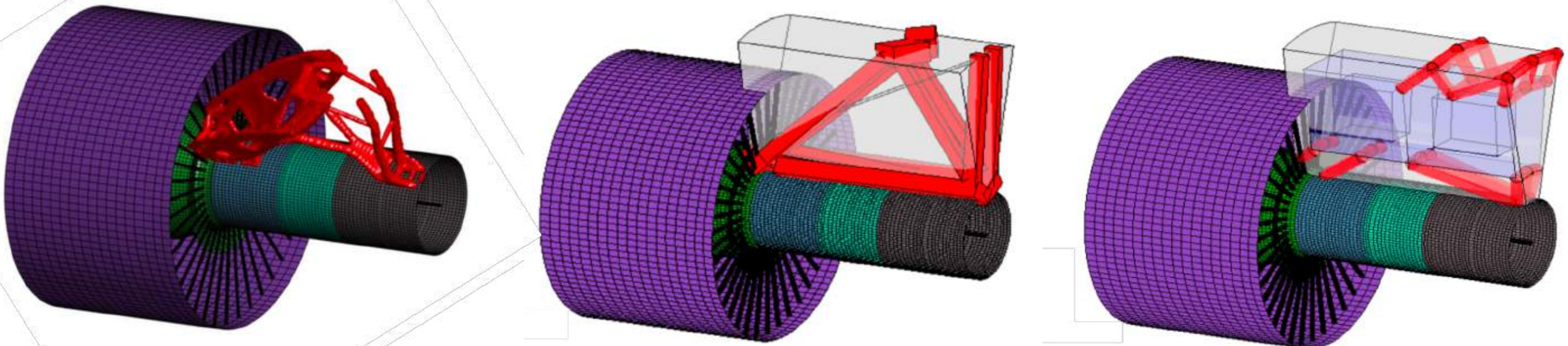




Bionic Design? AIRBUS

RESULTS OF SIMONE CONIGLIO's PHD at AIRBUS

under the supervision of Christian Gogu and I



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.

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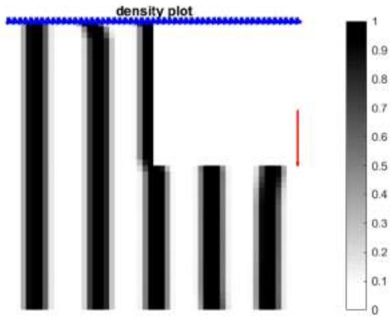
How to **ECO**design tomorrow's structures?

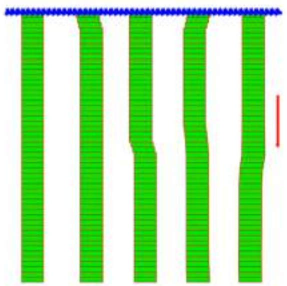
Prof. Joseph Morlier, Vilas Bhat*, Edouard Duriez, Enrico Stragiotti

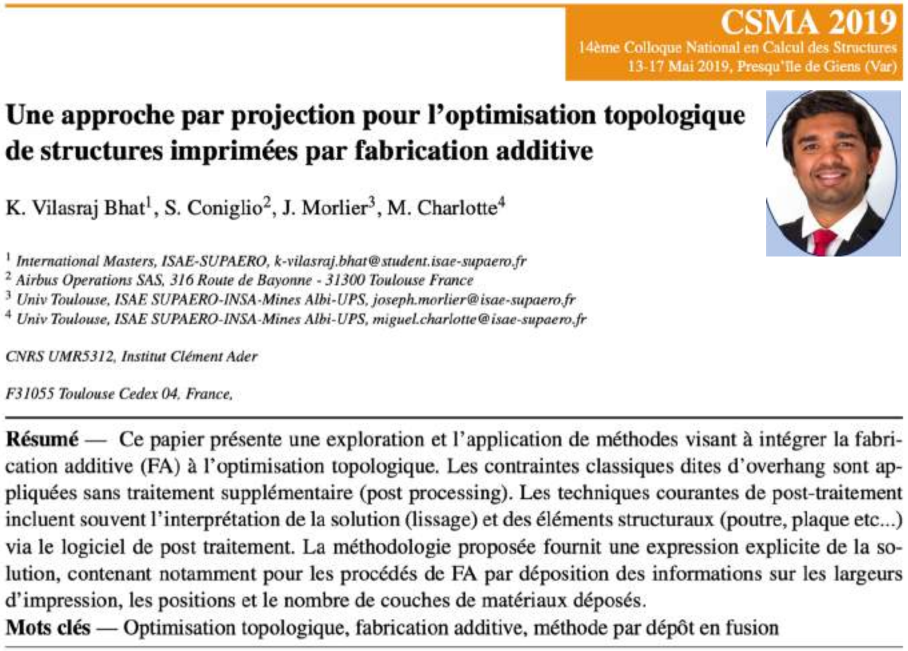
#Multiscale aerostructures
#Reasoned HPC
#AI4E
#MDO including Ecodesign of Materials & Process, 3Dprinting, SHM …

*

Again… we started with a SUPAERO's student project







CSMA 2019

14ème Colloque National en Calcul des Structures
13-17 Mai 2019, Presqu'île de Giens (Var)

Une approche par projection pour l'optimisation topologique de structures imprimées par fabrication additive

K. Vilasraj Bhat[1], S. Coniglio[2], J. Morlier[3], M. Charlotte[4]

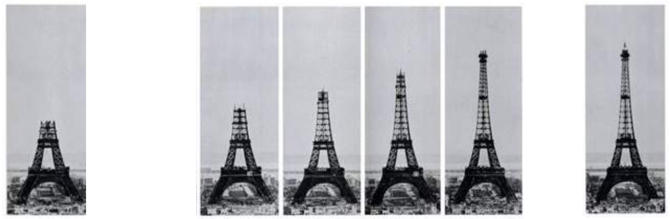
[1] *International Masters, ISAE-SUPAERO, k-vilasraj.bhat@student.isae-supaero.fr*
[2] *Airbus Operations SAS, 316 Route de Bayonne - 31300 Toulouse France*
[3] *Univ Toulouse, ISAE SUPAERO-INSA-Mines Albi-UPS, joseph.morlier@isae-supaero.fr*
[4] *Univ Toulouse, ISAE SUPAERO-INSA-Mines Albi-UPS, miguel.charlotte@isae-supaero.fr*

CNRS UMR5312, Institut Clément Ader

F31055 Toulouse Cedex 04, France,

Résumé — Ce papier présente une exploration et l'application de méthodes visant à intégrer la fabrication additive (FA) à l'optimisation topologique. Les contraintes classiques dites d'overhang sont appliquées sans traitement supplémentaire (post processing). Les techniques courantes de post-traitement incluent souvent l'interprétation de la solution (lissage) et des éléments structuraux (poutre, plaque etc...) via le logiciel de post traitement. La méthodologie proposée fournit une expression explicite de la solution, contenant notamment pour les procédés de FA par déposition des informations sur les largeurs d'impression, les positions et le nombre de couches de matériaux déposés.

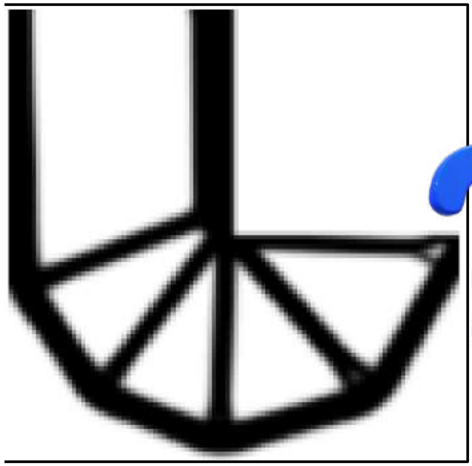
Mots clés — Optimisation topologique, fabrication additive, méthode par dépôt en fusion

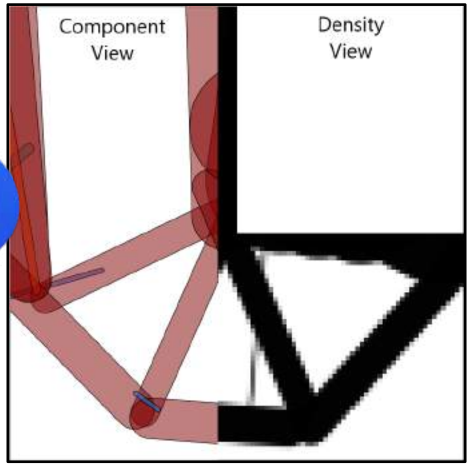


$N_x = N_y = 52$
$v_f = 0.4$
$5\ printing\ components$
$18\ printing\ intervals$
$5 \times 18 \times 2\ design\ variables$

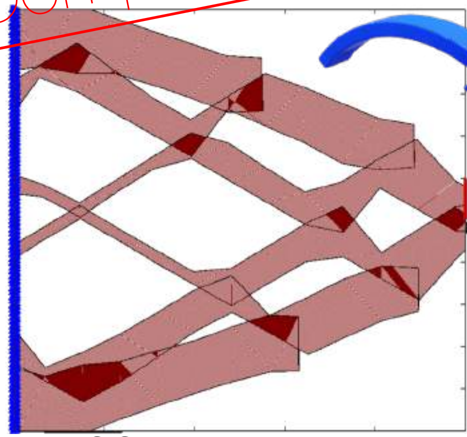
GGP For ALM?

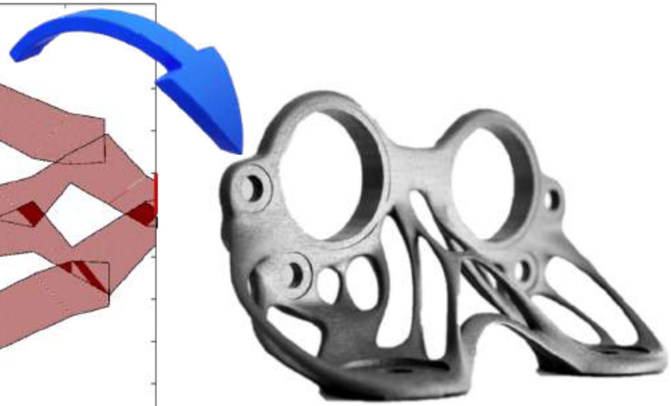
New paper in Elsevier's Computer & Graphics


SIMP



GGP

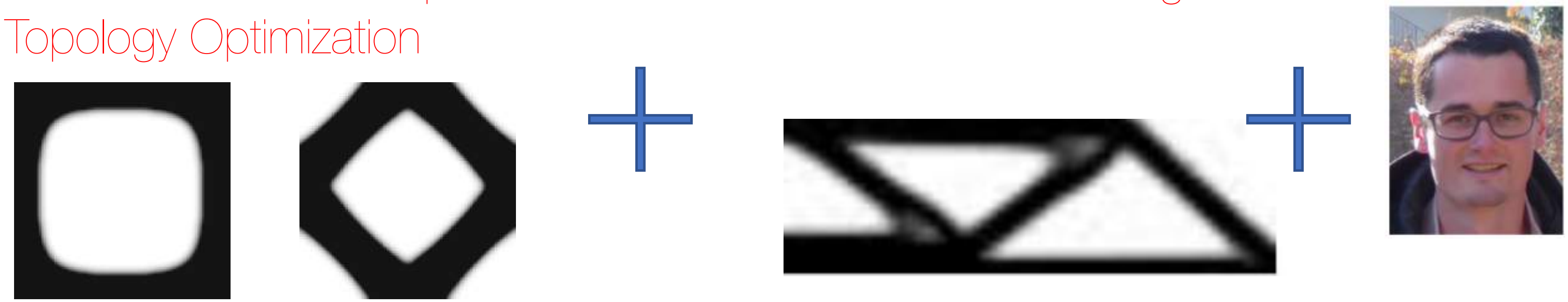

GGP for 3D printing


3D Printed part

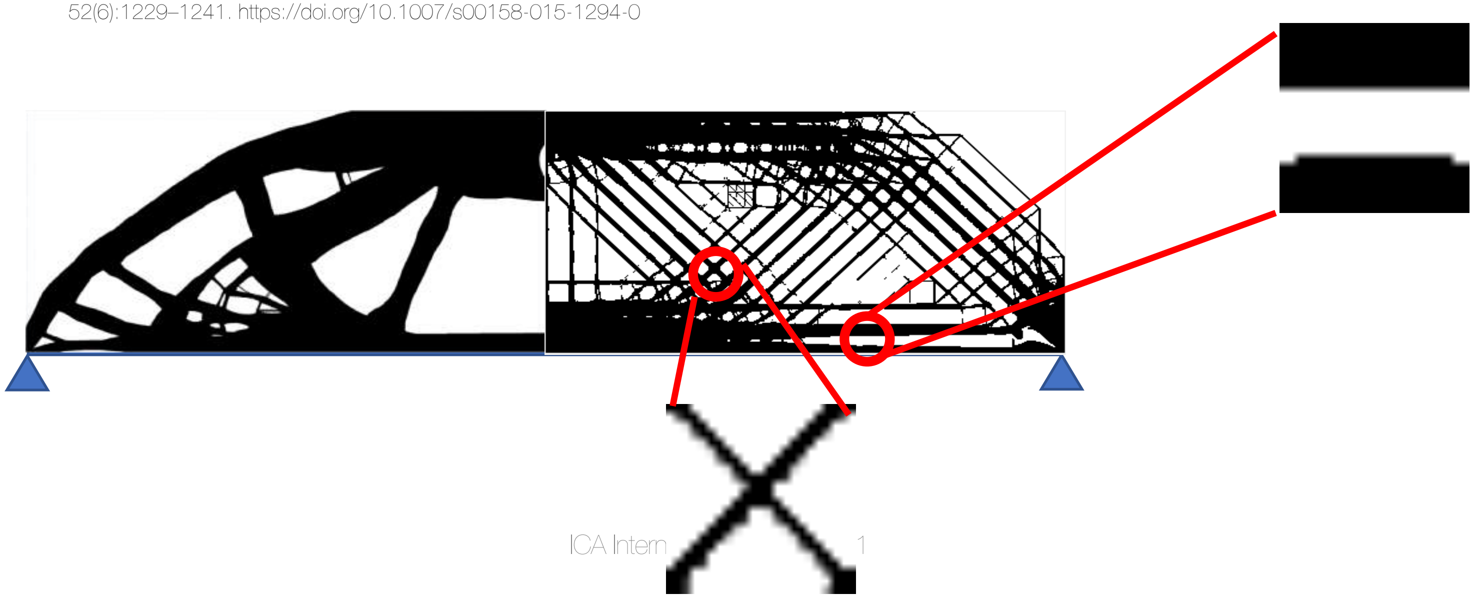
G. Capasso, V. Bhat, S. Coniglio, J. Morlier, C. Gogu, Topology Optimization of Additive Layer Manufacturing products using Generalized Geometric Projection, WCCM-ECCOMAS 2020

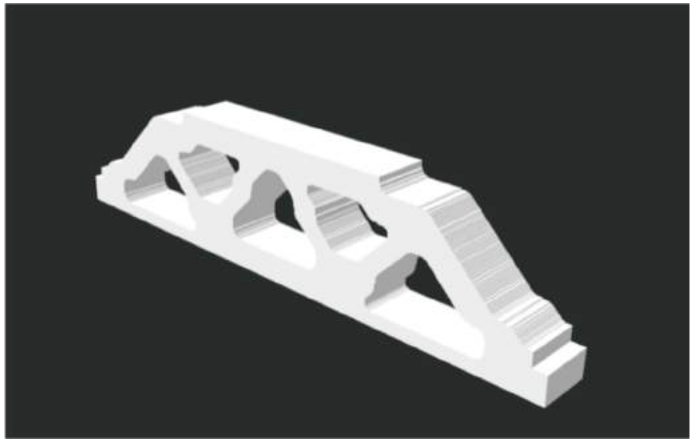
Multi-scale TO

i.e. Write a two level optimization that combines Unit cell design & Topology Optimization

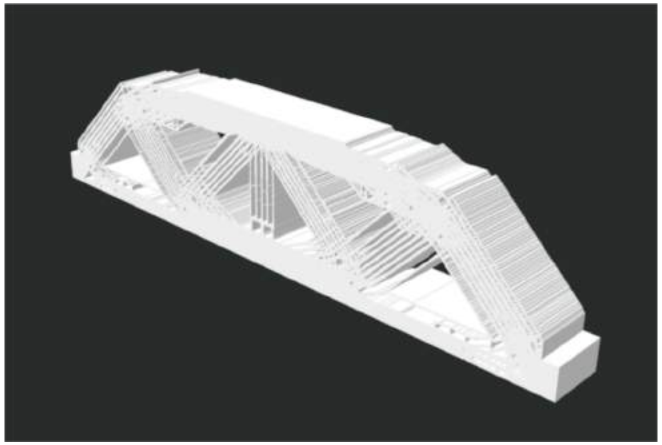


Xia L, Breitkopf P (2015) Design of materials using topology optimization and energy-based homogenization approach in Matlab. Struct Multidisc Optim 52(6):1229–1241. https://doi.org/10.1007/s00158-015-1294-0



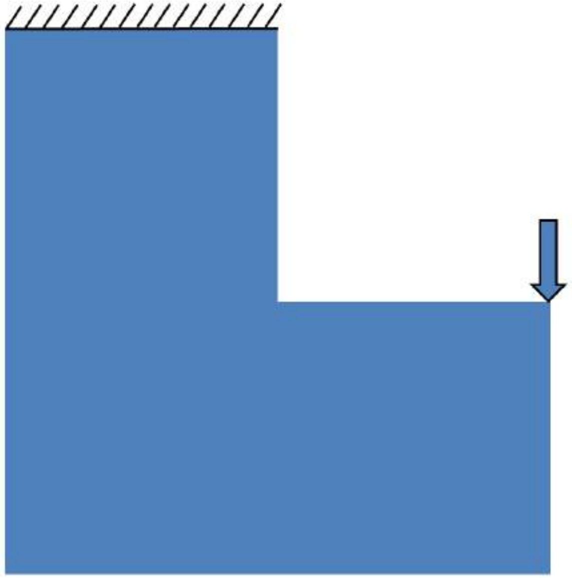


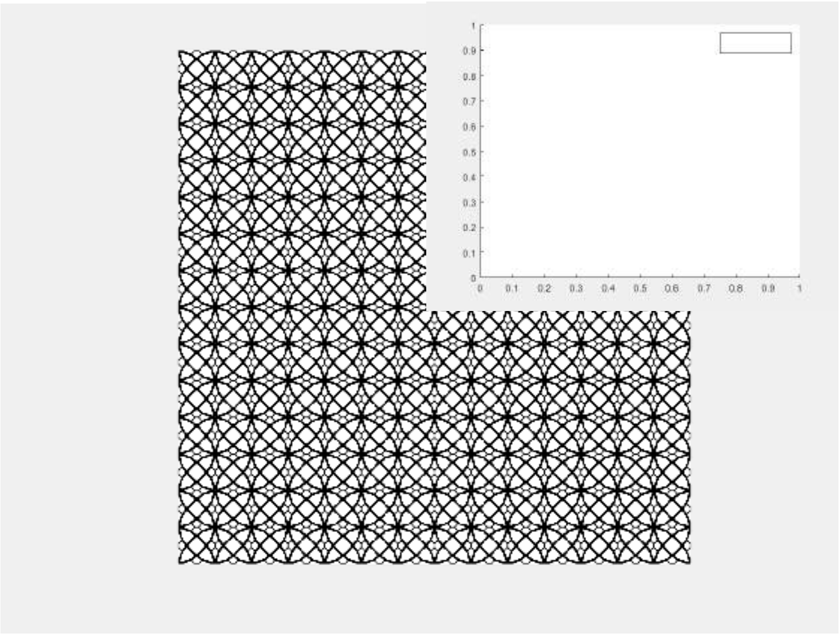
Versus



EMTO on L-shape (cellular /architectured materials)

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.

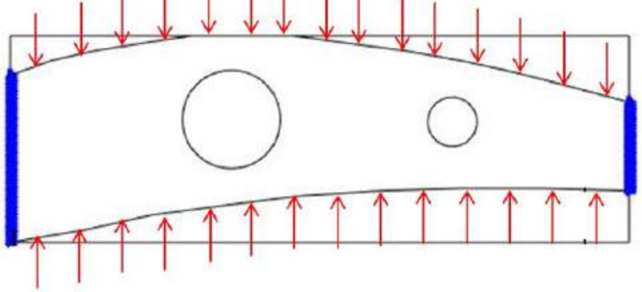


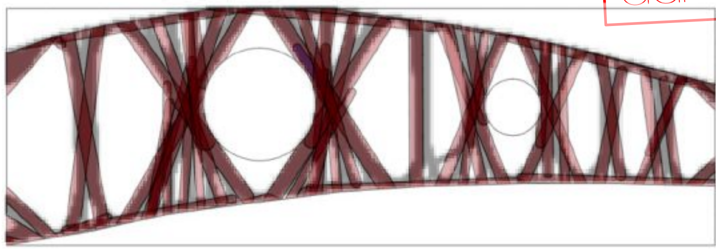


https://github.com/mid2SUPAERO/EMTO

Aircraft rib design

- Again Only pressure loads

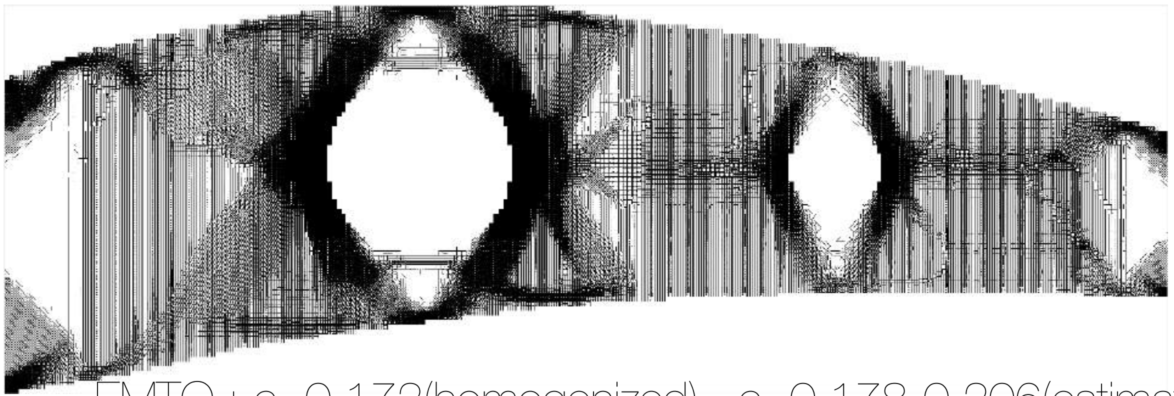




SIMP : c=0.198

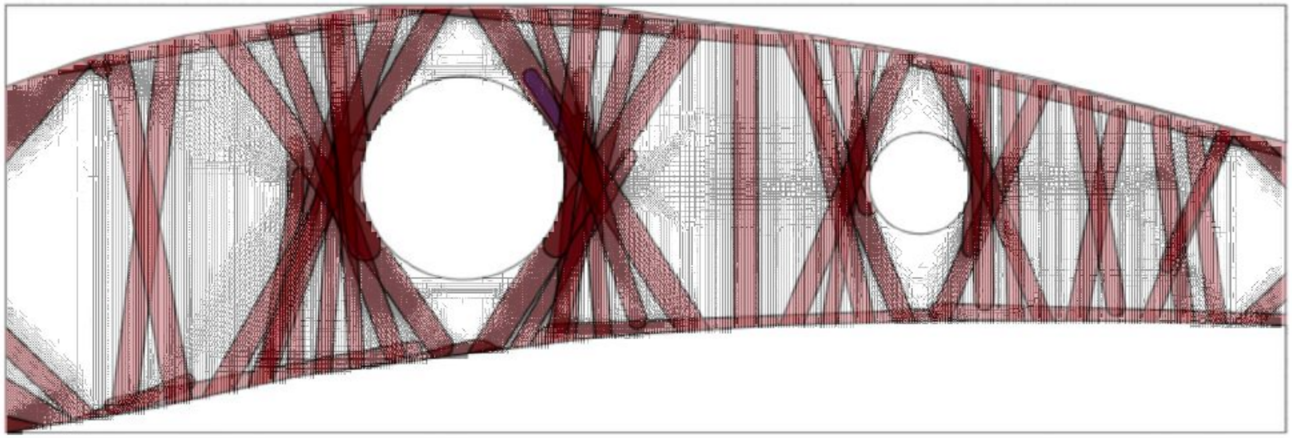
GGP := EASY EXPLORATION of POTENTIAL DESIGN OF STRUCTURES

GGP-AGP: C=0.165

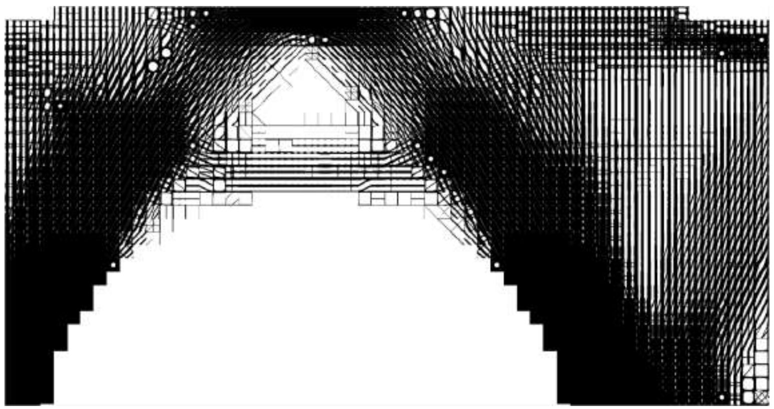


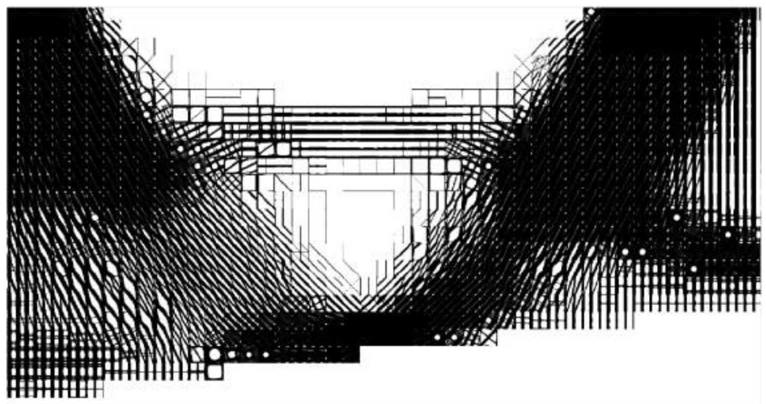
EMTO : c=0.172(homogenized) c=0.178-0.206(estimate)

EMTO vs GGP



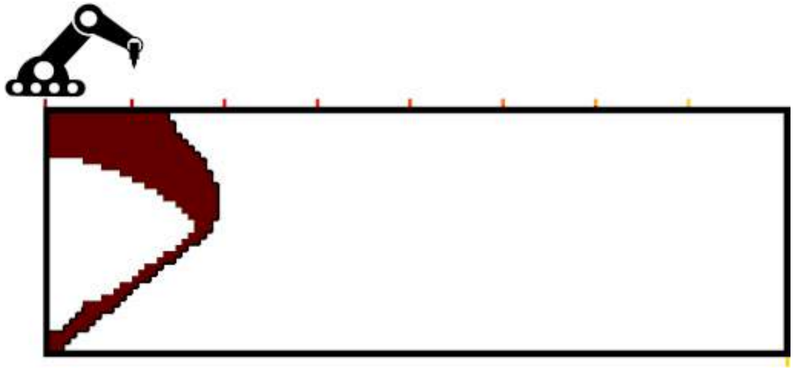
Multiscale approach is a complete REDESIGN: Creation of multiple paths for internal forces





It should be manufactured by machine

Conclusions

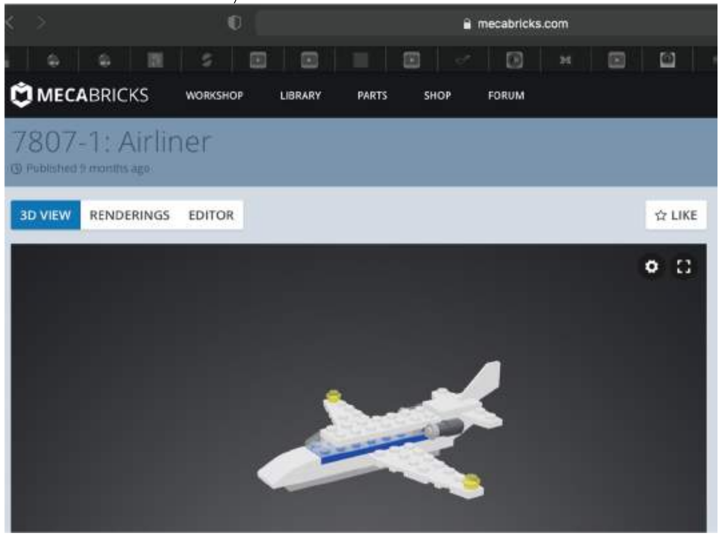


- In Phase with Computational fabrication (see Jun Wu's TUDelft research)

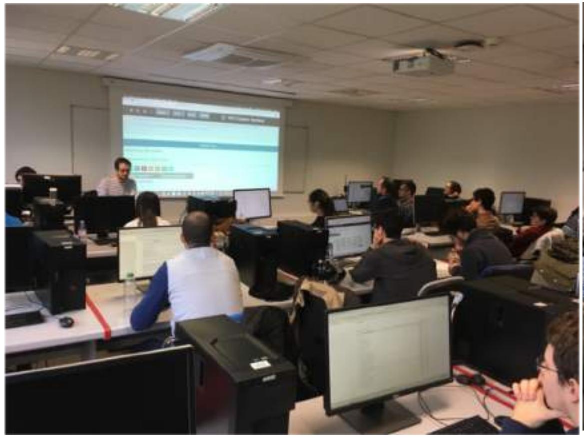
- NextGen Aerostructures : Structural mass optimization → CO2 optimization & optimal Manufacturable solution using ALM & AFP (Edouard'& Enrico's thesis)

- Et oui on peut construire une aerostructure en LEGO ;)

https://www.mecabricks.com/en/models/0DvYp8rdj9e



If you want to start in design optimization



- Sensitivity Of Finite Element Code
- Structural/Topology Optimization
- Continuous Constrained Optimization
- Surrogate/DOE using **SMT**
- UQ
- Artificial Intelligence For Engineers
- Reduced Order Modeling
- MDO using **Openmdao**

https://github.com/jomorlier/mdocourse

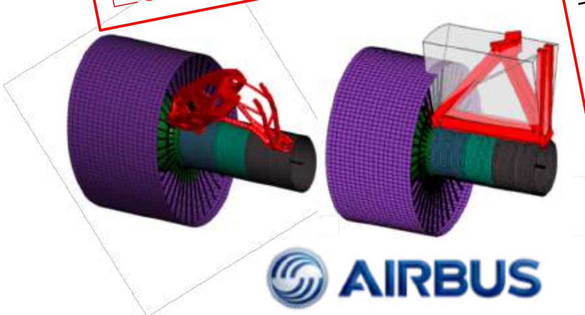
https://github.com/jomorlier/mdo_ml_21

https://github.com/jomorlier/OptimizationCourse

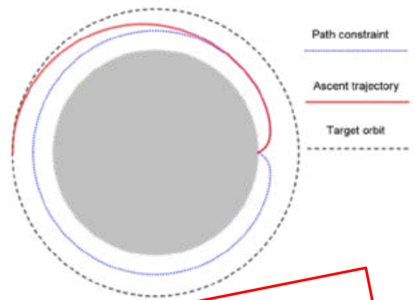
INSTITUT CLÉMENT ADER

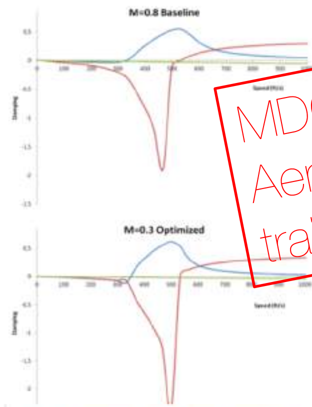
https://ica.cnrs.fr/author/jmorlier/

Structural Optimization & Ecodesign

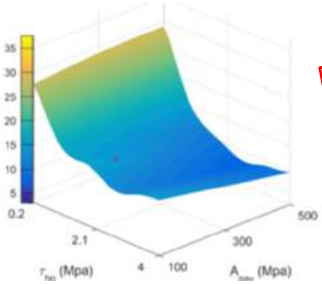


THANK for Your ATTENTION

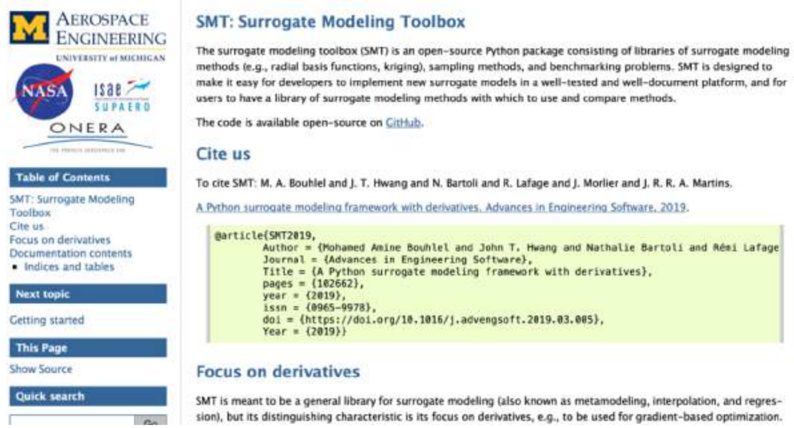




MDO with Aeroelasticity, trajectory or control



#AI4E
Artificial Intelligence For Engineers



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}}
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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.

https://github.com/SMTorg/smt