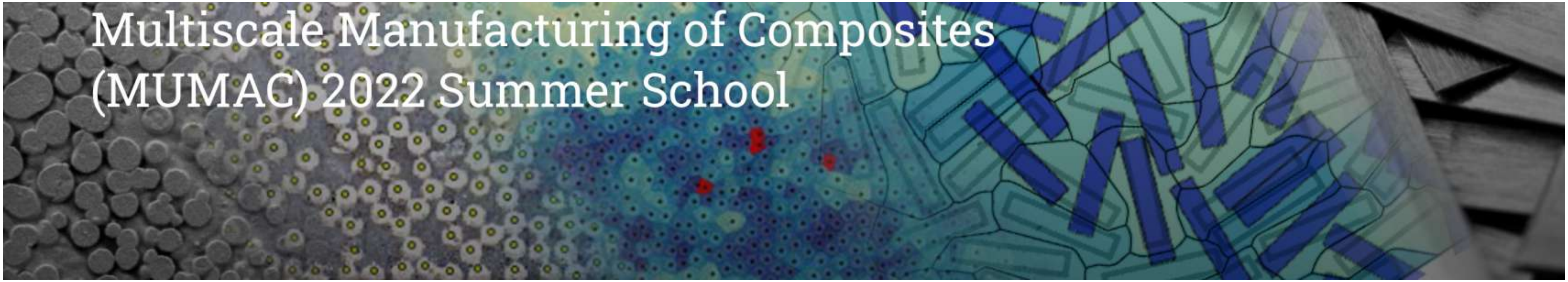
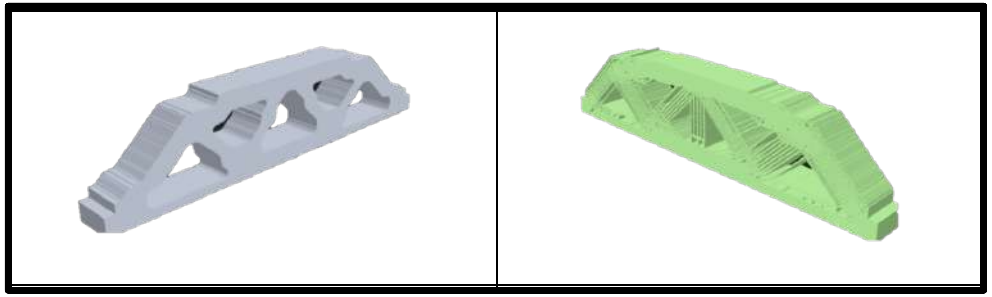


Topology optimization & eco-efficient design



Professor Joseph Morlier

ISAE-SUPAERO, FRANCE

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

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

ICA INSTITUT CLÉMENT ADER

Au programme

Duration	Description	Agenda
15’	Design Optimization	Refresh
15’	Computing Derivatives	Mathematical Background
15’	Topopt review	Need a break ?
15’	Current CAD-CAE	Quiz
15’	GGP for ALM	Our research
15’	Ecodesign	That’s new

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 -

Au programme

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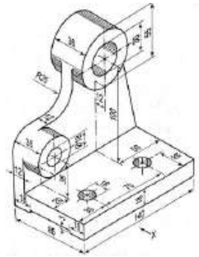
Current CAD-CAE

Practical Engineering Skills

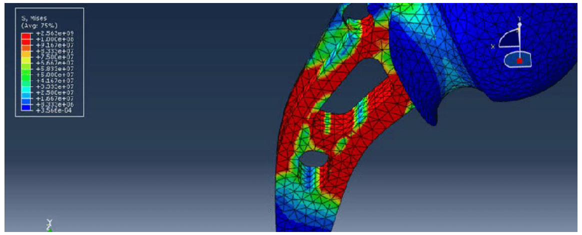


Current research shortcut this path

CAD design

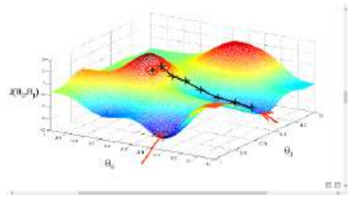
(engineering drawings)

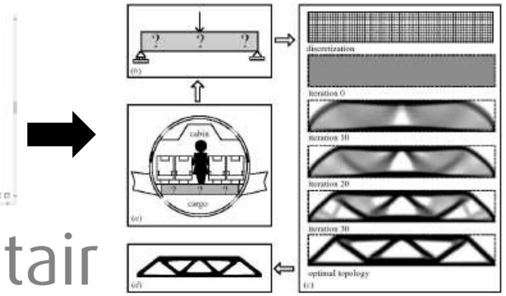
Finite Element Simulations



(stress analysis)

Gradient descent optimization
(TopOpt)





Additive Manufacturing
(future of industrial standards of manufacturing)

Software list

https://www.topology-opt.com/software-list
abaqus, nastran, ansys, comsol, ls dyna etc…

https://www.materialise.com/en/cases/materialise-3-matic-makes-topology-optimization-more-attractive

Mechanical Learning of Additive Manufacturing Parts

- Highlights of MATLS 2H04A (2018) – Structure Materials Design Project

McMaster University

Compression tests of students' designs
(video click to play: crushed samples will disappear)

Sessional Instructor: Dr. Bosco (Hiu Ming) Yu, PhD
2018

Mechanical Learning of Additive Manufacturing Parts

- Highlights of MATLS 2H04A (2018) – Structure Materials Design Project

Mechanical Learning of Additive Manufacturing Parts

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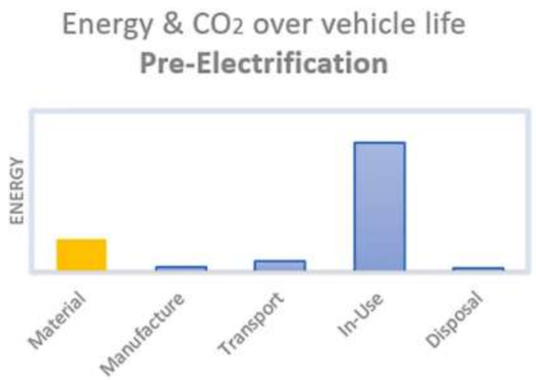
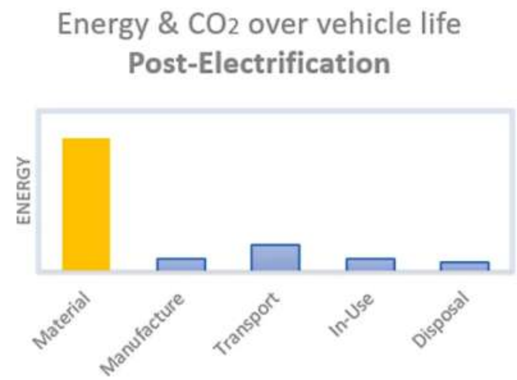
Compression tests of students' designs

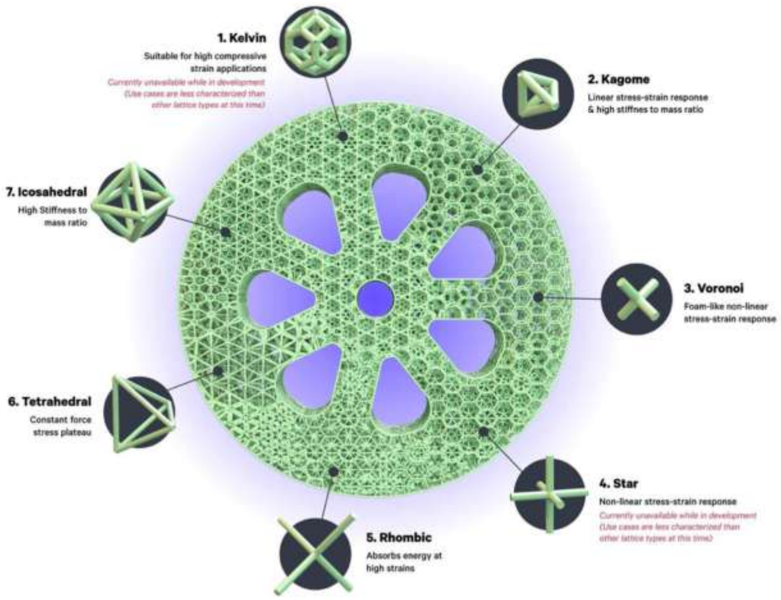
(video click to play: crushed samples will disappear)

Material/Process as new design variables

Eco Material selection
Eco Process selection





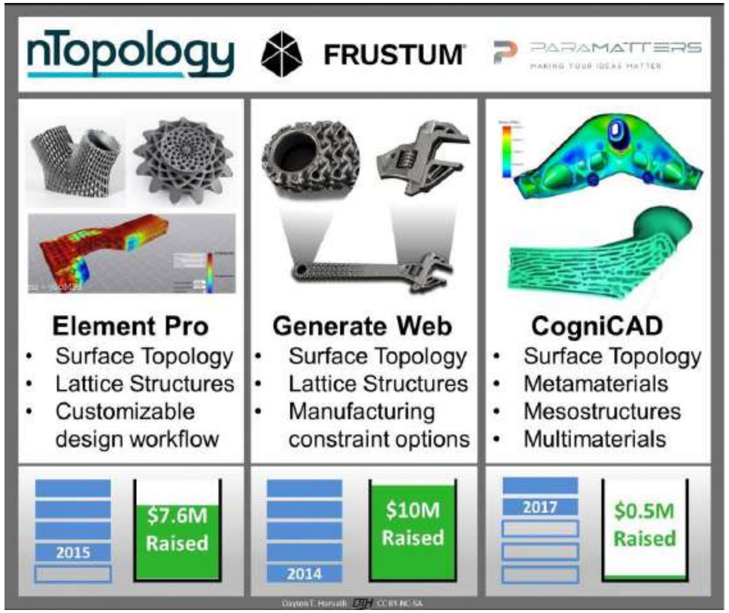


Unit cell design (anisotropy)
Digital materials

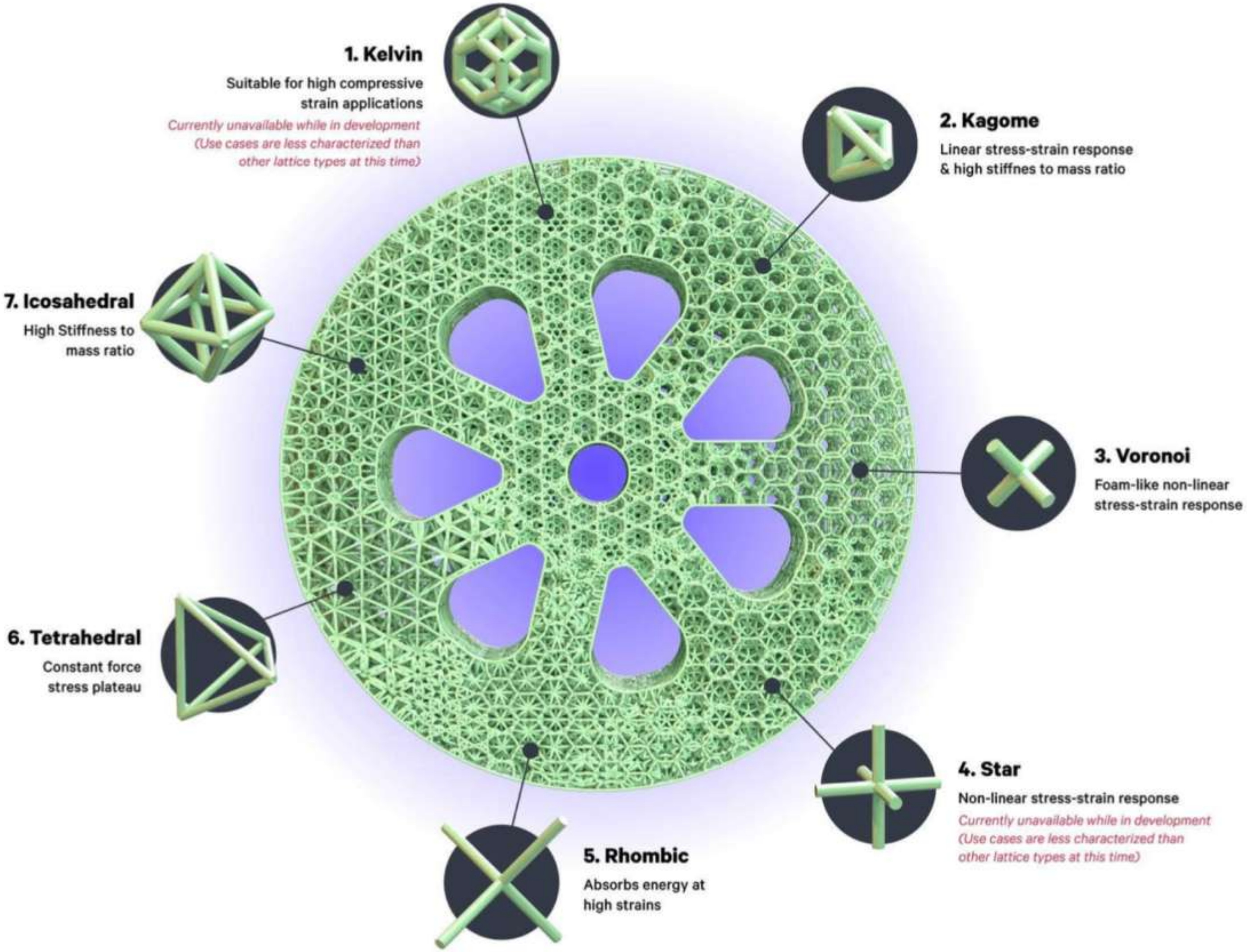
Softwares for **hierarchical design**

Conventional CAD programs do not work well
New players are emerging

Examples:
- ntopology (see case studies): https://ntopology.com/
- additiveflow: https://www.additiveflow.com/
- Hyperganic
- ParaMatters: https://paramatters.com/
- Fusion 360 (Autodesk)



Carbon example



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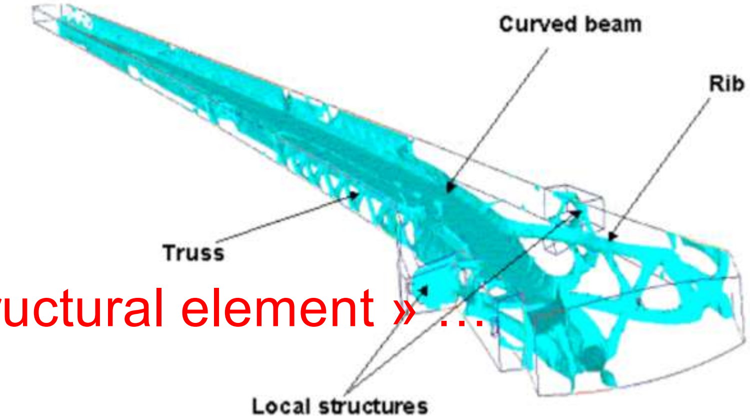
GGP for ALM

Reproducible Research

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

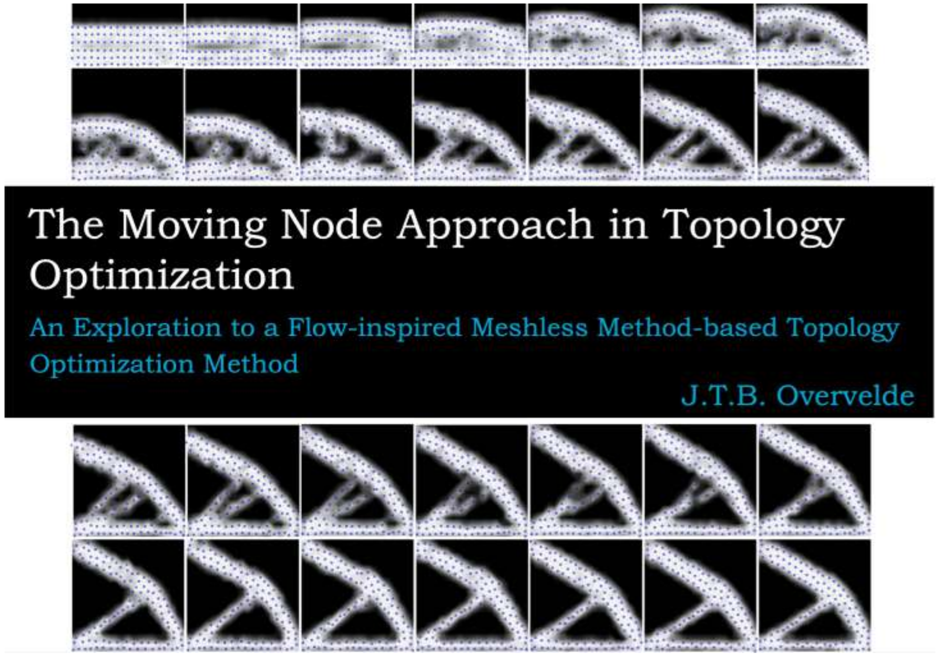
In 2016 I was searching to differentiate my TopOpt research

My idea was to use meshless method in TopOpt for « explicit » 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

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

State of the art

Design variables update

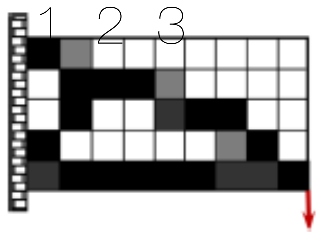
Interpretation

Model update
Density, Young modulus

Density based

variables : material density

$x_1 = 1$
$x_2 = 0.5$
$x_3 = 0$
...

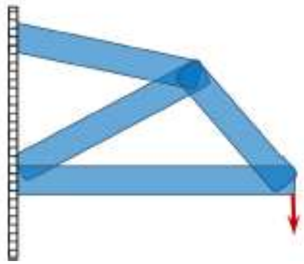


Innovative approach to help engineering solution identification : Components are placed in design space according to variables and material density are derived accordingly.

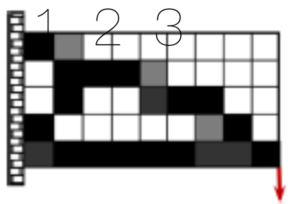
Lagrangian approaches

Variables : geometrical data

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



Projection

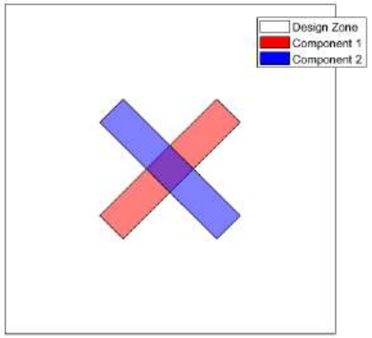


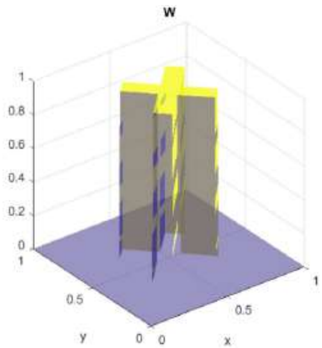
[12] Zhang, Weisheng, Jian Zhang, and Xu Guo. "Lagrangian description based topology optimization—a revival of shape optimization." Journal of Applied Mechanics 83.4 (2016): 041010.

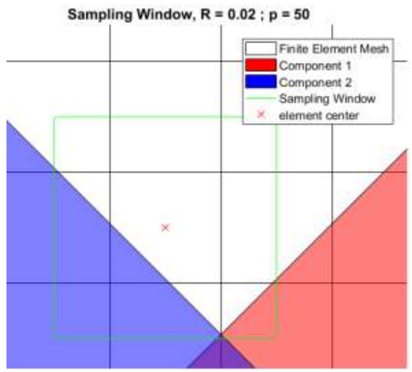
Design is made of engineering bricks like: beam, plate, brick….

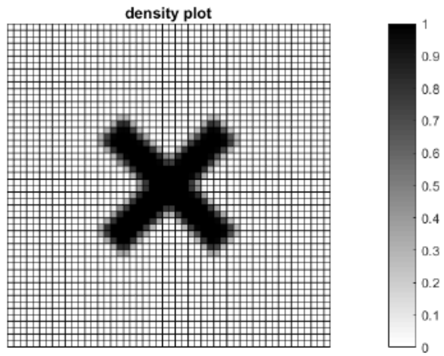
Generalized Geometric Projection

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









[Coniglio et al. 2019]

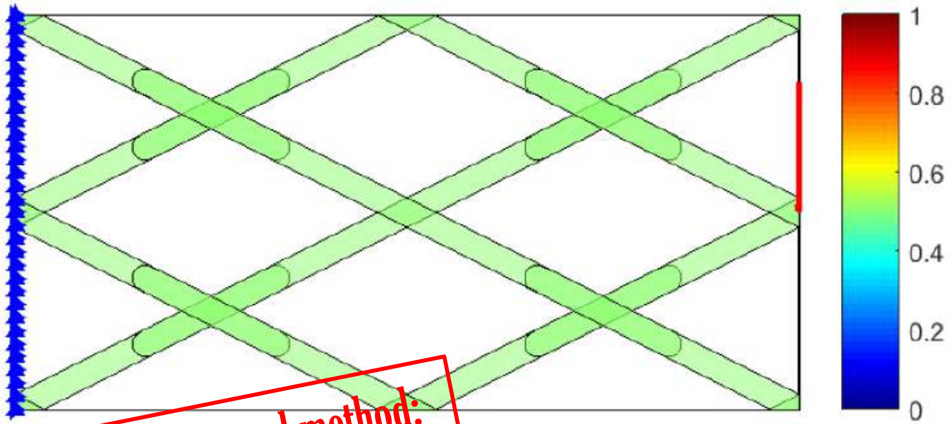
$$\mathbf{D}(\{X_g\}, \boxed{p}, \boxed{R}) = \{\{X\} \in \mathbb{R}^{d_g} \mid \| \{X\} - \{X_g\} \|_{2p} \leq R\}$$

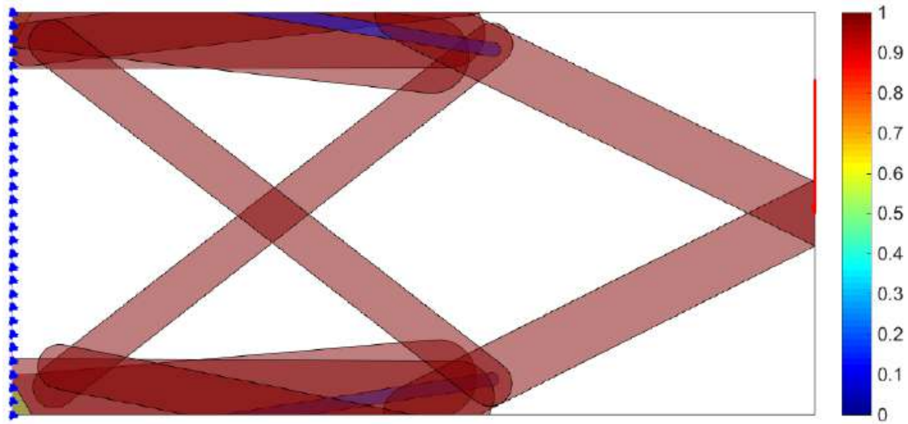
$$\delta_i^{el}(\boxed{W_i}, p, R) = \frac{\int_{\mathbf{D}(\{X_g^{el}\},p,R)} W_i(\{X\},\{X_i\},\{r\})d\Omega}{\int_{\mathbf{D}(\{X_g^{el}\},p,R)} d\Omega}$$

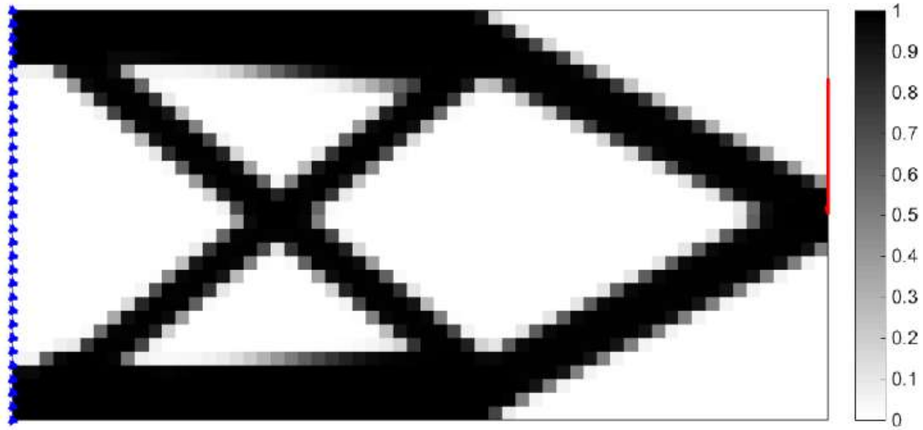
$$E^{el} = \boxed{\mathbb{M}}(\{\delta^{el}\}_c, E, E_{min}, \kappa)$$

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

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





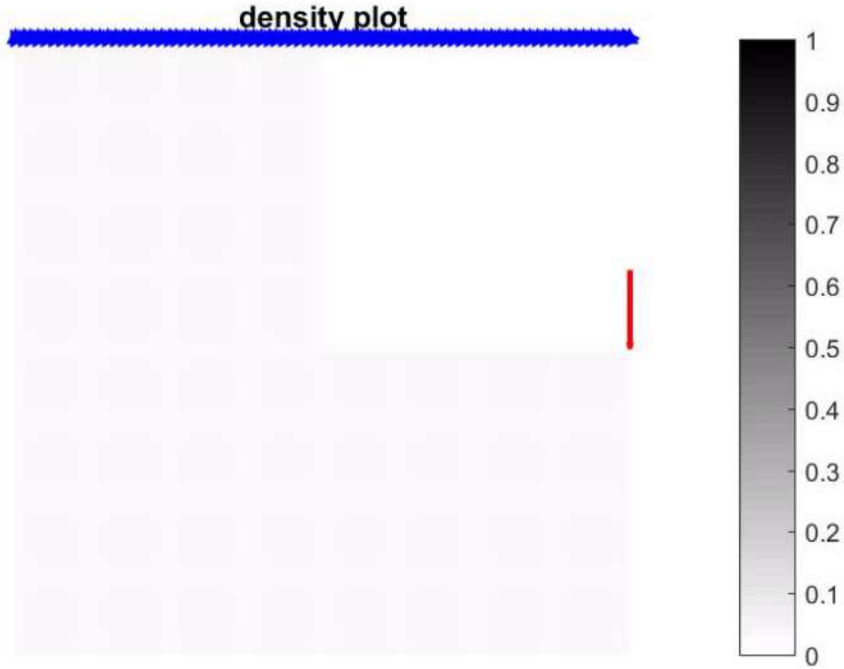


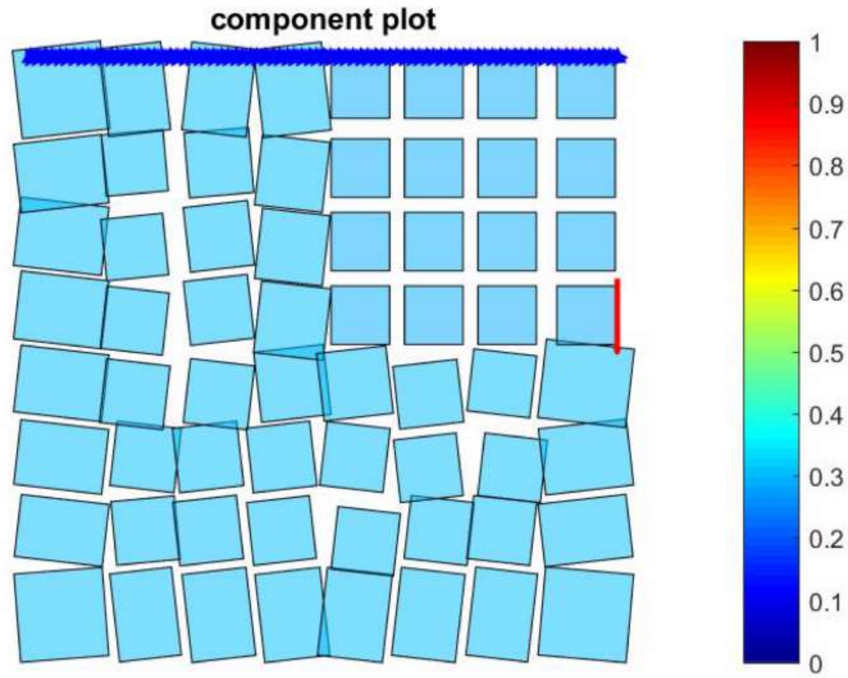
For every Gradient based method:
X0 sensitivity

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

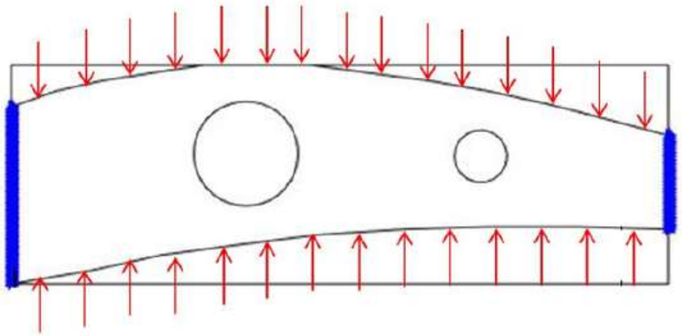
Results MNA, 8*8*6=384 design variables minC st Volfrac=0,4

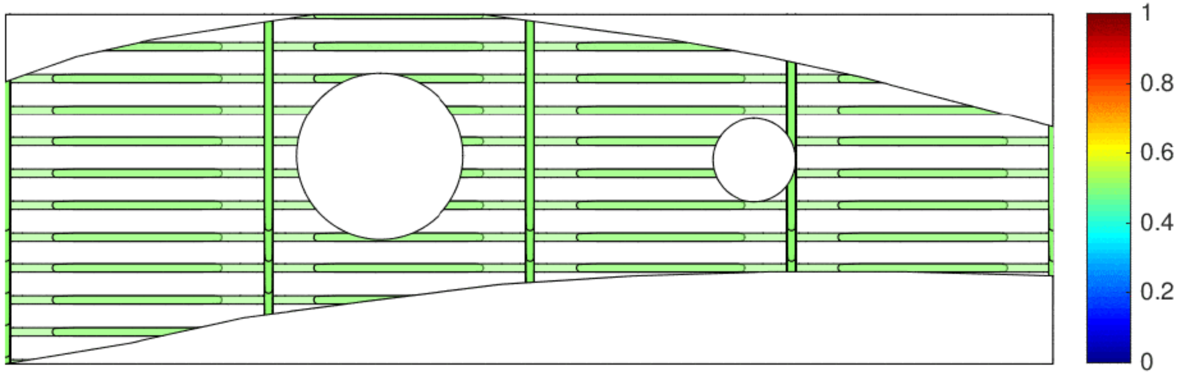
At the end, explicit assembly of components!





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





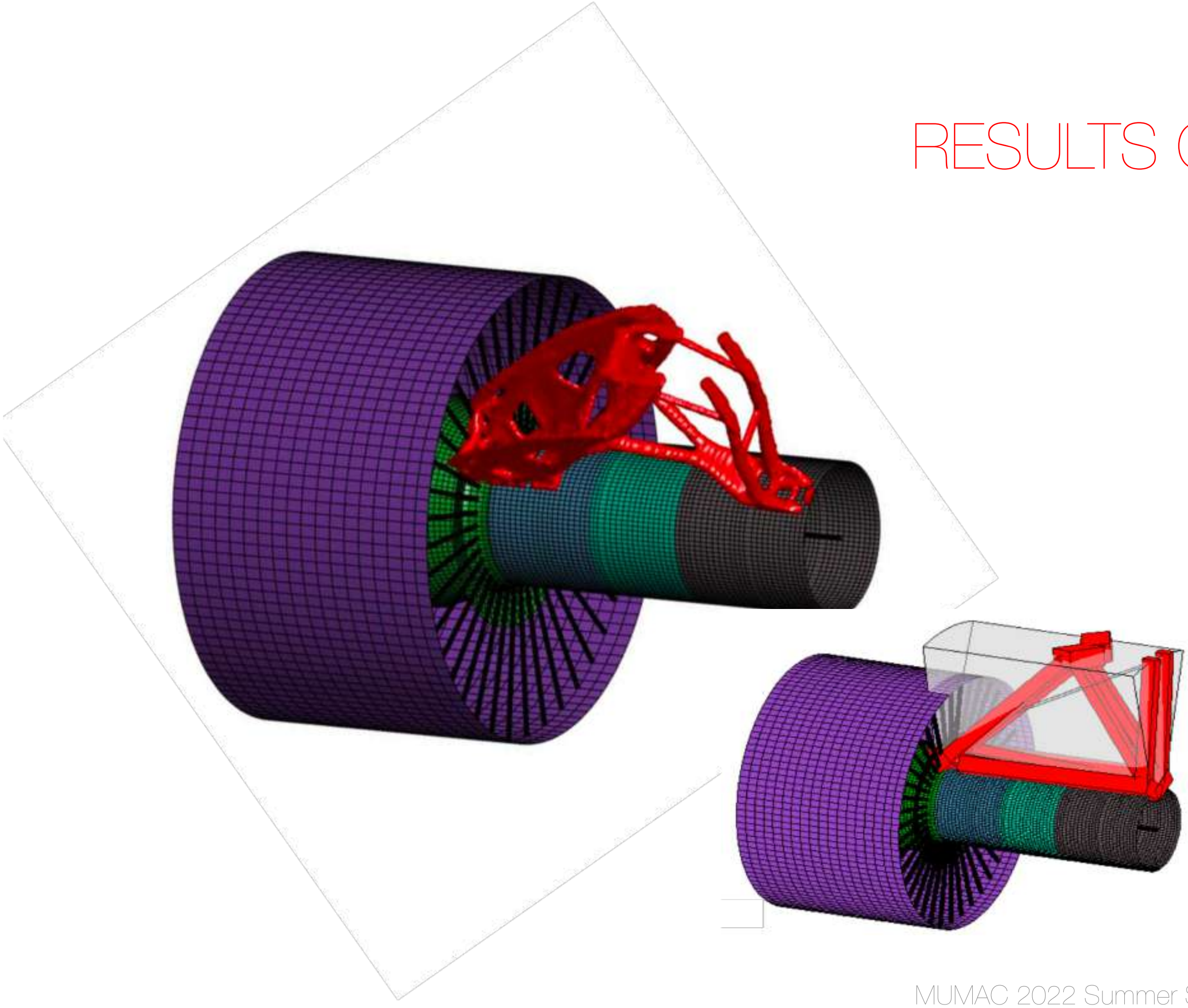
https://github.com/topggp/blog

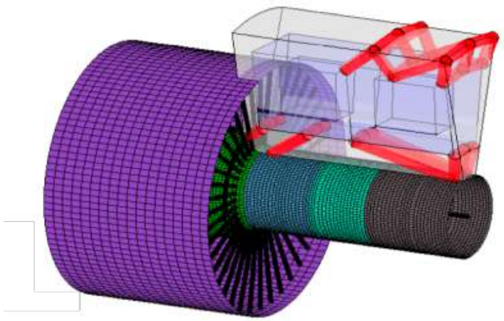
Bionic SIMP vs EXPLICIT TRUSS vs EXPLICIT BOX

RESULTS OF SIMONE CONIGLIO PHD

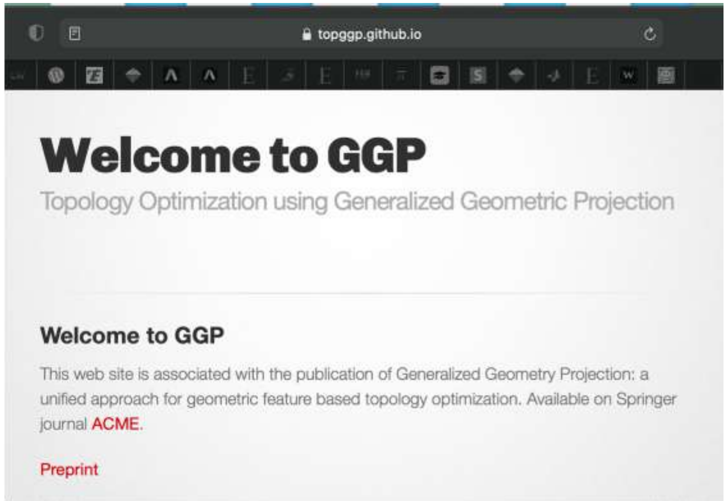
AIRBUS

TSFC + STRESS
ABAQUS REANALYSE





Different Programing language &app



Matlab (historic top88)
code by S. CONIGLIO: [Matlab's topggp]

Python
code by J. CRUZ-FERREIRA-MATOS: [Python's topggp]

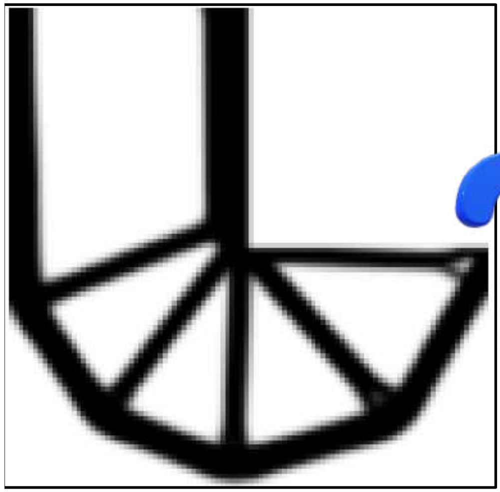
Julia (differential programing)
code by R. GRAPIN & J. MORLIER: [Julia's topggp]

Applications for Aerospace
Tutorials available by V. BHAT and J. MORLIER
[Aerospace's topggp]

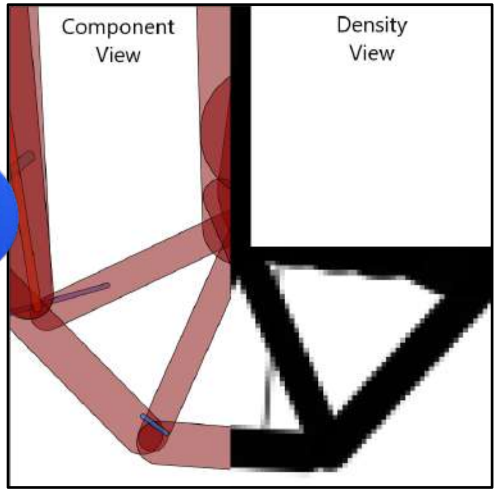
Applications for ALM
Tutorials available by G. CAPASSO, V. BHAT S. CONIGLIO, C. GOGU and J. MORLIER
[ALM's topggp]

GGP For ALM?

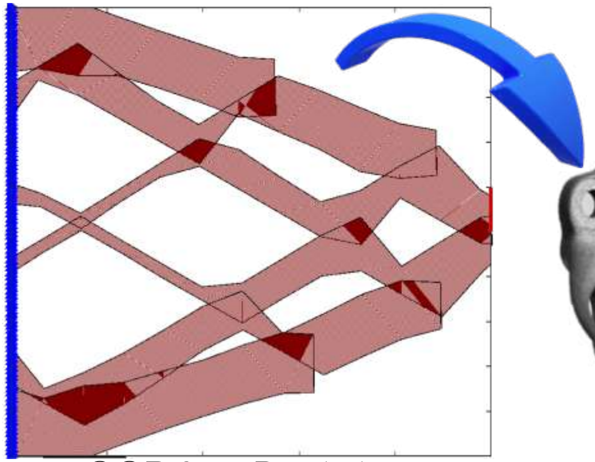
Prof, How can I do that?



SIMP



GGP

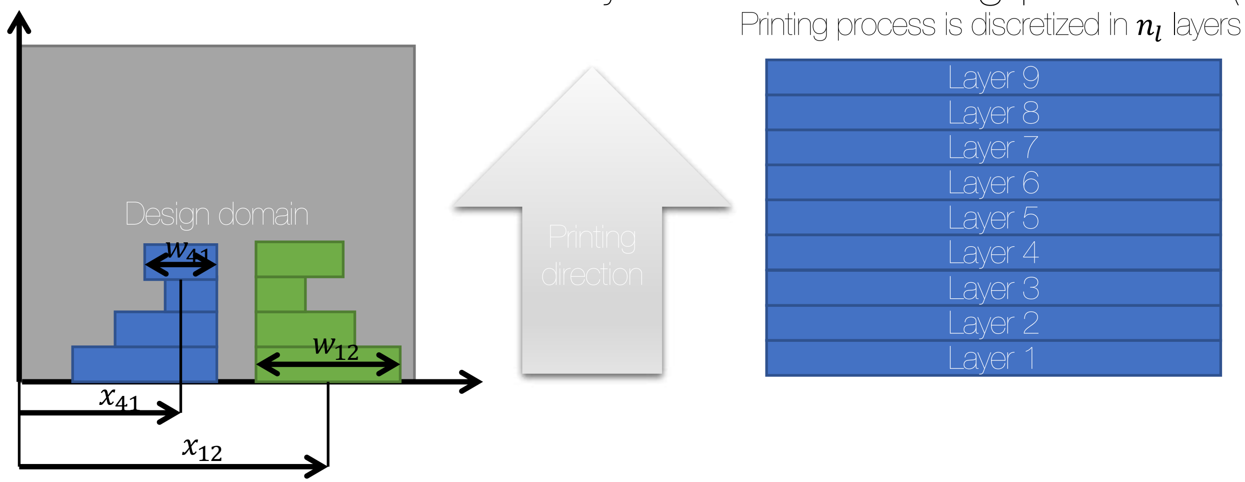


GGP for 3D printing

3D Printed part

ALM based on explicit topopt

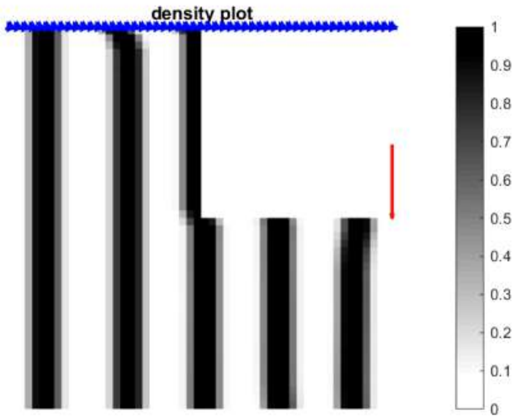
A solution is determined by its manufacturing process: (in this case printing path)

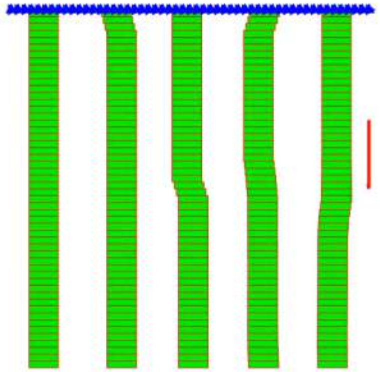


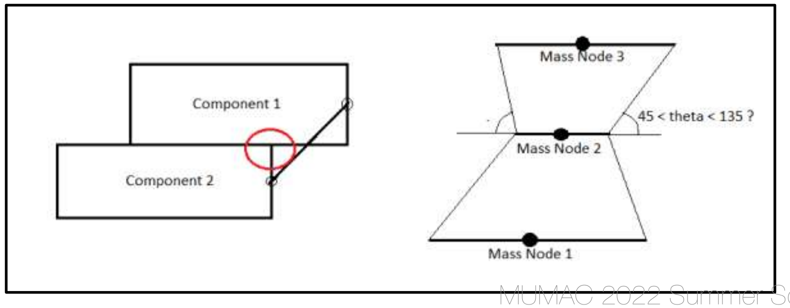
- MNA Components are replaced by printed branches
- Design variables will be printed branch position and width per layer: x_{li}, w_{li}
- For each layer a projection is made to get the solid model modulus

ALM based on explicit topopt

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







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

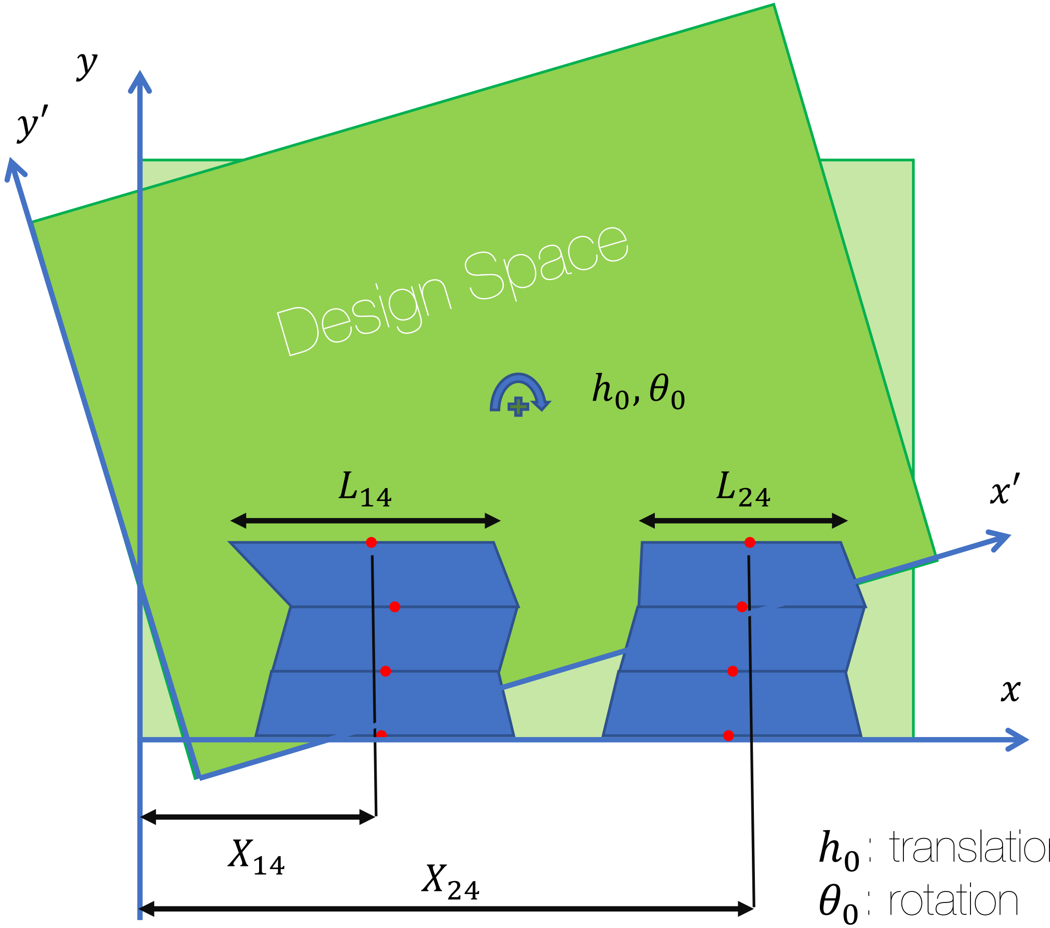
Results

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

Current approaches

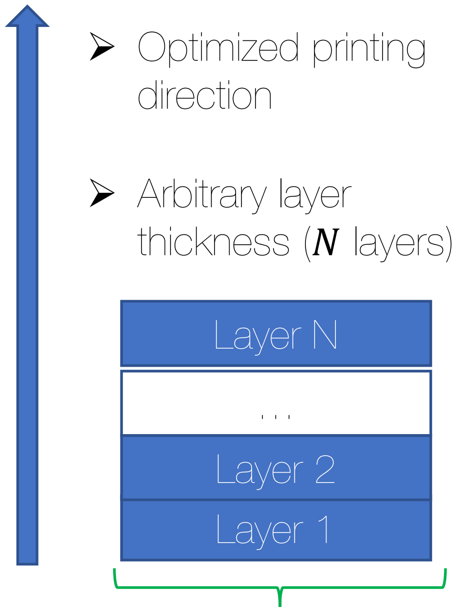
	Check on	Overhang angle	Bridge length	Optimal printing **plane**	Comment
SIMP [Leary et al. 2014]	Boundaries	Yes	No	No	Additional **iterations**
AM Filter (SIMP-based**)** [Langelaar 2015]	Densities	Yes	No	No	One constraint **per element**
Level-set [Allaire et al. 2017]	Boundaries	Yes	Yes	No	Implicit **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: Last Results



h_0: translation
θ_0: rotation

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



Component $\boldsymbol{j}$

Problem Statement

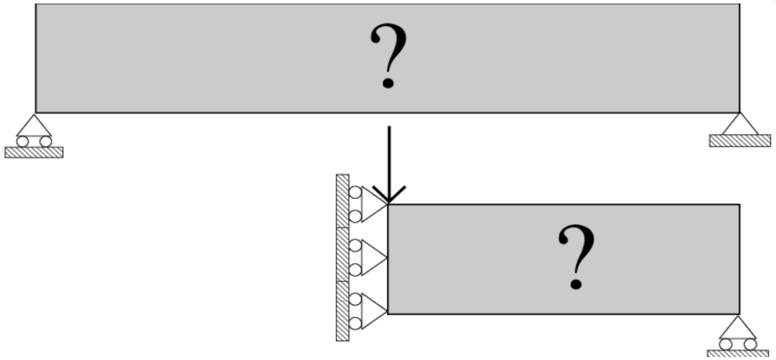
$$\begin{cases} min & & C(X, U_f) \\ s.t.: & & V \leq V_0 \\ & \theta_{ij} \leq \theta_{max} & \forall\, i = 1, \dots, N \quad j = 1, \dots, M \\ & BL_{ij} \leq BL_{max} & \forall\, i = 1, \dots, N \quad j = 1, \dots, M \end{cases}$$

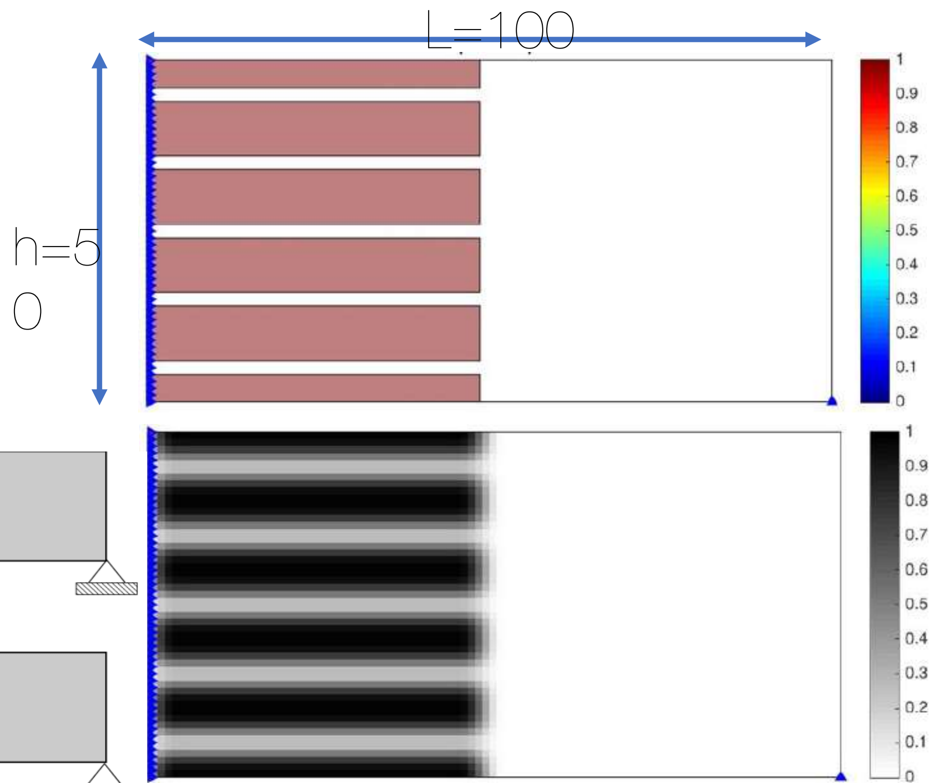
- N layers per component
- N+1 segments per component
- M components
- 2 features per segment (X_k, L_k)
- 2 features per component (h_j, m_j)
- 2 global features (h_0, θ_0)

→ $2M(N+2)+2$ 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

Parameter	Quantity
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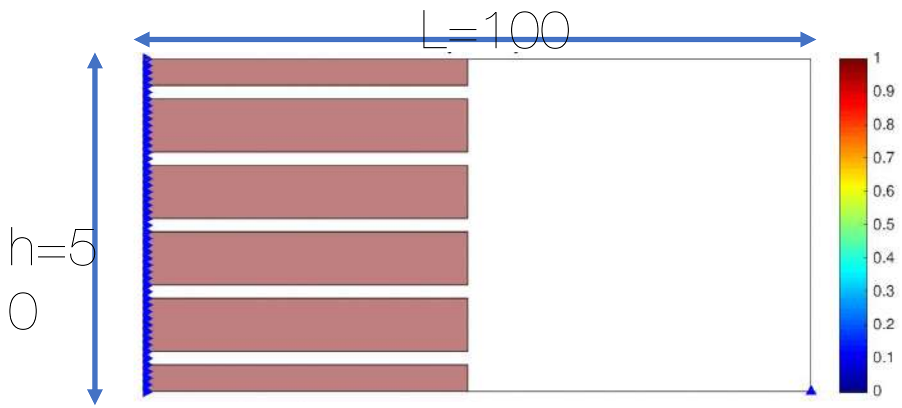
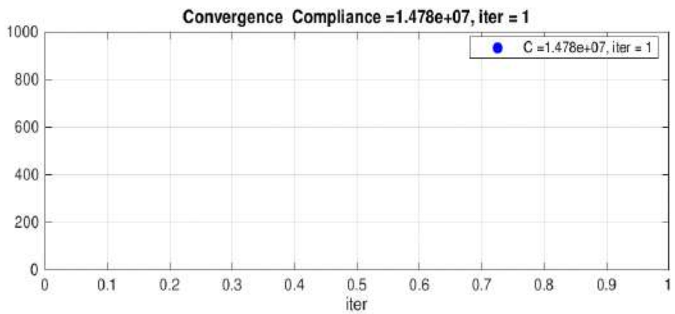


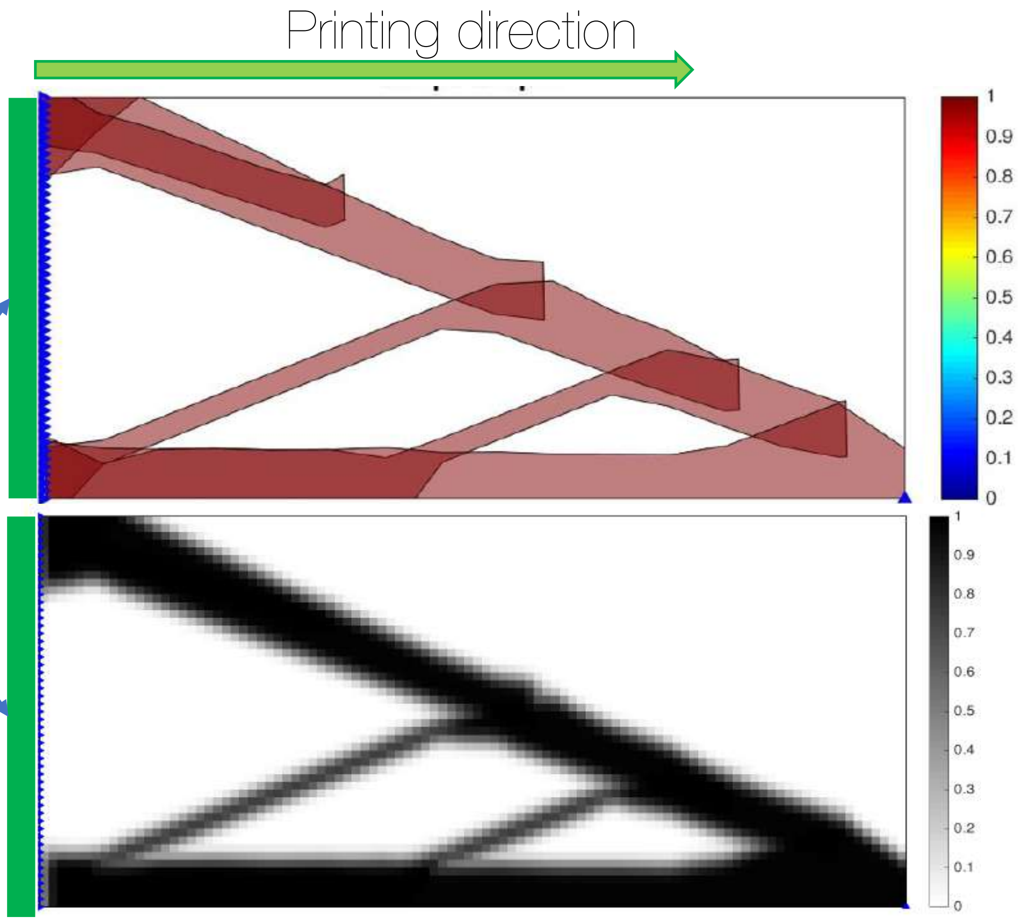


MBB Final Results

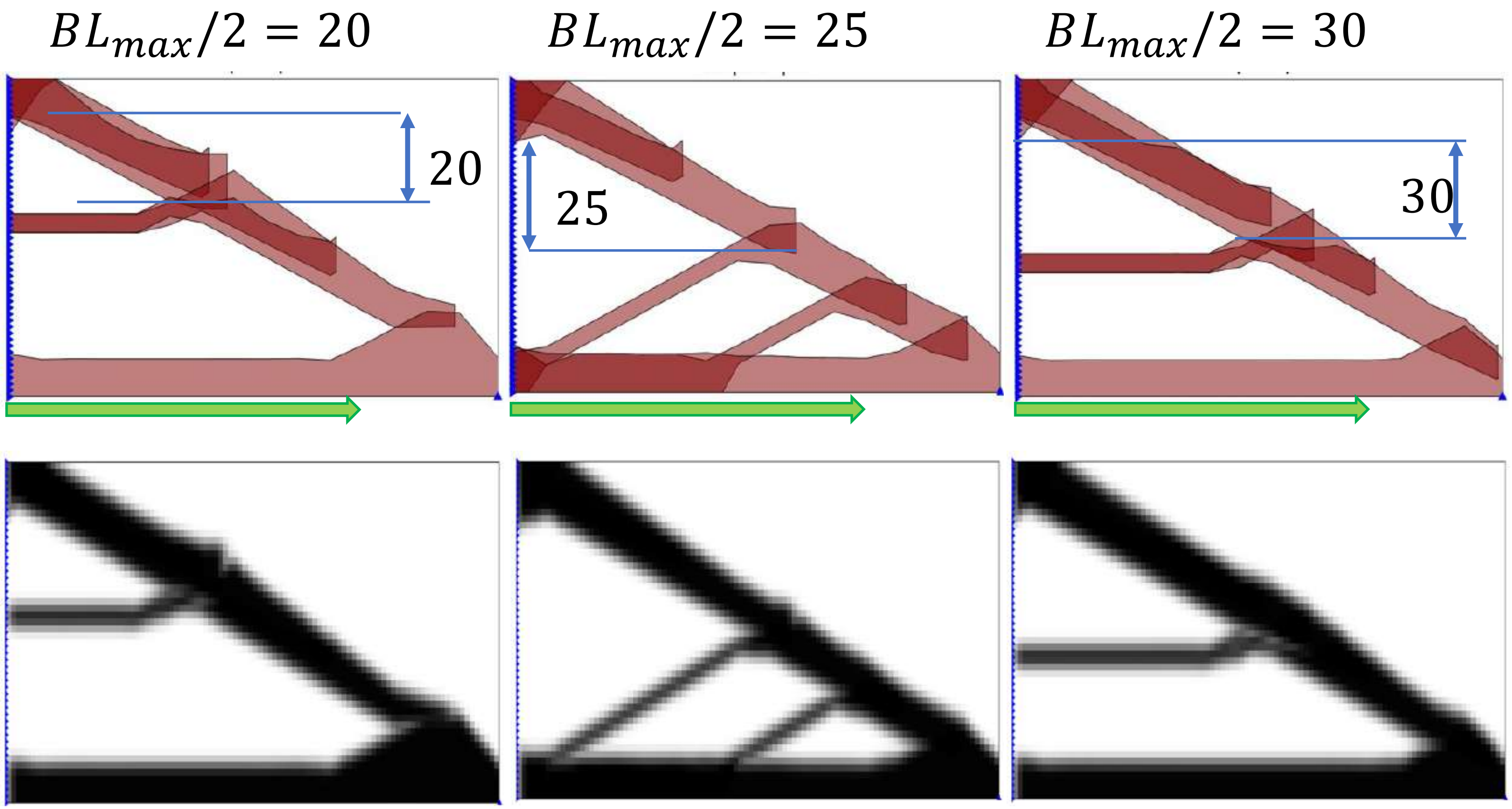
Compon
ent plot

Printin
g plan

Densiti
es
plot



Bridge length variation



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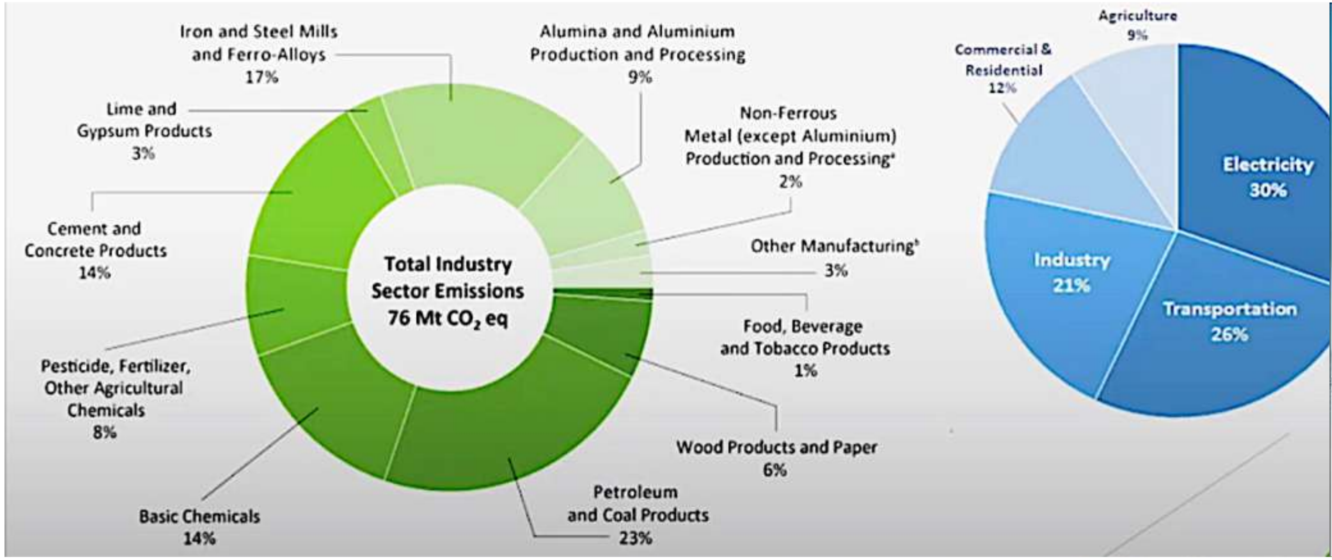
Ecodesign

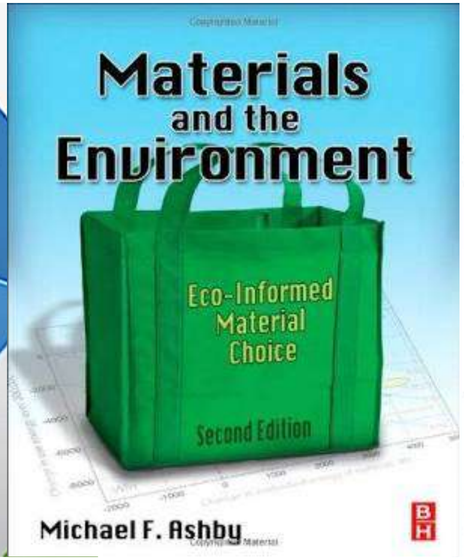
How to **ECO**design tomorrow’s structures?

#Structural materials used in a massive way → huge environmental impact

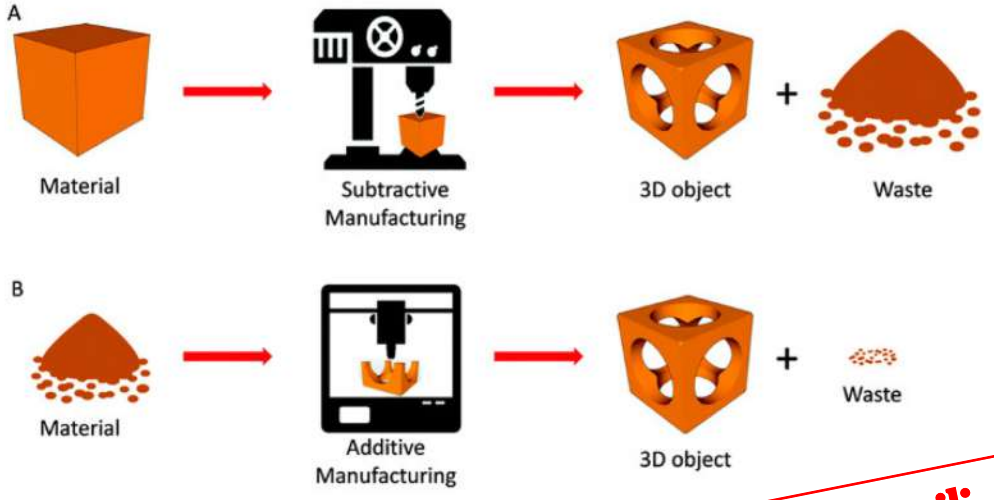
#The essential technologies for the transition, in particular green energy, will translate into considerable demand for metals that have become strategic.

#In anticipation of 2050, the total tonnage of concrete, steel, aluminum etc… necessary for the development of these energies will be 2 to 8 times the world production of 2010. !!!





Why Metallic 3D printing?

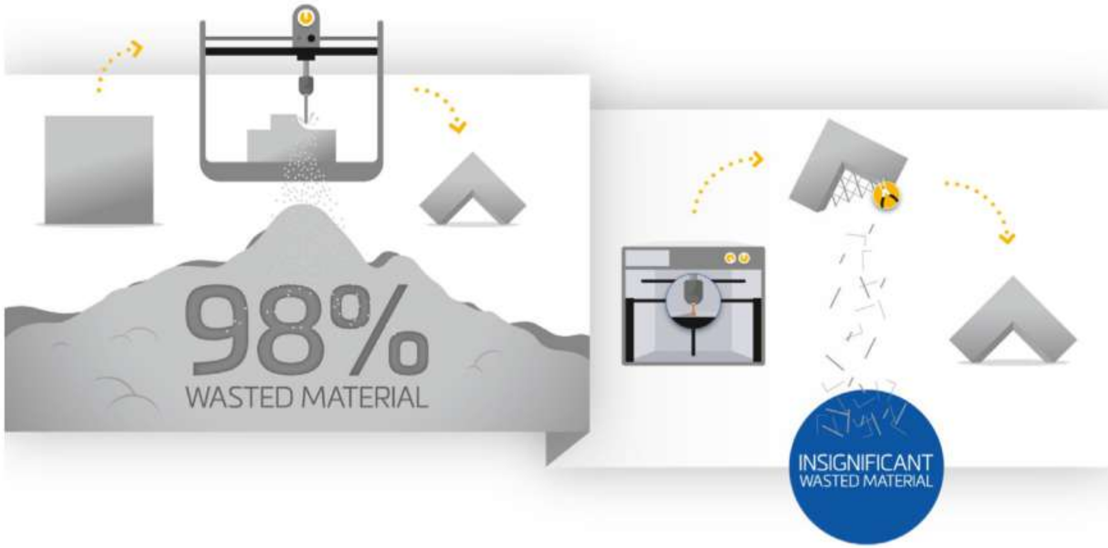


+Near 100% material utilization
+Recyclability
+LCA of 3D printing machine
+Monitoring

'Buy to-Fly' Ratio

- Traditional subtractive manufacturing machining techniques often result in a costly imbalance between the weight of raw material required to make a specific component, and the weight of the component itself — a relationship more commonly referred to (from its aerospace heritage) as the 'Buy-to-Fly' ratio.

https://www.materialise.com/sites/default/files/resources/Whitepaper_Buy-to-Fly-Ratio_E.pdf

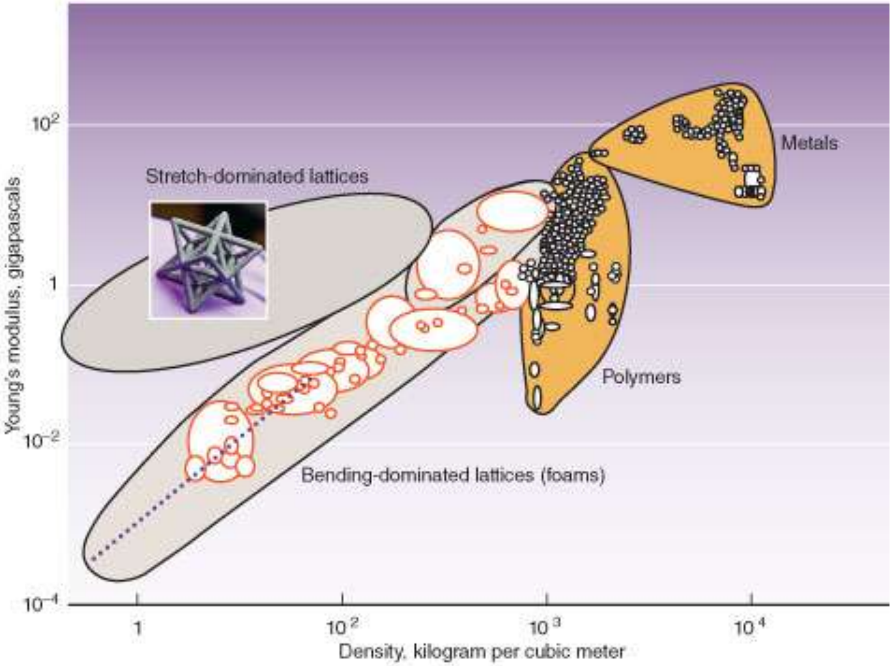


Reducing environmental impact ?

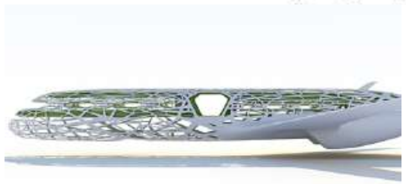
Near 100% material utilization, a high degree of material recyclability and reduced energy consumption* (almost no additional tooling and less power required to move/manipulate lighter parts for product construction) has significant environmental benefits **whilst also generating cost-efficiencies.**

sometimes the references are contradictory *In general, the reported specific energy values **for AM unit processes are 1 to 2 orders of magnitude higher** compared to conventional machining and injection molding processes.

The ERA of DIGITAL MATERIALS

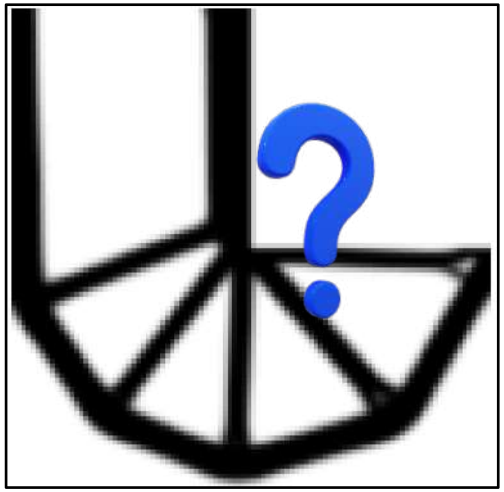


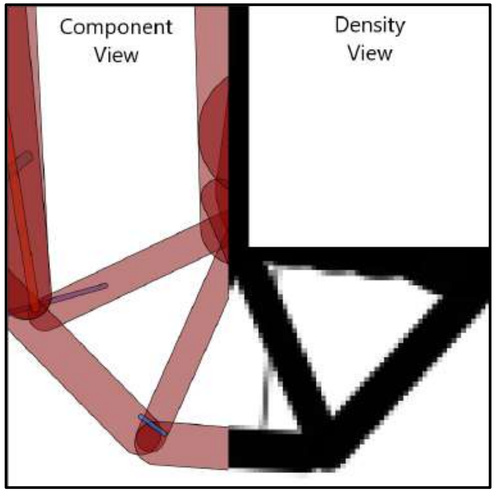
(a) (b)

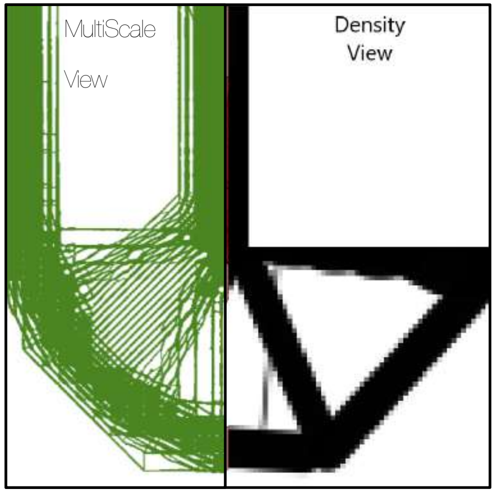


Chris Spadaccini (llnl,USA)
"By controlling the architecture of a microstructure, we can create materials with previously unobtainable properties in the bulk form."

How to do Eco efficient Ultralight Structures?

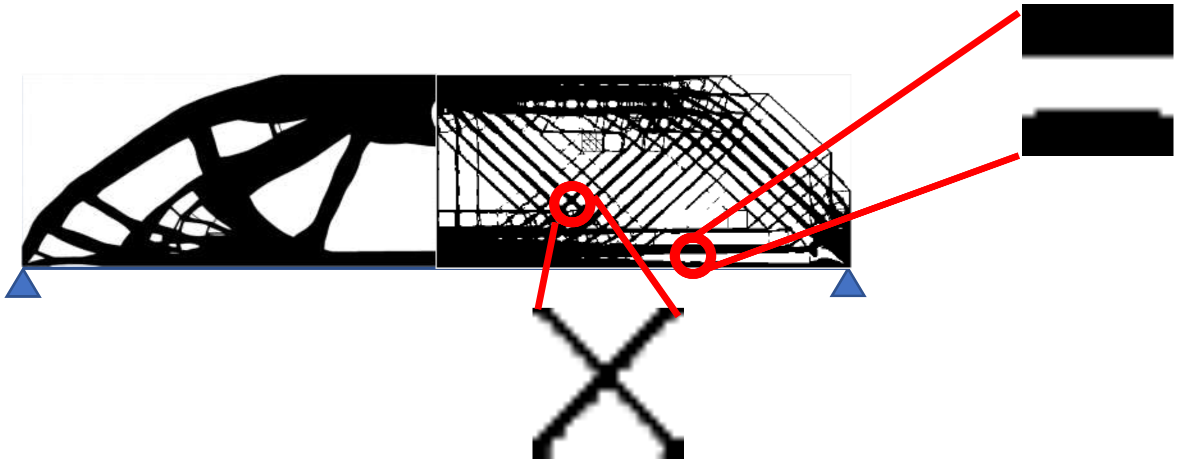




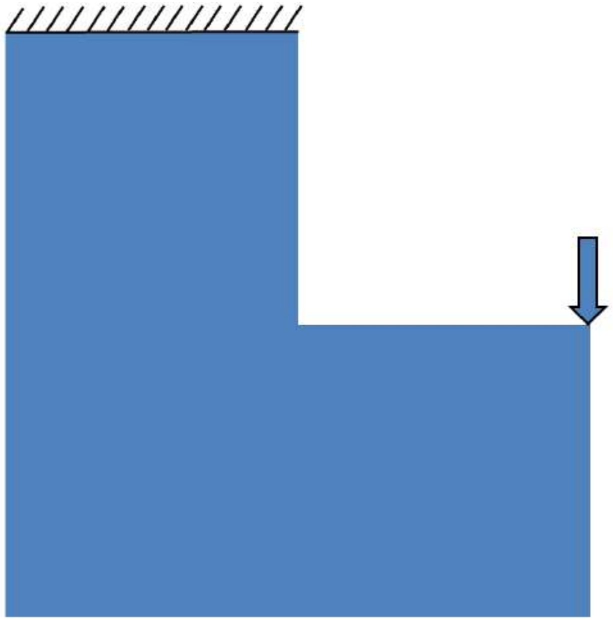


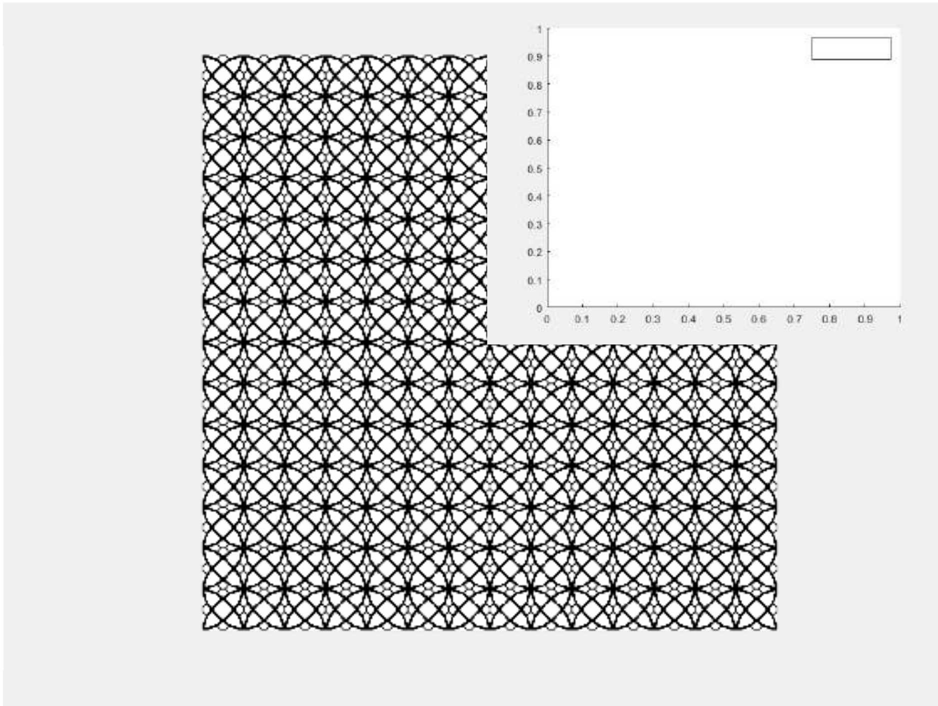
Multi-scale TO

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



EMTO on L-shape (cellular /digital materials)



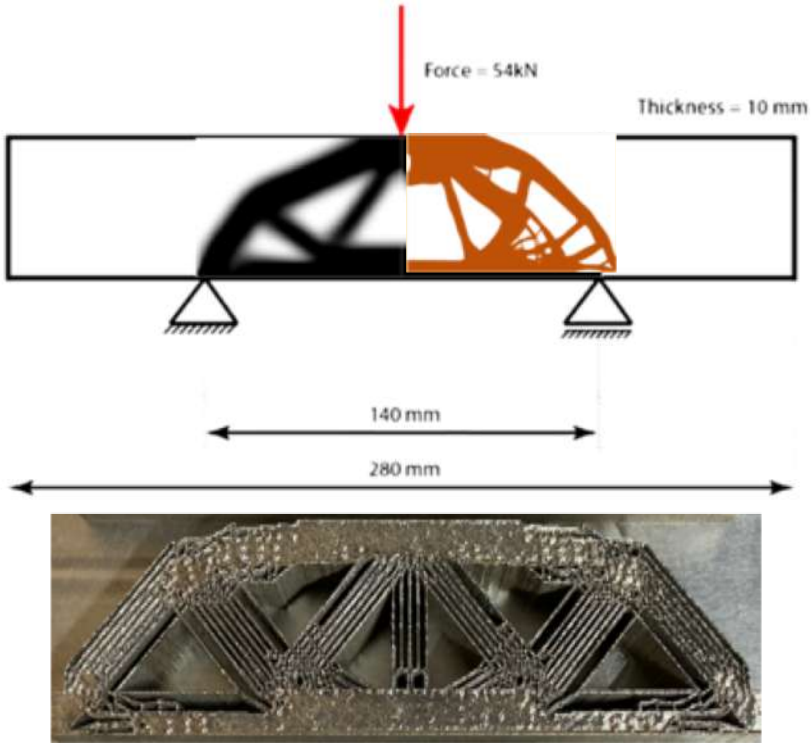


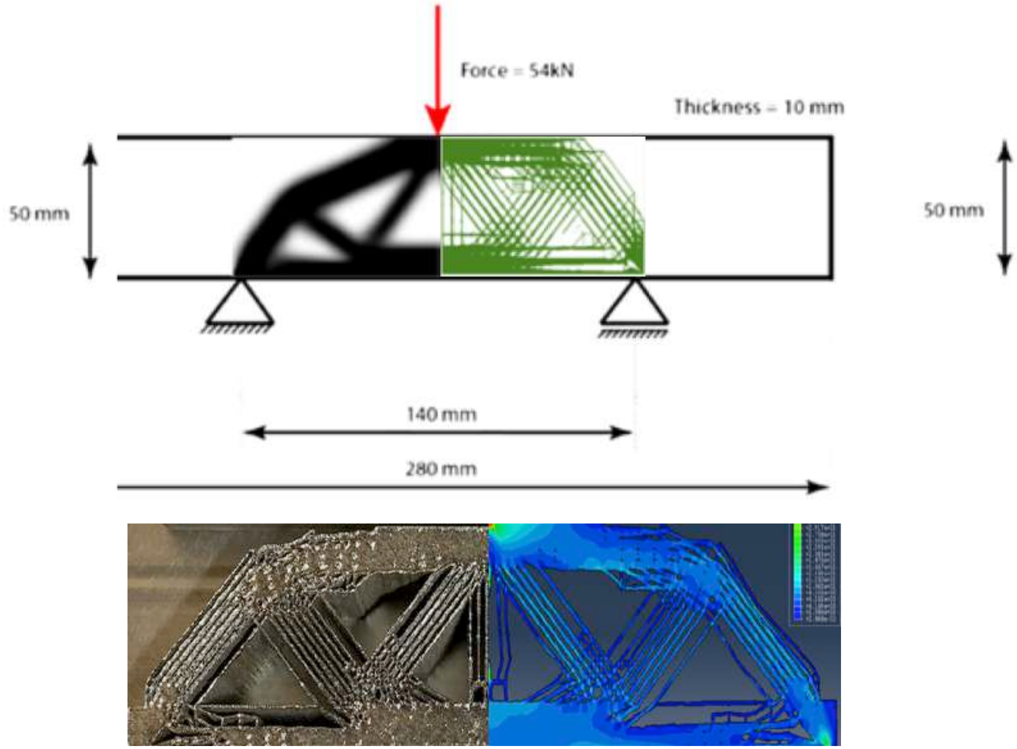
https://github.com/mid2SUPAERO/EMTO

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

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

Print it , Test it





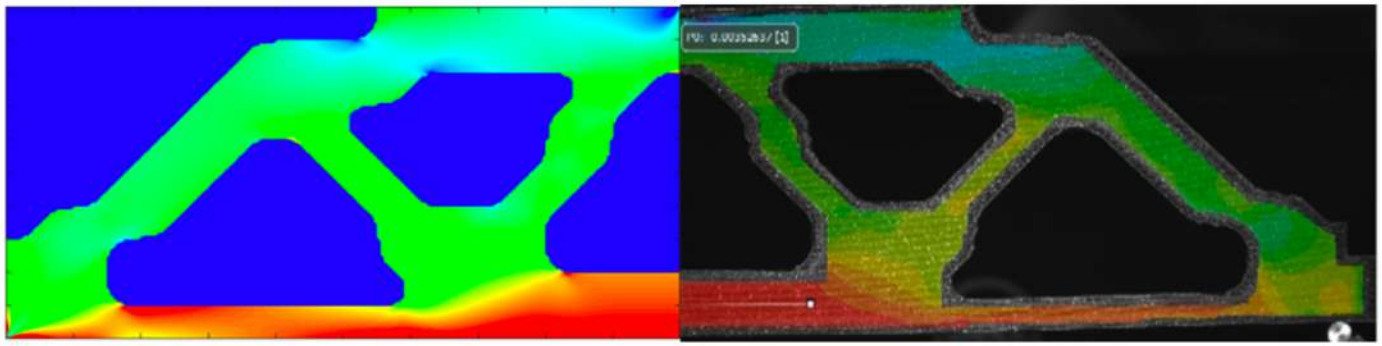
Selective Laser Melting (**SLM**)

EMTO 3pts bending (EXP)

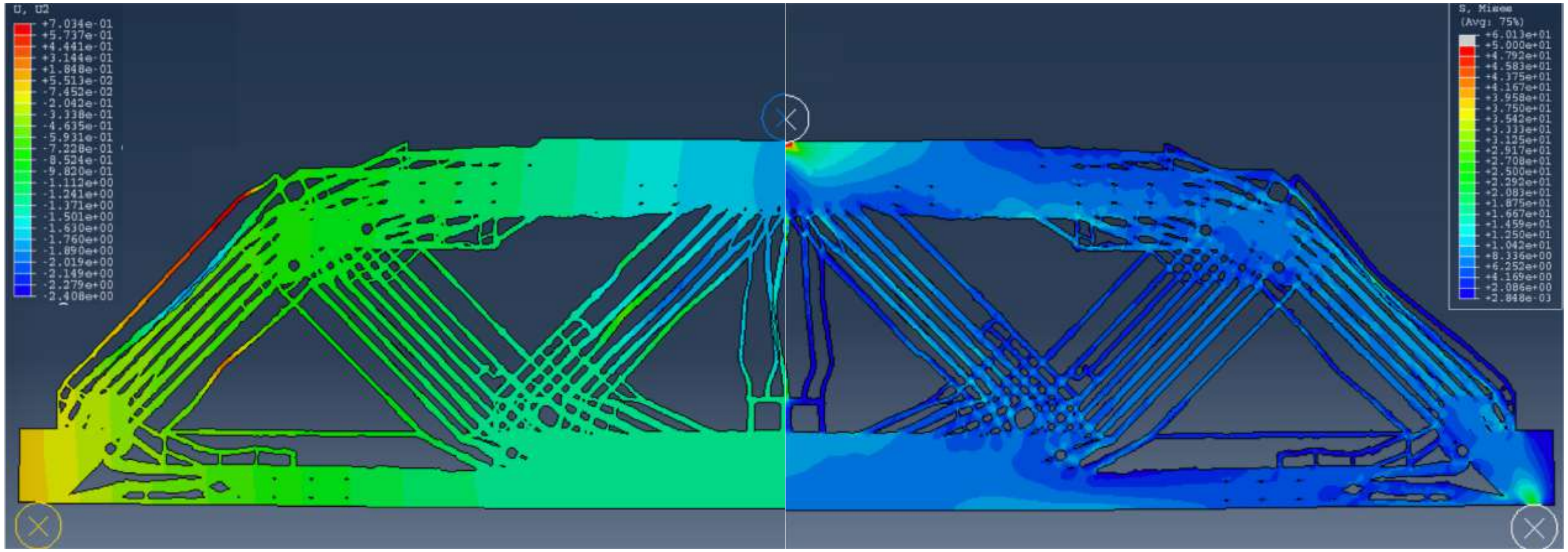
EXPERIMENTATION

Comparison

between numerical (left) and experimental (right) horizontal strain fields for the design obtained through top88 and smoothing, for a force of 1320N. The experimental field can't be obtained too close to the part border. The correspondence between the two fields can be observed.



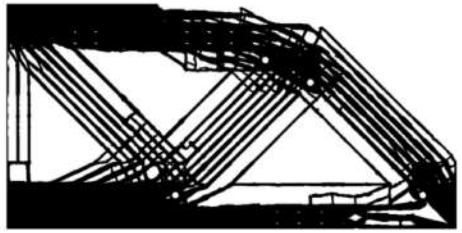
EMTO 3pts bending (disp vs stress)



ABAQUS REANALYSE

and Local Buckling?

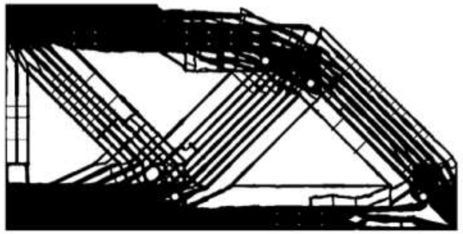
(a) The MBB beam problem.



(b) Output of EMTO.

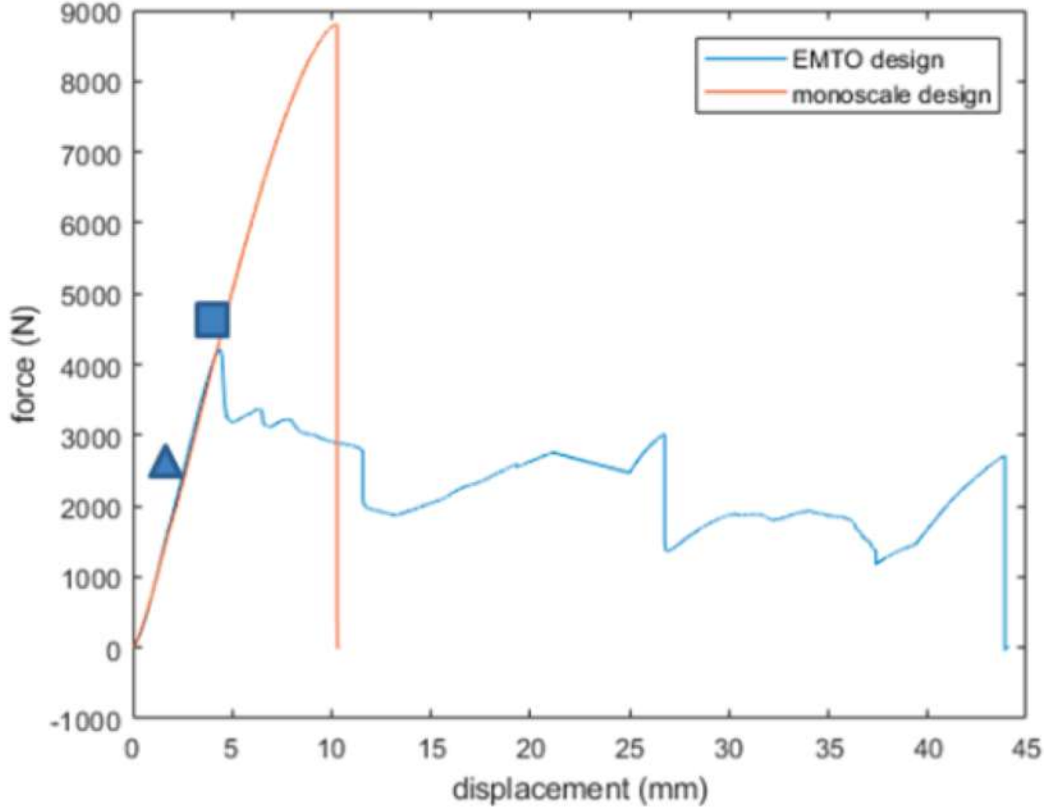
(c) Cell buckling scores. The selected cells are circled in red.

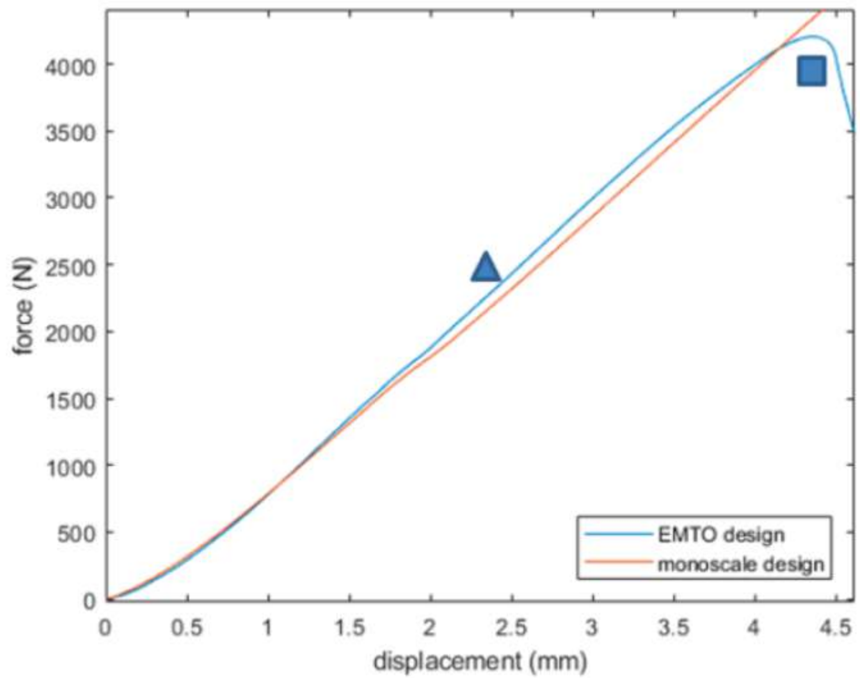
(d) Micro-structures with cubicity=1 corresponding to each selected cell.



(e) Final design post-treated for buckling : the micro-structures with cubicity=1 are superimposed on the design and the global volume fraction is brought back to its initial value.

Who is the most rigid ?





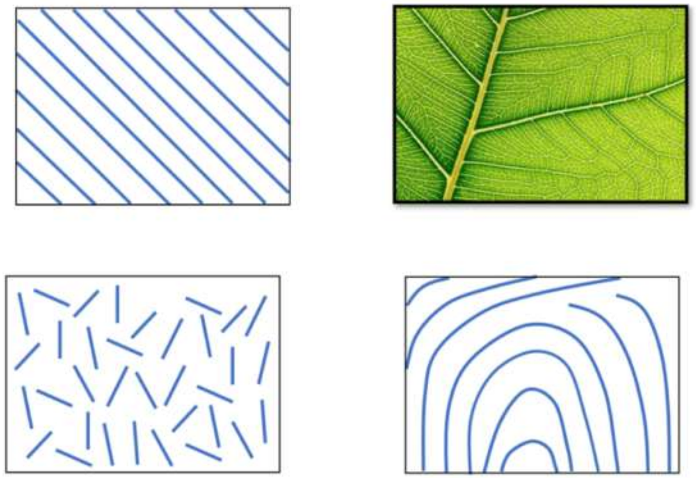
- Multiple load paths possible in the multi-scale designs.
- mono-scale design breaks in a very brutal and complete way, completely destroying the structure.
- Ability for multi-scale designs to absorb much more energy.

POST TREATMENT for Buckling

Table 4: Results after buckling mitigation post-treatment (BMPT) compared to other topology optimization methods.

Method	planar stiffness (N/m^2)	VS top88 (std)	VS numerical
top88 smoothed	5.80×10^7	- (-)	-6.00%
EMTO	6.21×10^7	+7.45% (4.20%)	-4.17%
EMTO + BMPT	6.19×10^7	+7.50% (10.6%)	-4.48%

Why Composites 3D printing?



Regular and periodic

Natural (optimal?)

Random

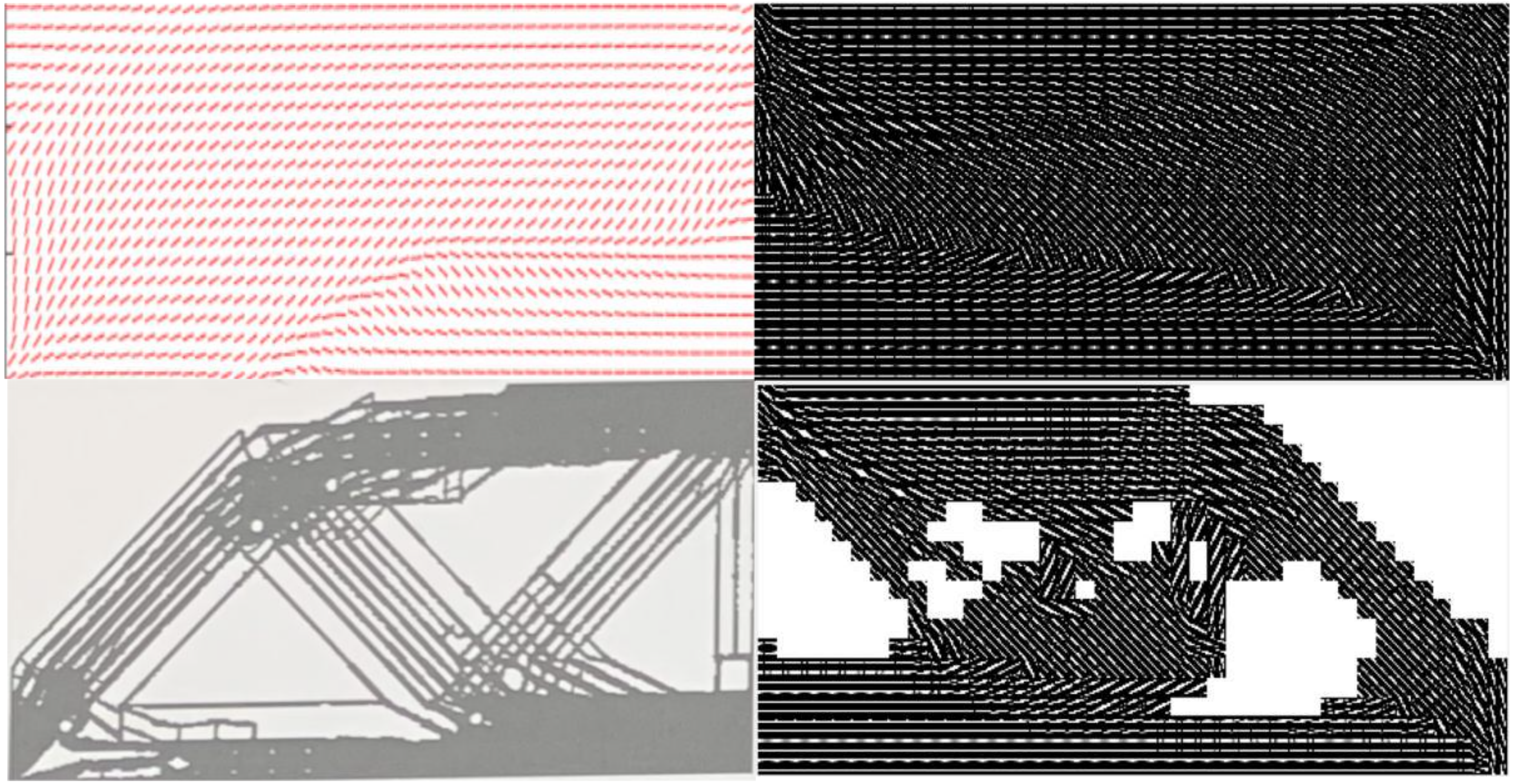
Non-periodic and specific (optimal)

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

Restrict "EMTO" for Fiber Placement (cubicity=0)

Stegmann and Lund (2005) idiscrete material optimization (DMO)

EMTO

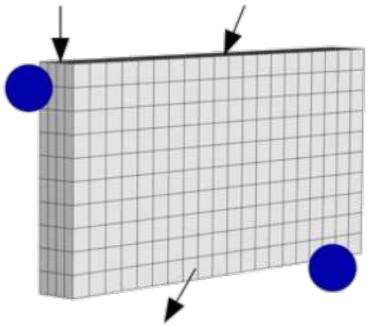


EMTO_FP
volfrac=1

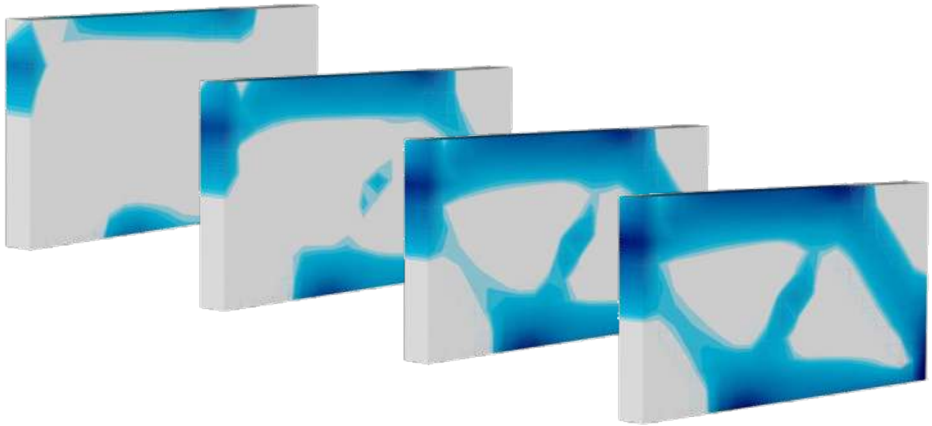
EMTO
volfrac=0.5

A simple way to do Ecodesign with Topology Optimization?

Start with Topology Optimization



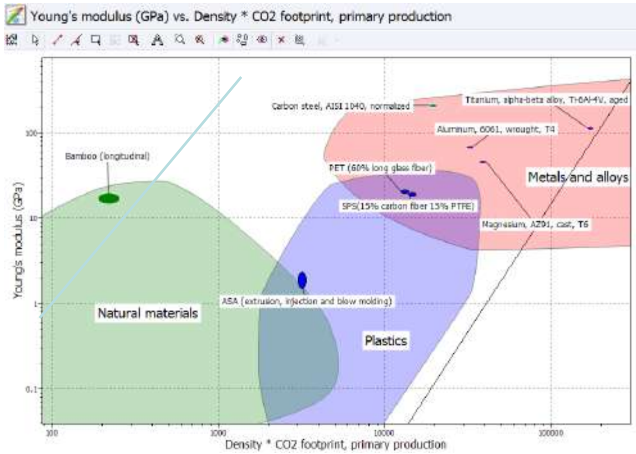
Inputs: Material, BCs and Loading



Outputs: design of a „stiff" bicycle frame

CO2 footprint minimization (Ashby's method)

Inputs: Type of Structures, materials



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

Outputs: Optimal material (bamboo) with optimal Design

$$\underset{mat,\mathcal{D},t}{\arg\min} \quad CO_2^{tot}(mat,\mathcal{D},t)$$

$$s.t. \quad \delta \leq \delta_{max}$$

$$mat = \{E, \rho, CO^i_{2mat}\} \in \Phi$$

$$0 < v_f(\mathcal{D}) \leq 1$$

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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]

Time to conclude

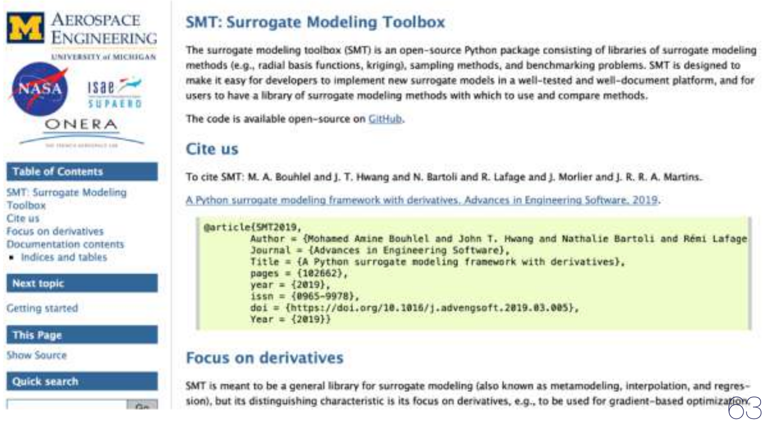
Duration	Description	Agenda
15’	Design Optimization	Refresh
15’	Computing Derivatives	Mathematical Background
15’	Topopt review	Need a break ?
15’	Current CAD-CAE	Quiz
15’	GGP for ALM	Our research
15’	Ecodesign	That’s new

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/



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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.

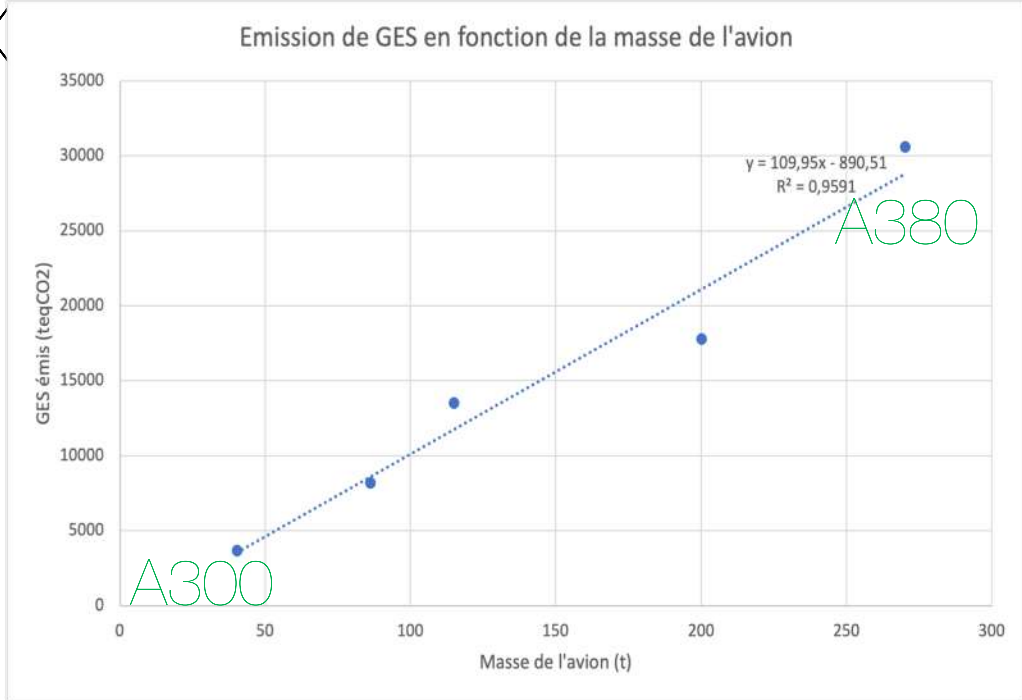
A Python surrogate modeling framework with derivatives, Advances in Engineering Software, 2019.

```
@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.

First Order Approx



At the first order

min {mass} is close to min {CO2}

SUSTAINABLE ULTRALIGHT STRUCTURE BASED ON DIGITAL FABRICATION AND ARCHITECTED MATERIALS:

EcoDesign for Additive Manufacturing •Topology Optimization •Multidisciplinary Design Optimization •Surrogate Modeling

Materials + Manufacturing Process:=

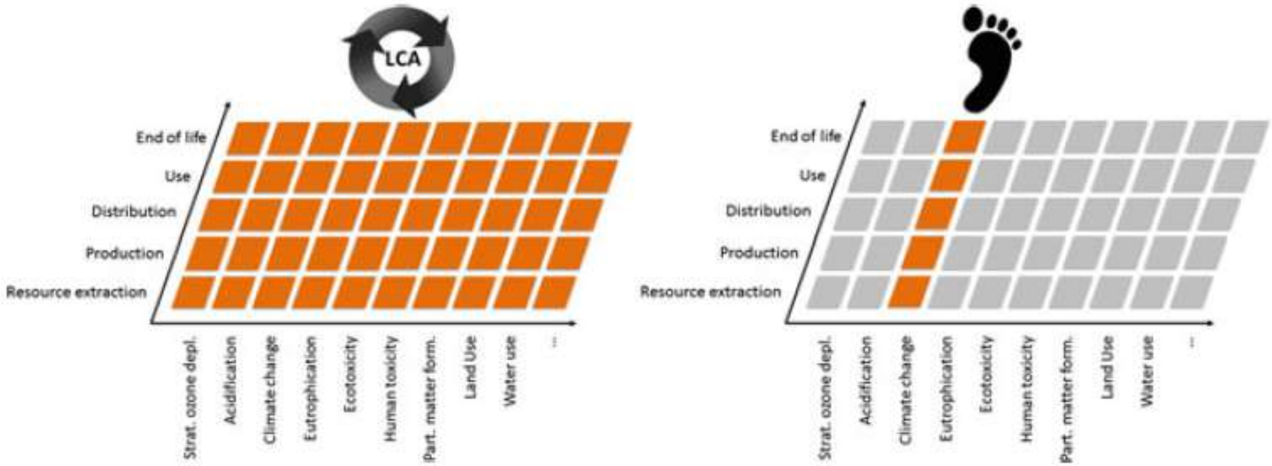
Carbon Footprint

Energy requirement

Water withdrawal

Generation of waste

→ Take environmental issues into account from the design phase and throughout the life cycle (LCA)



Perspectives

→ Multiobjective formulation CO_2 versus Cost

→ Natural Fiber / Resin Eco-selection

→ Material performance prediction by AI (e.g. recycled composites)

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

To review

https://github.com/jomorlier/mdo_ml_21

(MDO_ML 2021)

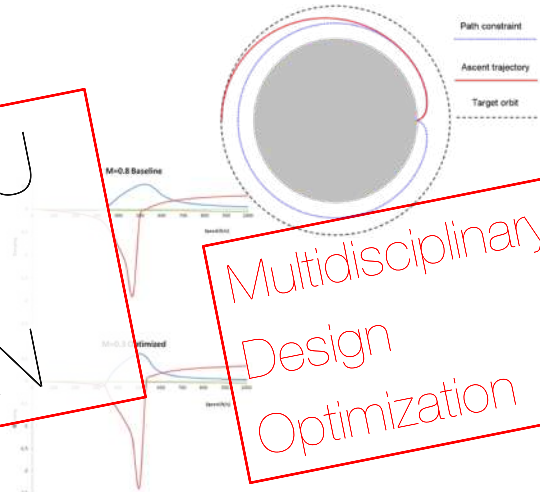
https://www.youtube.com/watch?v=geptVGimkYY&list=PL_TG7DdVYSp_fcwKATnwPRnJHGOyaiPPX&index=9&t=2443s

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

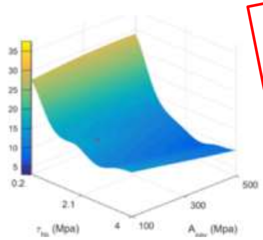
INSTITUT CLÉMENT ADER

Structural Optimization & Ecodesign

THANK YOU for Your ATTENTION

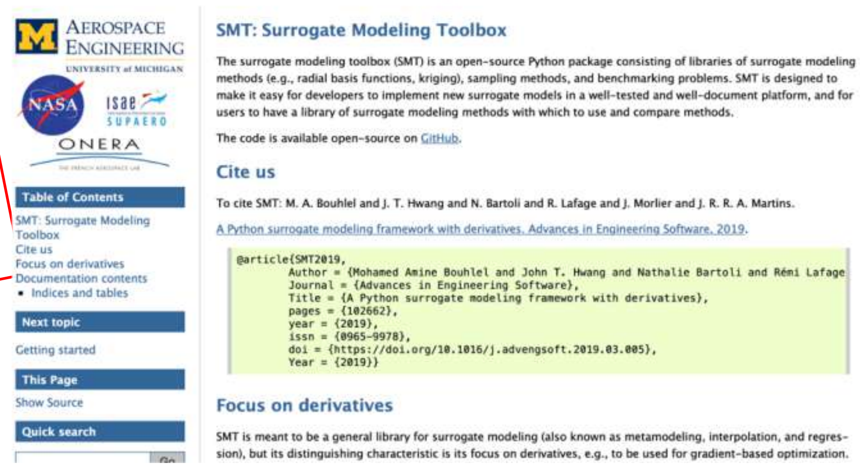


Multidisciplinary Design Optimization



#AI4E Artificial Intelligence For Engineers

https://github.com/SMTorg/smt



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