How to achieve optimal design of sustainable aerostructures?

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About Me?

- SA-I* group leader

Sustainable Aerostructures Initiative

SA-I

Cleaner Environmental Systems
Volume 9, June 2023, 100114

A fast method of material, design and process eco-selection via topology optimization, for additive manufactured structures

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

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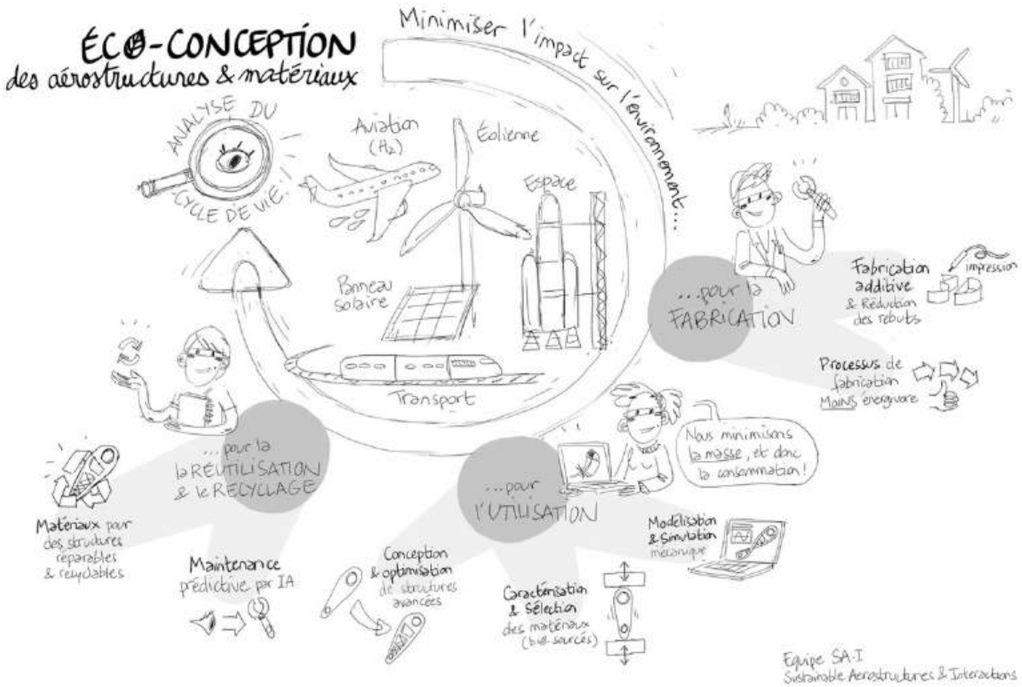
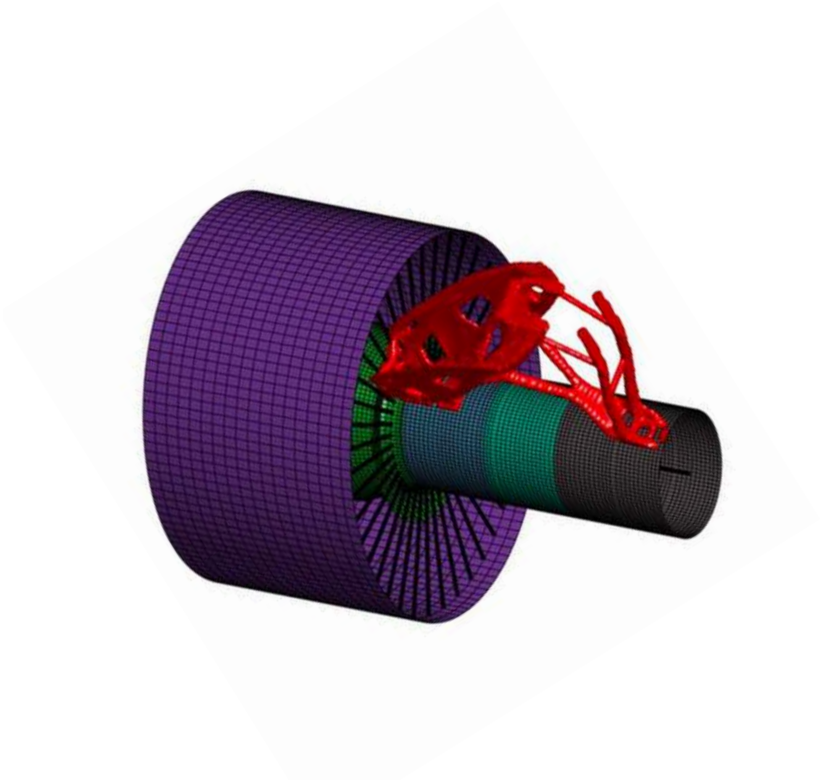
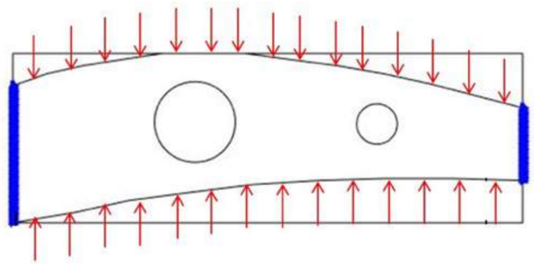
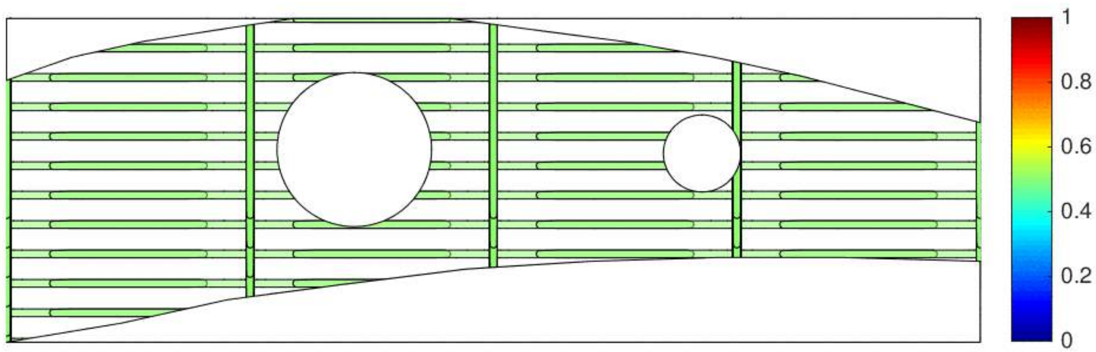


About Me? https://ica.cnrs.fr/en/author/jmorlier/

- Prof in Structural and Multidisciplinary Optimization





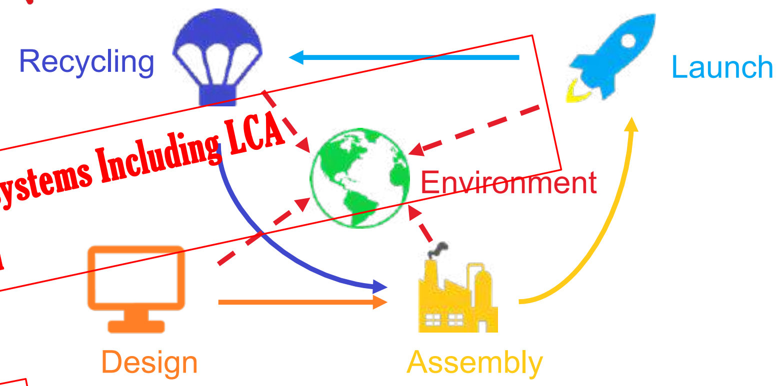


https://topggp.github.io/blog/

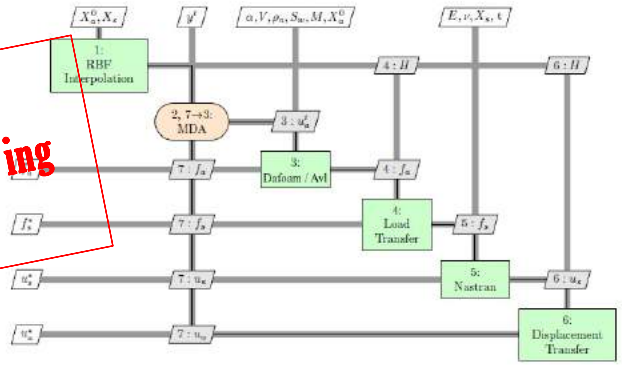
About Me? https://ica.cnrs.fr/en/author/jmorlier/

- 6 PhDs, 3 MsCs

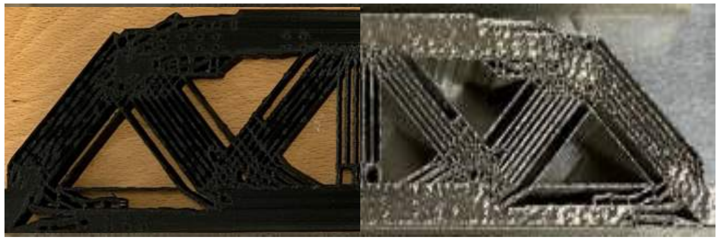
MDO for Aerospace systems Including LCA := EcoOptimization



MDO for Aeroelastic Wing design

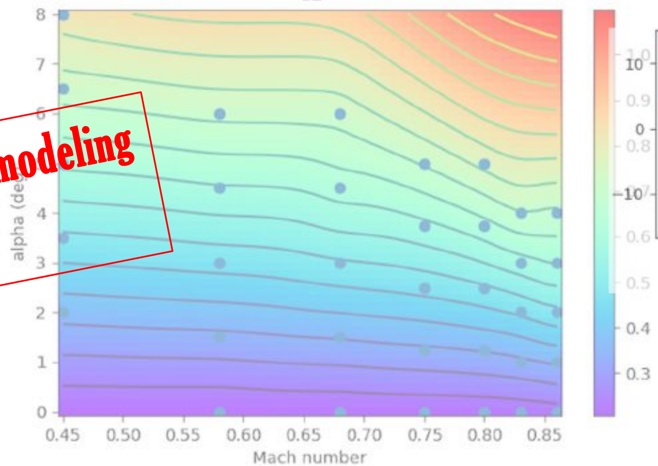


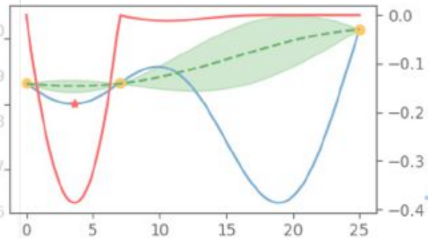
Digital fabrication



https://github.com/SMTorg/SMT

Surrogate modeling AI4E





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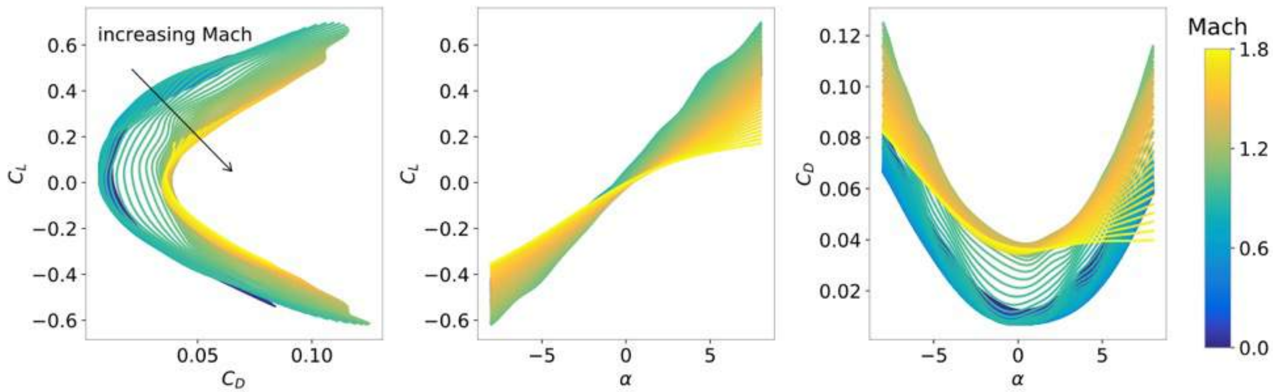
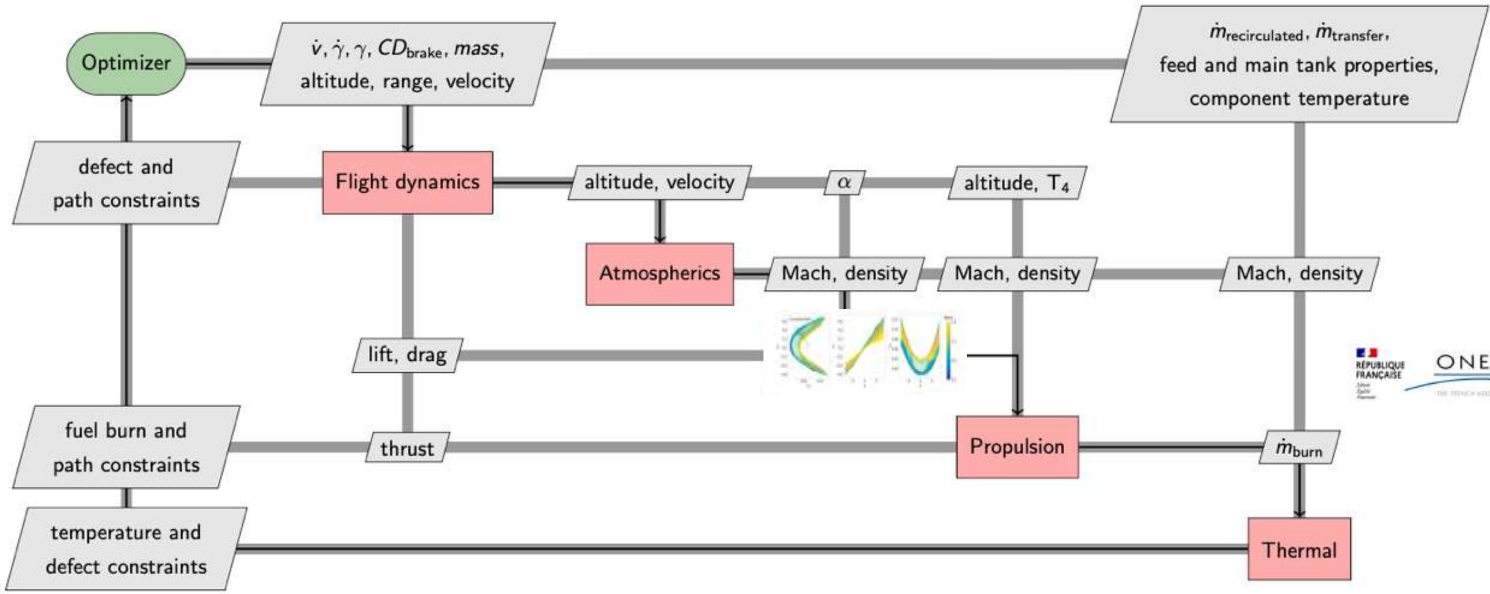
MDO in a Nutshell





https://github.com/SMTorg/SMT

Jasa, J. P., Brelje, B. J., Gray, J. S., Mader, C. A., & Martins, J. R. (2020). Large-Scale Path-Dependent Optimization of Supersonic Aircraft. Aerospace, 7(10), 152.

4 disciplines

- Low cost satellite
- HALE: No propulsion

→Only CO2 footprint PP (no Fuel Burn)

www.nature.com/scientificreports

scientific reports

Check for updates

OPEN

CO_2 footprint minimization of solar-powered HALE using MDO and eco-material selection

Edouard Duriez[1,3], Víctor Manuel Guadaño Martín[2,3] & Joseph Morlier[1,3]

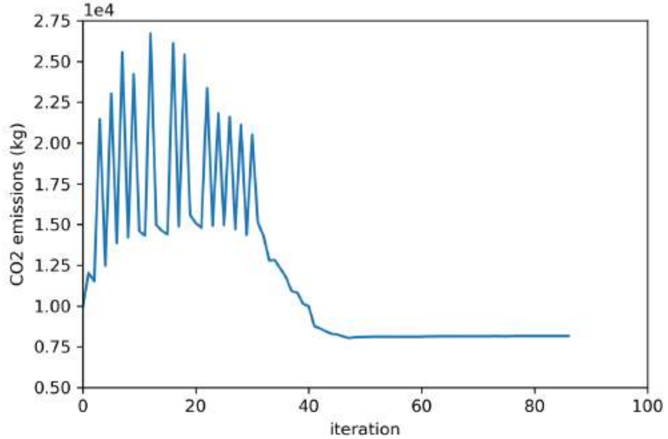
$$\text{Embodied carbon (kgCO}_2\text{e)} = \sum_{\text{Sum for all materials}} \left(\boxed{\text{Quantity (kg)}} \times \boxed{\text{Carbon factor (kgCO}_2\text{e/kg)}} \right)$$

Discipline	Method	Implementation	References
Aerodynamics	VLM	OAS	28
Structure	Wingbox beams	OAS	17
Energy	Simple in-house method	Section "OpenAeroStruct to Eco-HALE"	Data from[14]
Environmental	Proportional to mass	Section "MDO framework summary"	Data from[29,30]

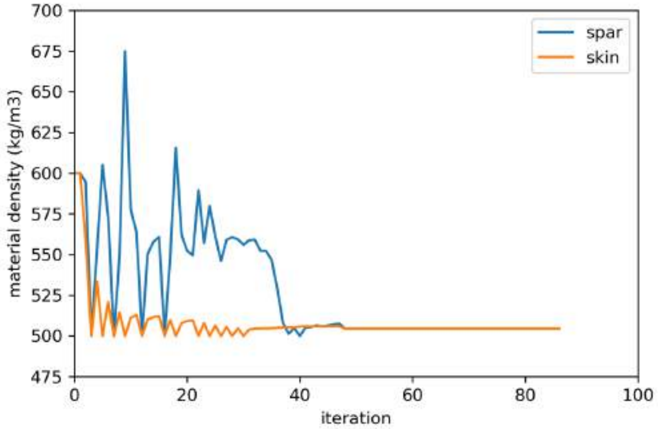
CO2 footprint minimization

X* is a UHAR Wing ;)

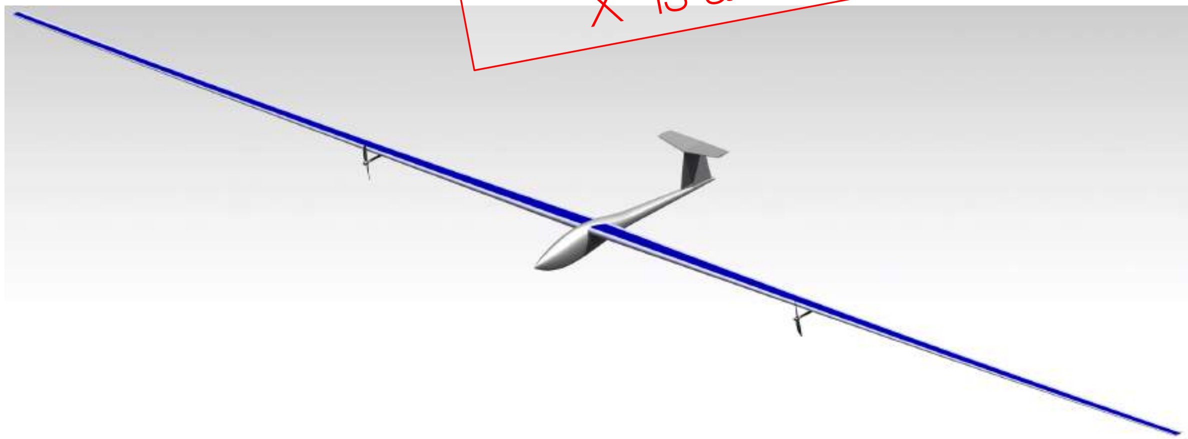
(a) Objective function: total CO2 emitted:



(b) Material density for skins and spars:



Convergence graphs

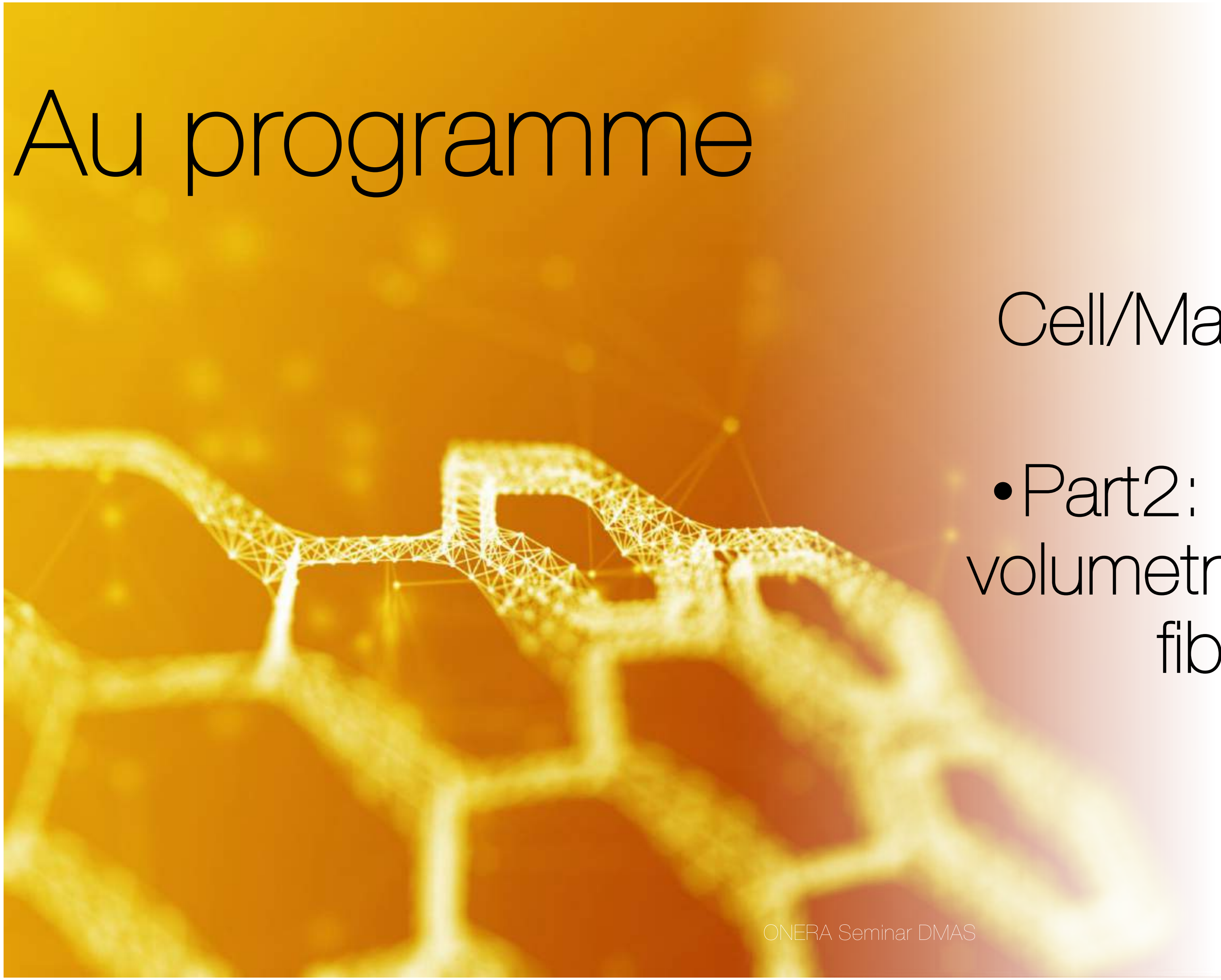


CAD model of the optimal HALE obtained

A slight increase in the total weight of the drone leads to an increase in the weight of the battery and the solar panel in order to propel a heavier drone,

But also to: an increase in the weight of the wing structure that induces a more important lift to compensate → increase in the overall weight of the drone.

→"snowball" effect.



Au programme

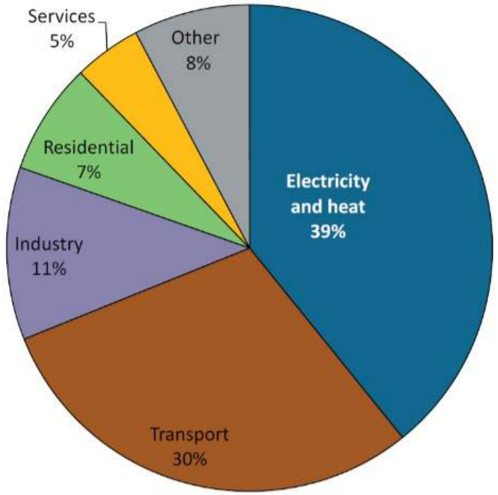
- Part1 :Unit Cell/Material/Process as design variables
- Part2: Ecodesign of 3D volumetric structures with fiber/resin topology optimization
- Bonus SMT2.0

Au programme

- **Part1 : Unit Cell/Material/Process**
- Part2: Ecodesign of 3D volumetric structures with fiber/resin topology optimization
- Bonus SMT2.0

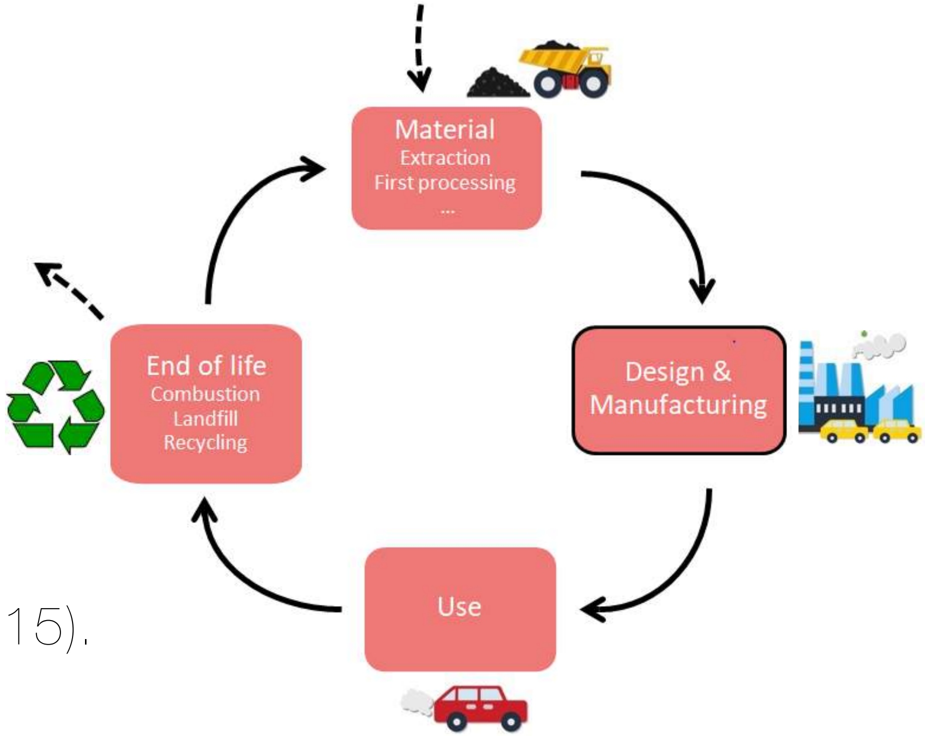
Thanks to Edouard Duriez

Overview



CO_2 emissions of the OECD (2015).

International Energy Agency IEA. Energy and CO2 emissions in the OECD. 2017

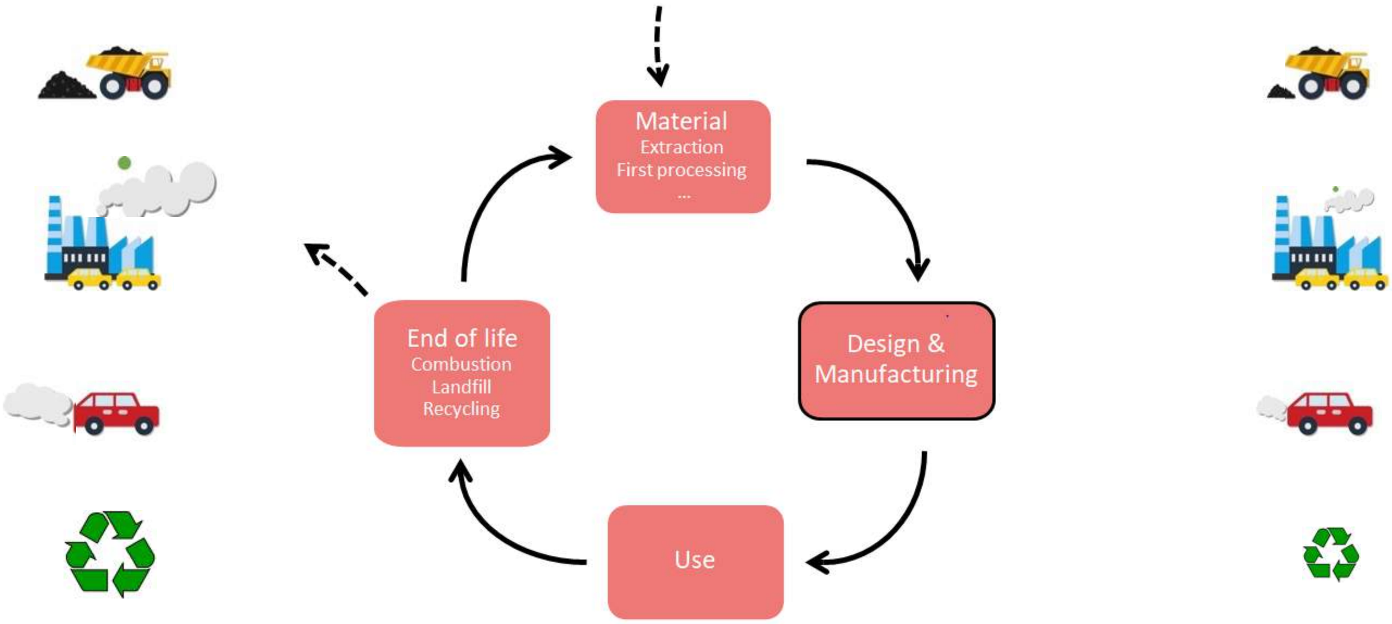


Vehicle life cycle

Q : How to find structural designs, materials and additive manufacturing processes with the lowest life-cycle CO_2 footprint?

Hypothesis 1

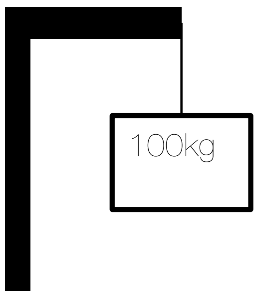
- CO_2 emissions minimization of parts
  - If material choice is imposed => mass minimization

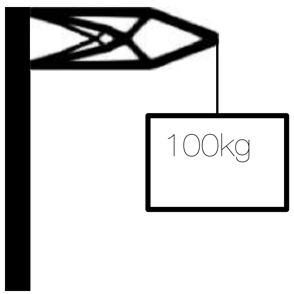


Vehicle life cycle

Hypothesis 1

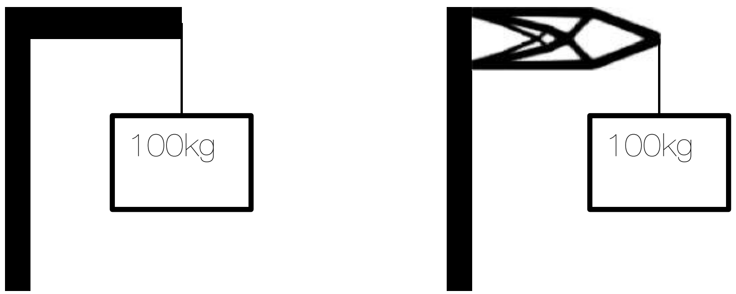
- Mass minimization of parts
  - Redesign through topology optimization
    => same performance





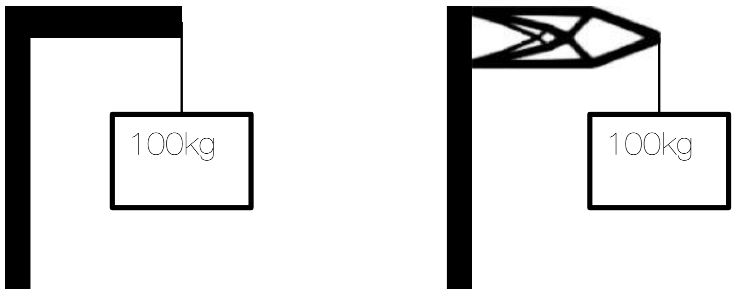
Hypothesis 1

- Mass minimization of parts
  - Redesign through topology optimization
    => same performance but lower mass

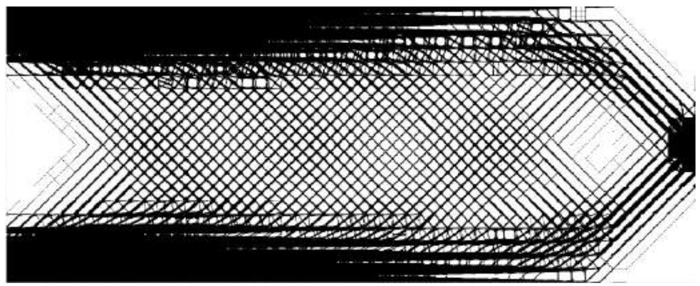


Hypothesis 1

- Mass minimization of parts
  - Redesign through topology optimization
    => same performance but lower mass



– One step further : multiscale topology optimization



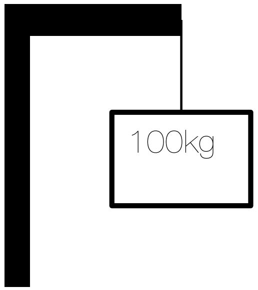
Ecodesign/Manufacturing

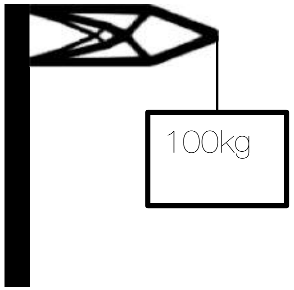
- Mass minimization of parts
  - And some additional constraints

(see Enrico's PhD)

- Reparability
- Fail-safe design
- Reusability and robot for assembly (see NASA MADCAT)

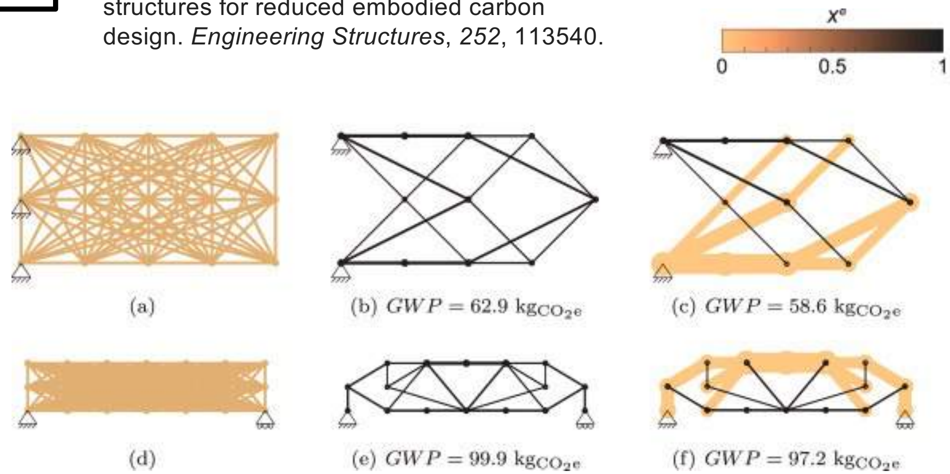
Liu, Y., Wang, Z., Lu, H., Ye, J., Zhao, Y., & Xie, Y. M. (2023, September). Layout optimization of truss structures with modular constraints. In *Structures* (Vol. 55, pp. 1460-1469). Elsevier.

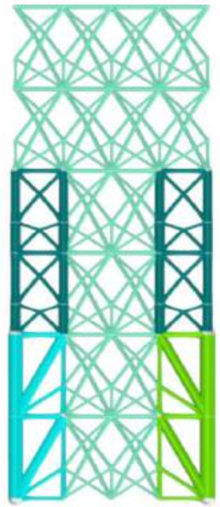




- Multimaterial
- GWP under stress

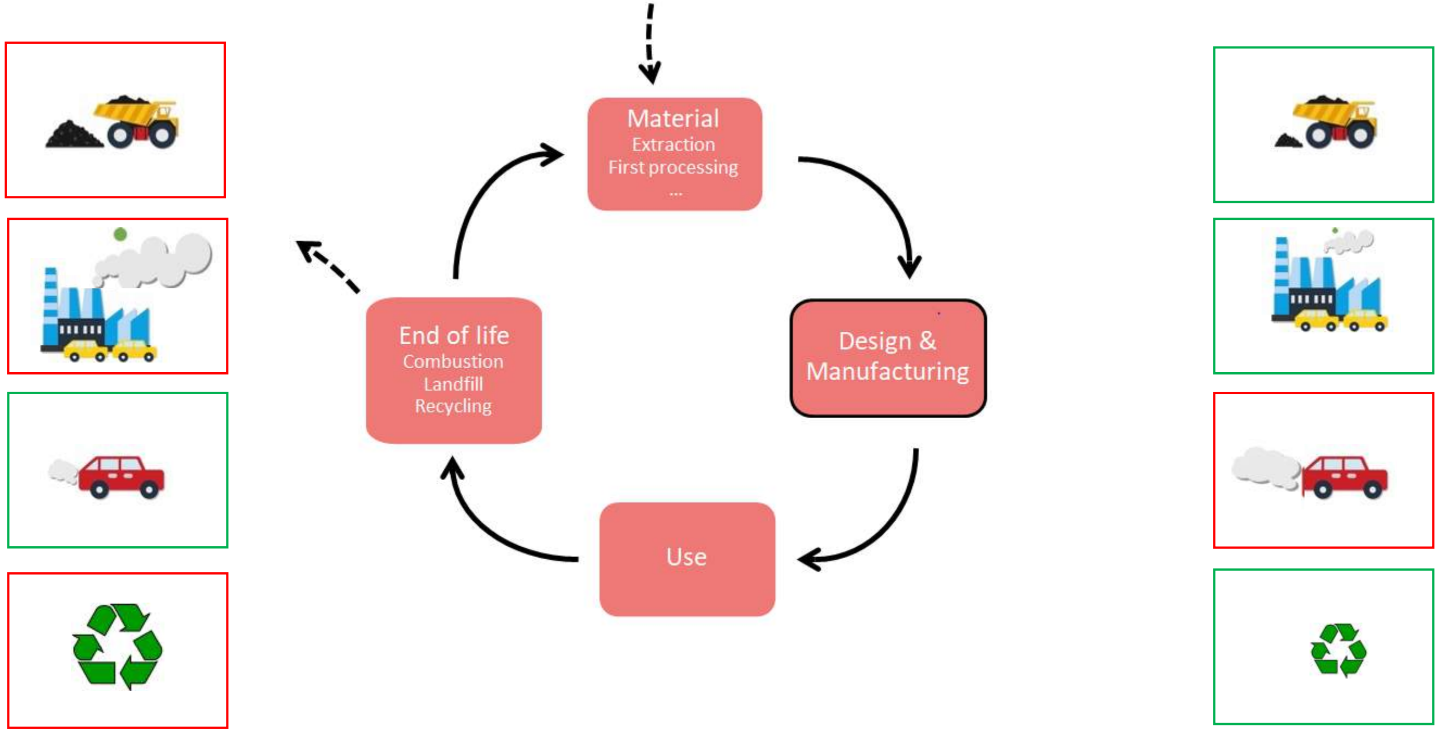
Ching, E., & Carstensen, J. V. (2022). Truss topology optimization of timber–steel structures for reduced embodied carbon design. *Engineering Structures*, *252*, 113540.





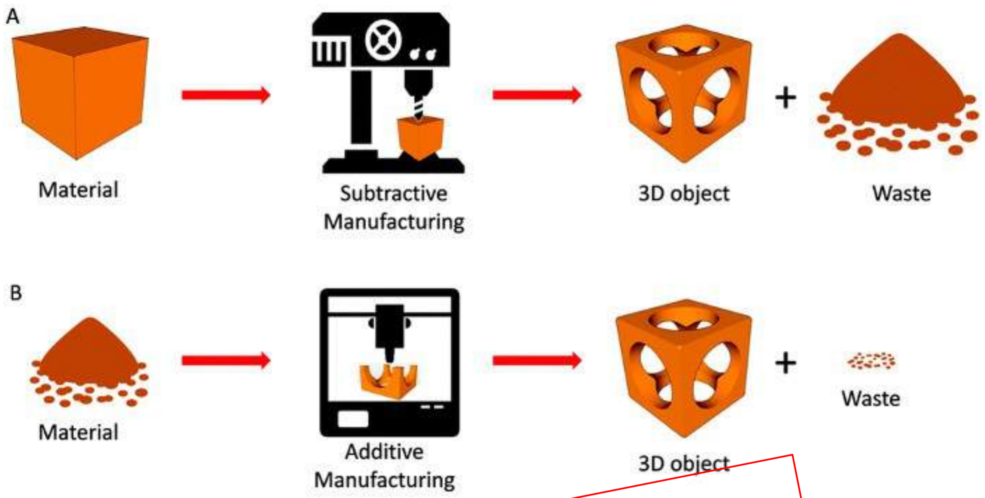
Hypothesis 2

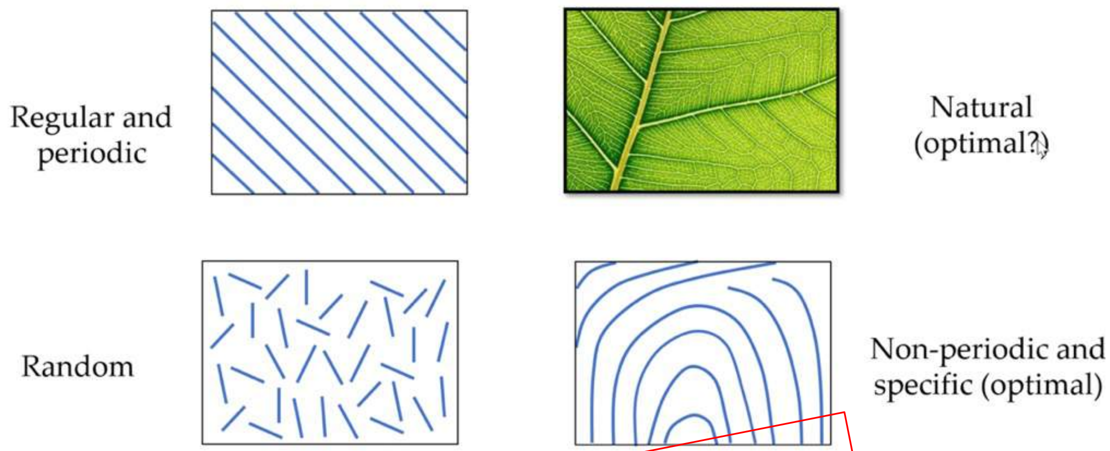
- CO_2 emissions minimization of parts
  - If material choice is free => more complicated
  - → scope of the part of the tallk



Process is AM, but WHY?

https://dfam.substack.com/p/dfam-education-in-2022





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

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

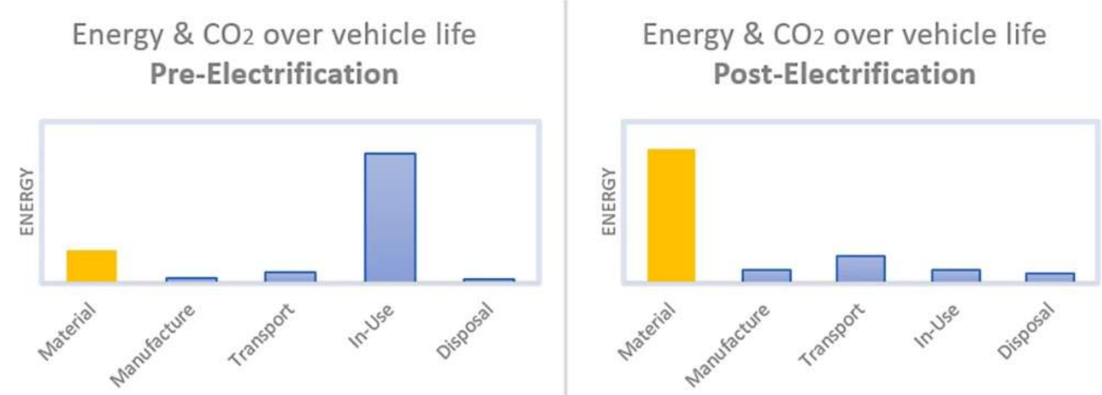
Ecodesign and Additive Manufacturing

AM environmental opportunities*	AM environmental risks**
Lower mass	Higher specific energy demand
Improved resource efficiency	Longer manufacturing times
Durability (repair/replacement)	Quality issues
Reduced transport	New process (tooling / choices)

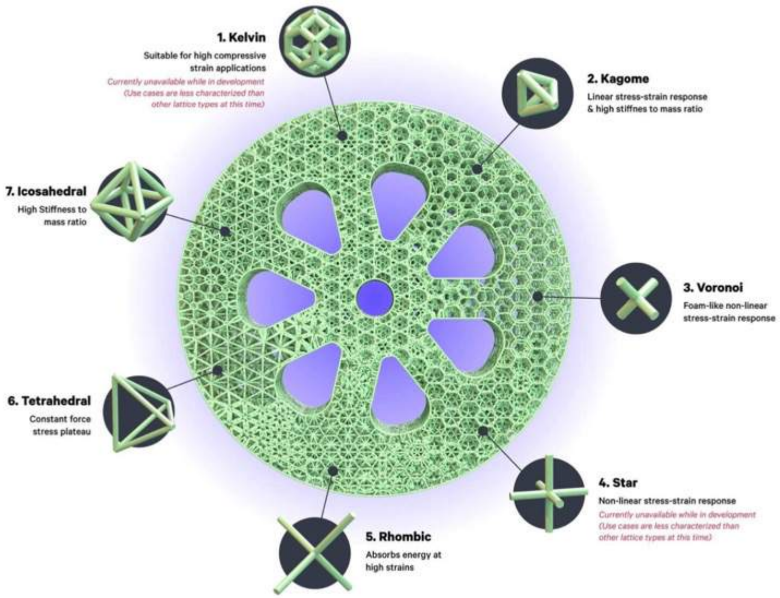
*S. Ford and M. Despeisse. « Additive manufacturing and sustainability : an exploratory study of the advantages and challenges ». en. In : J. of Cleaner Production 137 (nov. 2016),
*R. Huang, M. Riddle, D. Graziano, Joshua Warren, Sujit Das, Sachin Nimbalkar, Joe Cresko and Eric Masanet. « Energy and emissions saving potential of additive manufacturing : the case of lightweight aircraft components ». en. In : J. of Cleaner Production 135 (nov. 2016)
**C. Herrmann, W. Dewulf, M. Hauschild, A. Kaluza, S. Kara and S. Skerlos. « Life cycle engineering of lightweight structures ». en. In : CIRP Annals 67.2 (jan. 2018)
**D. Chen, S. Heyer, S. Ibbotson, K. Salonitis, J. G. Steingrímsson and S. Thiede. « Direct digital manufacturing : definition, evolution, and sustainability implications ». en. In : J. of Cleaner Production 107 (nov. 2015)

Material/Process as new design variables in MDO

Eco Material selection
Eco Process selection



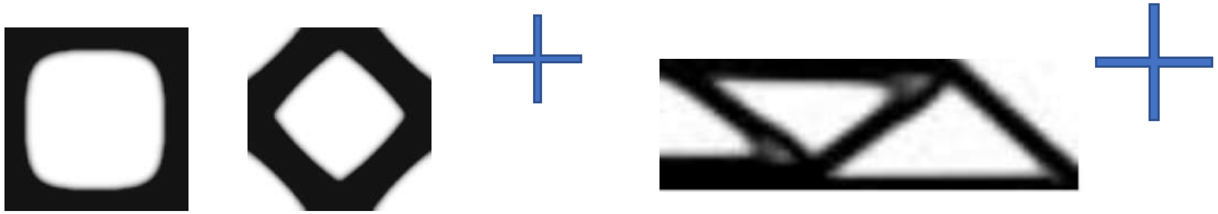
https://www.ansys.com/blog/the-impact-of-materials-on-sustainability-part-2

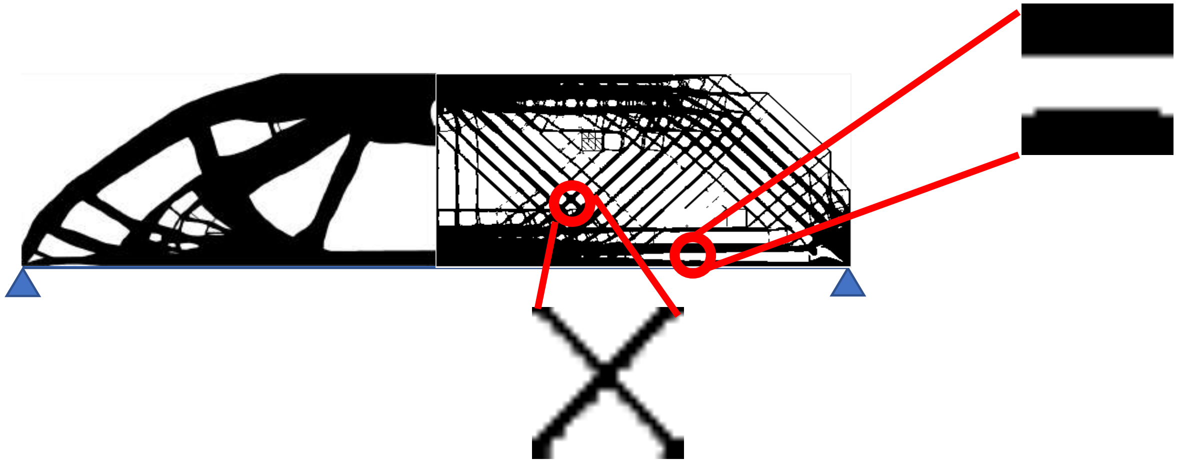


Unit cell design (anisotropy)
Digital materials

Multi-scale TO (well connected+ locally-oriented)

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

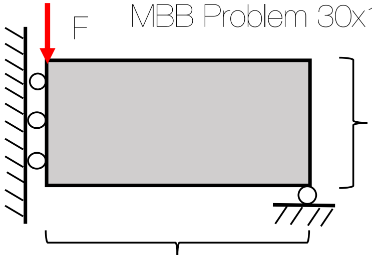




Xia L, Breitkopf P (2015) Design of materials using topology optimization and energy-based homogenization approach in Matlab. Struct Multidisc Optim 52(6):1229–1241. https://doi.org/10.1007/s00158-015-1294-0
Wu, Jun, Ole Sigmund, and Jeroen P. Groen. "Topology optimization of multi-scale structures: a review." Structural and Multidisciplinary Optimization 63.3 (2021): 1455-1480.

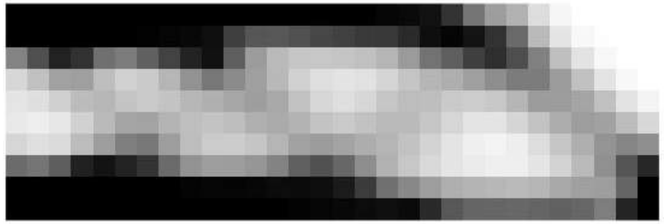
EMTO results

MBB Problem 30x10 macro elements

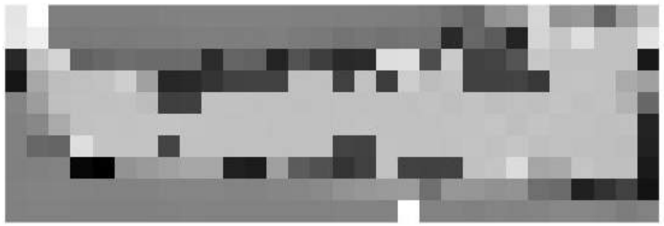


Theoretical compliance 192.7

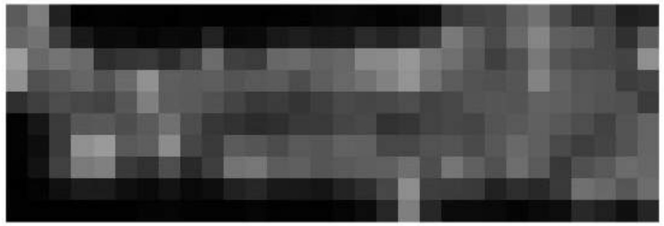
Density of the cells



Orientation of the cells



Cubicity of the cells

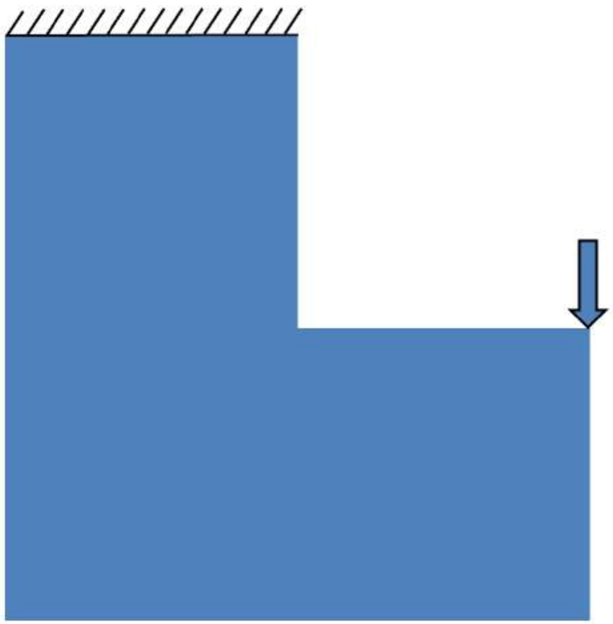


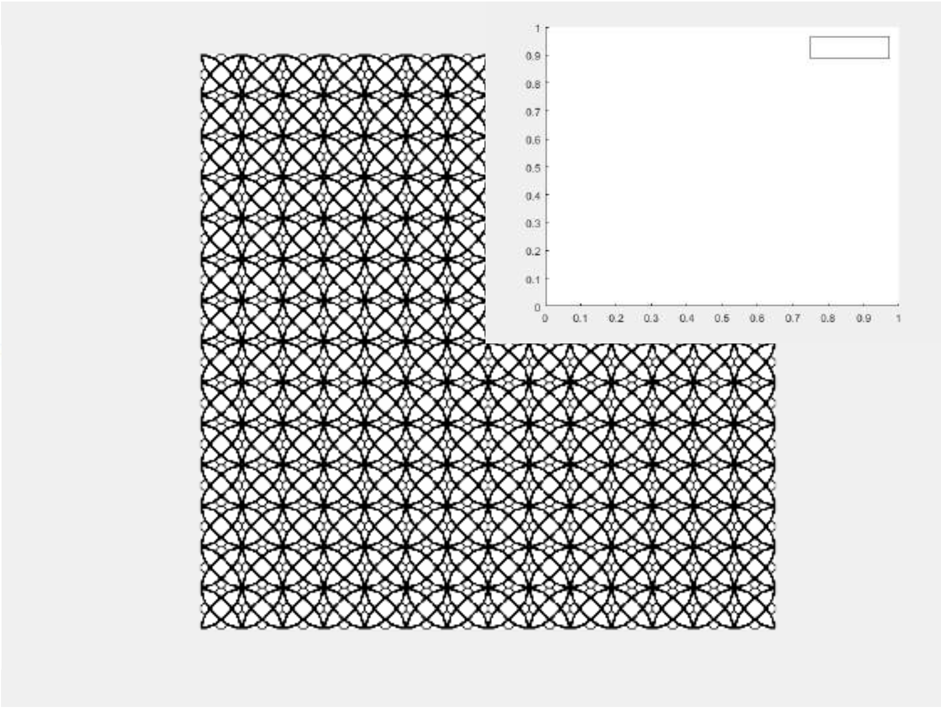
Structure Database and post-treatment

EMTO MBB solution

top88 MBB solution

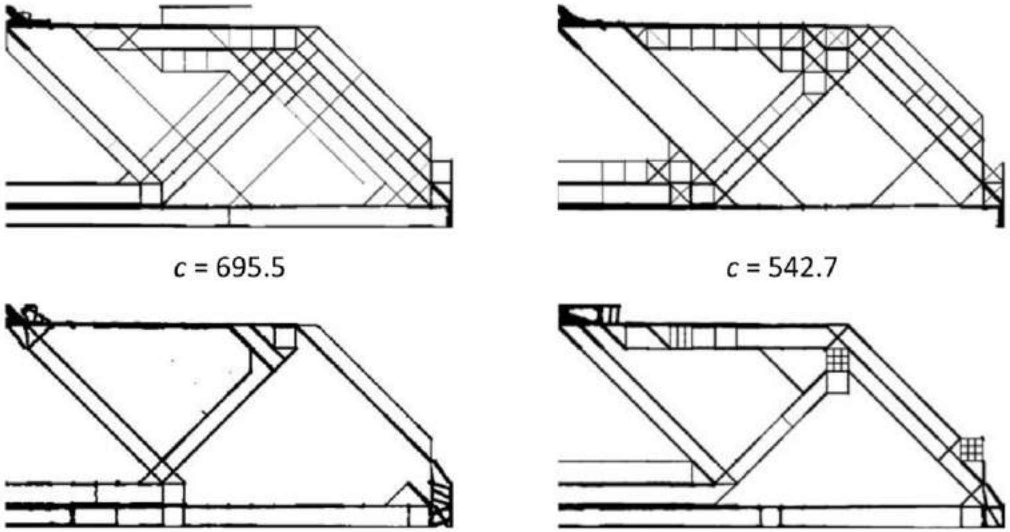
EMTO on L-shape (cellular /digital materials)





https://github.com/mid2SUPAERO/EMTO

Do you see a difference (Top2Bottom)?



c = 695.5 c = 542.7

c = 1417.8 c = 858.3

(a) Volume fraction 0.126. (b) Volume fraction 0.127.

Fig. 23. Examples obtained for a 20 × 10 macro-scale grid half MBB beam for different volume fractions, both for the new database (top figures) and the original EMTO one (bottom figures). The compliance is reported below each structure.

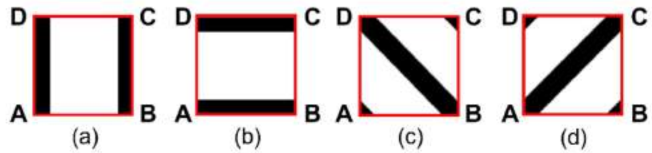


Fig. 6. The 4 β-dependent groups of beams. **(a)** AD and BC are defined by the parameter β_1; **(b)** AB and CD are defined by the parameter β_2; **(c)** BD is defined by the parameter β_3; **(d)** AC is defined by the parameter β_4. Here, the 4 designs are obtained by assigning the value 0.2 to the related parameter.

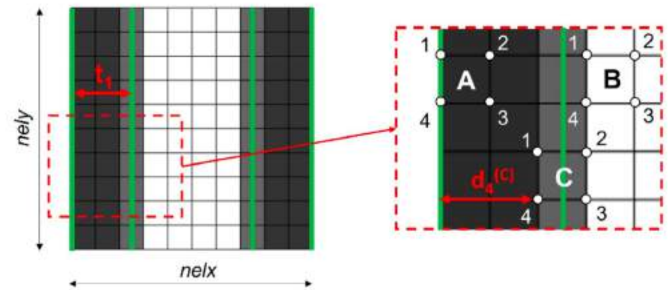
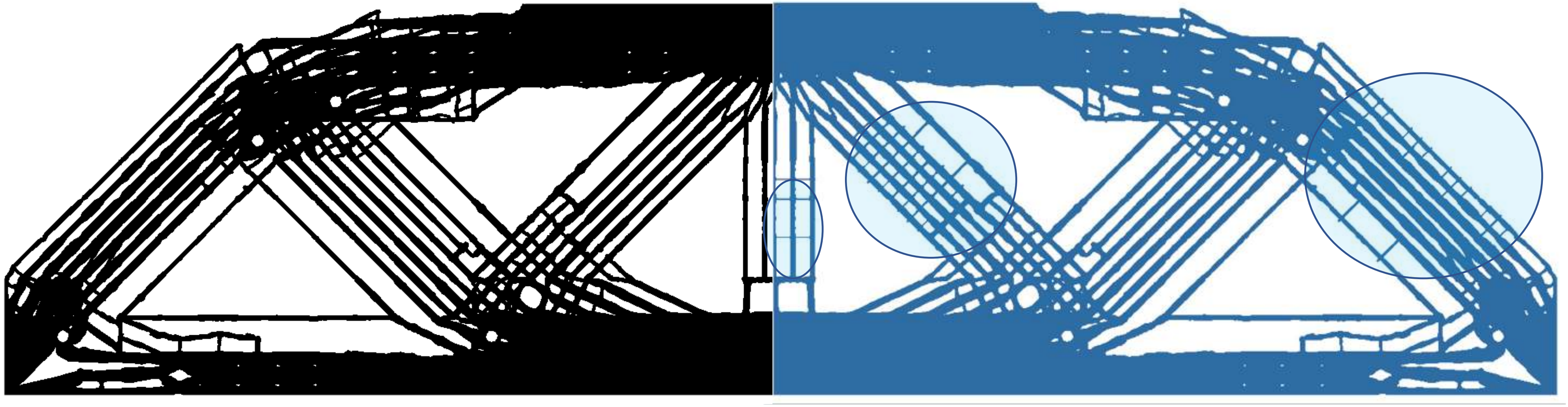


Fig. 7. Detail to understand the implementation for the unit cell: the element A is completely inside the beam so is black; the element B is completely outside the beam so is white; the element C is half covered by the beam, so the value assigned is 0.5 and is grey.

The Ex-EMTO allows to get truss-like ultra-light designs with very simple shapes.

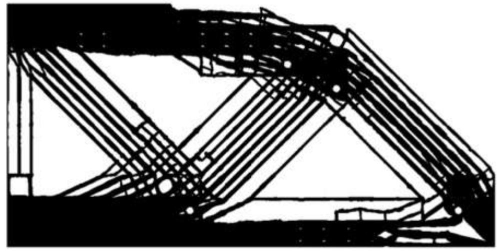
https://github.com/mid2SUPAERO/Ex-EMTO

Do you see a difference (Left2Right)?



and Local Buckling?

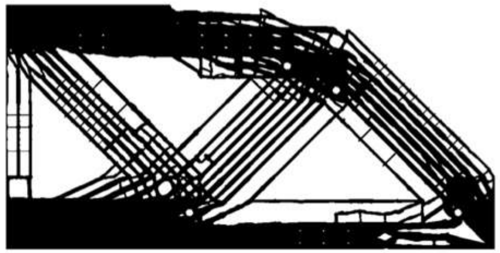
(a) The MBB beam problem.



(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.

First zoom

Procedia CIRP

Volume 109, 2022, Pages 454-459

Ecodesign with topology optimization

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

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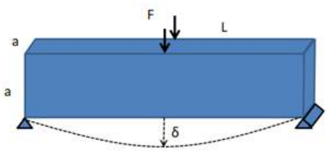
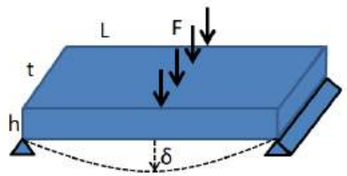
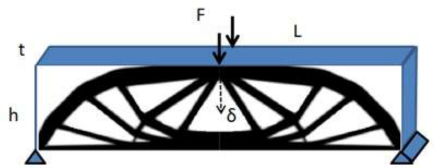
https://doi.org/10.1016/j.procir.2022.05.278 Get rights and content

Missing point from Ashby's theory:
The absence of a simple analytical relation between compliance and volume fraction.





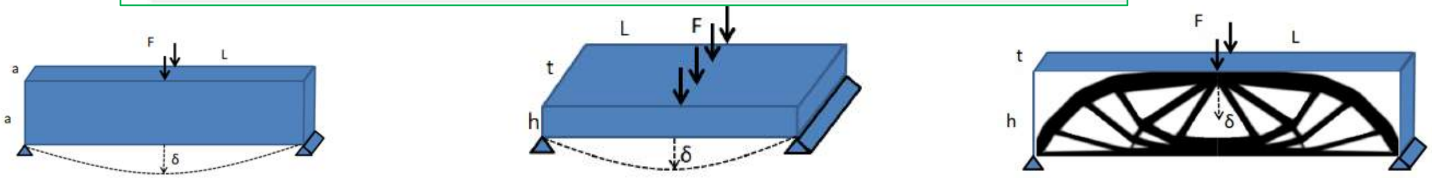


Material index

- If fixed material and process, CO_2 minimization = mass minimization
- Material choice through indices introduced by Ashby

  => uncouple material choice and part sizing
- Include the geometrical design ($\mathfrak{D}$) in the variables :

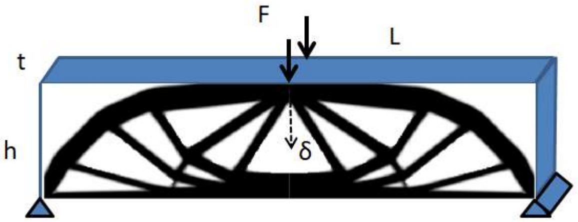
Properties	Bending beam (Ashby)	Bending plate (Ashby)	Duriez et al. (2022b)
Free variables	a, m	h, m	t, $\mathscr{D}$, m
Fixed	L, $\mathscr{D}$	L, t, $\mathscr{D}$	L_{max}, h_{max}
Constraint	δ_{max}	δ_{max}	δ_{max}



Ashby, M.F., 2004. Materials selection in mechanical design. 2. ed., reprinted ed., Elsevier Butterworth-Heinemann, Amsterdam.

Deriving the material index

- Problem considered:



$$\underset{mat,\mathcal{D},t}{\arg\min} \quad CO_2^{tot}(mat,\mathcal{D},t)$$
$$\text{s.t.} \quad \delta \le \delta_{max}$$
$$mat = \{E,\rho,CO^{i}_{2mat}\} \in \Phi$$
$$0 < v_f(\mathcal{D}) \le 1$$

- Objective function:

$$CO_2{}^{tot} = CO_2{}^{mat} \times M + CO_2{}^{veh} \times LD \times M$$

How many miles does an airplane like a 777 fly over the course of its lifetime?

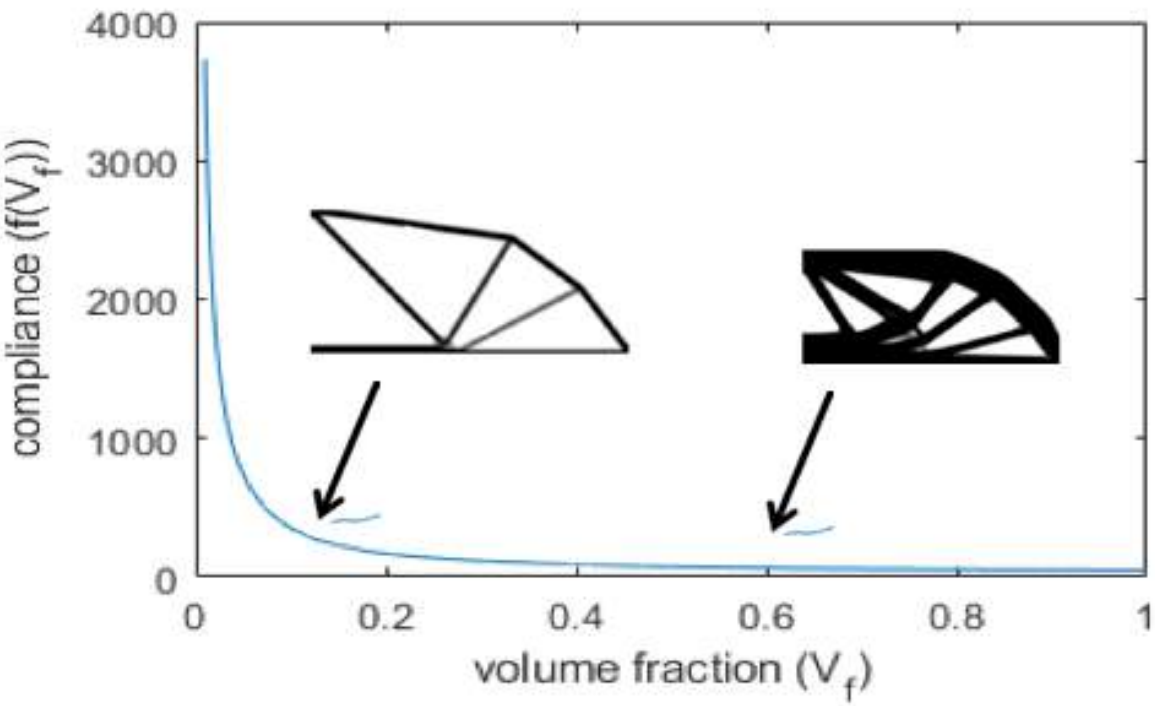
777: A 30-year lifetime. 3,500 hours a year as an average. An average speed of 500 miles per hour. 30 x 3500 x 500 = 52,500,000 miles i.e. LD.

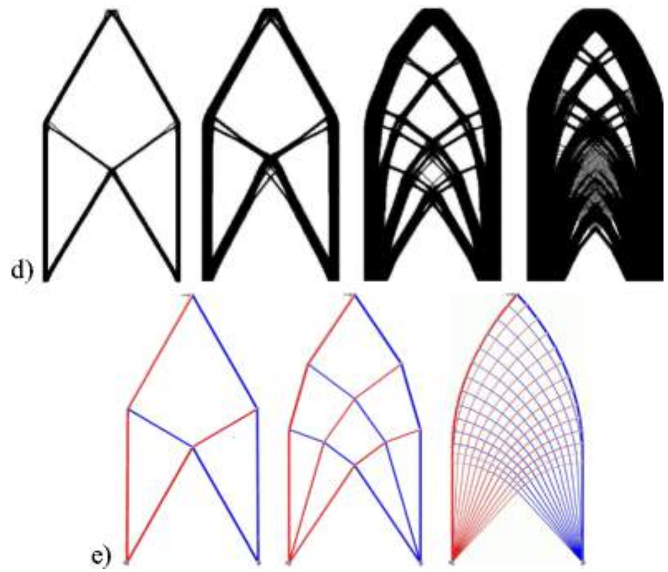
Topology optimization pareto front

V_f : volume fraction (ratio of space containing material)

f(V_f) : compliance – volume fraction pareto front

Edouard Duriez, Miguel Charlotte, Catherine Azzaro-Pantel et al. On some properties of the compliance-volume fraction Pareto front in topology optimization useful for material selection., 27 December 2022, PREPRINT (Version 1) available at Research Square [https://doi.org/10.21203/rs.3.rs-2390440/v1]

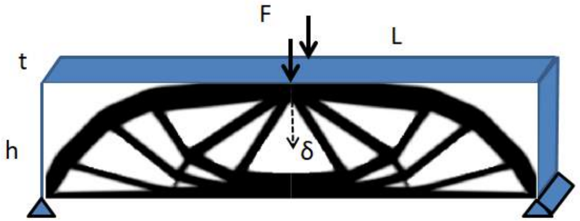




Sigmund, O., Aage, N., & Andreassen, E. (2016). On the (non-) optimality of Michell structures. *Structural and Multidisciplinary Optimization*, *54*, 361-373.

Deriving the material index

- Problem considered:



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

- Objective function:

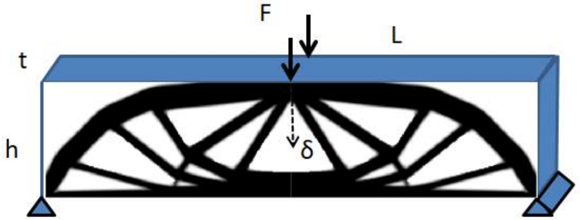
$$CO_2{}^{tot} = CO_2{}^{mat} \times M + CO_2{}^{veh} \times LD \times M$$

Deriving the material index

starting from $C = U^T K U = U^T F = U(i_F)F(i_F) = FU(i_F)$

$$M = \rho t L h V_f$$

- Problem considered:



compliance

$$C \leq F\delta_{max}$$

$$\frac{f(V_f)F}{tE} = \delta_{max}$$

If t is a free variable, it can be chosen as in compliance to achieve the minimum mass.

$$t = \frac{f(V_f)F}{\delta_{max}E} \quad \text{thus} \quad M = \frac{LhF}{\delta_{max}}\frac{\rho}{E}f(V_f)V_f$$

$$CO_2^{tot} = \underbrace{(CO_2^{mat} + LD\ CO_2^{veh}) \times \frac{\rho}{E}}_{\text{Material } f_3(M)} \underbrace{\frac{LhF}{\delta_{max}}}_{\text{functional } f_1(F)} \underbrace{f(V_f)V_f}_{\text{topology index } f_2(G)}$$

REMINDER !!

- Many materials
- Competing properties

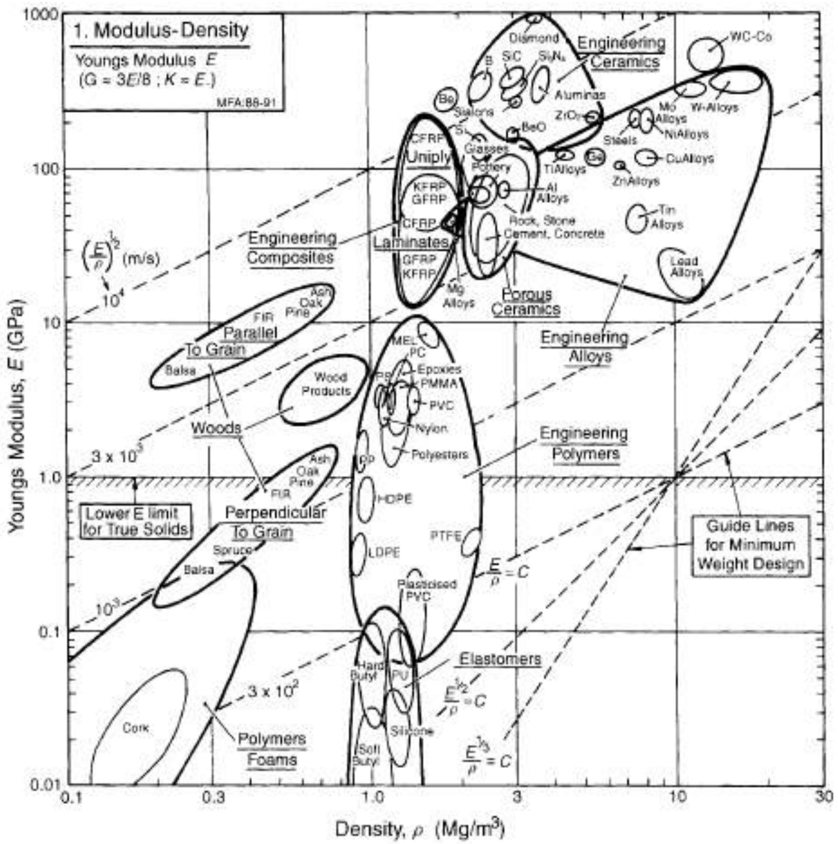
- => Ashby indexes: $f_3(M)$

P=$f_1(F) \times f_2(G) \times f_3(M)$

F: Functional constraints

G: Geometrical constraints

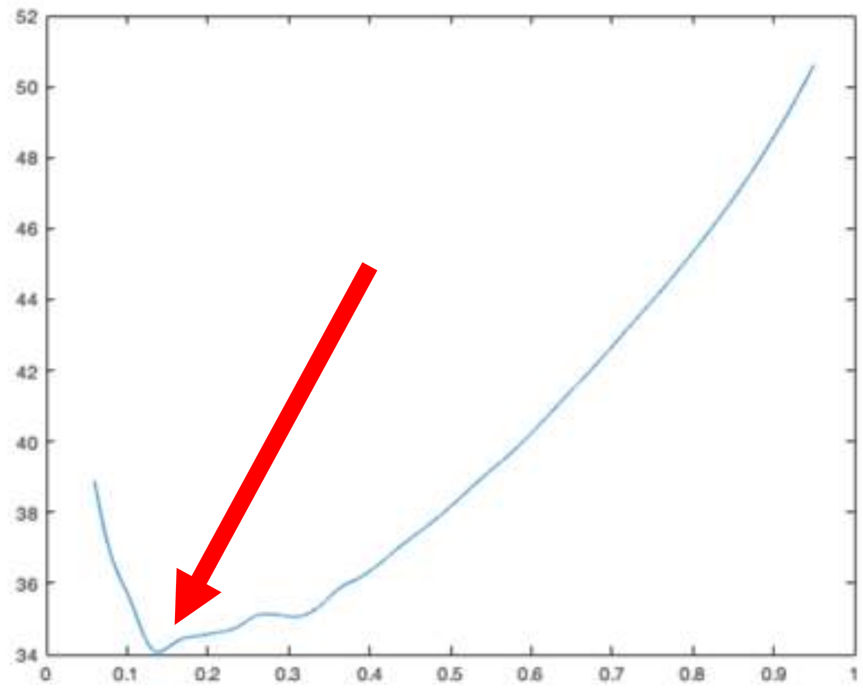
M: Material properties



M. F. Ashby et Kara Johnson. « Materials and Design : The Art and Science of Material Selection in Product Design ». In : 2002.

Minimize topology index

topology index $f_2(G)$



- Topology index : $f(V_f)V_f$:
  Minimize this to minimize mass
- Thickness t is finally adjusted to satisfy constraint

Data for Material index

functional improvement can be found in lightweight components for transport systems

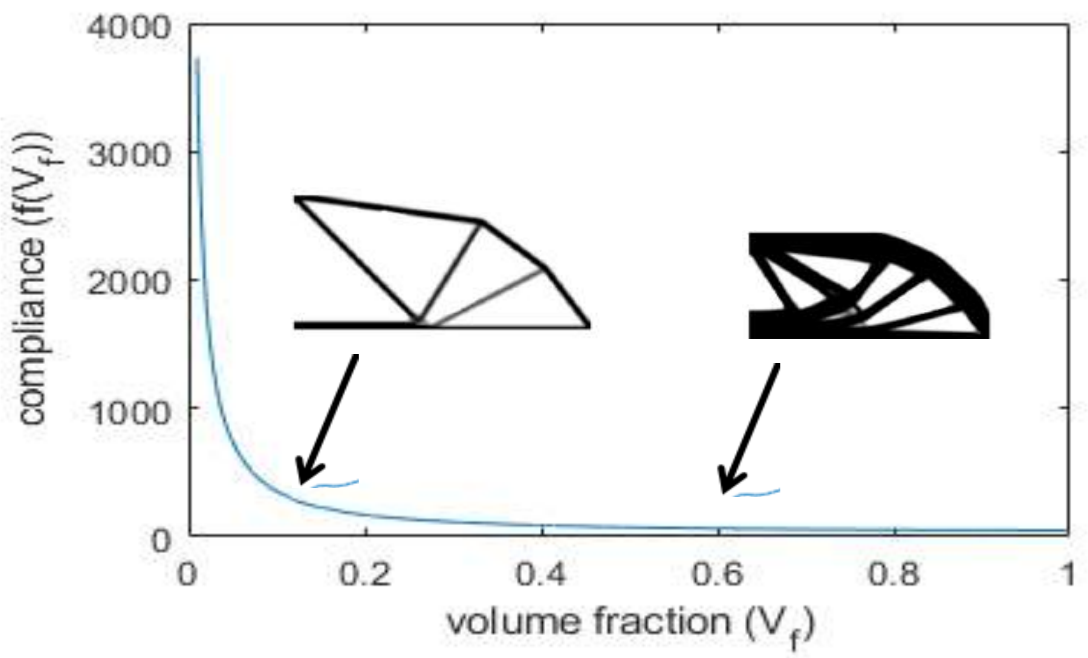
Table 8. Fuel consumption reduction coefficients for different vehicle types and related life time impact savings per kg of weight reduction.

Transport system	Energy source	FRC [26]	Service life	Eco-Impact (ReCiPe H/A)	Life time savings (ReCiPe H/A)	Equivalent electrical energy
Gasoline car	Gasoline	0.5 l / (100kg*100km)	200000km	0.121 Pts/l	1.21 Pts/kg	85 MJ
Diesel car	Diesel	0.24 l / (100kg*100km)	200000km	0.141 Pts/l	0.68 Pts/kg	48 MJ
Short distance train	Electricity	300 kJ / (1000kg*km)	$3.5*10^6$ km	0.051 Pts/kWh	14.88 Pts/kg	1050 MJ
Long distance train	Electricity	100 kJ / (1000kg*km)	$10*10^6$ km	0.051 Pts/kWh	14.17 Pts/kg	1000 MJ
Short distance aircraft	Kerosene	12.5 ton / (100kg*year)	25 year	0.134 Pts/l	335 Pts/kg	23647 MJ
Long distance aircraft	Kerosene	103 ton / (100kg*year)	25 year	0.134 Pts/l	2760 Pts/kg	194852 MJ

Kellens, Karel, et al. "Environmental impact of additive manufacturing processes: does AM contribute to a more sustainable way of part manufacturing?." *Procedia Cirp* 61 (2017): 582-587.

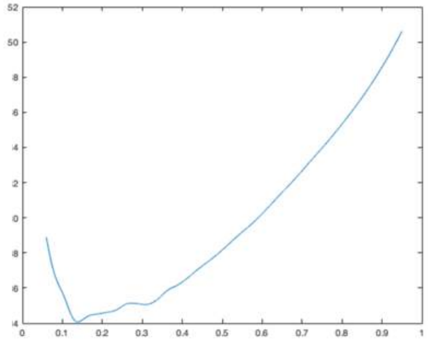
Code

```
%Al alloy Stainless Steel Ti alloy inconel
Emat=[70.8, 197, 115, 205].*10^9;
rhomat=[2795, 7915, 4425, 7900];
co2mat=[13, 6.15, 40.4, 15.5];
L=2; %m
h=0.5; %m
delta_max=0.005;
F=20000;
lveh=100000000;  %km

life=25;
FRC=103; %tonco2/100kg/year
lifekero=FRC*life*1000/100;  %kgco2/kg
%from ADEME : jet A in France or europe :  3.83kgeCO2/kg.
emitkero=3.83; %kgco2 / kg kerosen
lifeco2=lifekero*emitkero;
co2veh=lifeco2/lveh; %kgCO2/km

load('complHRr3.csv')
cP1=complHRr3(:,2);
%filtering
   win=1000;
   xgauss=0:1:win-1;
   sig=win/8;
   ygauss=1/(sig*sqrt(2*pi))*exp(-0.5*(xgauss-(win-1)/2).^2./sig^2);
   cFiltG=conv(cP1,ygauss);
   cFiltGT=cFiltG(win:end-win);
%
%cpareto=complHRr3(:,2); %raw pareto %Pando % multistart
cpareto=cFiltGT;
vpareto= 0.01:0.0001:1;
vpareto=vpareto(win/2:end-win/2-1);%
figure(1)
plot(vpareto, cpareto);
```



Code (bis)

```
figure(2)
plot(vpareto,vpareto'.*cpareto);

[optimalvfv,optimalvf]=min(vpareto'.*cpareto);
optVf=vpareto(optimalvf);

%Al alloy Stainless Steel Ti alloy inconel
for material=1:4 % 2 or 3 or 4

thick(material)=cpareto(optimalvf)*F/delta_max/Emat(material);
mass(material)=L*h*thick(material)*optVf*rhomat(material);
co2mat(material)
Idx_veh(material)=(Emat(material)/rhomat(material))*(co2mat(material)+lveh*co2veh)
Idx_bridge(material)=(Emat(material)/rhomat(material))*(co2mat(material))

Impact_CO2veh(material)=(co2mat(material)+lveh*co2veh)*mass(material);

Impact_CO2bridge(material)=(co2mat(material))*mass(material);
```



Al alloy Stainless Steel Ti alloy inconel

Material $f_3(M)$ IS

$$Idx = (CO_2{}^{mat} + LDCO_2{}^{veh}) \times \frac{\rho}{E}$$

Search for lower Idx
depending on the application

mass = 5.3807 5.4761 5.2445 5.2525

co2mat = 13.0000 6.1500 40.4000 15.5000

Impact_CO2veh = 1.0e+05 * 5.3073 5.4011 5.1744 5.1809

Impact_CO2bridge = 69.9492 33.6783 211.8788 81.4133

Idx_veh = 1.0e+12 * 2.4985 2.4548 2.5641 2.5596

Idx_bridge =1.0e+09 * 0.3293 0.1531 1.0499 0.4022

Results

- Results change depending on the application:

- Aircraft

Material	E (GPa)	ρ (kg/m^3)	CO^i_{2mat} $(kgCO_2/kg)$	Idx $(kgCO_2/N/m)$
Al alloy	70.8	2795	13.0	3.90×10^{-3}
Stainless steel	197	7915	6.15	3.97×10^{-3}
Ti alloy	115	4425	40.4	3.80×10^{-3}
Inconel 713	205	7900	15.5	3.81×10^{-3}

mass : 5,24kg 5.2445

CO_2 emissions:
517 tons 1.0e+05 * 5.1744

- Pedestrian bridge

Material	E (GPa)	ρ (kg/m^3)	CO^i_{2mat} $(kgCO_2/kg)$	Idx $(kgCO_2/N/m)$
Al alloy	70.8	2795	13.0	5.13×10^{-7}
Stainless steel	197	7915	6.15	2.47×10^{-7}
Ti alloy	115	4425	40.4	1.56×10^{-6}
Inconel 713	205	7900	15.5	5.97×10^{-7}

mass : 5,47kg 5.4761

CO_2 emissions:
33,67 kg 33.6783

To go deeper

ELSEVIER

Cleaner Environmental Systems

Volume 9, June 2023, 100114

A fast method of material, design and process eco-selection via topology optimization, for additive manufactured structures

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

Properties	Bending beam (Ashby)	Bending plate (Ashby)	Duriez et al. (2022b)	Our problem
Free variables	a, m	h, m	t, $\mathscr{D}$, m	$\mathscr{D}, m, p$
Fixed	L, $\mathscr{D}$	L, t, $\mathscr{D}$	L_{max}, h_{max}	L_{max}, h_{max}, t_{max}
Constraint	δ_{max}	δ_{max}	δ_{max}	δ_{max}

Au programme

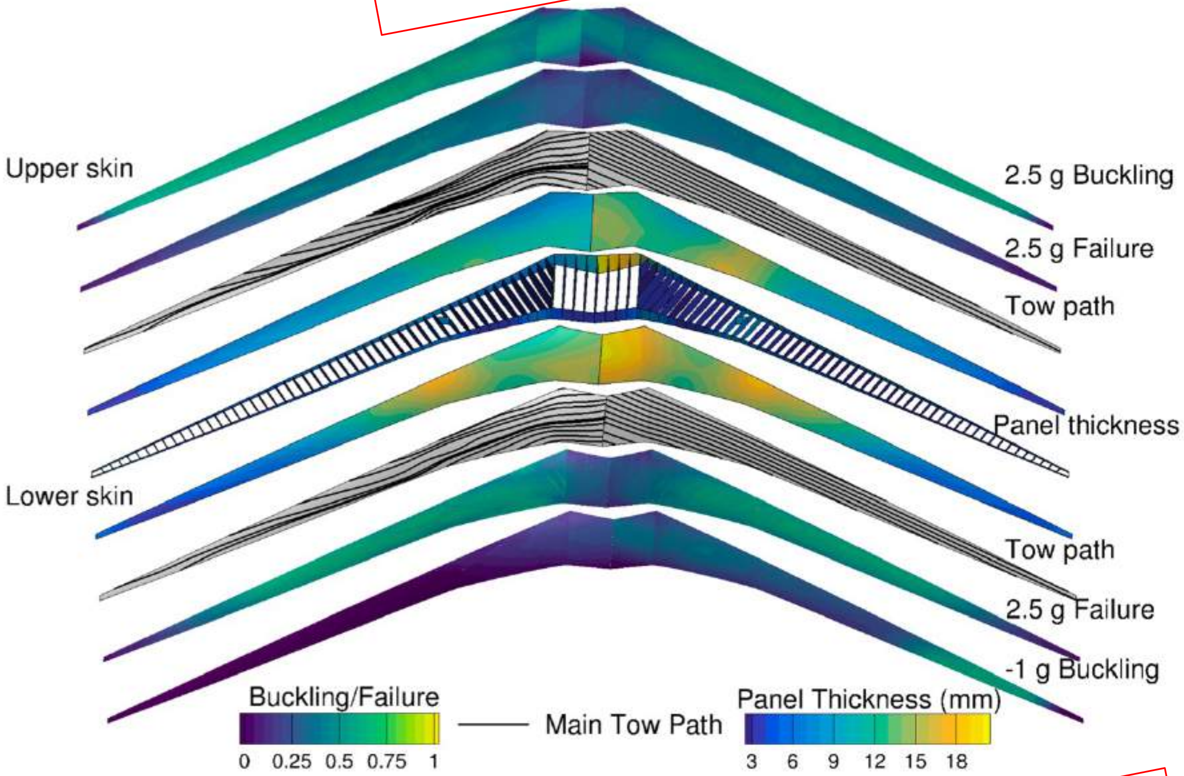
- Part1:Unit Cell/Material/Process as design variables
- **Part2: Ecodesign of 3D volumetric structures with fiber/resin topology optimization**
- Bonus SMT2.0

Thanks to Enrico Stragiotti (Déjà vu), Alexandre Coehlo and Gustavo Asai

Composites Fiber Placement as DVs

https://www.compositesworld.com/articles/tow-steering-part-2-the-next-generation

X* is a UHAR Wing ;)

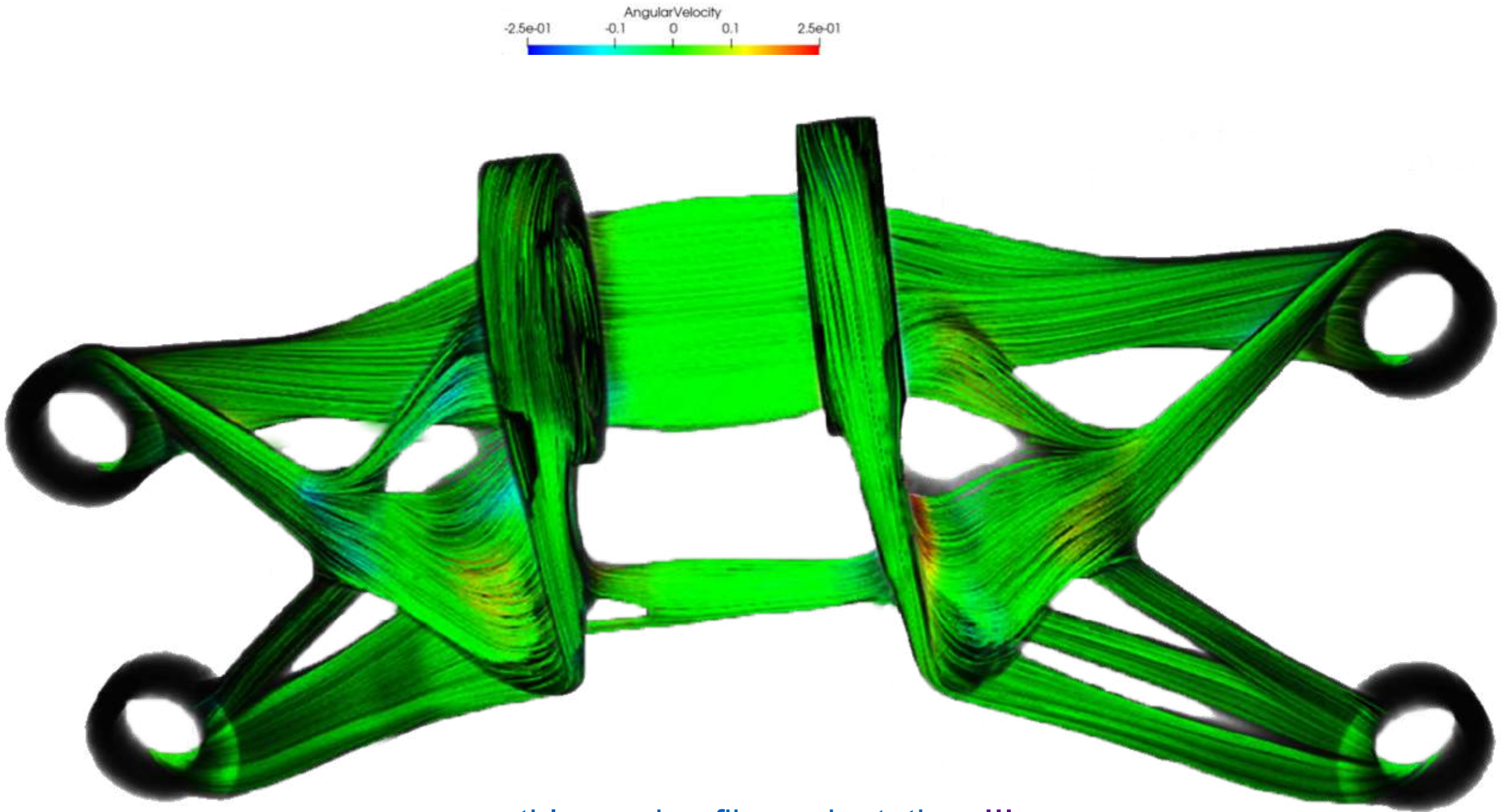


Brooks, T. R., Martins, J. R., & Kennedy, G. J. (2019). High-fidelity aerostructural optimization of tow-steered composite wings. Journal of Fluids and Structures, 88, 122-147.

Brooks, T. R., Martins, J. R., & Kennedy, G. J. (2020). Aerostructural tradeoffs for tow-steered composite wings. Journal of Aircraft, 57(5), 787-799.

Lower wing mass, Less fuel burn

GE Bracket by Schmidt et al., Struct. Multidiscip. Optim. (2020)



smoothly varying fiber orientations!!!

First in 2D:

In-plane fibre orientations

- Optimisation problem formulation

$$\min_{\boldsymbol{\rho},\boldsymbol{\theta}} c(\boldsymbol{\rho},\boldsymbol{\theta}) = \sum_e \rho_e^p \, \boldsymbol{u_e^T} \, \boldsymbol{k_0}(\theta_e) \, \boldsymbol{u_e^T}$$

$$\text{s.t.} \begin{cases} \frac{V(\boldsymbol{\rho})}{V_0} \leq f \\ \boldsymbol{KU} = \boldsymbol{F} \\ 0 < \rho_{min} \leq \boldsymbol{\rho} \leq 1 \\ -\pi \leq \boldsymbol{\theta} \leq \pi \end{cases}$$

solved with initial random point

- Filters

$$\rho_e \widetilde{\frac{\partial c}{\partial \rho_e}} = \frac{1}{\sum_i H^\rho_{ei}} \sum_i H^\rho_{ei} \, \rho_i \frac{\partial c}{\partial \rho_i}$$

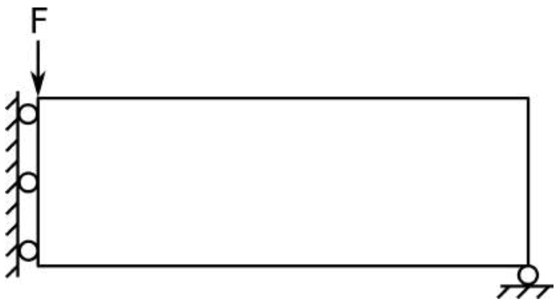
$$H^\rho_{ei} = \max(0, r_\rho - \Delta(e,i))$$

$$\tilde{\theta}_e = \frac{1}{\sum_i H^\theta_{ei} \, \rho_i} \sum_i H^\theta_{ei} \, \rho_i \theta_i$$

$$H^\theta_{ei} = \max(0, r_\theta - \Delta(e,i))$$

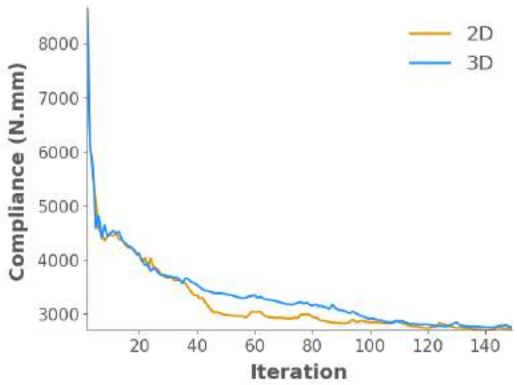
Problem 1 - MBB beam

2D and in-plane 3D solutions were compared to verify the sensitivity calculations for 3D elements

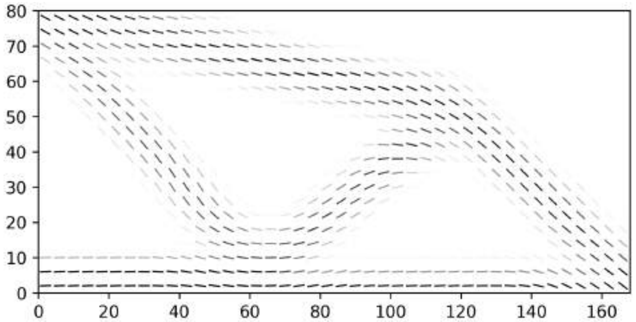


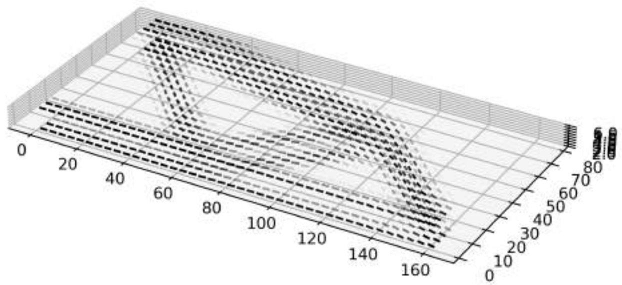
- Half MBB beam, 186 mm $\times$ 80 mm $\times$ 8 mm
- Element size: 4 mm
- Volume fraction constraint: 0.3
- Density filter radius: 8 mm $\Rightarrow$ 3D layers behave similar to 2D
- Orientation filter radius: 20 mm
- Same initial orientation: 50°

Problem 1 - MBB beam



- 2D - Comp. = 2691 N.mm
- 3D - Comp. = 2733 N.mm





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CO2?

In this work, the environmental impact of the structure is measured in terms of the mass of CO_2 emitted during material production $CO_{2,mat}$ and during its use in a long distance aircraft $CO_{2,use}$, following the methodology from [1], adapted to composite materials. The value used to compare different designs is the total footprint $CO_{2,tot} = CO_{2,mat} + CO_{2,use}$.

The impact of the material production depends on the total mass M and the CO_2 intensity of the material $CO^i_{2,mat}$ (mass of CO_2 emitted per mass of material). Its expression is given by (8), where ρ_f is the fiber density, $CO^i_{2,f}$ is the fiber CO_2 intensity, ρ_m is the matrix density, $CO^i_{2,m}$ is the matrix CO_2 intensity, and V_f is the fiber volume fraction in the composite material.

$$CO_{2,mat} = M \cdot CO^i_{2,mat} = M \cdot \frac{\rho_f V_f CO^i_{2,f} + \rho_m (1 - V_f) CO^i_{2,m}}{\rho_f V_f + \rho_m (1 - V_f)}$$

The impact of the use phase is calculated as the emissions that would be saved if the component was lighter. Reducing the mass by 1 kg in a long distance aircraft leads to a reduction of 98.8 tCO_2 during its lifetime [1], i.e., $CO_{2,use} = M \cdot 98.8\ \mathrm{t}CO_2/\mathrm{kg}$.

CO2?

	Material	ρ (kg/m^3)	E (GPa)	ν	CO_2^i (kg CO_2/kg)
Fibers	Bamboo	700	17.5	0.39	1.0565
	Flax	1470	53.5	0.355	0.44
	Hemp	1490	62.5	0.275	1.6
	HM Carbon	2105	760	0.105	68.1
	S-Glass	2495	89.5	0.22	2.905
Resins	PLA	1255	3.45	0.39	2.28
	PETG	1270	2.06	0.403	4.375
	Epoxy	1255	2.41	0.399	5.94

CO2?

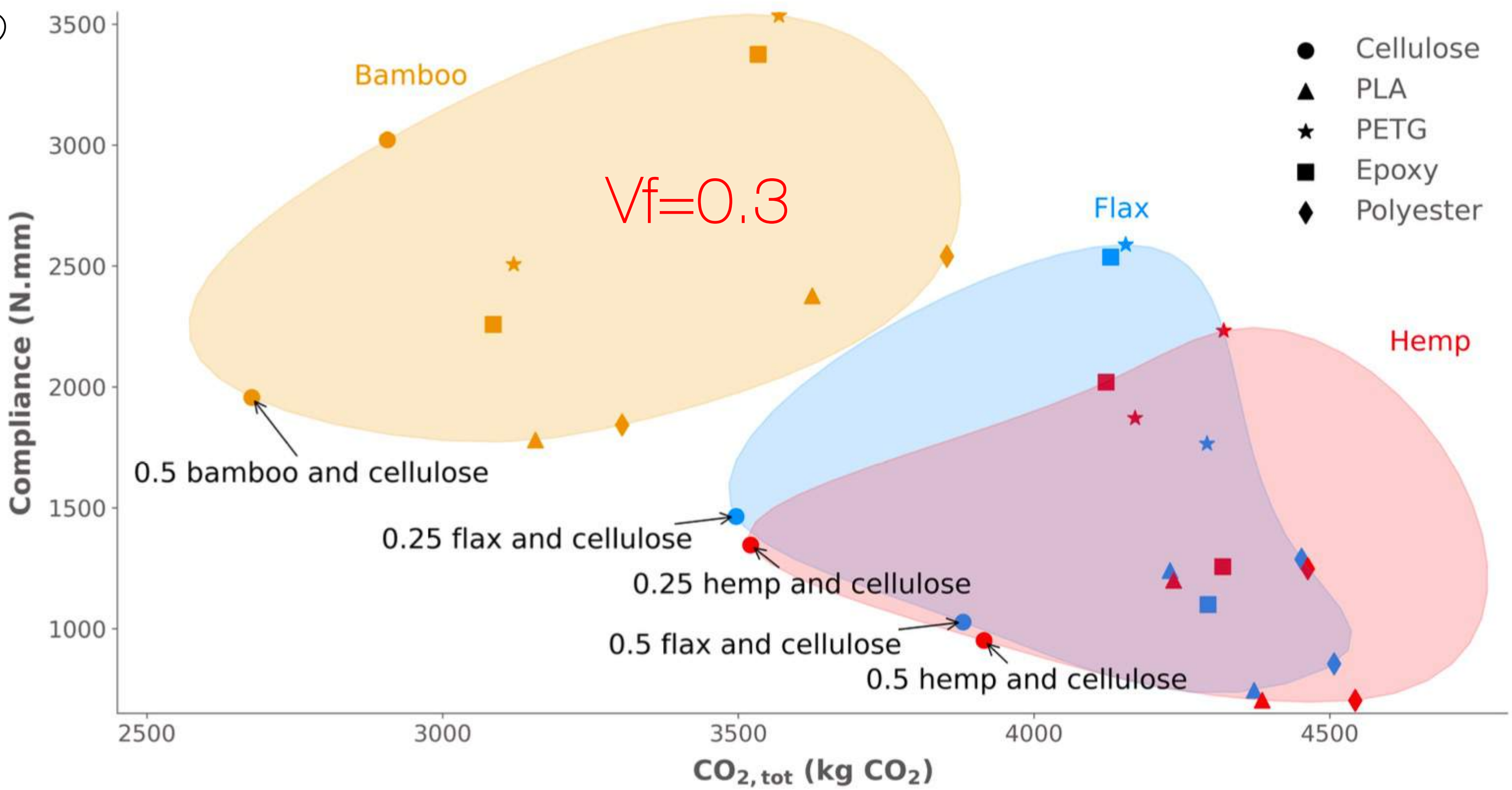


FIGURE 4 – Compliance versus CO_2 footprint of the optimal designs with natural fibers. Each design is represented by its fiber and resin.

Maps of compliance versus C02

Vf=0.65

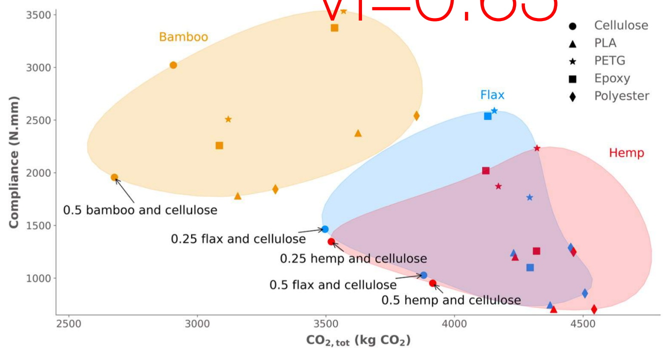


FIGURE 4 – Compliance versus CO_2 footprint of the optimal designs with natural fibers. Each design is represented by its fiber and resin.

Vf=0.3

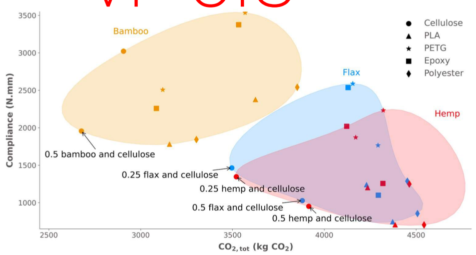


FIGURE 4 – Compliance versus CO_2 footprint of the optimal designs with natural fibers. Each design is represented by its fiber and resin.

For non structural parts

COMPARISON AT HIGH COMPLIANCE

For nonstructural parts, where providing stiffness is not the main function, e.g. aircraft interior, fiber-glass is a typical choice. A bamboo/cellulose design was considered as substitute to minimise footprint for fixed f .

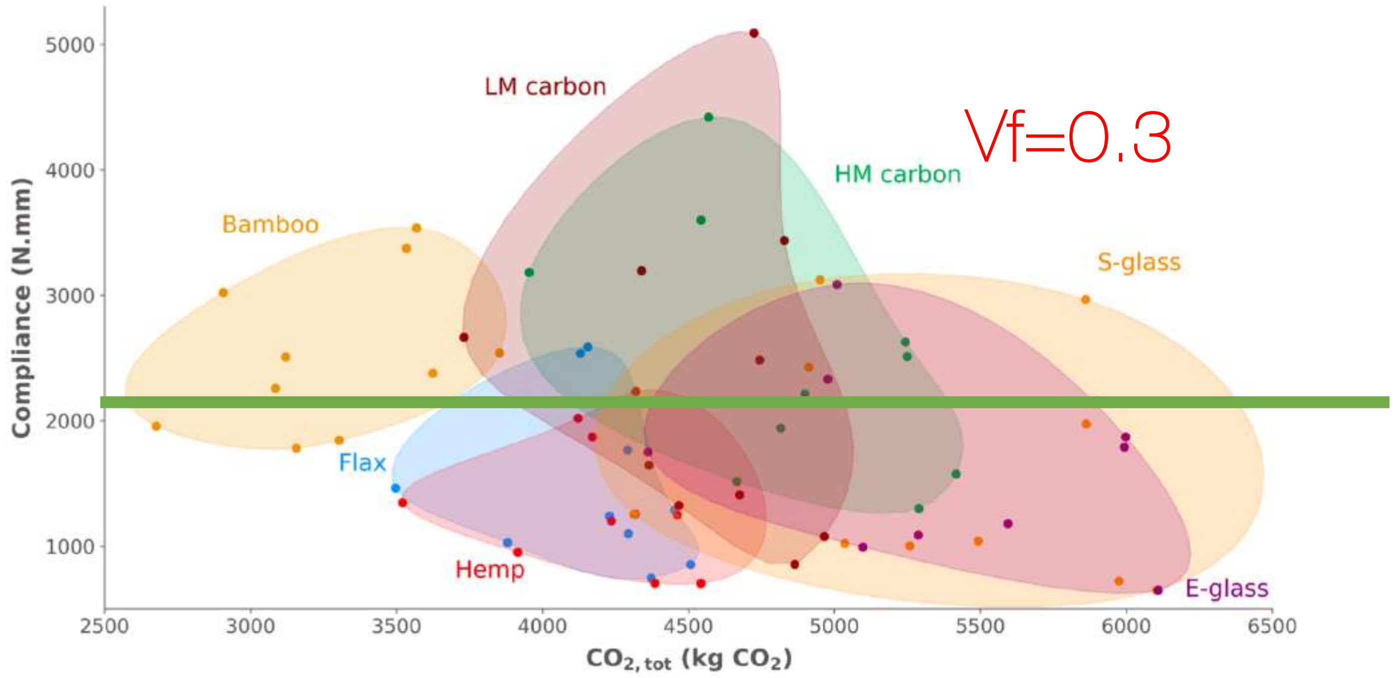


FIGURE 3 – Compliance versus CO_2 footprint of the optimal designs. Each point represents a fiber/resin/V_f combination, colored and grouped by fiber.

For non structural parts

TABLE 4 – Structures optimised for minimum footprint at $f = 0.35$.

fiber	Resin	Compliance (N.mm)	M (g)	$CO_{2,tot}$ (kg CO_2)
S-glass	Polyester	604	72.7	7173
Bamboo	Cellulose	2049	31.7	3122

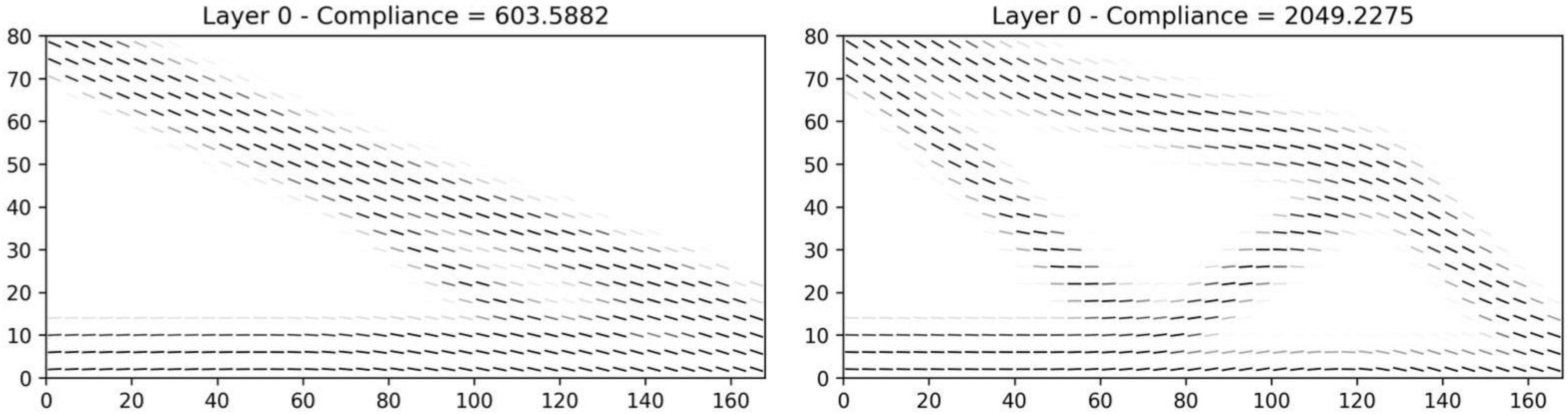


FIGURE 6 – Final designs optimised at $f = 0.35$: S-glass/polyester (left) and bamboo/cellulose (right).

Results for f = 0.35 are shown in Fig. 6 and Table 4, bamboo presents 56.4% less mass and $CO2$ emission with 3.4 times more compliance, which might be acceptable when loading is not critical.

For structural parts

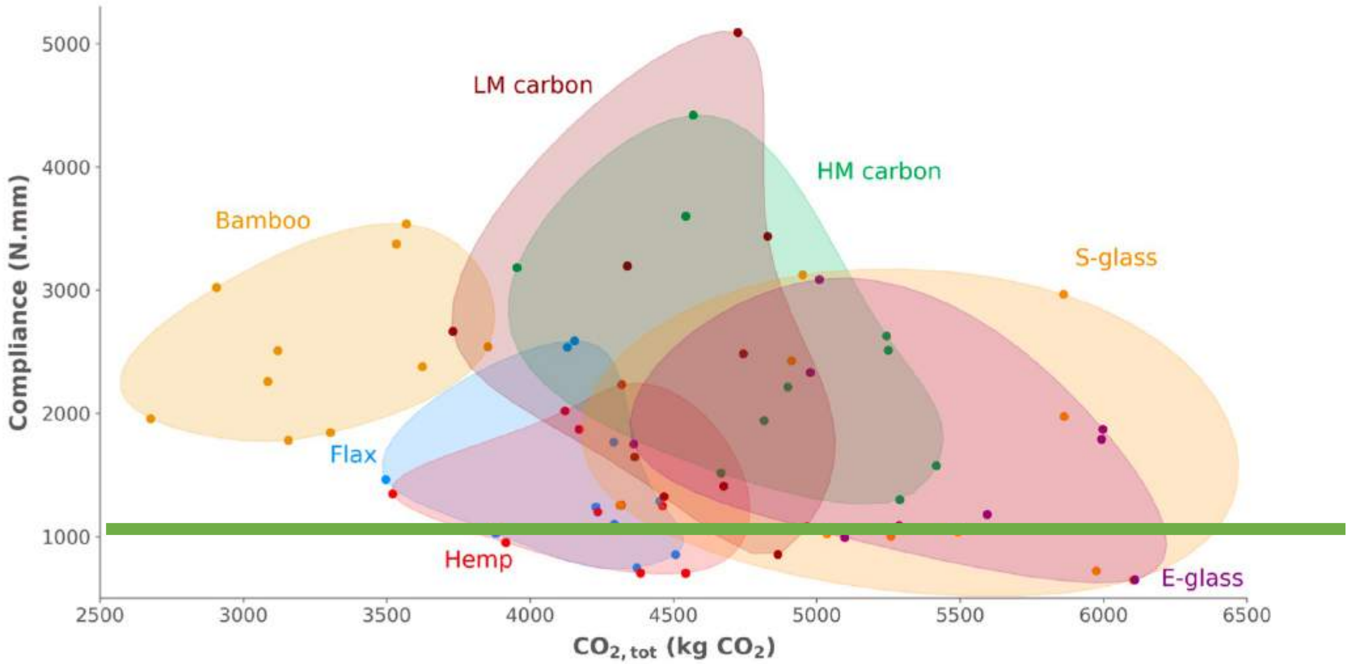
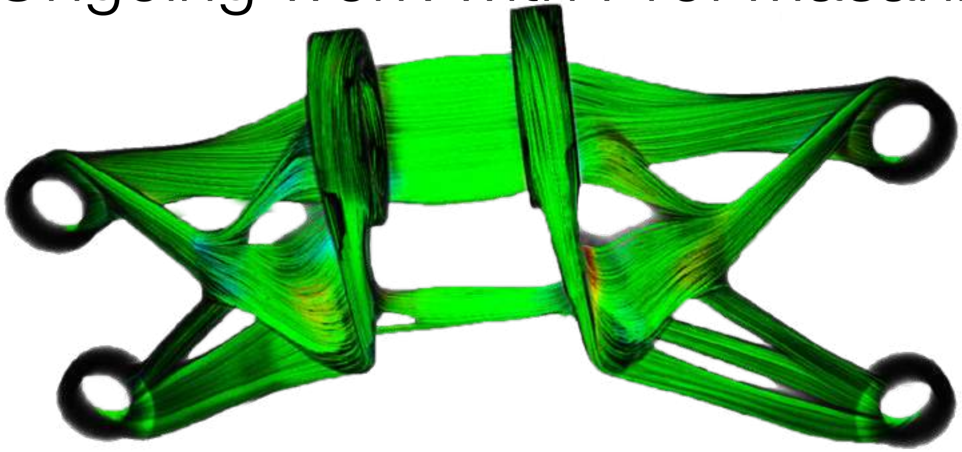


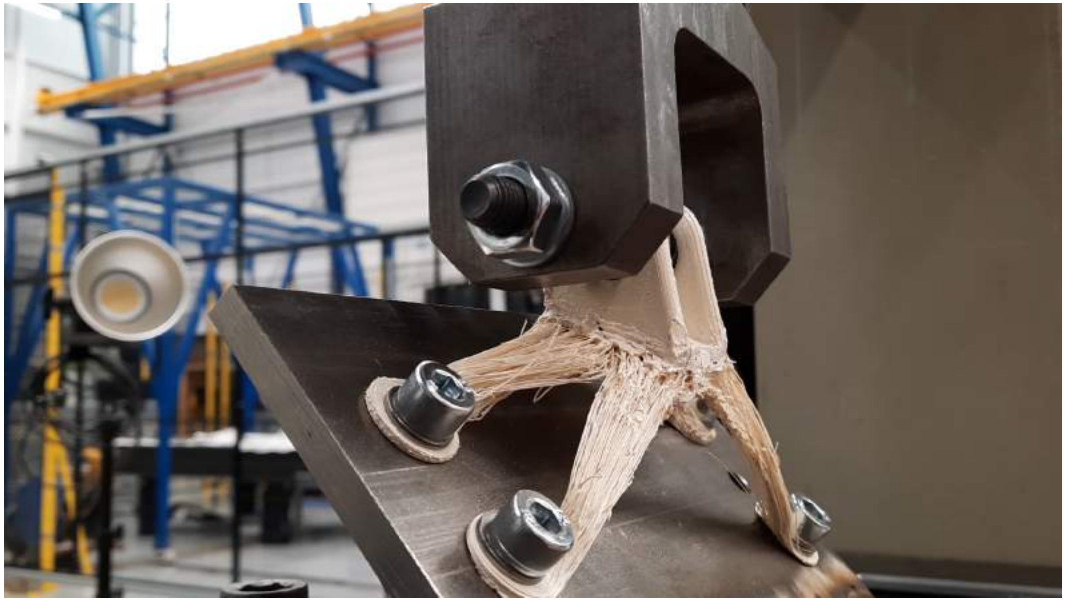
FIGURE 3 – Compliance versus CO_2 footprint of the optimal designs. Each point represents a fiber/resin/V_f combination, colored and grouped by fiber.

COMPARISON AT 1100N.MM

For main structural components, where stiffness is an important requirement, carbon fiber is typically used. A HM carbon/epoxy, an S-glass/polyester and a hemp/PLA design (all with 0.5 fiber volume fraction) were optimised to achieve a compliance of 1100 N.mm by varying V*f* .

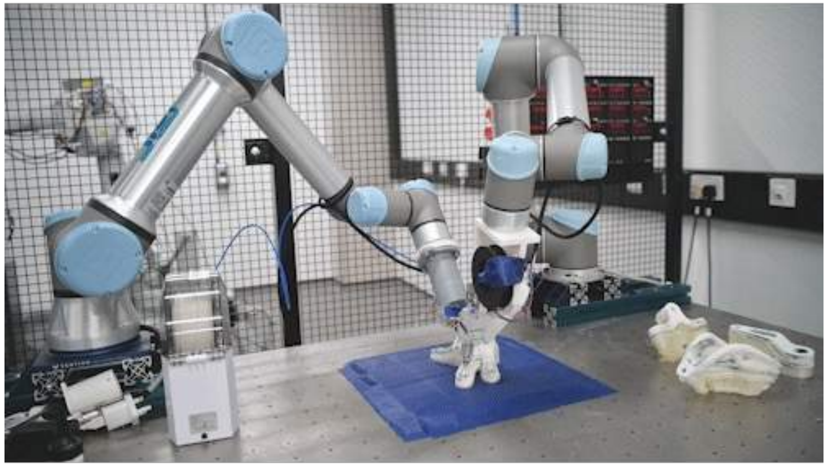
Ongoing work with Prof Masania



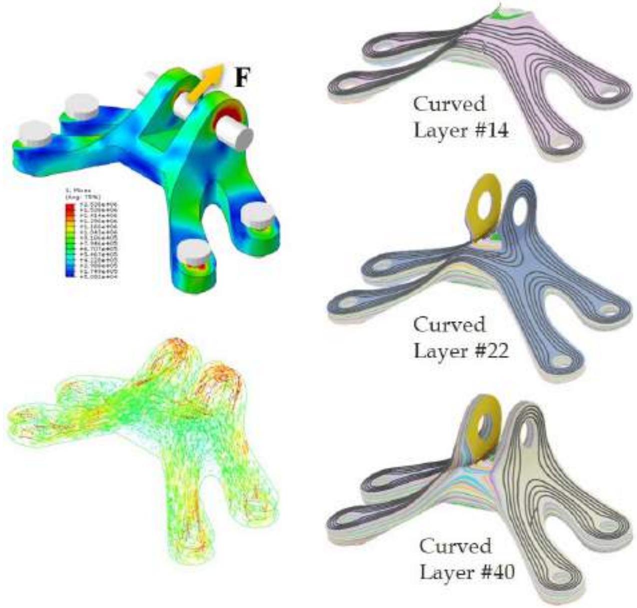


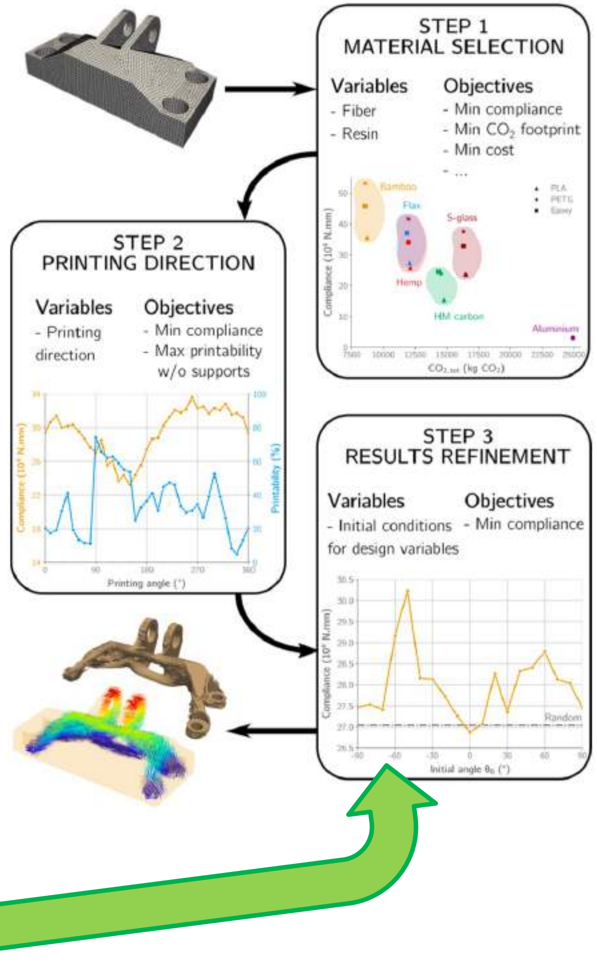
2.5x stronger
-50% weight

Ongoing work https://www.youtube.com/watch?v=7Jxyu9uRMLo



Fang, G., Zhang, T., Huang, Y., Zhang, Z., Masania, K., & Wang, C. C. (2024). Exceptional mechanical performance by spatial printing with continuous fiber: Curved slicing, toolpath generation and physical verification. *Additive Manufacturing*, 104048.





[UNPUBLISHED]From Manufacturable to EcoOptimized part
https://github.com/mid2SUPAERO/SOMP_Ansys

Add Ecomaterial selection, printability and of course opensource framework
(but need an ANSYS LICENCE)

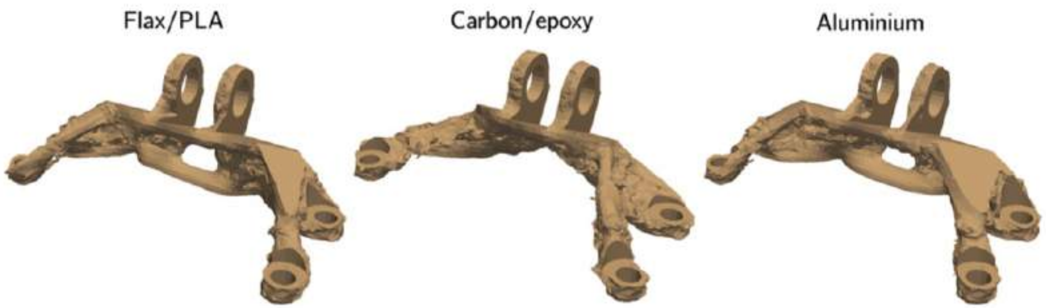


Figure 9: Isosurfaces of density 0.55 for different materials.

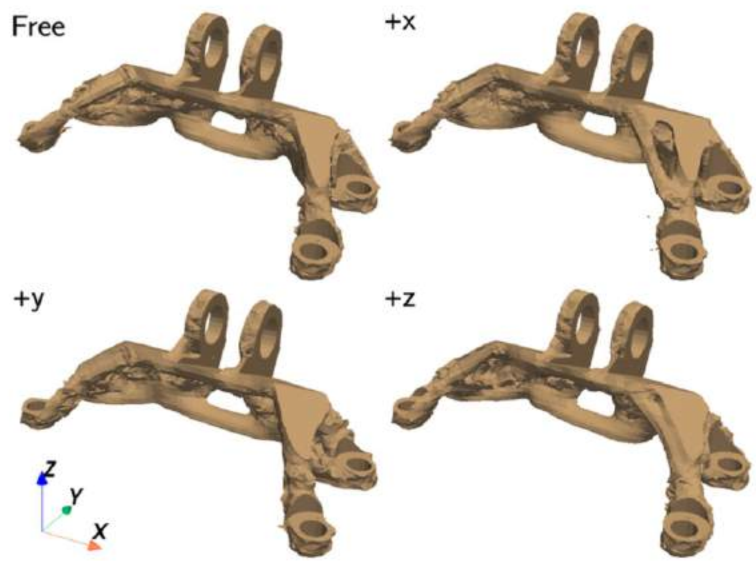


Figure 10: Isosurfaces of the optimal designs for each printing direction.

https://github.com/mid2SUPAERO/SOMP_Ansys

Add Ecomaterial selection, printability and of course opensource framework
(but need an ANSYS LICENCE)

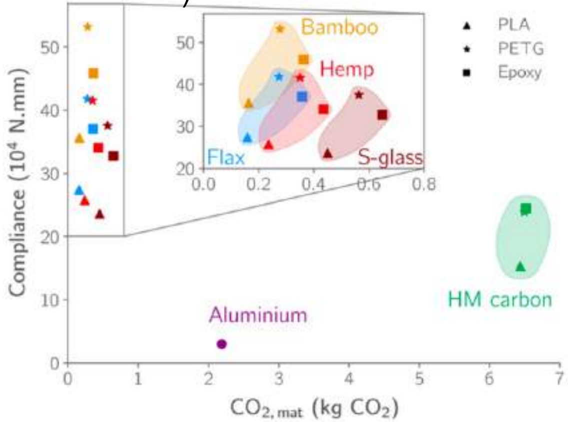


Figure 7: Compliance versus material production footprint of the optimal designs, grouped by fiber.

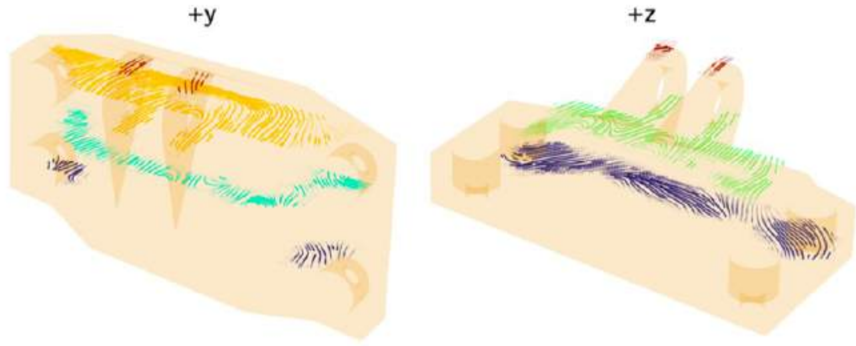


Figure 11: Examples of fiber distribution on slices of the optimal designs.

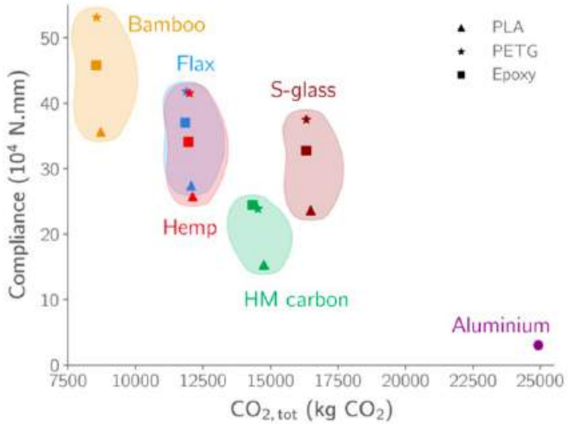


Figure 8: Compliance versus total footprint of the optimal designs, grouped by fiber.

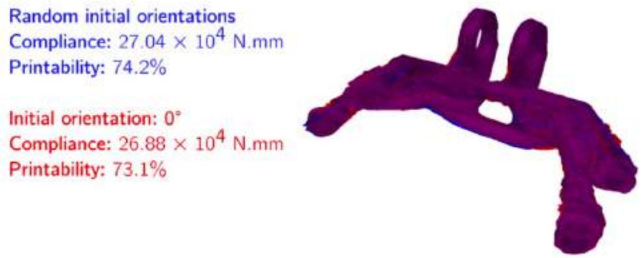


Figure 16: Isosurfaces of the optimal designs for random and 0° initial orientations.

https://github.com/mid2SUPAERO/SOMP_Ansys

Au programme

- Part1:Unit Cell/Material/Process as design variables
- Part2: Ecodesign of 3D volumetric structures with fiber/resin topology optimization
- **Bonus SMT2.0**

Bonus (Extracted from a recent poster https://gdr.igaia.cnrs.fr)

SMT 2.0: A Surrogate Modeling Toolbox
applied to Material Discovery

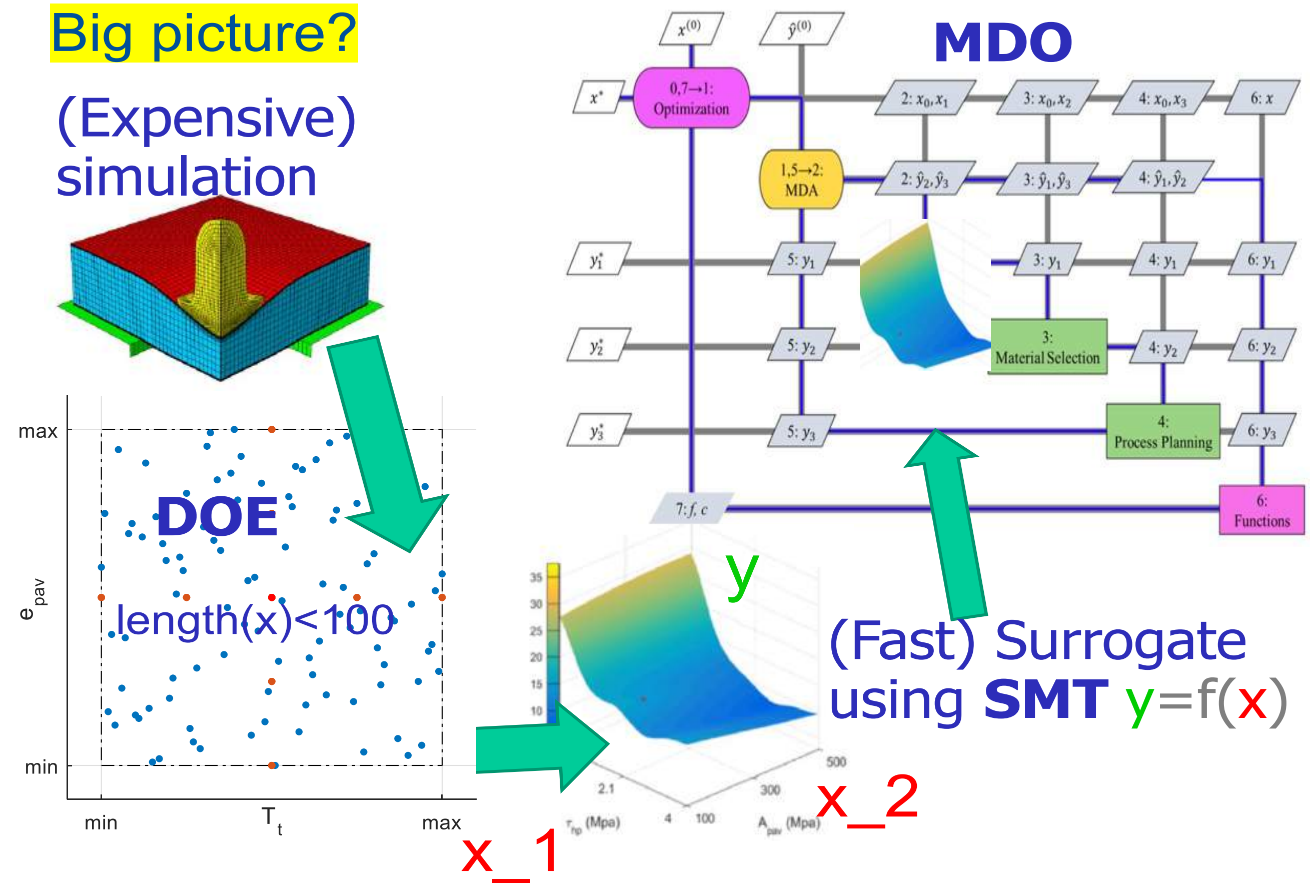
Prof. Joseph Morlier

Paul Saves, Nathalie Bartoli, Thierry Lefebvre

(ONERA)

github.com/SMTorg/smt

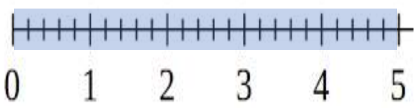
Main Idea


Big picture?
(Expensive) simulation
DOE
length(x)<100
max
min
e_{pav}
min
T_t
max
MDO
$x^{(0)}$
$\hat{y}^{(0)}$
x^*
0,7→1: Optimization
1,5→2: MDA
2: x_0, x_1
3: x_0, x_2
4: x_0, x_3
6: x
2: $\hat{y}_2, \hat{y}_3$
3: $\hat{y}_1, \hat{y}_3$
4: $\hat{y}_1, \hat{y}_2$
y_1^*
5: y_1
3: y_1
4: y_1
6: y_1
y_2^*
5: y_2
3: Material Selection
4: y_2
6: y_2
y_3^*
5: y_3
4: Process Planning
6: y_3
7: f, c
6: Functions
y
(Fast) Surrogate using **SMT** y=f(x)
x_1
x_2
500
300
100
2.1
4
A_{pav} (Mpa)
35
30
25
20
15
10

Can we applied SMT2 to Material Discovery?

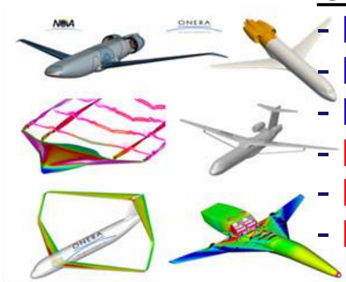
Variables types:

- Continuous (x)
- Ex: wing length



- Integer (z)
- Ex: winglet number

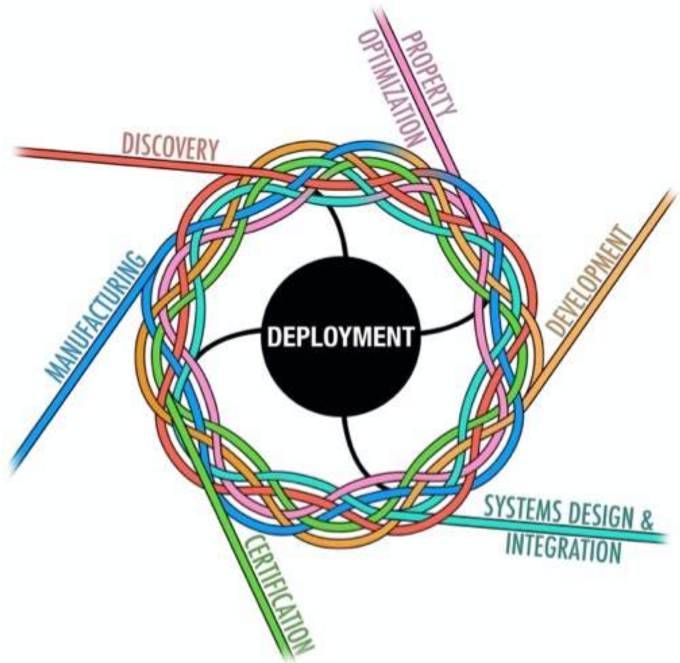
- Categorical (u)
- Ex: Plane shape / material properties



__Categorical variables__:
n variables, n=2
u1= shape
u2= color

__Levels:__ L_i levels for I in 1,..n,
$L_1=3$, $L_2=2$
Levels(u1)= square, circle, rhombus
Levels(u2)= blue, red

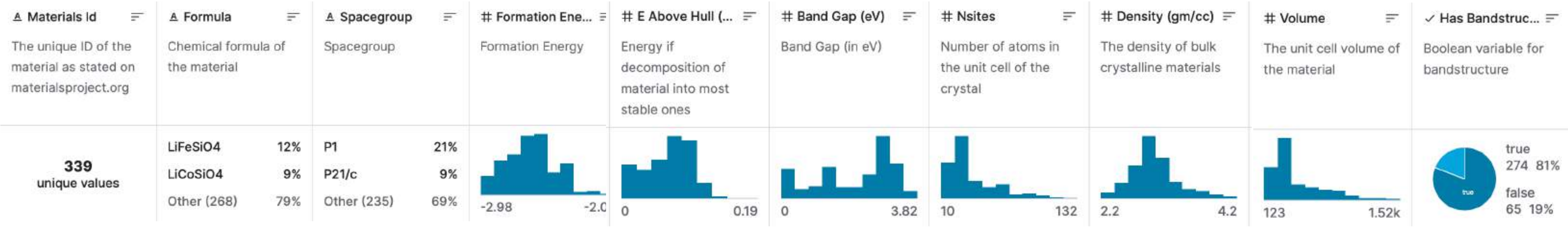
__Categories:__ $\prod_{i=1}^{n} L_i$, 2*3=6
- Blue square
- Blue circle
- Blue rhombus   6 possibilities
- Red square
- Red circle
- Red rhombus



www.mgi.gov

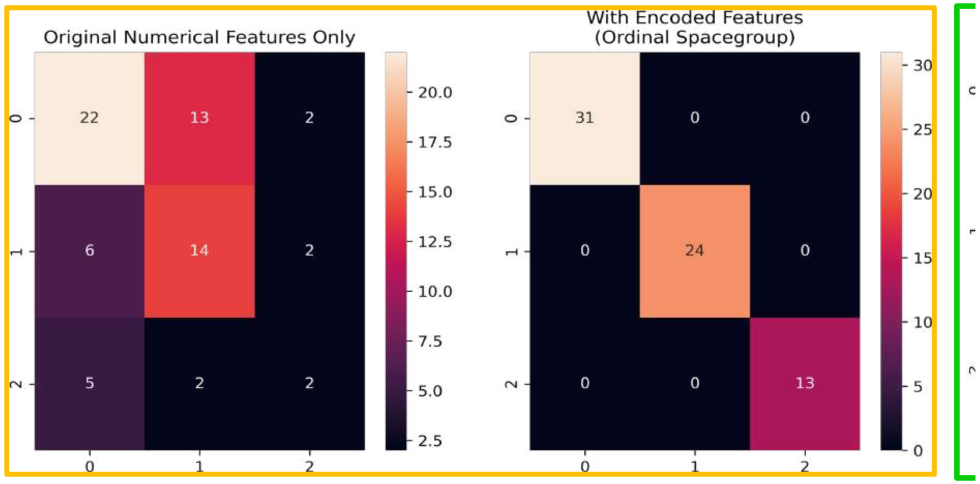
Data

Example in Battery Engineering Agrawal, D., **Crystal System Properties for Li-ion batteries**, Properties of Li-ion silicate to predict the crystal system class of the battery, Kaggle, March 2020.

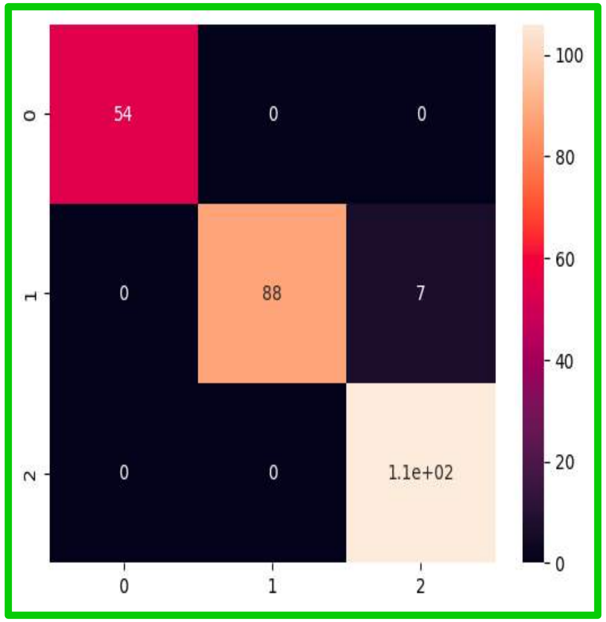


Bonus

Predict y the crystal structure type (monoclinic, orthorhombic, triclinic)
from x Lithium-ion physical and chemical compound information
i.e. learn from learning database y=f(x)



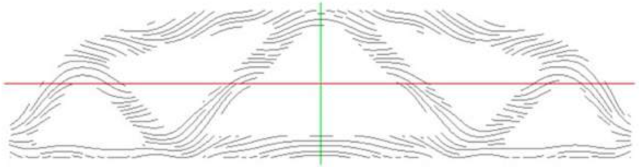
scikit-learn with <u>80/20</u> dtree w/wo specific features (*sf*)

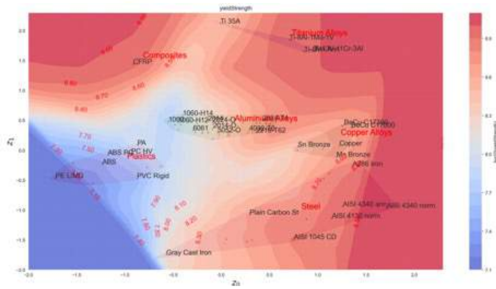


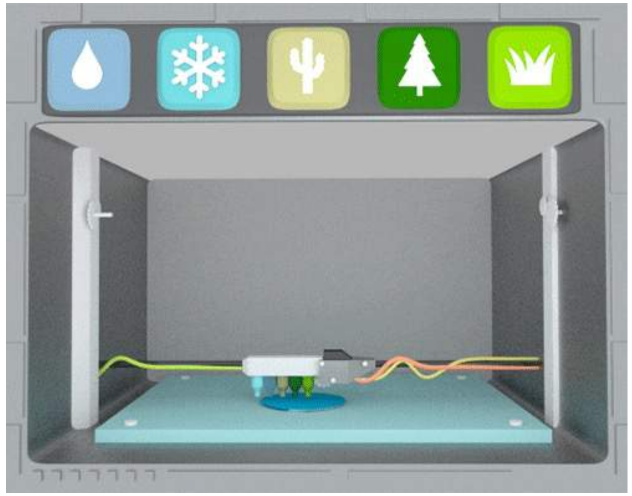
SMT with <u>10/90 (!!)</u> wo sf

Conclusions

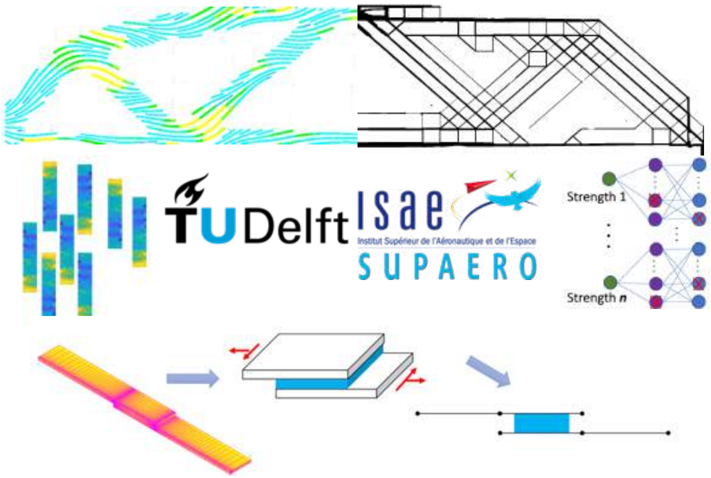
- *Proof of concept of greener aerostructures*
- *Design acceleration through SMT2.0*
- Link between education and research in the topic of sustainable aerostructures
- This is also the topic of our LISA project with TU DELFT AE





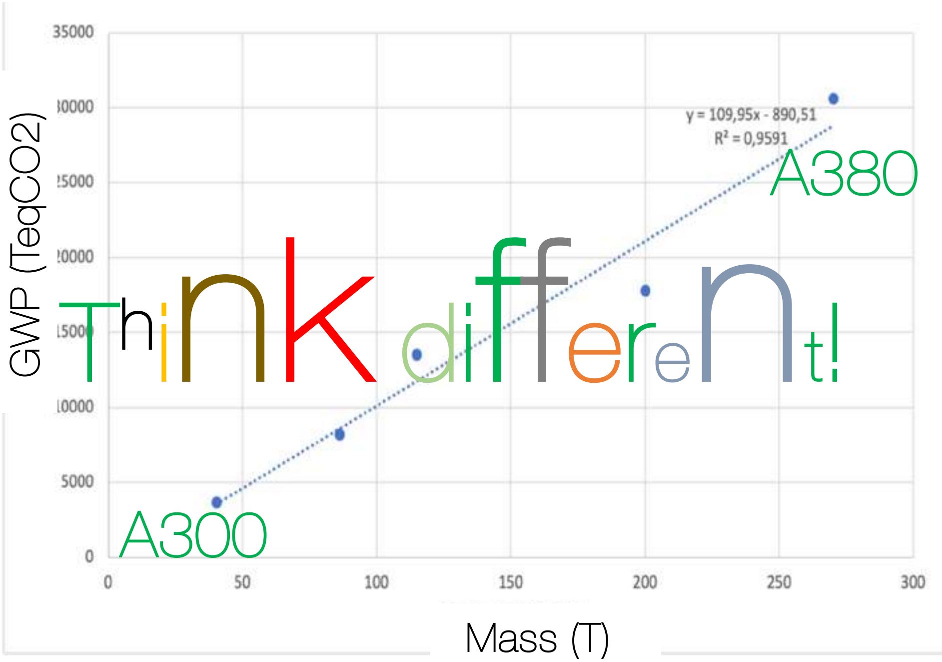


Source: 3D Printing World Environment Day GIF By General Electric



Perspectives

- In aircraft design:
- min {mass} is proportional to min {CO2PP}
- Manufacturing <1% of total aircraft emissions
- This is not true for launchers, HALE drones…
- So there is work for us!!!



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