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

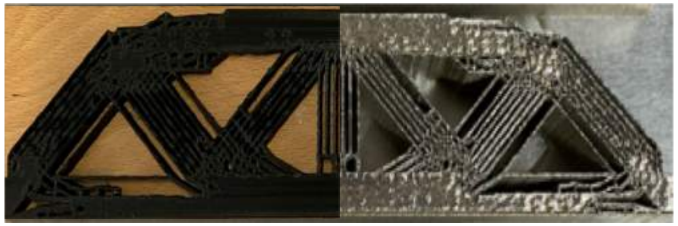
joseph.morlier@isae-supaero.fr

ICA
cnrs
dépasser les frontières
isae
Institut Supérieur de l'Aéronautique et de l'Espace
SUPAERO

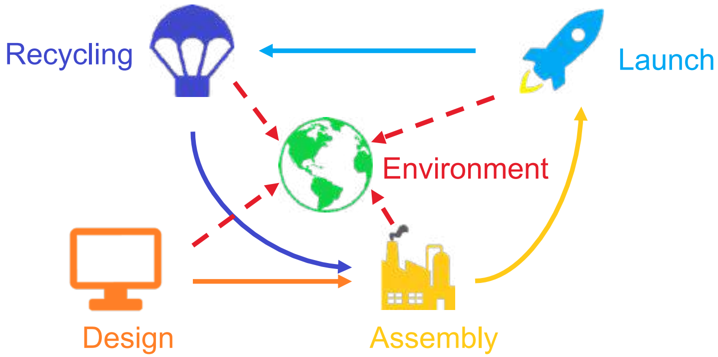
About Me? https://ica.cnrs.fr/en/author/jmorlier/

- 6 PhDs, 3 MsCs

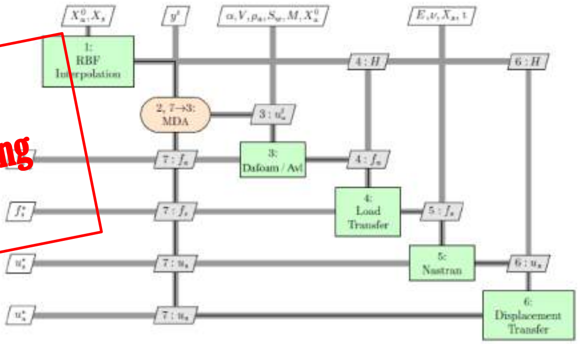
Digital fabrication



EcoOptimization

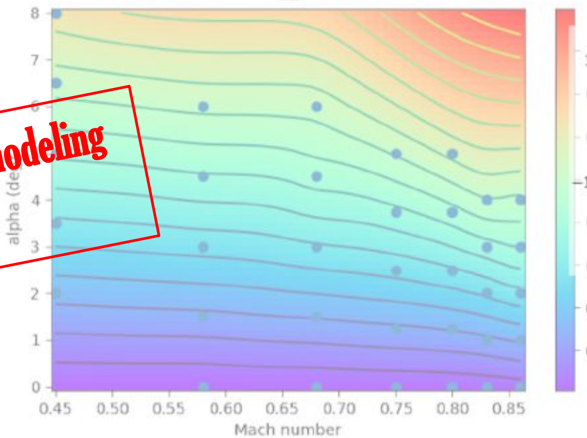


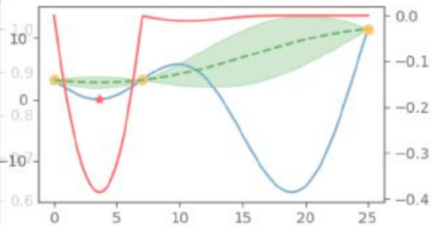
MDO for Aeroelastic Wing design



https://github.com/SMTorg/SMT

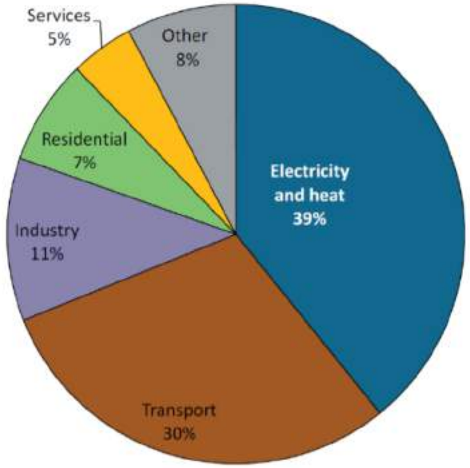
Surrogate modeling AI4E





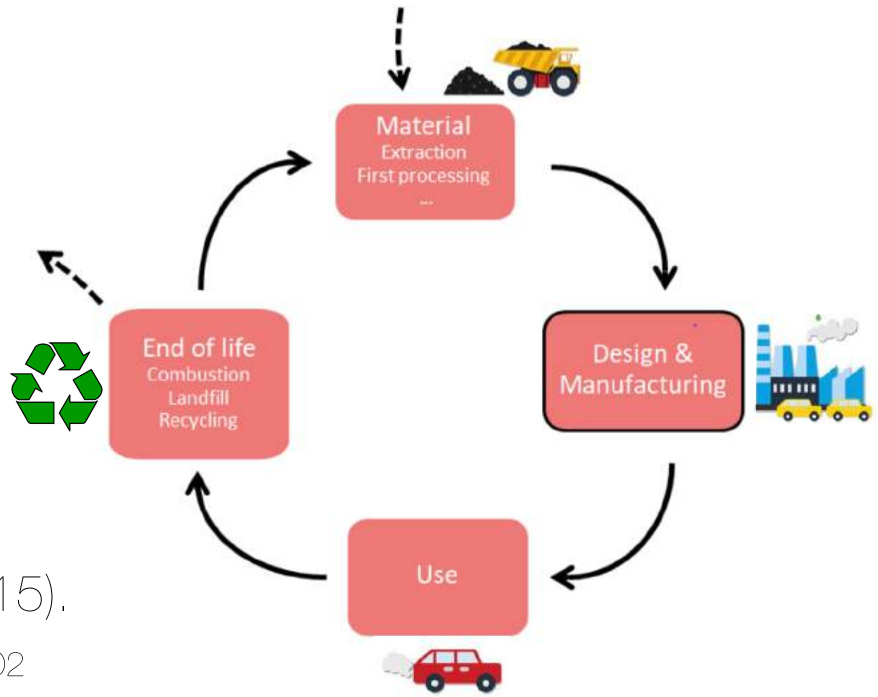
AIRBUS
ONERA THE FRENCH AEROSPACE LAB
POLYTECHNIQUE MONTRÉAL UNIVERSITÉ D'INGÉNIERIE
RMIT UNIVERSITY
TU Delft

Overview



CO_2 emissions of the OECD (2015).

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

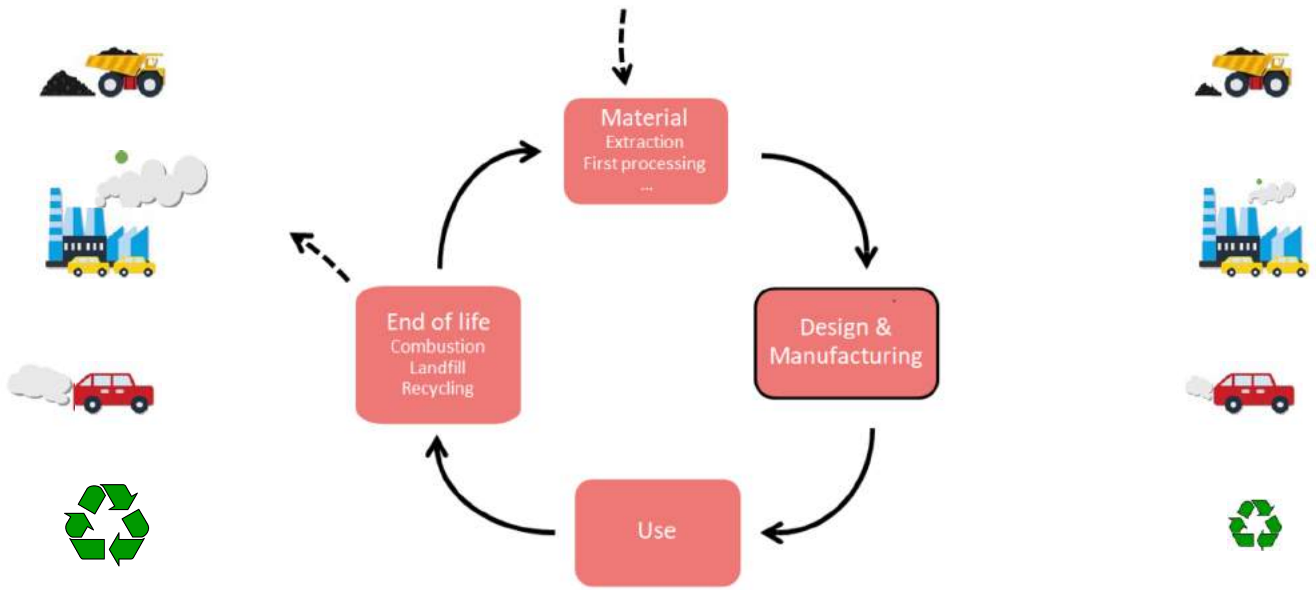


Vehicle life cycle

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

Hypothesis 1

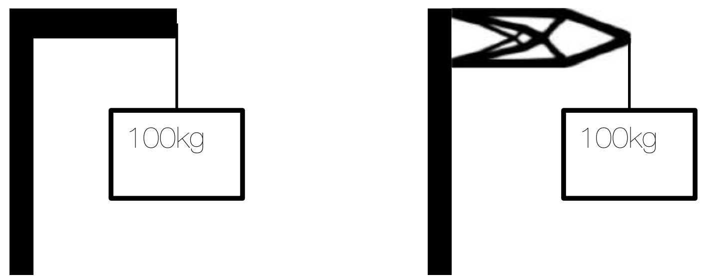
- CO_2 emissions minimization of parts
  - If material choice is **imposed** => mass minimization



Vehicle life cycle

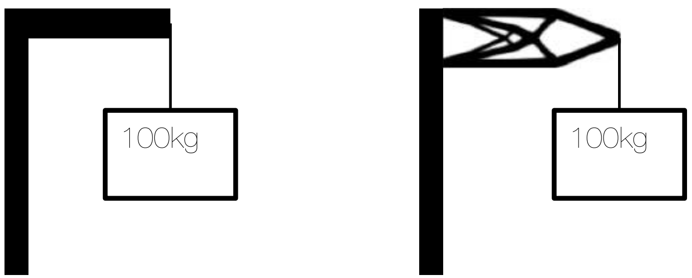
Hypothesis 1

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



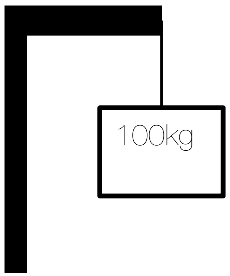
Hypothesis 1

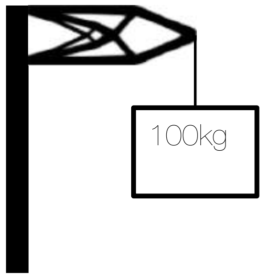
- Mass minimization of parts
  - Redesign through topology optimization
    => same performance but lower mass



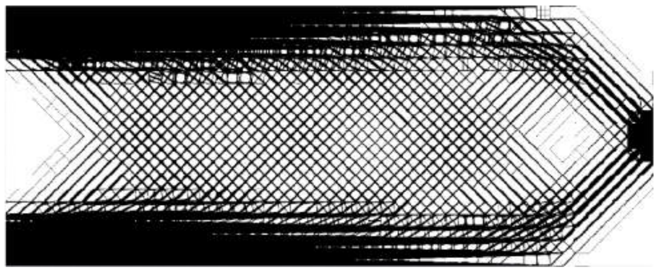
Hypothesis 1

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



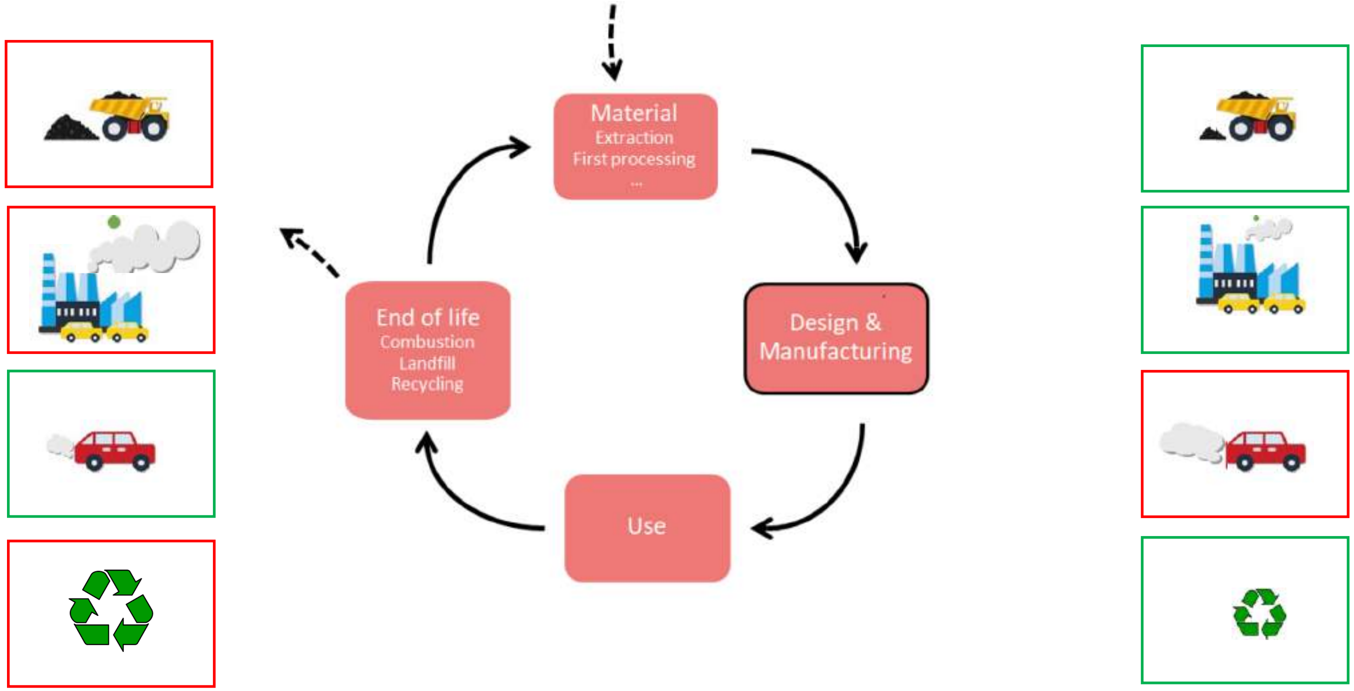


– One step further : multiscale topology optimization



Hypothesis 2

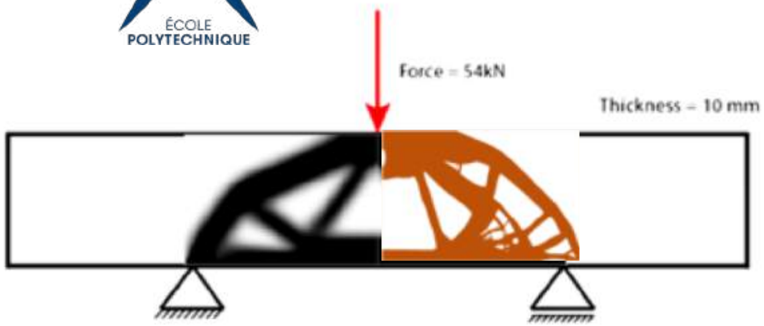
- CO_2 emissions minimization of parts
  - If material choice is **free** => more complicated
  - **→ scope of the part of the tallk**

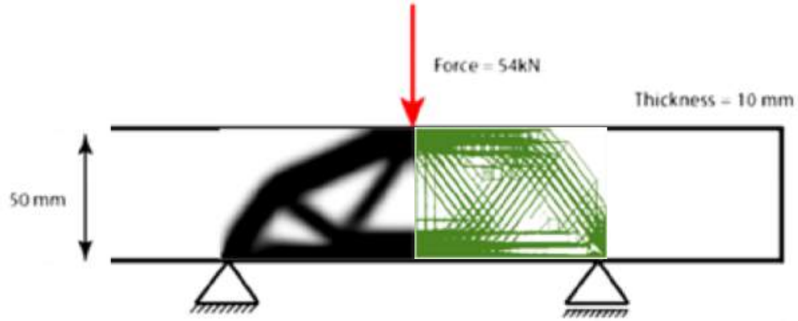


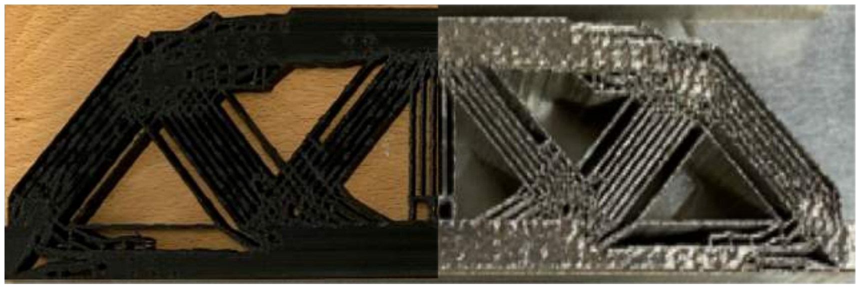
How to **ECO**design tomorrow's structures?

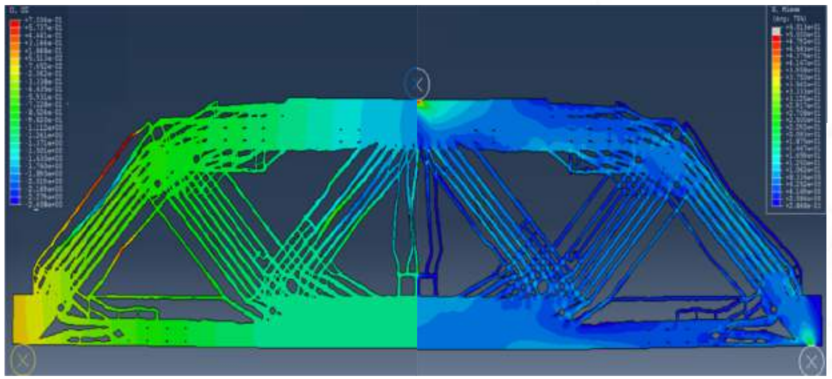
Prof. Joseph Morlier, Edouard Duriez, Miguel Charlotte, Catherine Azzaro-Pantel

Design2print !









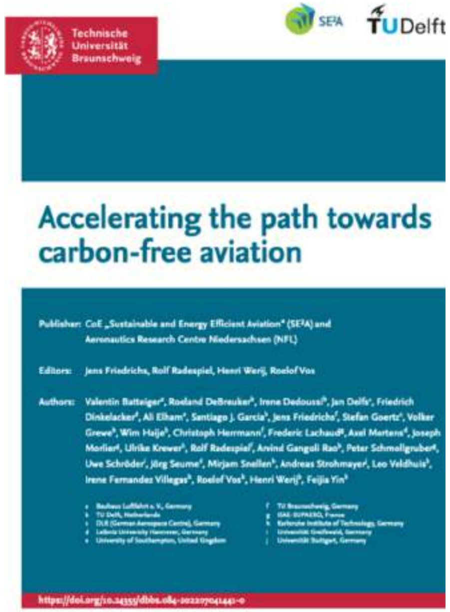
Au programme

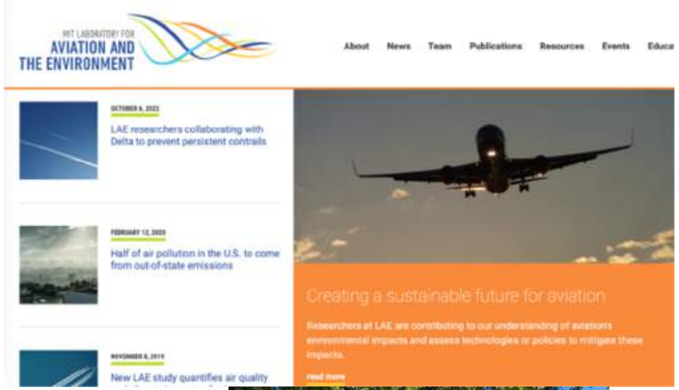
- Part1: Sustainable Aerostructures Initiative @ISAE-SUPAERO
- Part2: On some new developments on ECODESIGN and TOPOPT @ICA

Au programme

- **Part1: Sustainable Aerostructures Initiative @ISAE-SUPAERO**
- Part2: On some new developments on ECODESIGN and TOPOPT @ICA

Beaucoup d'initiatives

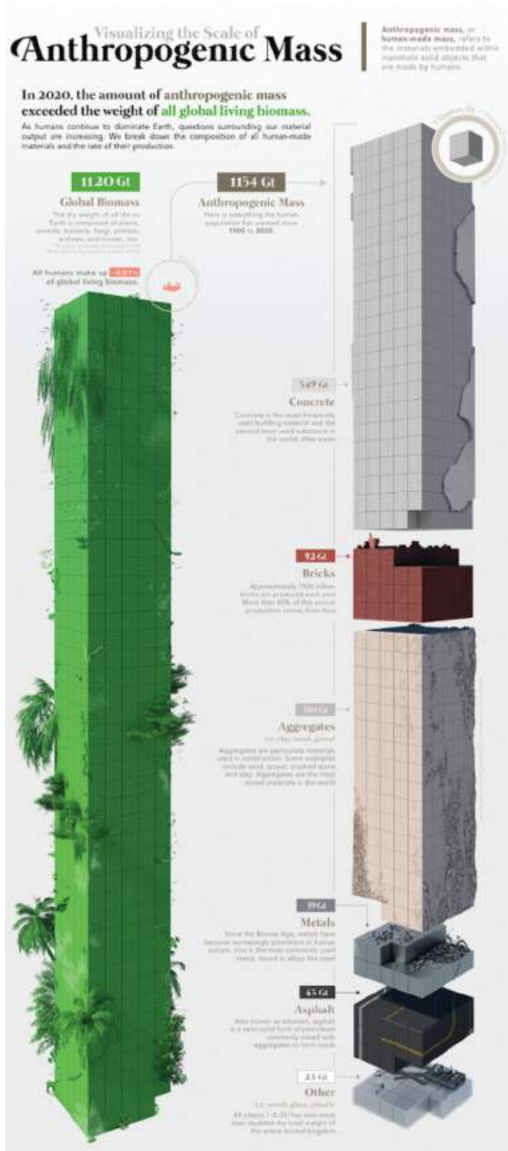




https://www.tudelft.nl/en/ae/sustainable-aviation
https://www.cranfield.ac.uk/themes/aerospace/aviation-and-the-environment
https://www.imperial.ac.uk/green-aviation/about-us/
https://ae.gatech.edu/sustainable-transportation-energy-systems
https://www.tu-braunschweig.de/en/se2a
https://uwaterloo.ca/sustainable-aeronautics/
https://www.utias.utoronto.ca/centre-for-research-in-sustainable-aviation/
https://isa-toulouse.com
…

Constat

Over the past century Anthropogenic mass has increased rapidly, doubling approximately every 20 years. The collective mass of these materials has gone from 3% of the world's biomass in 1900 to being on par with it today



IDEE

SA-I

Sustainable Aerostructures & Interactions

« Co-construction du lien Enseignement-Recherche-Innovation au DMSM à travers la thématique des Structures Aérospatiales durables & Interactions »

Pédagogie DD @ISAE-SUPAERO

FISE	COA 303	Aéronefs plus électriques	Electif
FISE	EACS 210	Innover durablement par le Design Thinking	Electif
FISE	EISC207	Impact climatique de l'aviation : situation actuelle et perspectives	Electif
FISE	ETE 301	Energie & climat	Electif
FISE	ETE 302	Economie & écologie	Electif
FISE	ETE 303	Energie & mix énergétique	Electif
FISE	ETE 304	Transport & intermodalité	Electif
FISE	ETE 305	étude de cas en optimisation	Electif
FISE	EAEP 108	Transition énergétique, quel rôle pour l'ingénieur	Electif
FISE	EAEP 111	Physique des ordres de grandeur pour un monde en transition	Electif
FISE	EAEP 210	Propulsion éolienne	Electif
FISE	DD201	Introduction aux enjeux environnementaux	Tronc commun
FISE	EMSM 104	Ecoconception	Electif
FISE	EACS 208	Economie circulaire	Electif
FISE	AC4	Low-tech ou high-tech : quelles technologies pour demain ?	
FISE	AC4	Ecologie et Machine, interroger l'Anthropocène	
FISE	AC4	L'ingénieur au cœur de l'approche éthique : éthique des sciences & d	
FISE	AC4	Philosophie et écologies	
FISE	AC4	Pour un design éco-responsable : concevoir & fabriquer un objet	
FISE	D-SAT307	Enjeux contemporains de la technique : une introduction de la philos	
FISA	UE5IE2	Développement durable et RSE	
MAE	1MAE013	Introduction to climate change issue (Climate collage)	
MAE	2MAE006	Aviation & Environment	
MS	MS ASAA Modu	certification émissions CO2, polluants moteur, bruit	
MS	MS ASAA Modu	certification d'aéronefs décarbonés: aéronefs électrique, à hydrogène e	
MS	MS AES Modul	certification de l'hydrogène dans les structures avion pour la décarbo	
MS	MS AES	SA410 Modelling and recycling of shells	

SM 104: Ecoconception (20étudiants, electifs 30h)

 # ACV
 # Diagramme d'Ashby
 # Ecoselection de matériaux
 # matériaux biosourcés et agromatériaux
 # Ecodesign@AIRBUS
PROJET (ANSYS GRANTA)

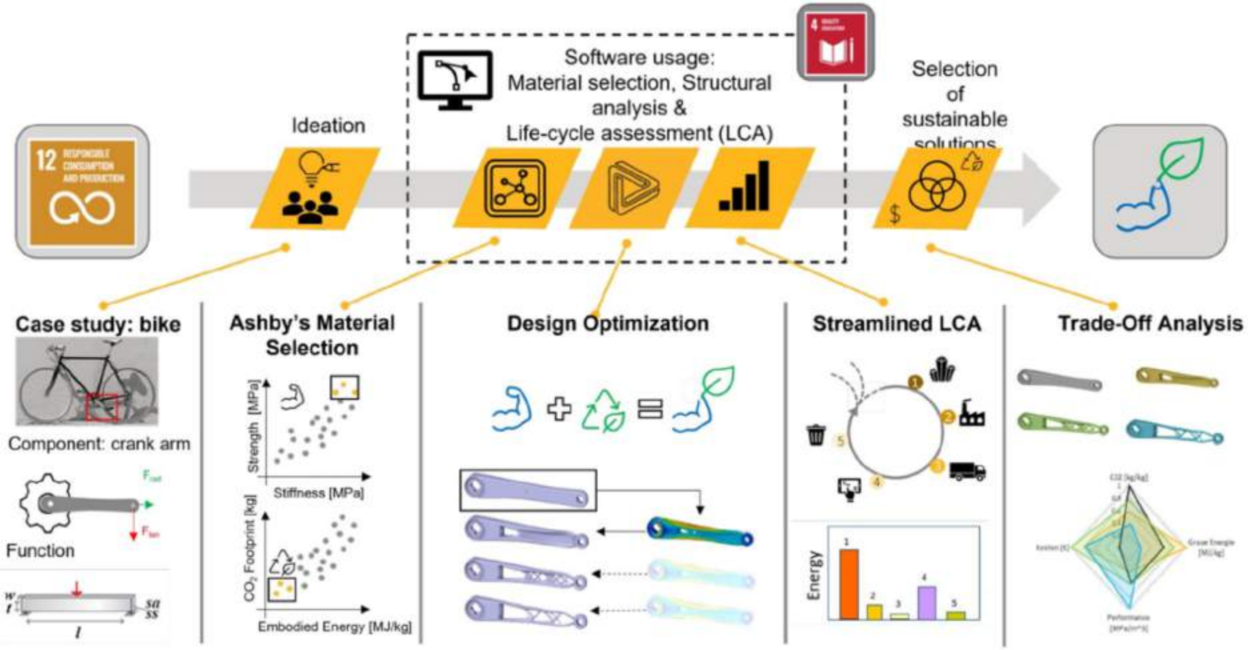
Evolution Filière Structures et matériaux

SM 3xx: Outils pour l'éco-conception (40 étudiants, TC 10H)

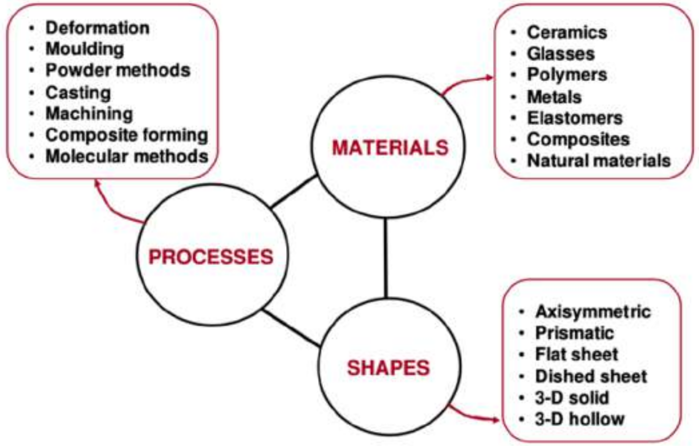
- **ACV, Eco-sélection des matériaux & conception optimale**

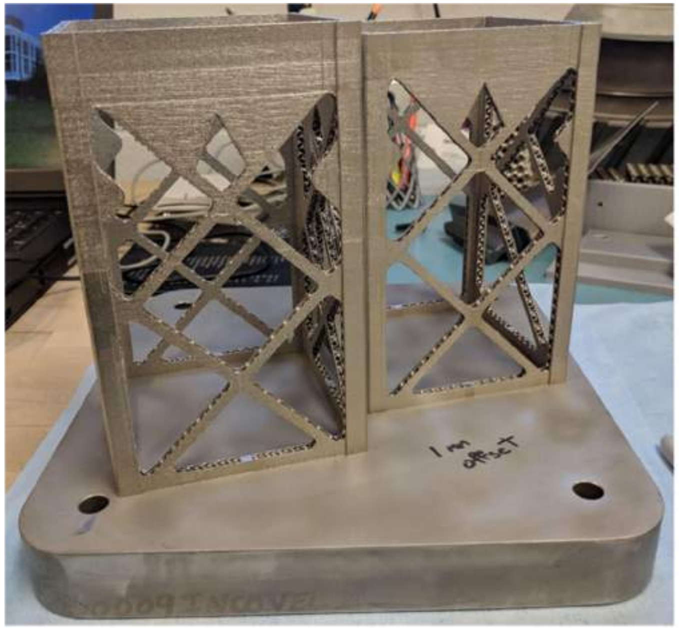
challenge éco-conception:
contraintes fortes: faisabilité en 20h, ACV rapide, Bilan CO2, ALM

Ansys
GRANTA

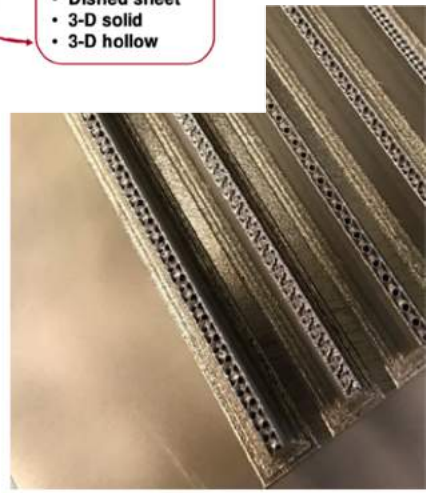


Qu’est qu’une Aérostructure optimisée





Key Statistics
Weight reduction
50% lighter
Stiffness increase
20% stiffer
Lead time
33% faster production
Assembly consolidation
From 150 parts to 25
Material
From Aluminum to Inconel 718
Manufacturing process
Concept Laser M2 Series 5



https://ntopology.com/case-studies/air-force-optimizes-cubesat-using-architected-materials/

Qu'est qu'une Aérostructure durable ?

- min Masse → min CO_2

  Primary Production
  (thèse Edouard Duriez)

- \+ Respect des contraintes environnementales

LCA & eco selection

- Material
- Process
- from cradle to grave

…

Water withdrawal

Generation of waste

Use recycled:
Fibers
Resin
Metals
Reuse & Repair

Carbon Footprint

Energy requirement

Project d'innovation avec des élèves de 3eme année @SUPAERO

https://github.com/mid2SUPAERO/AD_EnvironementalImpact

C. ATIN S. DURA A. LASSERRE B. ROIRON R. ZUPPO

Based on the work of Eleonore Pierrat @DTU
Pierrat, E., Rupcic, L., Hauschild, M. Z., & Laurent, A. (2021).
Global environmental mapping of the aeronautics manufacturing sector.
Journal of Cleaner Production, *297*, 126603.

Etape matériaux

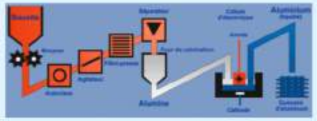
L'étape matériaux correspond à la fabrication et au transport des matériaux de base de l'aéronautique. 4 matériaux sont principalement utilisés :

Extraction pétrole brut	Extraction fer	Extraction aluminium	Extraction titane
			
Production CFRP	Production alliages d'acier	Production alliages d'alumi-nium	Production alliages titane

Transport aux fabricants

L'étape matériaux né-cessite de grandes quantités d'eau.

Les acteurs de cette étape sont indépen-dants des constructeurs aériens.



Production de l'aluminium par électrolyse

La Chine reste le principal producteur de métaux.

Part de la production mondiale de la Chine

Ces 4 matériaux représentent **80%** *des matériaux utilisés dans l'aéronau-*

Indicateurs étape matériaux

7 MtCO2e	390 M m3	29 TWh
Empreinte Carbone (EC)	Retrait d'Eau (RE)	Besoin Energie (BE)
L'équivalent des émissions du Paraguay	*Soit 1.5 fois la consommation en eau de Paris*	*Soit 5 centrales nucléaires*

Cycle de vie d'un avion (env. 30 ans)

Transport aux fabricants

7 MtCO2e
Empreinte Carbone (EC)
L'équivalent des émissions du Paraguay

390 M m3
Retrait d'Eau (RE)
Soit 1.5 fois la consommation en eau de Paris

29 TWh
Besoin Energie (BE)
Soit 5 centrales nucléaires

Etape manufacturière*

L'étape manufacturière correspond à la fabrication des appareils à partir des matériaux

Tier 3 : Producteurs de compo-sants — GKN AEROSPACE, MITSUBISHI HEAVY INDUSTRIES FRANCE

Tier 2 : Assembleurs de sous systèmes — BAE SYSTEMS, DAHER

Tier 1 : Assembleurs de sys-tèmes — SAFRAN, ROLLS ROYCE, UTC Aerospace Systems

Tier 0 : Assembleurs d'avions — AIRBUS, BOEING

**Résultats basés sur les données des 88 des 100 plus grandes entreprises du secteur*

L'étape manufacturière est très consommatrice en énergie et émet beaucoup de carbone (opérations à forte intensité énergétique).

Fabrication de l'A320

Indicateurs étape manufacturière

11.3 MtCO2e
Empreinte Carbone (EC)
L'assemblage nécessite beaucoup d'énergie

80 M m3
Retrait d'Eau (RE)
5 fois moins que pour l'étape matériaux

41 TWh
Besoin Energie (BE)
7 centrales nucléaires

MICROLEARNING?

Environmental impact of the aerospace manufacturing sector

HTTPS://MICROLEARNING.GROUPE-ISAE.FR

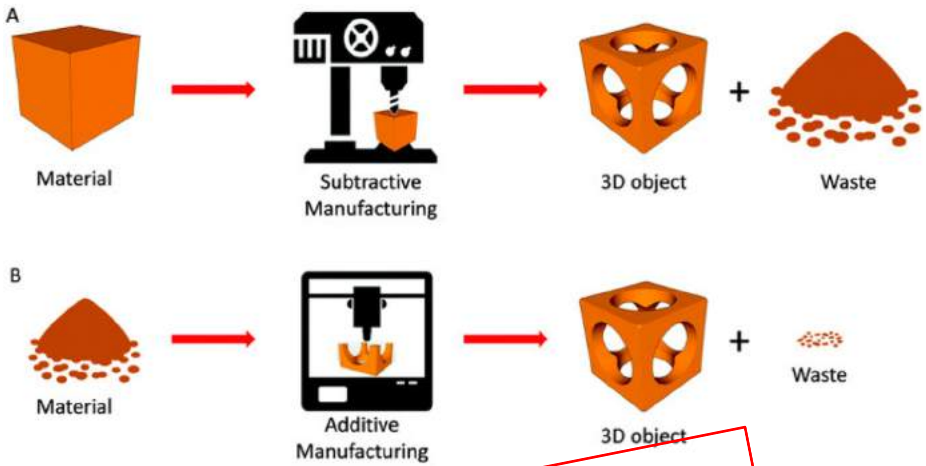
Au programme

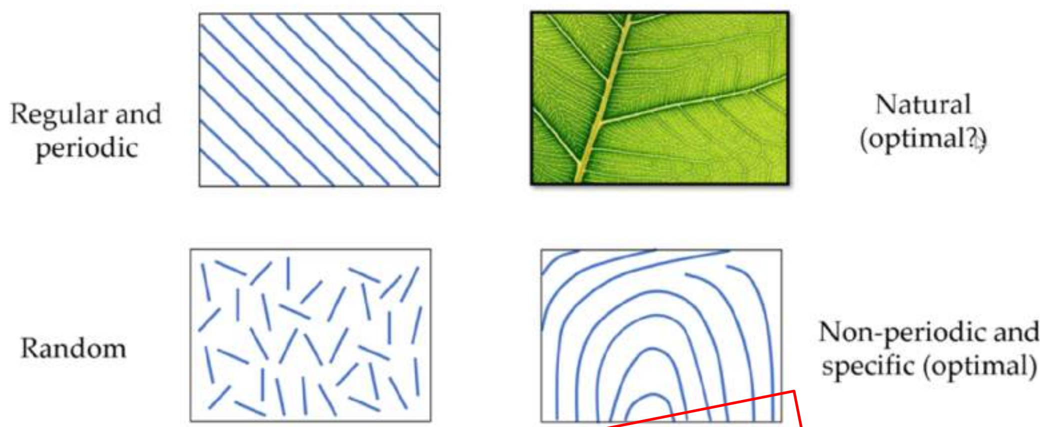
- Part1 : Sustainable Aerostructures Initiative @ISAE-SUPAERO
- **Part2: On some new developments on ECODESIGN and TOPOPT @ICA**

Merci à Edouard Duriez pour ses travaux de thèse!!

But Why **AM**?

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

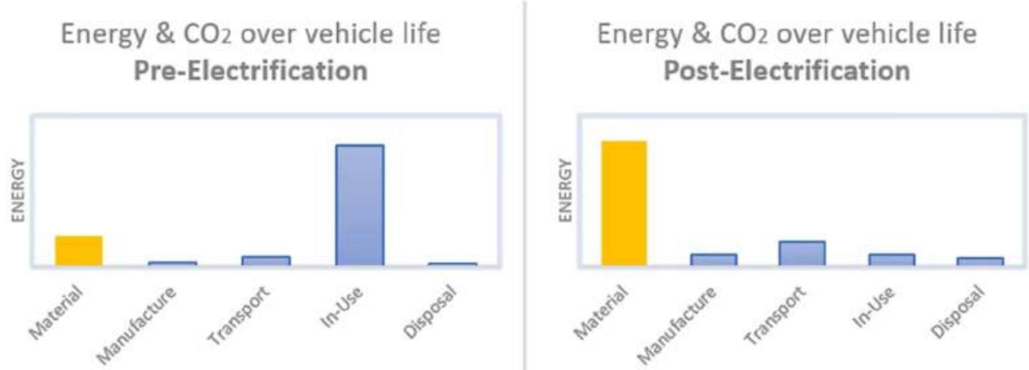
Ecodesign and Additive Manufacturing

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)

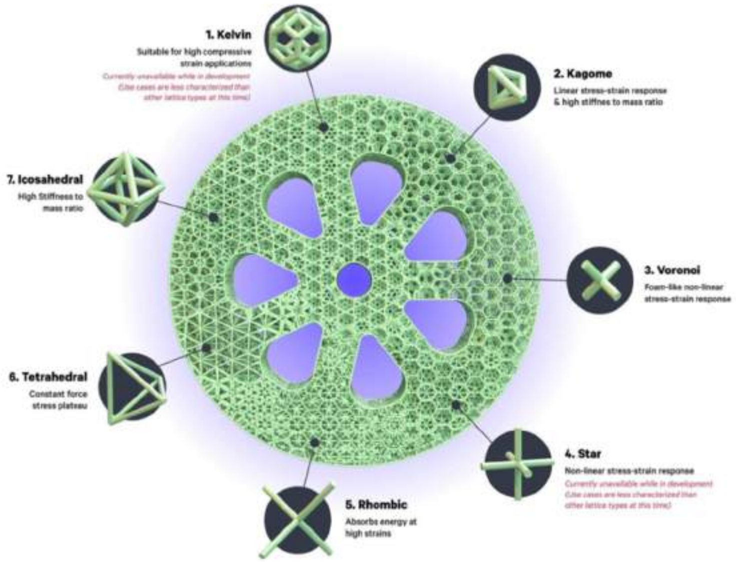
*S. Ford and M. Despeisse. « Additive manufacturing and sustainability : an exploratory study of the advantages and challenges ». en. In : J. of Cleaner Production 137 (nov. 2016),
*R. Huang, M. Riddle, D. Graziano, Joshua Warren, Sujit Das, Sachin Nimbalkar, Joe Cresko and Eric Masanet. « Energy and 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



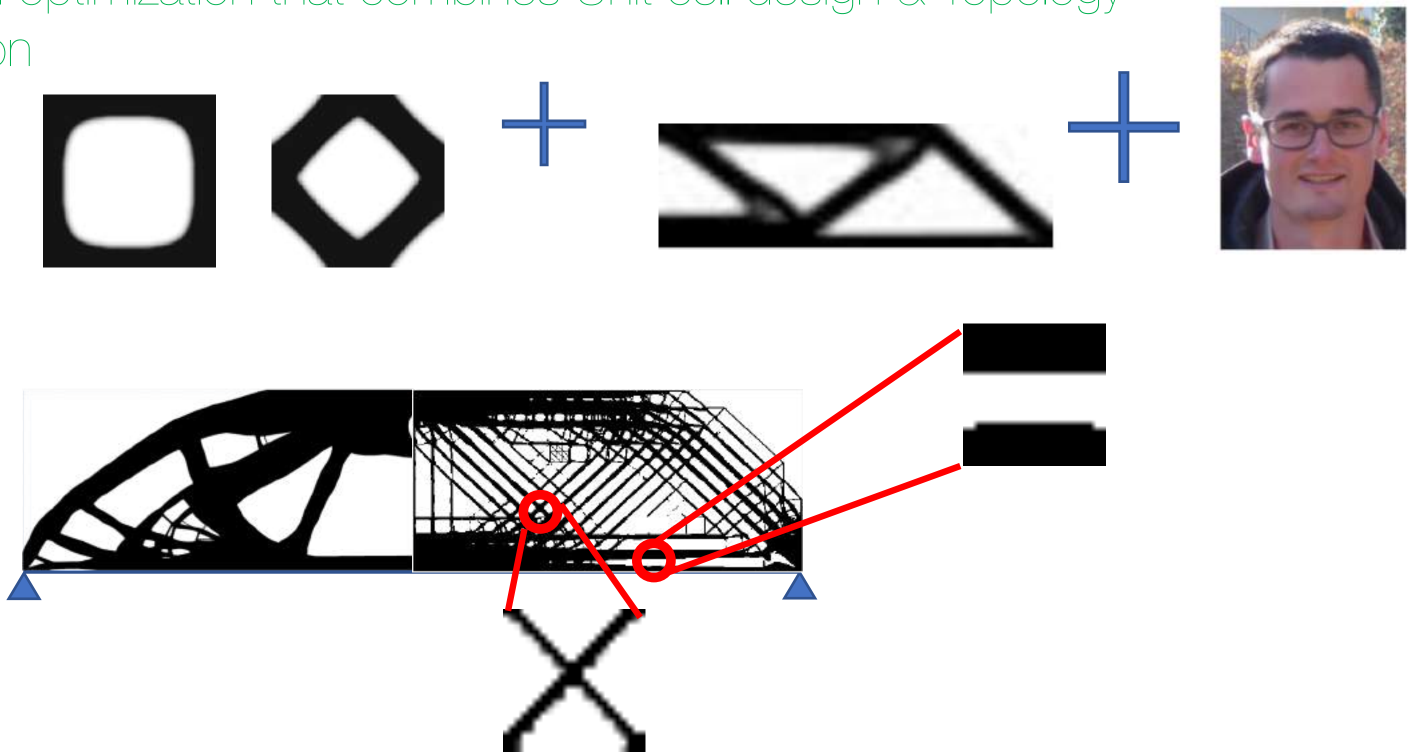
https://www.ansys.com/blog/the-impact-of-materials-on-sustainability-part-2



Unit cell design (anisotropy)
Digital materials

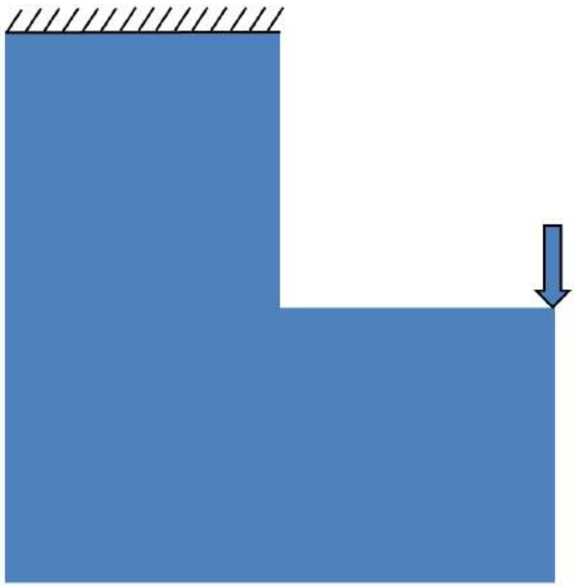
Multi-scale TO (well connected+ locally-oriented)

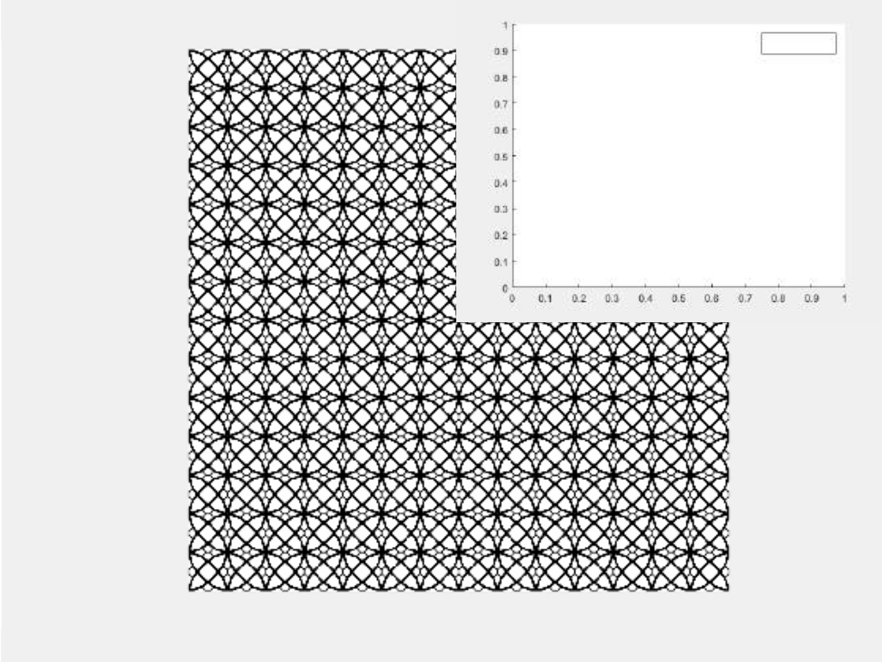
A two level optimization that combines Unit cell design & Topology Optimization



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.

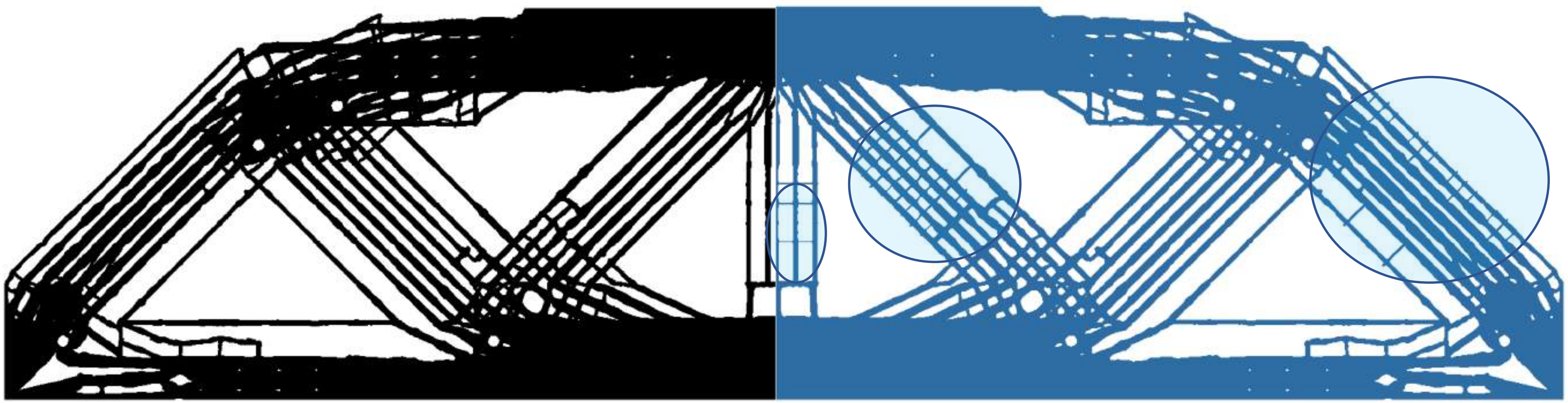
EMTO on L-shape (cellular /digital materials)





https://github.com/mid2SUPAERO/EMTO

Do you see a difference?



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]

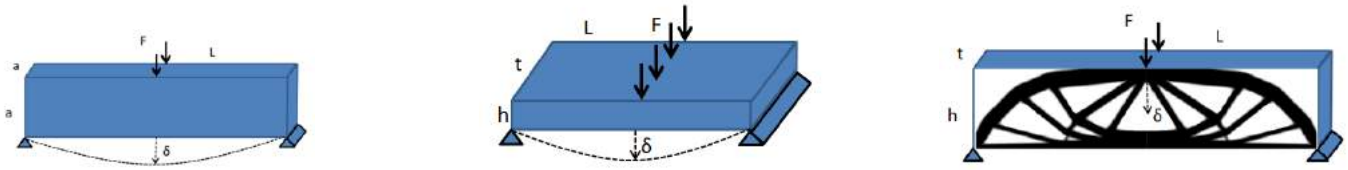
Show more

Share Cite

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.

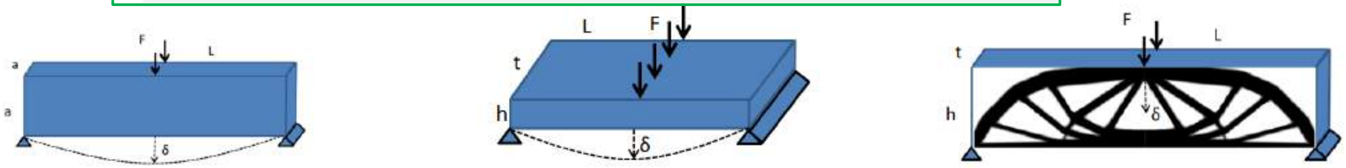


Material index

- 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 :

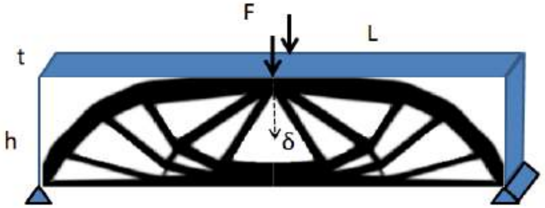
Properties	Bending beam (Ashby)	Bending plate (Ashby)	Duriez et al. (2022b)
Free variables	a, m	h, m	t, $\mathscr{D}$, m
Fixed	L, $\mathscr{D}$	L, t, $\mathscr{D}$	$L_{\max}$, $h_{\max}$
Constraint	$\delta_{\max}$	$\delta_{\max}$	$\delta_{\max}$



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

Deriving the material index

- Problem considered:



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

- Objective function:

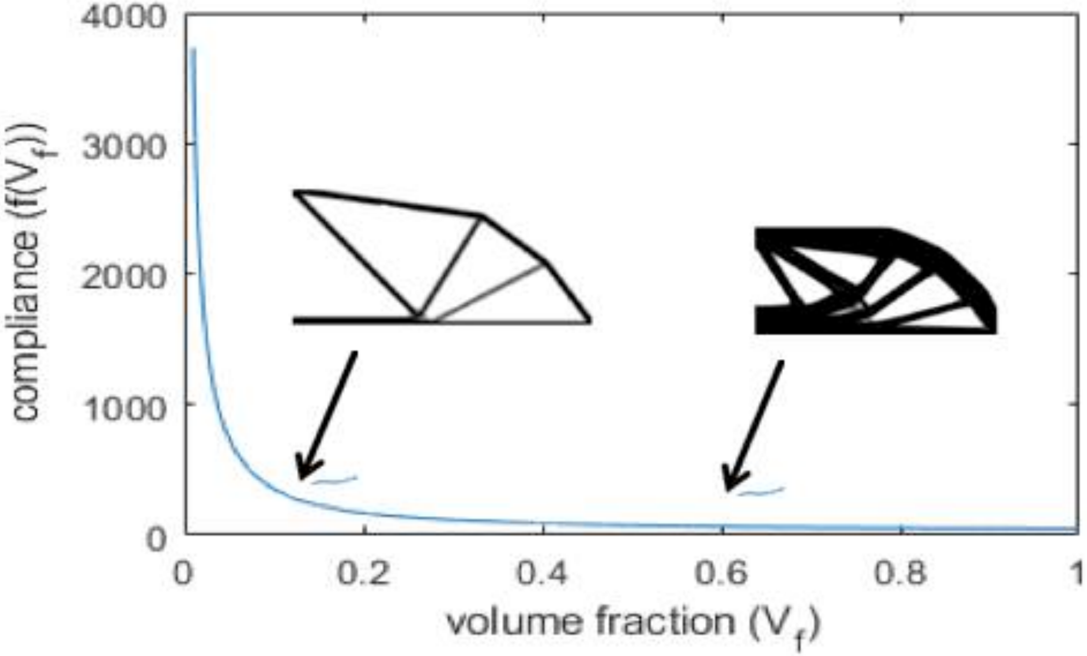
$$CO_2{}^{tot} = CO_2{}^{mat} \times M + CO_2{}^{veh} \times LD \times M$$

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.

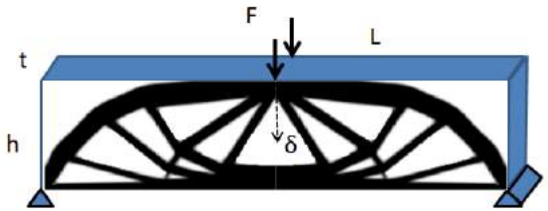
Topology optimization pareto front

- V_f : volume fraction (ratio of space containing material)
- f(V_f) : compliance – volume fraction pareto front



Deriving the material index

- Problem considered:



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

- Objective function:

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

Deriving the material index

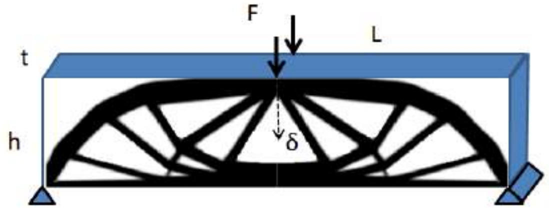
starting from

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

compliance

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

- Problem considered:



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

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

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

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

Material $f_3(M)$ functional $f_1(F)$ topology index $f_2(G)$

REMINDER !!

- Many materials
- Competing properties

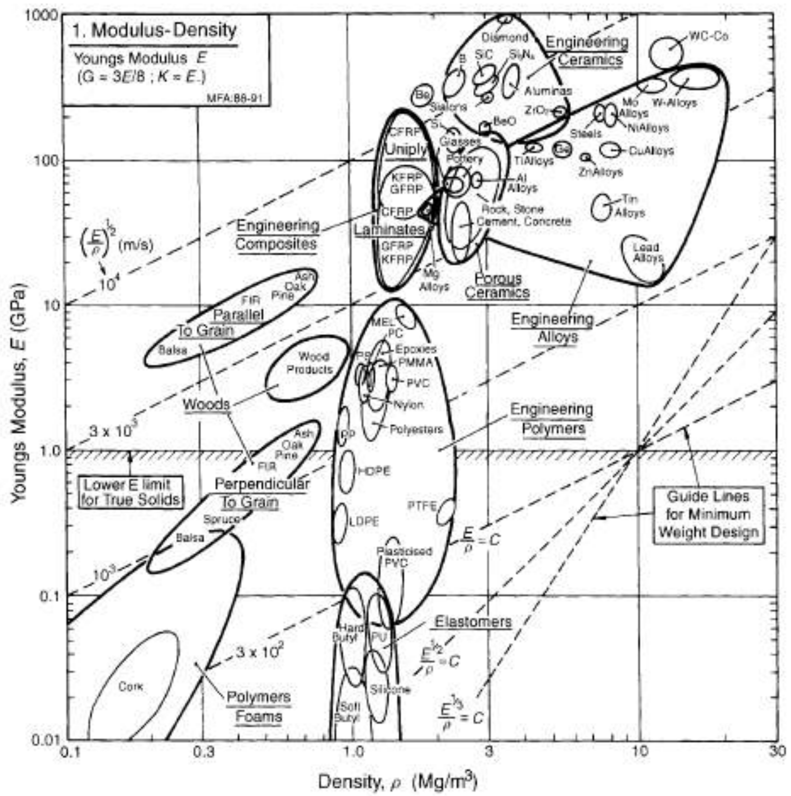
- => Ashby indexes: $f_3(M)$

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

F: Functional constraints

G: Geometrical constraints

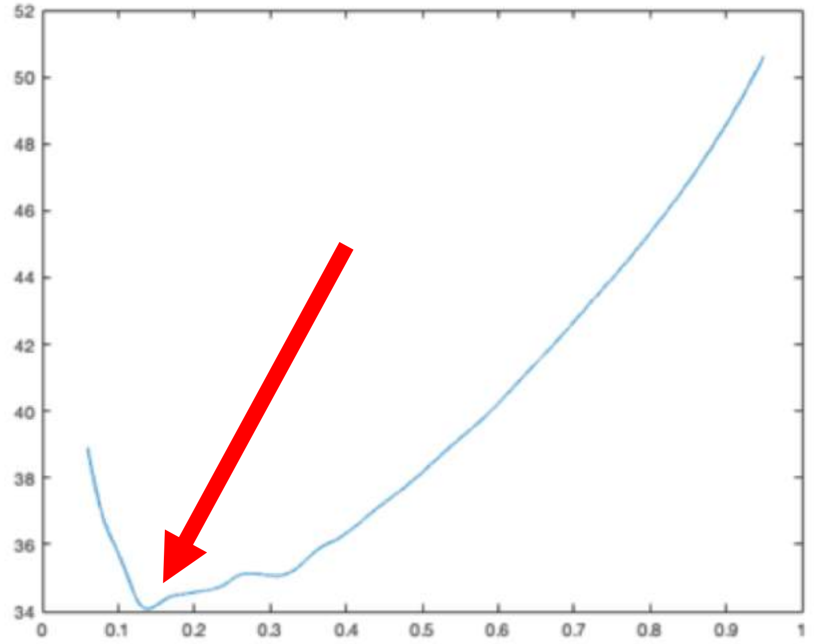
M: Material properties



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

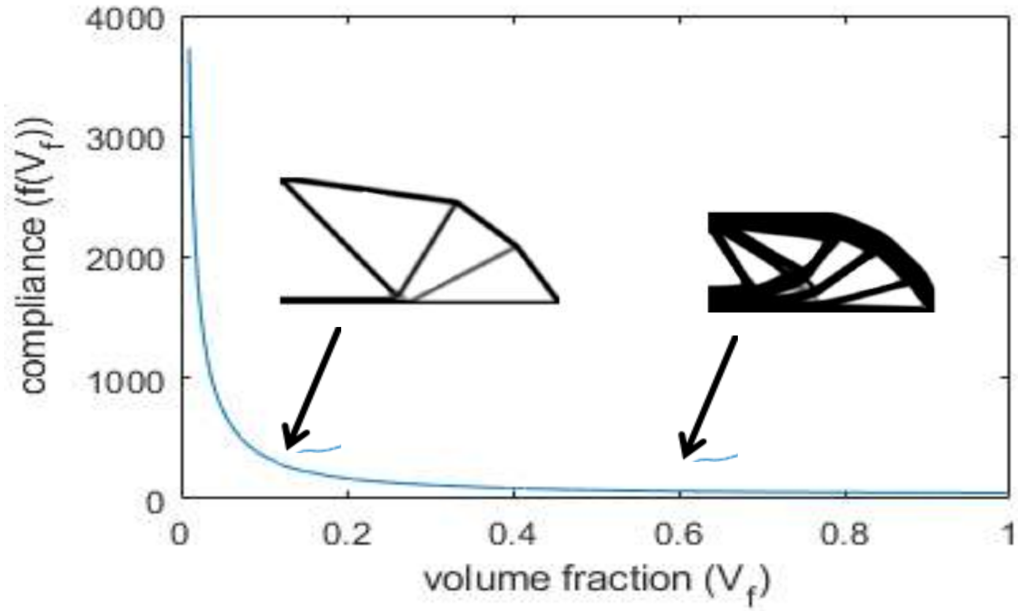
Table 8. Fuel consumption reduction coefficients for different vehicle types and related life time impact savings per kg of weight reduction.

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.

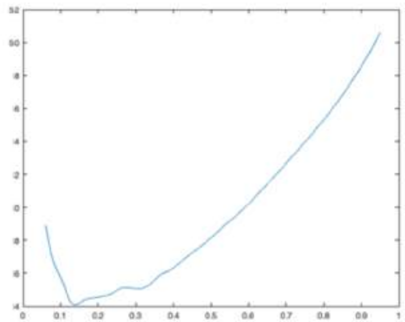
Code

```
%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;

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

$$Idx = \left(CO_2{}^{mat} + LD\,CO_2{}^{veh}\right) \times \frac{\rho}{E}$$

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:
33,65 kg 33.6783

Second zoom

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}

Ecodesign problem

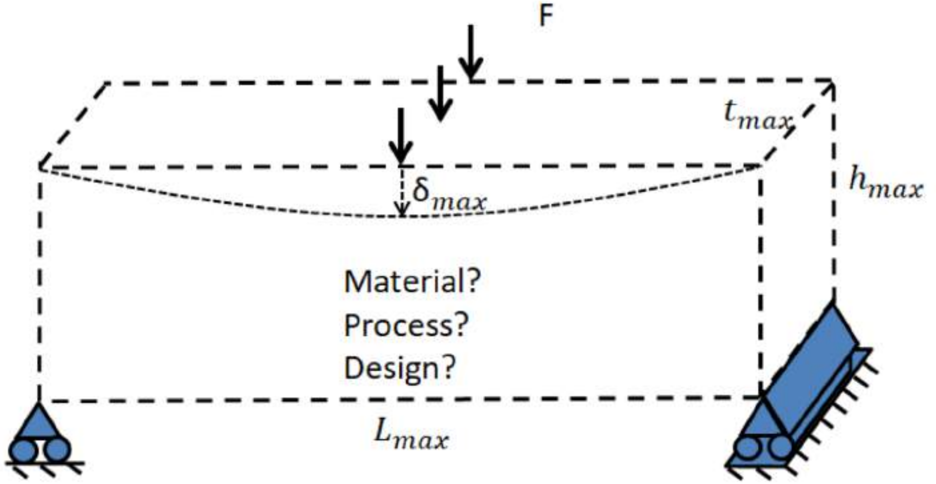
- $\min\limits_{m,p,\mathcal{D}} \quad CO_2^{tot}(m, p, \mathcal{D})$

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

  $\{m,p\} \in \Phi_{mat} \times \Phi_{pro}$

  $\mathcal{D} \subseteq [0, L_{max}] \times [0, L_{max}] \times [0, L_{max}]$

Main difference with previous problem



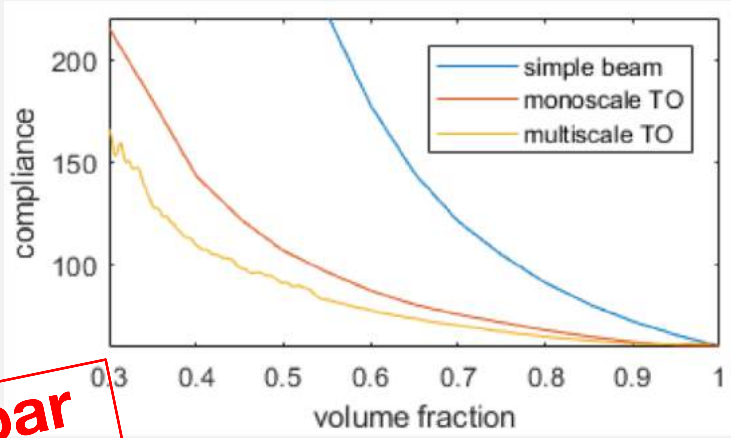
TO volume-compliance Pareto front

- $C_{opt}(V_f)$ Pareto front : optimal designs for each volume fraction
- Decreasing function of V_f

- Can be defined by $C_{opt}(1)$ and

ER(V_f) = - $V_f \dfrac{C'_{opt}(V_f)}{C_{opt}(V_f)}$

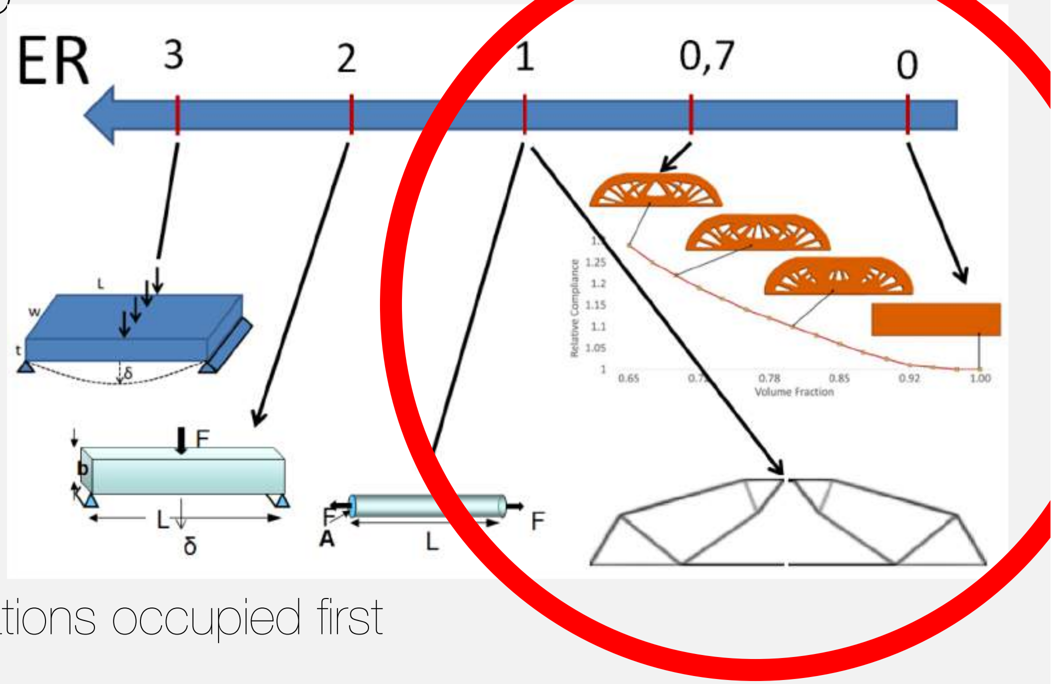
the Efficiency Ratio ER



Efficacité relative de la matière par rapport à la matière déjà présente

ER of TO volume-compliance front

- ER along the TO volume-fraction Pareto front has interesting properties :
  - $\lim_{V_f \to 0} ER = 1$
  - ER is a decreasing function
  - ER ≥ 0



- Interpretation : design freedom => best locations occupied first

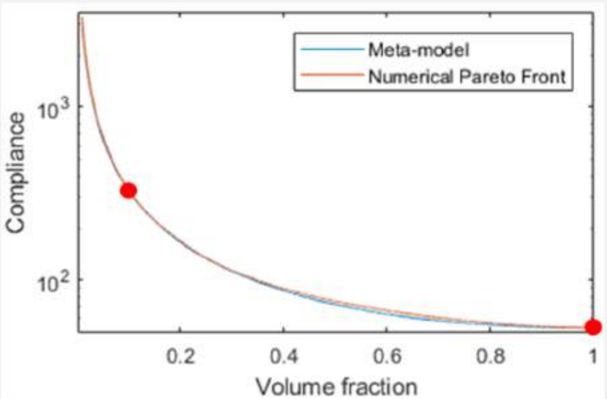
- Tentative demonstration under following hypothesis :
  - TO global optimum reached
  - "continuous" evolution of design along the Pareto front
- In practice, verified for all problems tested numerically

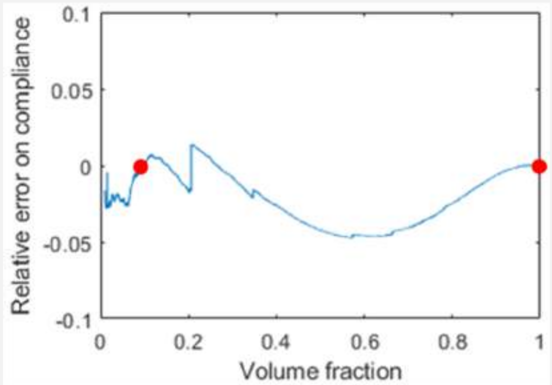
Metamodel of TO Pareto front

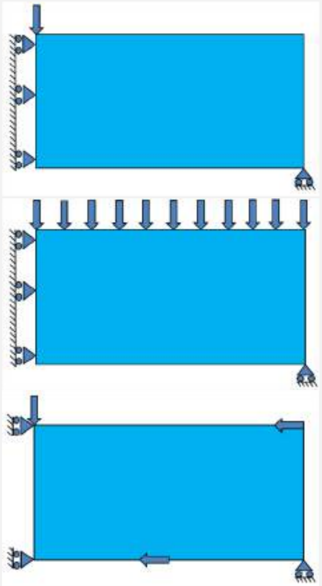
- ER properties can be used to build a metamodel of $C_{opt}(V_f)$:

$$C_{opt}^{meta}\,(V_f) = \mathrm{A}\left(\frac{1}{V_f} + \mathrm{B}\,{V_f}^{1/B}\right)$$

- 2 points needed to fit the metamodel, but only 1 TO.
- Numerical validation on MBB, bridge and "random" problem
  => maximum error of 6.4% !

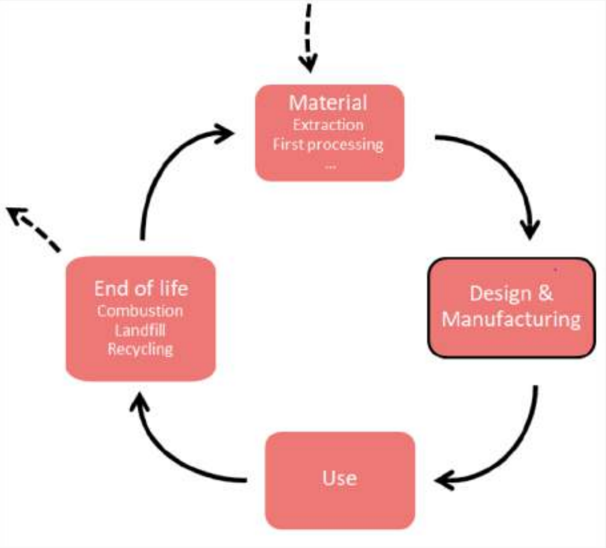






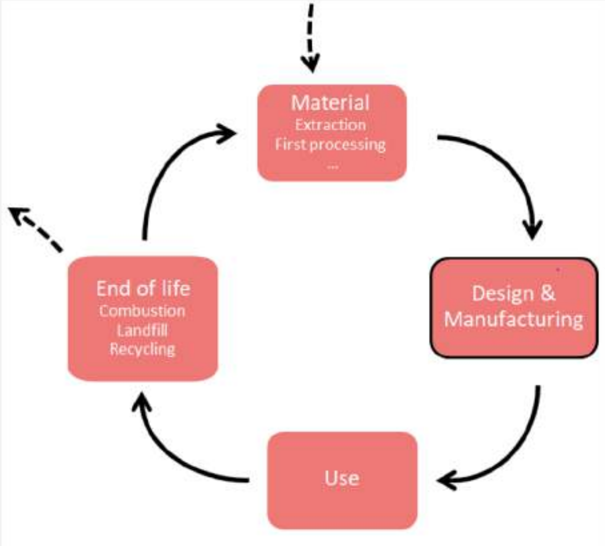
Ecodesign objective

- $$CO_2^{tot} = CO_2 i_m^{mat} \times M + CO_2 i_{m,p}^{pro} \times M + CO_2 i_m^{eol} \times M + CO_2 i^{tra} \times M + CO_2 i^{use} \times M$$



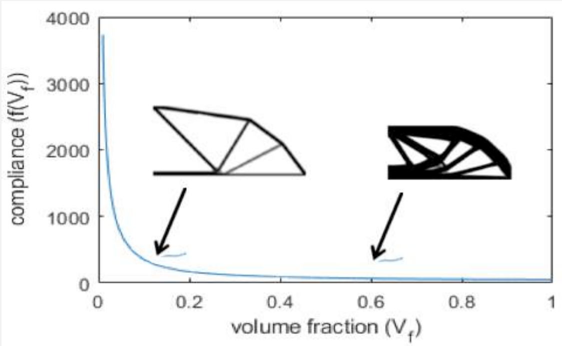
Ecodesign objective

- $$CO_2^{tot} = \boxed{CO_2 i_m^{mat}} \times M + \boxed{CO_2 i_{m,p}^{pro}} \times M + \boxed{CO_2 i_m^{eol}} \times M + \boxed{CO_2 i^{tra}} \times M + \boxed{CO_2 i^{use}} \times M$$
- $$CO_2^{tot} = (\boxed{CO_2 i_{m,p}} + \boxed{CO_2 i^{fix}})\times M$$



Ecodesign objective

Search for lower I^{tot}
depending on the application
How to inverse C_{opt}?



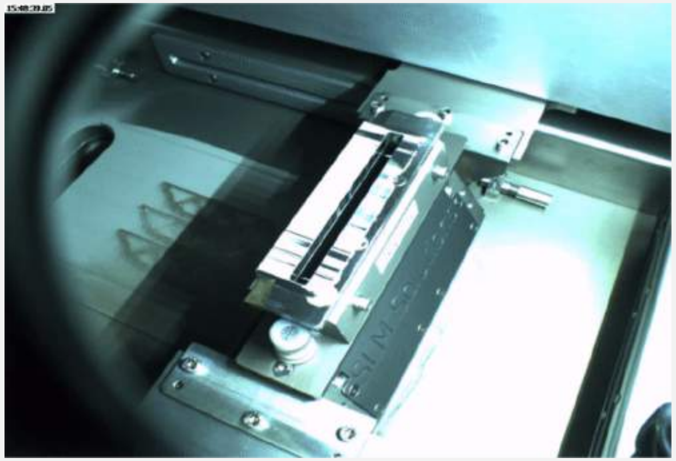
- $$CO_2^{tot} = \boxed{CO_2 i_m^{mat}} \times M + \boxed{CO_2 i_{m,p}^{pro}} \times M + \boxed{CO_2 i_m^{eol}} \times M + \boxed{CO_2 i^{tra}} \times M + \boxed{CO_2 i^{use}} \times M$$
- $$CO_2^{tot} = (\boxed{CO_2 i_{m,p}} + \boxed{CO_2 i^{fix}}) \times M$$
- $$CO_2^{tot} = (CO_2 i_{m,p} + CO_2\, i^{fix}) \times L_{max}\, h_{max} t_{max}\, \rho\, C_{opt}^{-1}\left(\frac{\delta_{max}\, E\, t}{F}\right)$$
- $$\boxed{I^{tot} = \rho \quad C_{opt}^{-1}\left(\frac{\delta_{max}\, E\, t}{F}\right) \times (CO_2 i_{m,p} + CO_2\, i^{fix})}$$

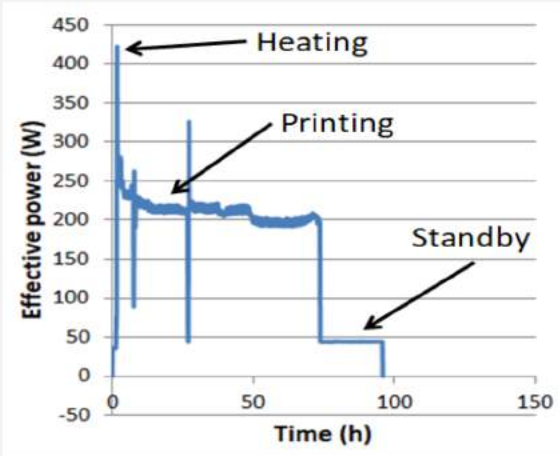
?functionali $f_1(F)$
?topology index $f_2(G)$
?Material $f_3(M)$

How to find data?

- Material and processes are highly coupled

  => database of material-process pairs
- Data sources :
  - Granta selector : E, ρ and emission data for production, recycling, eol
  - Literature : additive manufacturing process energy consumption completed with experimental measurements : AM process energy consumption





Some algorithmic part… for pair (m,p) selection

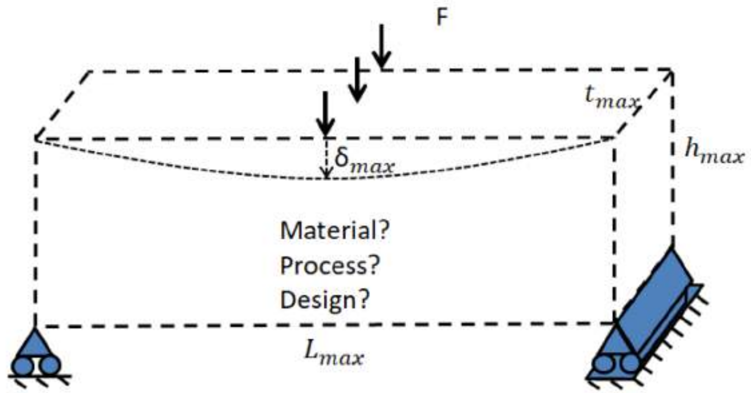
Material-process pair selection
- Step 1 : Screening based on functional constraint
- Step 2 : Screening of Pareto optimal pairs
- Step 3 : Screening using TO Pareto front properties
- Step 4 : Screening using TO front meta-model
- Step 5 : Final selection using index based on full TO (high cost)

Design selection
- Step 6 : TO at apropriate $\boldsymbol{V_f}$ to get $\mathfrak{D}$.

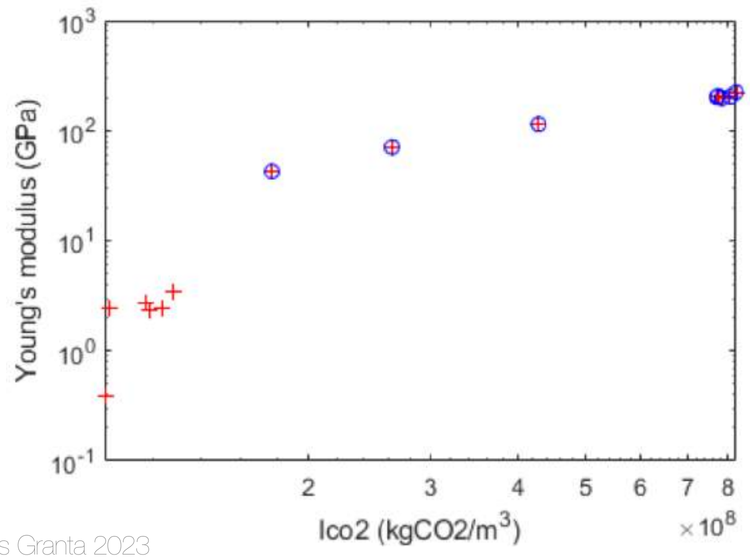
- Possible to skip step 5 depending on number of pairs left, performance gap between best candidates, …

Example 1

- MBB beam for **an aircraft** :
  - {L, h, t} = {2000, 500, 10}mm
  - F = 80kN
  - δ_{max} = 5mm
  - t=t_{max}



- Step 1 : $\delta > \delta_{max}$=> E > 42.5GPa

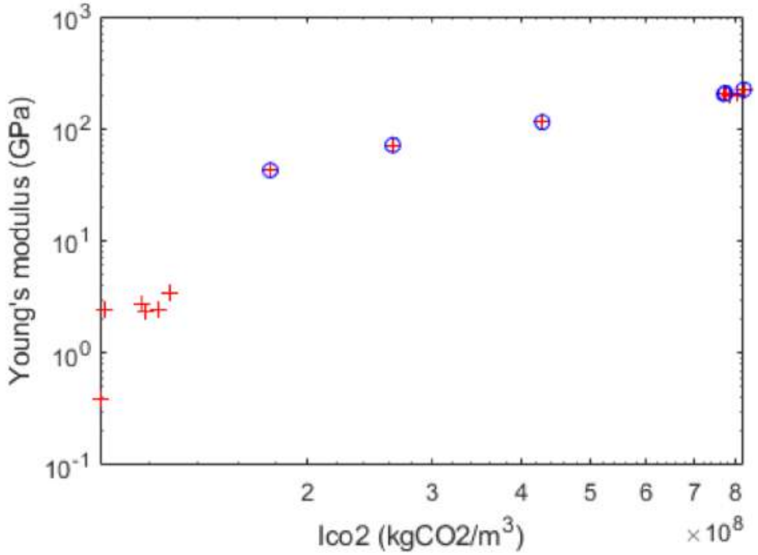


9 out of 16 pass

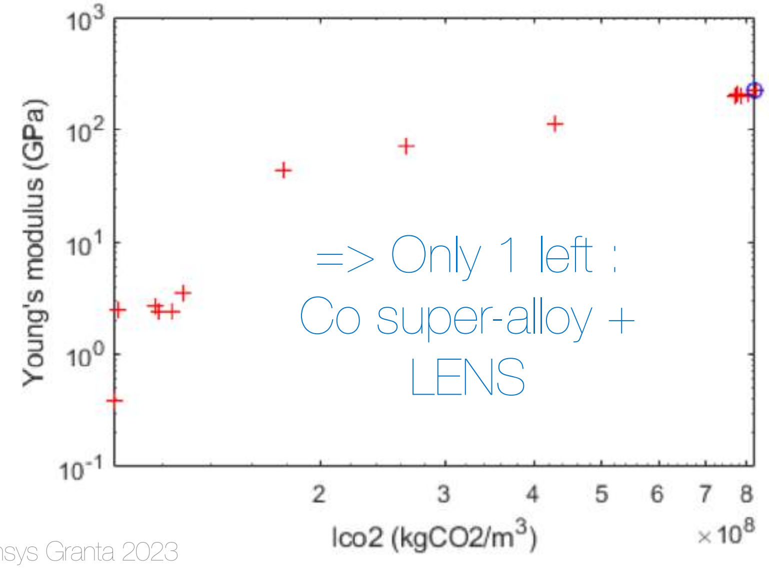
Example 1

- Step 2 : Pareto-optimal pairs only

6 out of 9 pass



- Step 3 : ER < 1 => only pairs with $\rho > \rho_{m1}$ can be optimal, with m1 the material with the best $\frac{E}{\rho}$ ratio.

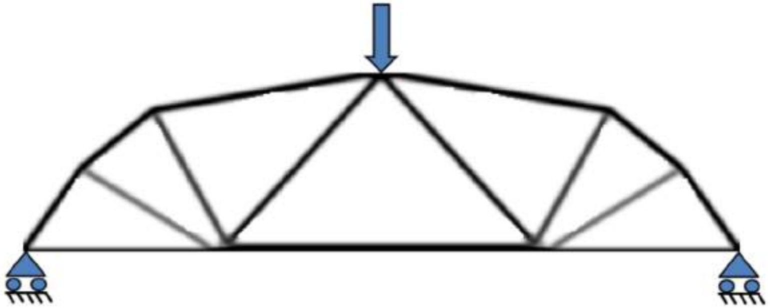


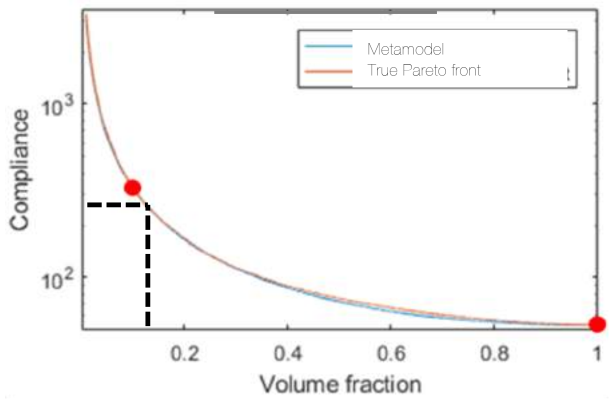
=> Only 1 left :
Co super-alloy +
LENS

Example 1

- Step 4 and 5 are not necessary for pair selection, but TO front metamodel or full TO are necessary to obtain V_f.

- $C_{opt}(V_f) = \frac{\delta_{max}\, E\, t}{F}$ => $V_f = 0.12$

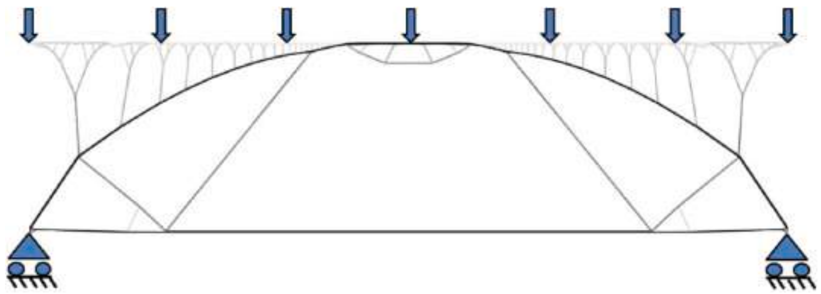




$CO_2^{tot} = 976\ tCO_{2eq}$ (99,96% during use phase)

Example 1: Bis→ Bridge design (MBB beam)

As it has the lowest index, the Magnesium-SLM pair is selected.
The volume fraction of the corresponding design is **Vf=0.01 (LB**),.



The GHG emissions over its life cycle are 82.3kgCO_{2eq}

Optimal design for the bridge problem: Magnesium alloy with SLM.

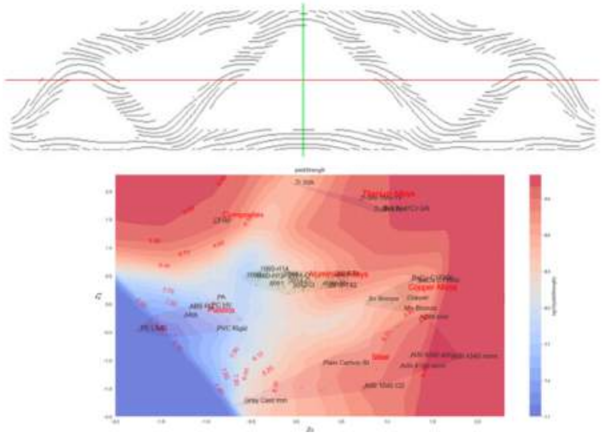
Au programme

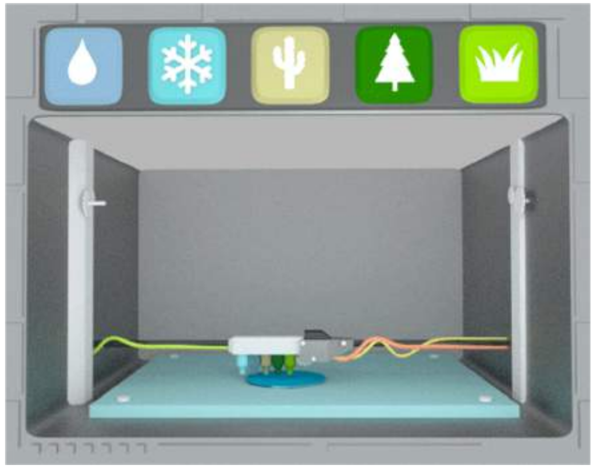
- Part1: Initiative Sustainable Aerostructures @ISAE-SUPAERO
- Part2: On some new developments on ECODESIGN and TOPOPT @ICA
- **Conclusions**

Conclusions

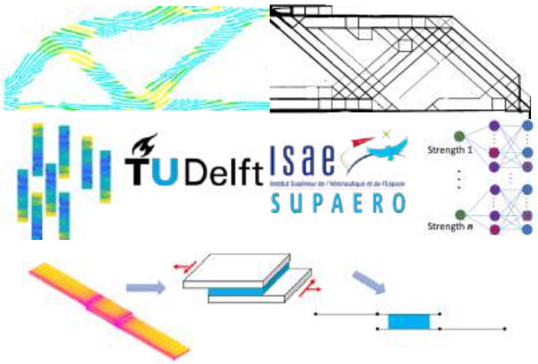
A fast method of material, design and process eco-selection via topology optimization for additive manufactured structures

- Approche académique→ ***Proof of concept***
- Lien enseignement-recherche-innovation (Placement de fibre/résine bio sourcées, optimisation multiobjectifs mass vs CO_2 via VAE)
- On recherche des partenaires pour aller plus loin





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



Ansys
GRANTA

Journées utilisateurs Ansys Granta 2023

Perspectives

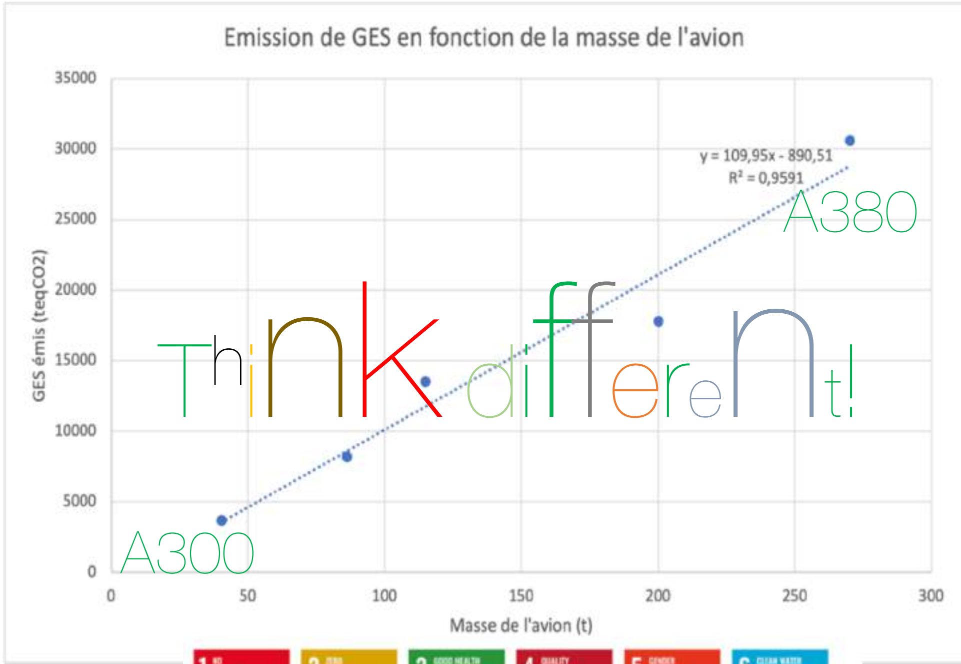
En conception avion:

min {mass} est proportionnel à min {$CO2_{PP}$}

Manufacturing <1% des émissions totales de l'avion

Ce n'est pas vrai pour les lanceurs, les drones HALE …

Il y a donc du travail !!!



MERCI

Institut Supérieur de l'Aéronautique et de l'Espace

10, avenue Edouard Belin – BP 54032
31055 Toulouse Cedex 4 – France
T +33 5 61 33 80 80

www.isae-supaero.fr