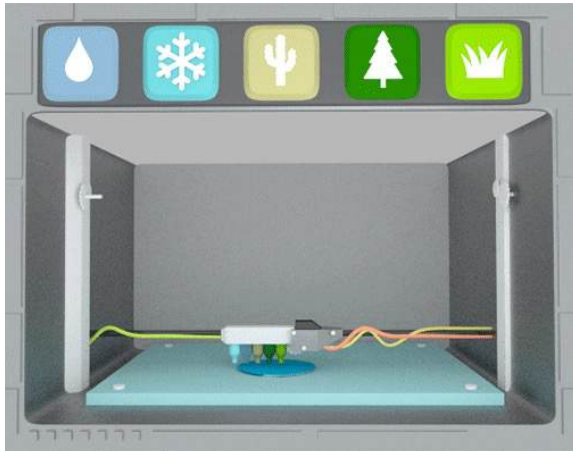


Source: 3D Printing World Environment Day GIF By General Electric

Latest advancements in engineering optimization technology

and its applications in supporting eco-friendly initiatives.

Prof. Joseph Morlier

ITB Seminar

TOPOPT & ALM

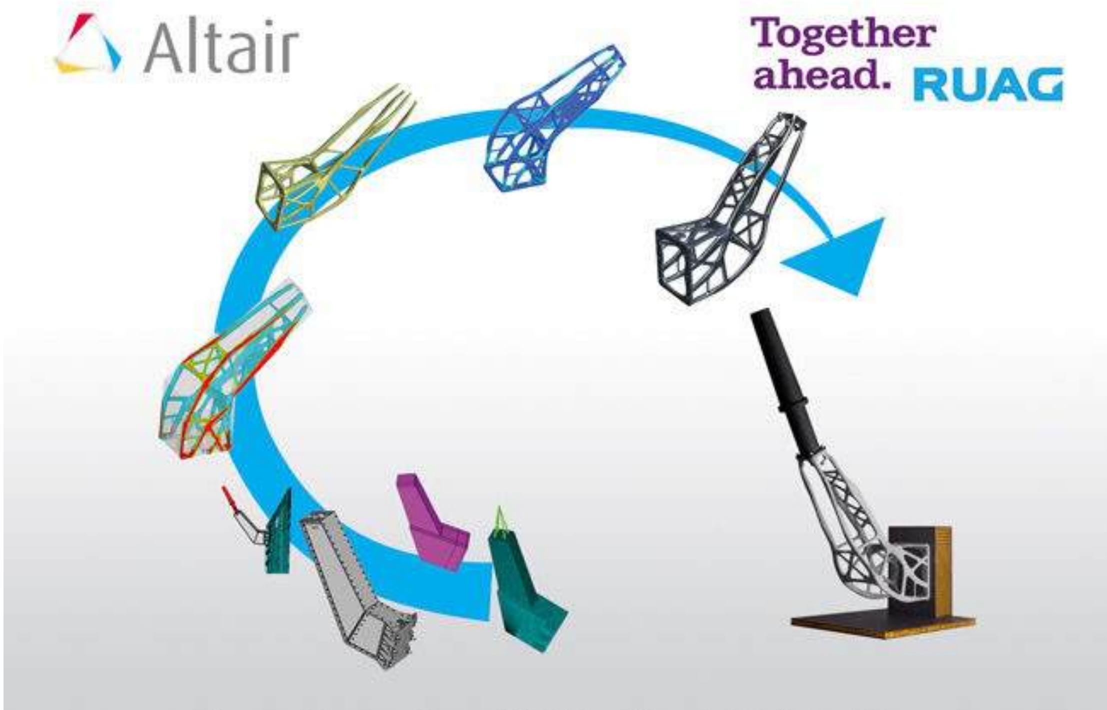
Topology Optimization

- Lightweight
- Free-form shape
- Customization
- Mechanically optimized

Additive Manufacturing

- Customization
- Geometric complexity

ALM

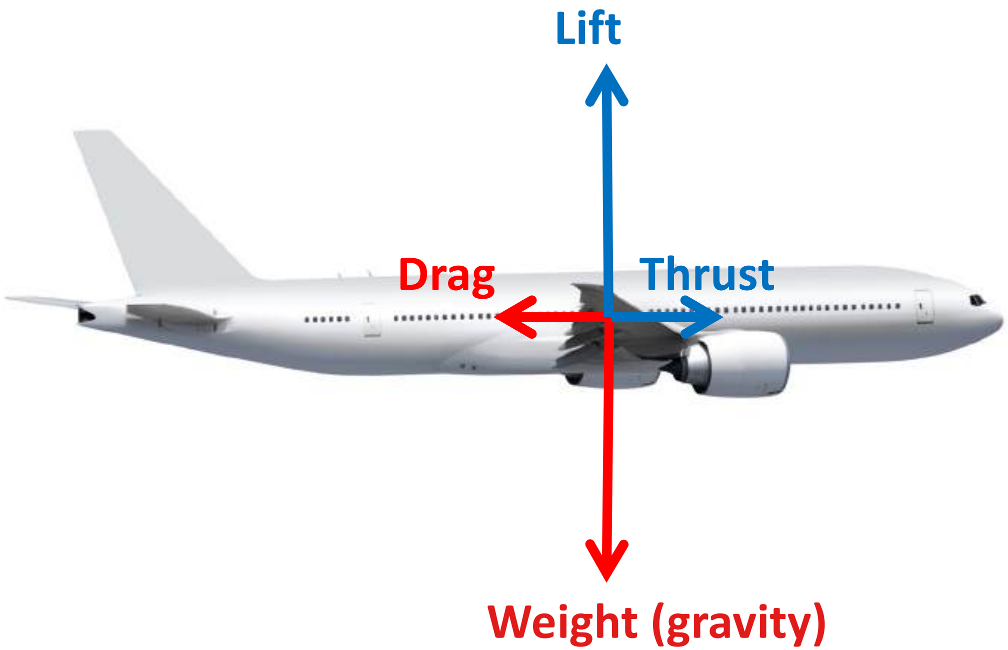


Processus de re-conception pour la fabrication additive par l'optimisation topologique

http://bcove.me/yg7pqkak

Energy-efficient planes are the key

And weight is a determining factor…



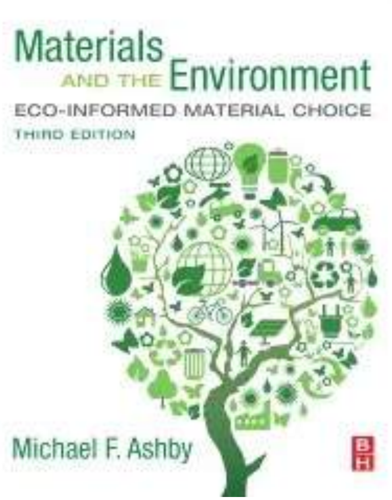
Why?

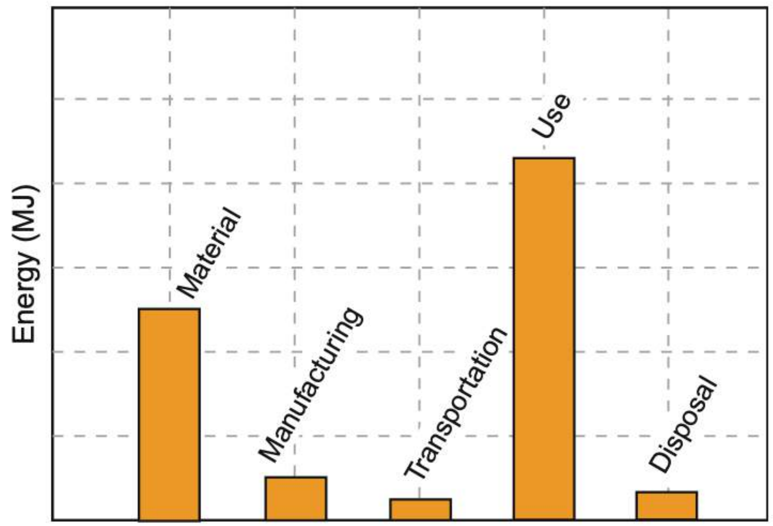
$$\underset{\text{aircraft weight reduction"}}{\text{"The rate of}} = \underset{\text{fuel weight burned"}}{\text{"The rate of}}$$

Since the endurance/range is defined by *cruise* conditions, the equilibrium steady flight conditions of T=D and L=W

$$\text{Range} = Vt_f = V \times \underbrace{\left(\frac{L}{D}\right)}_{\text{aircraft designer}} \times \underbrace{I_{sp}}_{\text{propulsion system designer}} \times \underbrace{\ln\left(\frac{W_i}{W_f}\right)}_{\text{structural designer}} .$$

Environnemental Footprint

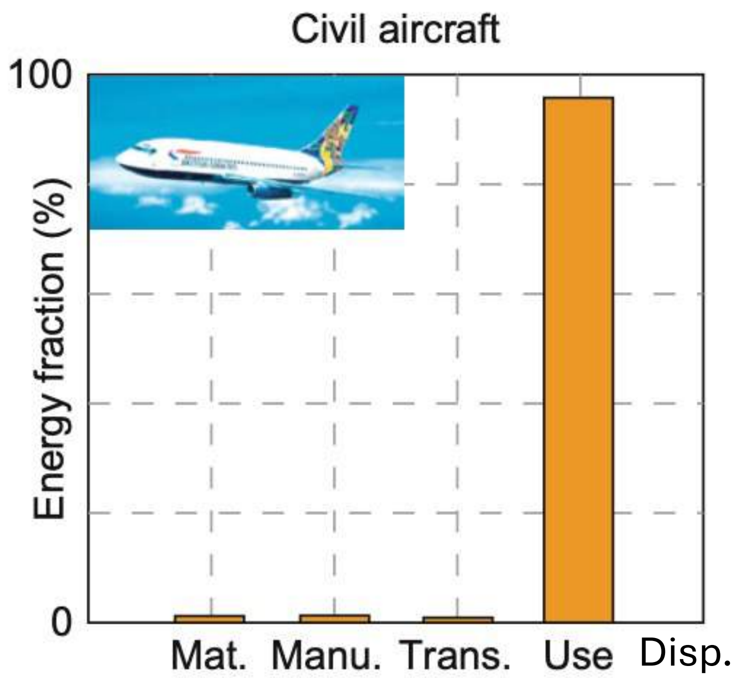




$\alpha\ CO_2$

Breakdown of energy into that associated with each life phase

Green aviation



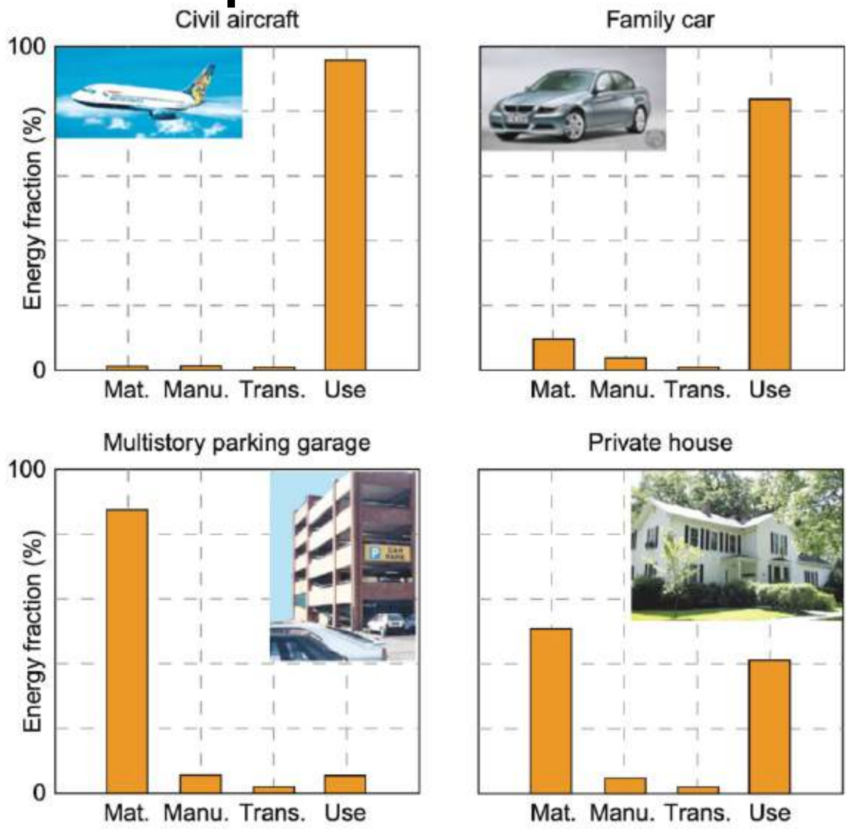
Embodied energy

$$E_e = \frac{\sum \text{Estimated energy required for primary production}}{\text{Mass of primary material production}}$$

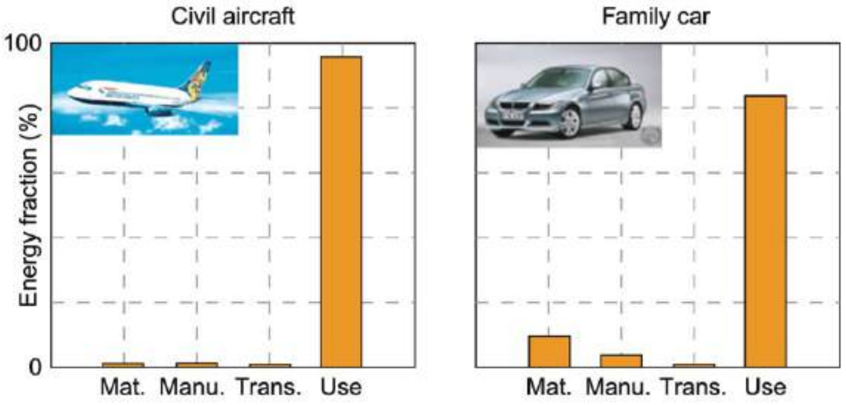
CO2 emission

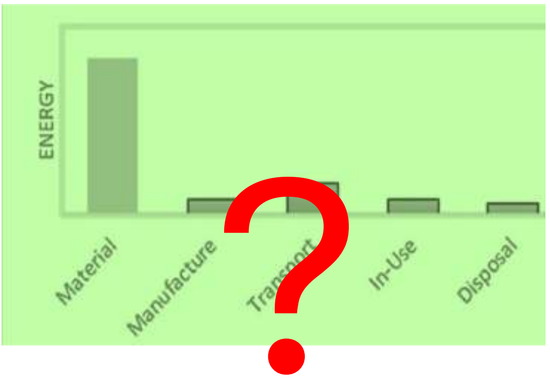
$$E_c = \frac{\sum \text{Mass of CO2 arising from production}}{\text{Mass of material produced}}$$

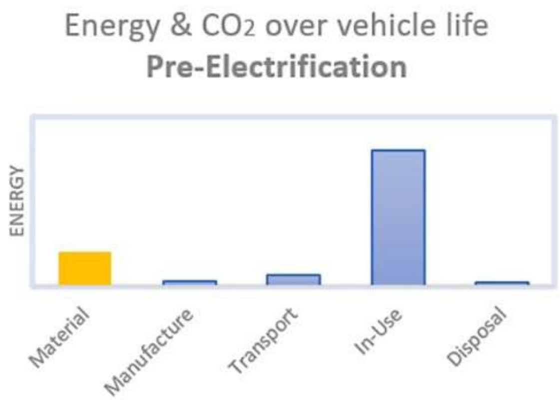
Different products … different impacts

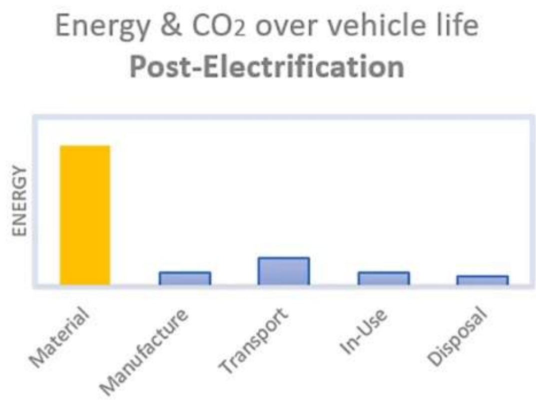


Electrification example (from automotive)



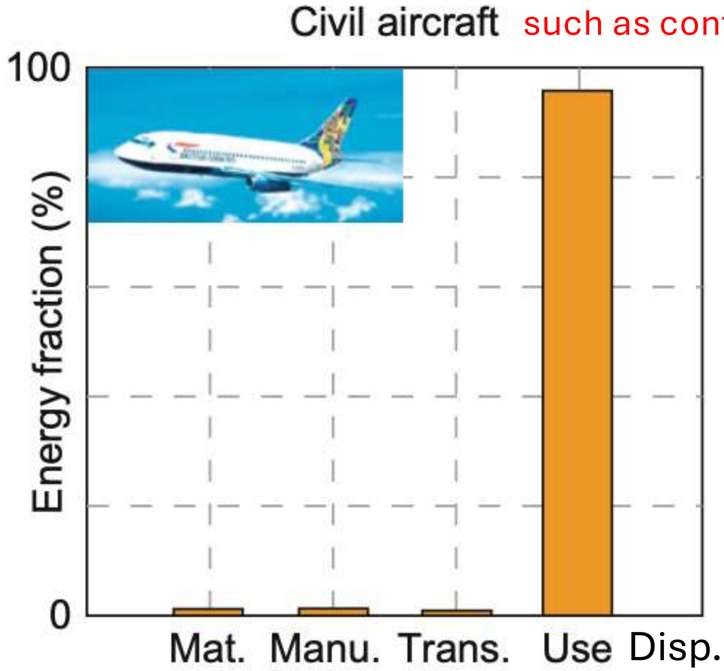




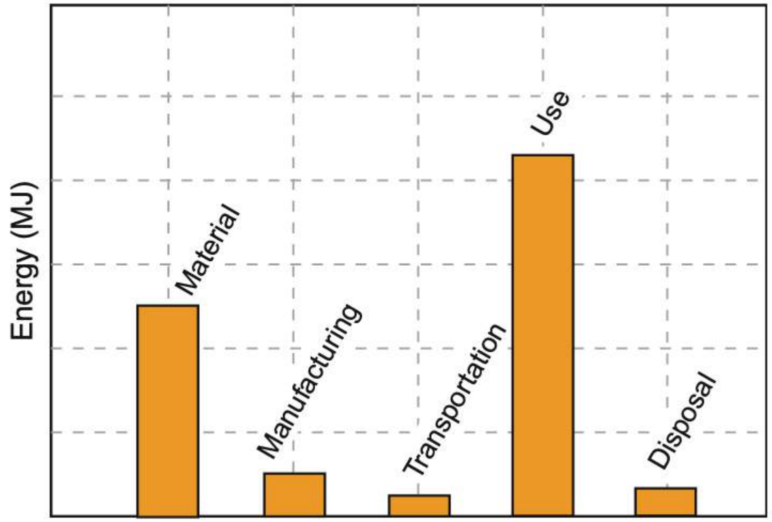


Energy ∝ CO_2 footprint

Fuel burn
+ non CO_2
such as contrails



Future Sustainable Air vehicule



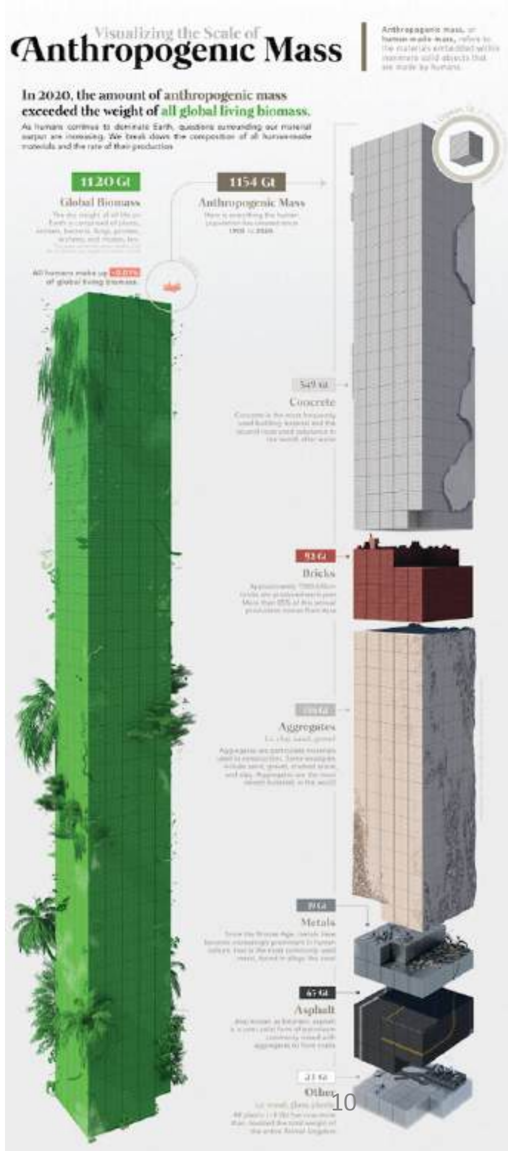
Breakdown of energy into that associated with each life phase

Hydrogène, SAF, Electric/Hybrid Propulsion…

An important figure

Massive Demand in Energy and Materials

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 [1]

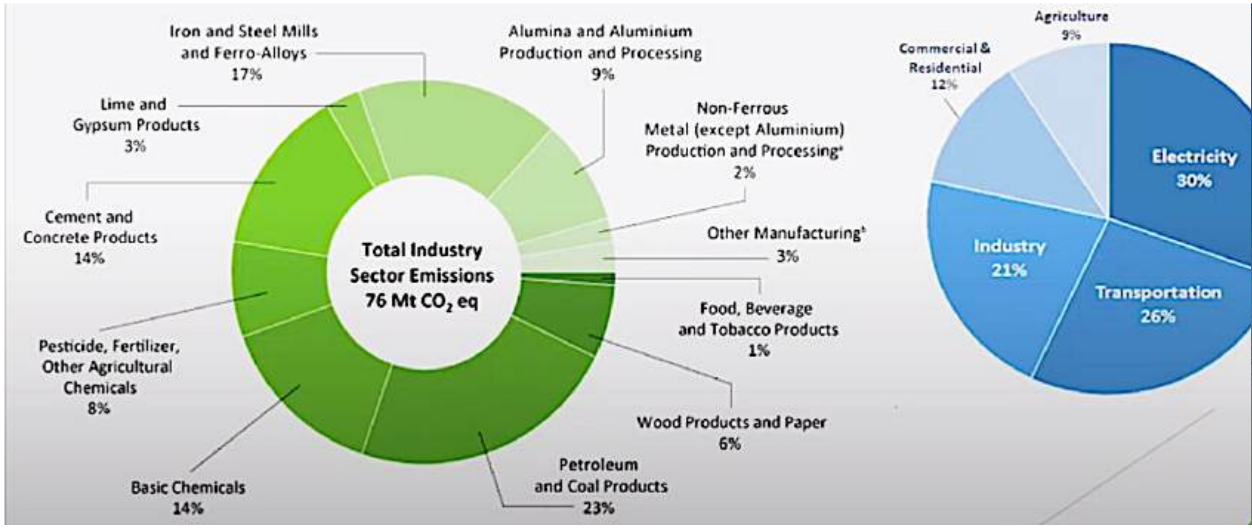


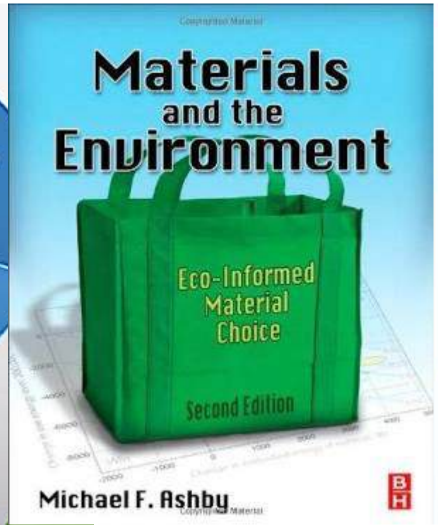
Materials and Energy ressources are linked and limited…

#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.

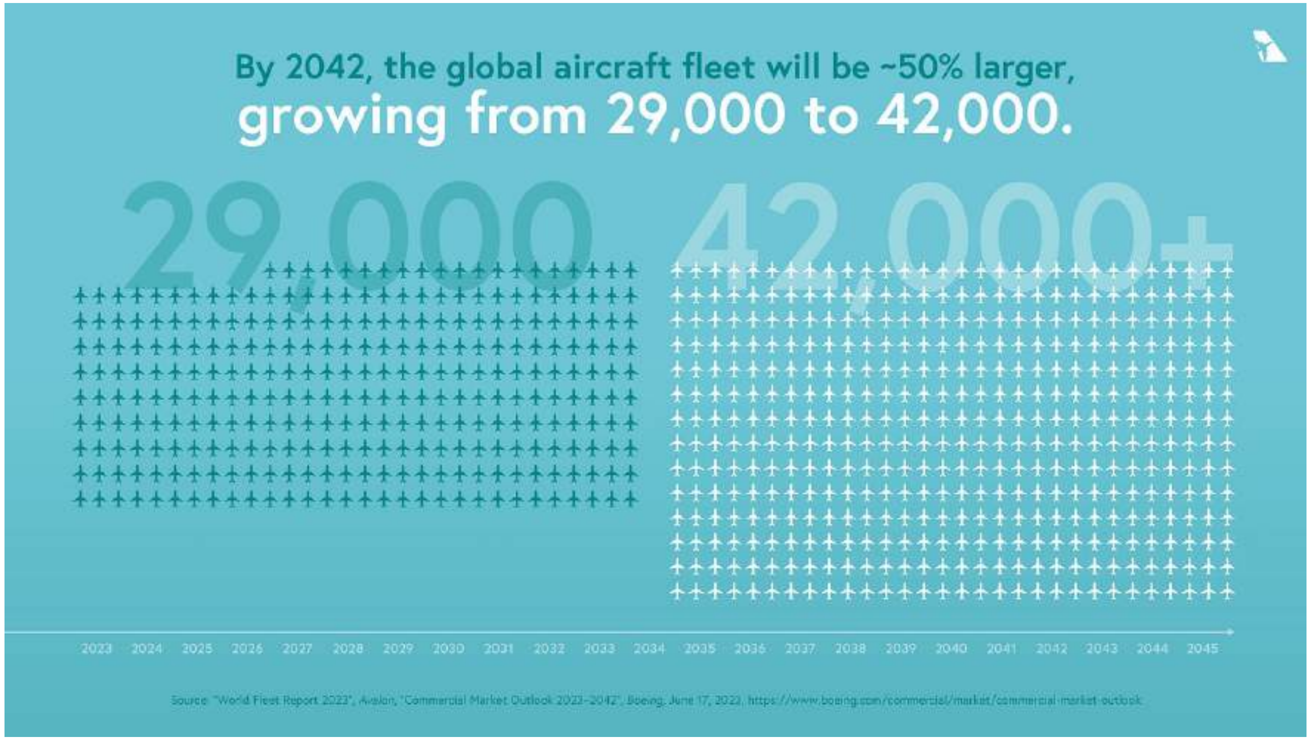
#In anticipation of 2050, the total tonnage of concrete, steel, aluminum etc… necessary for the development of these energies will be 2 to 8 times the world production of 2010. !!!





Sustainable aviation?

critical materials + Geostrategic problem→ cost of materials will increase … delay …



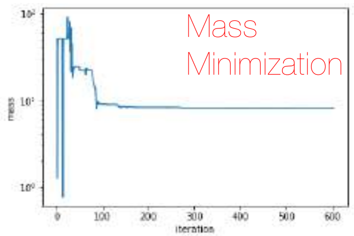
Aircraft Design

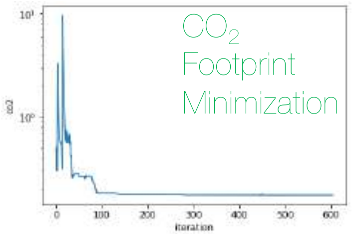
Fluid x control x physics x applied maths x structures &materials

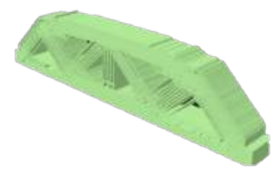
Topology x Material x Process

Strong coupling Between Disciplines

		1 Avionics group	2 Electrical group	3 Escape system	4 Armament	5 Landing gear	6 Hydraulics group	7 Flight control system	8 Environment and control system	9 Power plant group	10 Fatigue group	11 Aero elastic group	12 Stress group	13 Materials group	14 Fly wheel	15 Empennage group	16 Rear fuselage	17 Fuselage group
Avionics group	1	●	●	●	●	●	●	●	●	●						●	●	●
Electrical group	2	●	●	●	●	●	●	●	●	●					●	●	●	●
Escape system	3	●	●	●	●													●
Armament	4	●	●		●						●	●	●	●		●		●
Landing gear	5	●	●			●	●				●	●	●			●		●
Hydraulics group	6						●			●							●	●
Flight control system	7	●	●					●			●	●	●	●	●	●	●	●
Environment and control	8								●		●	●	●					●
Power plant group	9	●	●				●			●	●	●	●				●	
Fatigue group	10			●	●	●	●	●	●	●	●	●	●		●	●	●	●
Aero elastic group	11			●	●	●	●	●	●	●	●	●	●		●	●	●	●
Stress group	12		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Materials gruop	13										●	●	●	●	●	●	●	●
Empennage group	14	●	●					●			●	●	●	●	●		●	
Wing group	15		●		●	●				●	●	●	●	●		●	●	
Rear fuselage	16	●	●				●	●		●	●	●	●	●	●	●	●	●
Fuselage group	17	●	●	●		●	●	●	●		●	●	●	●	●	●	●	●



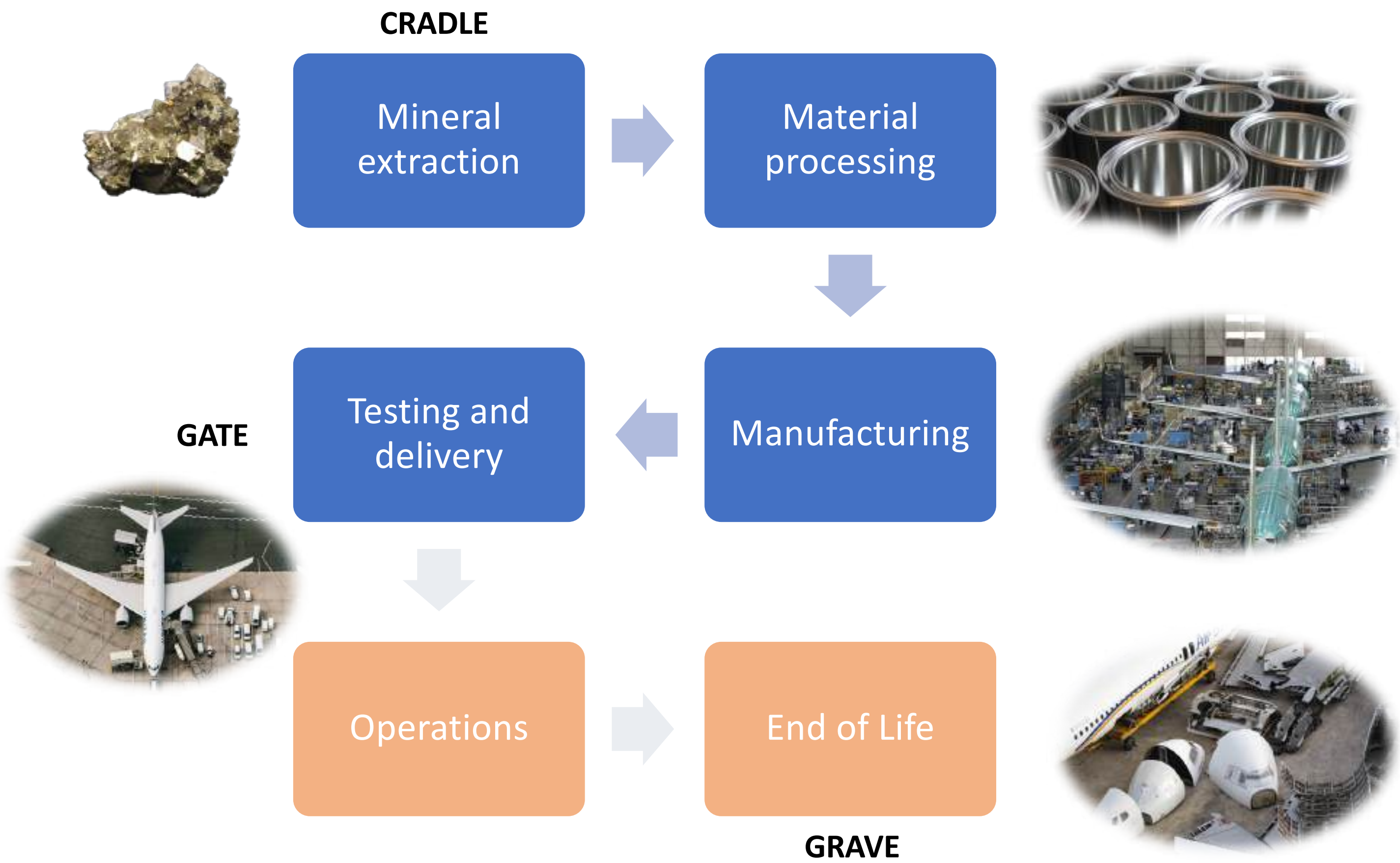




$$\text{Range} = V t_f = V \times \underbrace{\left(\frac{L}{D}\right)}_{\text{aircraft designer}} \times \underbrace{I_{sp}}_{\text{propulsion system designer}} \times \underbrace{\ln\left(\frac{W_i}{W_f}\right)}_{\text{structural designer}}.$$

Breguet was a French aircraft designer

The Life Cycle of an Aircraft



The Life Cycle of an Aircraft – ‘Cradle-to-Gate’

Cradle-to-gate is an assessment of a partial product life cycle
from resource extraction (cradle) to the factory gate

Mineral extraction

↓

Pure Material

↓

Alloy/Composite

↓

Machining

↓

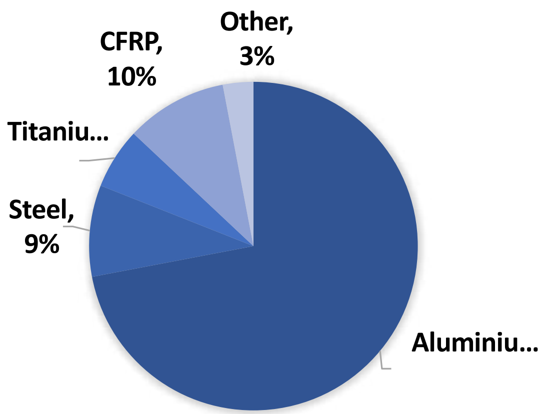
Assembly

Image sources:
[1] mineral-processing
[2] blast-furnace
[3] Alloy ingots
[4] machining
[5] Airbus-assembly-line

Materials used in an aircraft

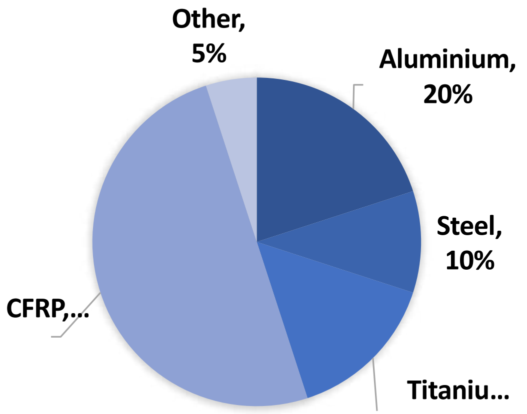
Metal airframe: e.g. a320

Source: [planespotters.net]



Carbon fiber airframe: e.g. a350

Source: [www.airliners.net]



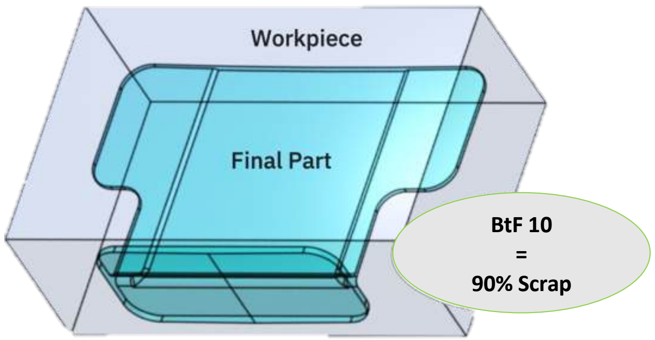
Environmental impact of material production

Material	Emissions t CO_2eq / t	Energy GJ / t
Aluminium[1]	14.9	162.8
Steel[1]	1.9	19.9
Titanium[1]	17	326
CFRP[2]	28	514

[1] T. E. Norgate et al, Journal of Cleaner Production, 2006
[2] cfconversions.de/sustainability/

Buy-to-Fly Ratio

$$BtF = \frac{\textit{Weight of raw material (Billet)}}{\textit{Weight of Final component}}$$



Process	Buy-to-fly
Machining	1.1 – 50
Hot closed die forming	1.2 - 1.5
Sheet metal forming	1.1 – 1.25
Extrusion	1.1 – 1.3
Permanent mold casting	1.0 – 1.2
Powder metallurgy	1.0 – 1.05

Source: Manufacturing Engg. Presentation, Assiut University

Material	Buy-to-fly
Aluminium	5
Steel	16
Titanium	10
CFRP	1.5

Source: E. Pierrat et al, Journal of Cleaner Production, 2021

Formula for estimation of total impact

Known parameters:

Empty weight of aircraft	$OWE_{aircraft}$
Impact for unit production of material (energy/kg OR CO2/kg)	e_m
Mass fraction of material in aircraft	F_m
Buy-to-Fly of material	BtF_m

*Total Environmental impact for **making 1 aircraft** (Energy, Emissions)*	=	$OWE_{aircraft} \times \Sigma(e_m \times F_m \times BtF_m)$

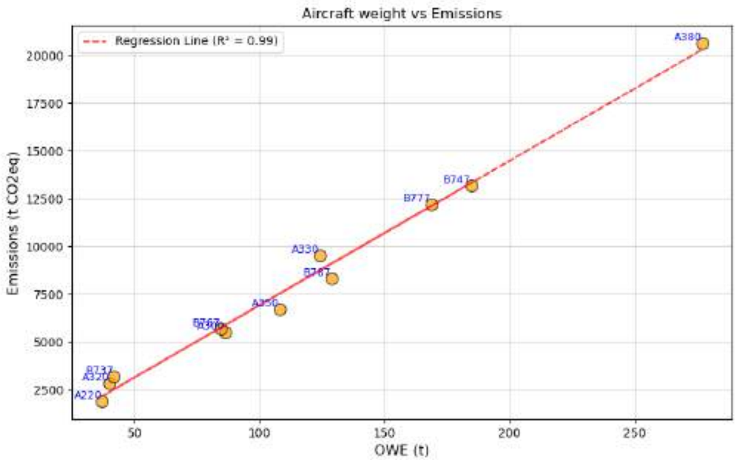
Manufacturing waste generated per material	=	$OWE_{aircraft} \times F_m \times (BtF_m - 1)$

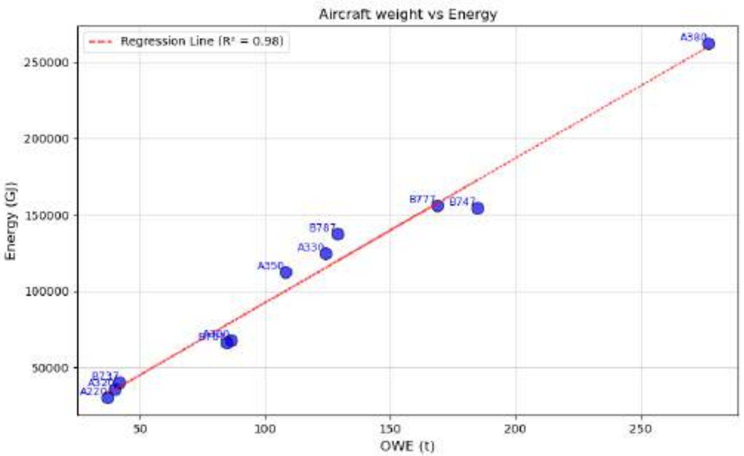
Assessing the impact of popular commercial aircraft

Approx Empty weight and Material Composition

Aircraft Family	OWE (t)	Aluminium	Steel	Titanium	CFRP
A300	86.2	**67%**	12%	4%	9%
A320	40	**72%**	9%	6%	10%
A330	124	**58%**	19%	8%	9%
A380	277	**75%**	7%	8%	7%
A350	108	19%	7%	14%	**53%**
A220	37	24%	1%	8%	**46%**
B737	41.7	**80%**	8%	8%	3%
B747	184.6	**81%**	13%	4%	1%
B767	84.5	**78%**	13%	2%	5%
B777	168.7	**70%**	11%	7%	12%
B787	128.8	20%	10%	15%	**50%**

Assessing the impact of popular commercial aircraft





Aircraft	Aluminium	Steel	Titanium	CFRP
A300	231	155	31	4
A320	115	54	22	2
A330	362	130	112	5
A380	831	291	199	10
A350	82	113	136	29
A220	36	6	27	9
B737	133	50	30	1
B747	598	360	66	1
B767	264	165	15	2
B777	472	278	106	10
B787	103	193	174	32

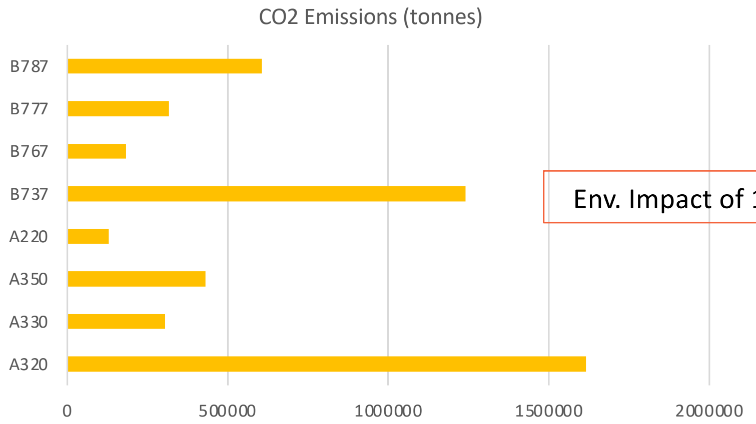
Calculated **manufacturing waste in tonnes** considering standard BtF ratios

- **Energy and Emissions** associated with manufacturing **increase linearly with aircraft weight**
- **Tremendous waste** is generated during manufacturing

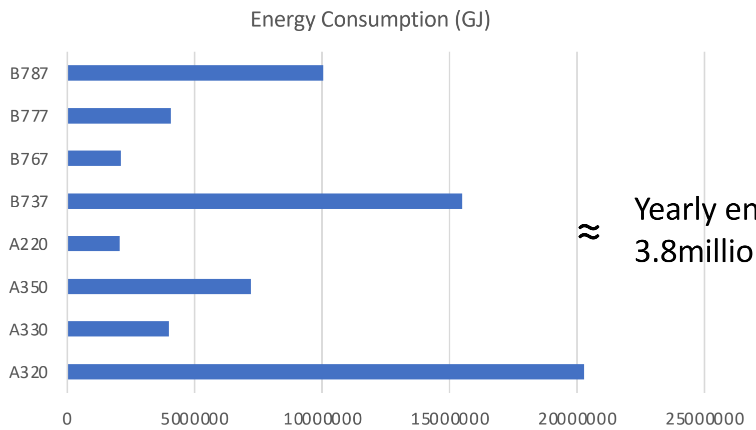
Assessing the impact of popular commercial aircraft

Estimated overall impact in year 2023 considering deliveries

Aircraft	Deliveries
A320	571
A330	32
A350	64
A220	68
B737	387
B767	32
B777	26
B787	73



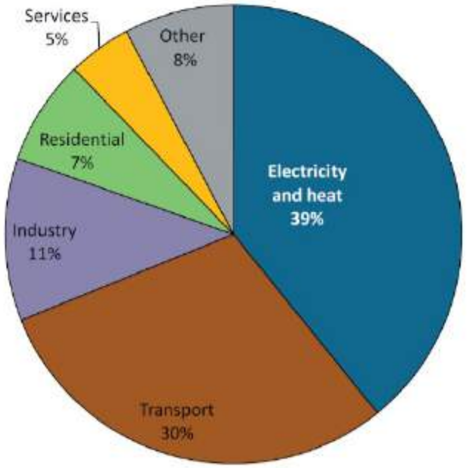
Env. Impact of 1 aircraft × Deliveries



≈ Yearly energy consumption of 3.8million households in France

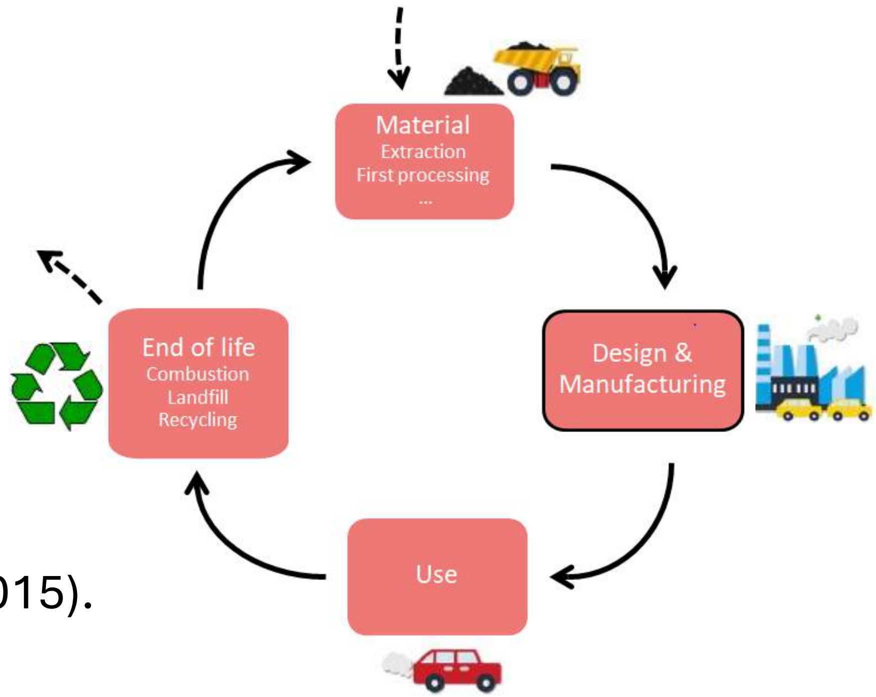
Single aisle aircraft programs (a320, B737) have larger impact as compared to wide body aircraft

Overview



CO_2 emissions of the OECD (2015).

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

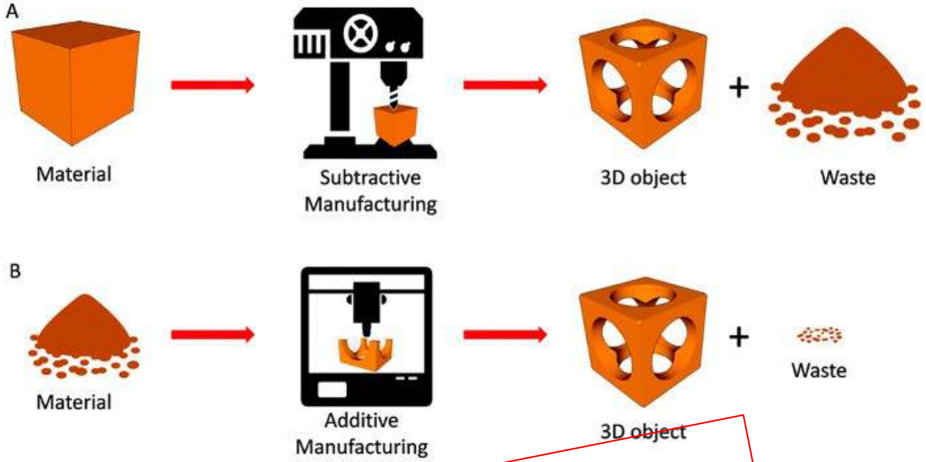


Vehicle life cycle

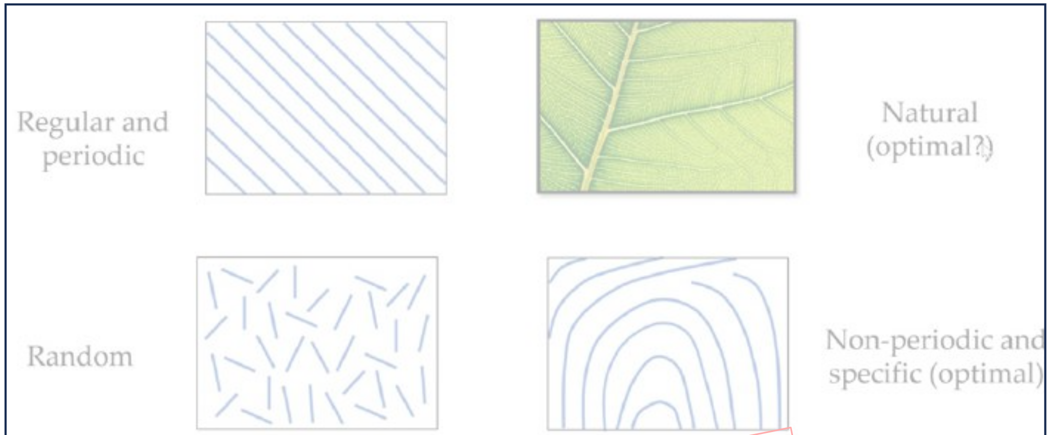
Q : How to find structural designs, materials and additive manufacturing processes with the lowest life-cycle CO_2 footprint**?**

Process is AM, but WHY?

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



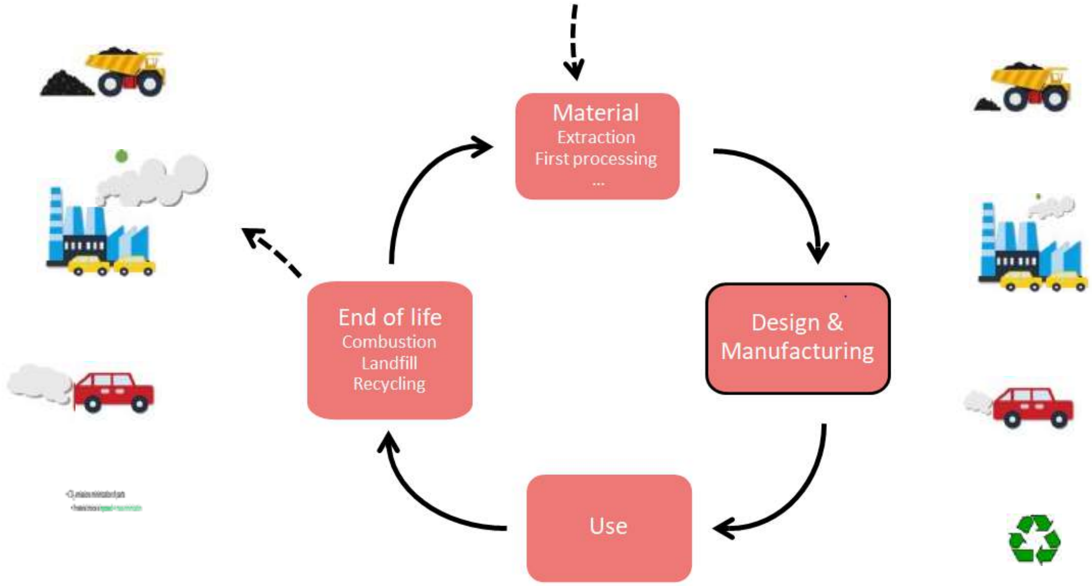
+Near 100% material utilization +Recyclability, Buy to fly ratio
+LCA of 3D printing machine
+Monitoring



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

Hypothesis 1

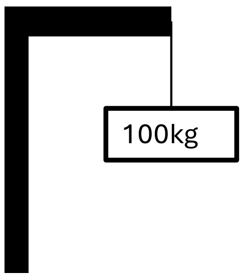
- CO_2 emissions minimization of parts
  - If material choice is **imposed** => mass minimization

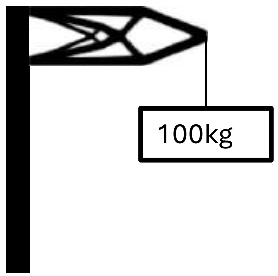


Vehicle life cycle

Mass minimization of parts

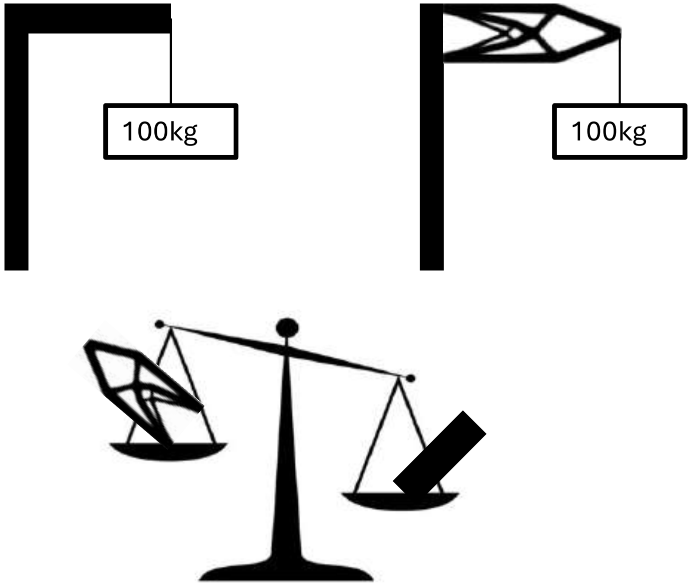
- Redesign through topology optimization
  => same performance





Mass minimization of parts

- Redesign through topology optimization
  => same performance but lower mass



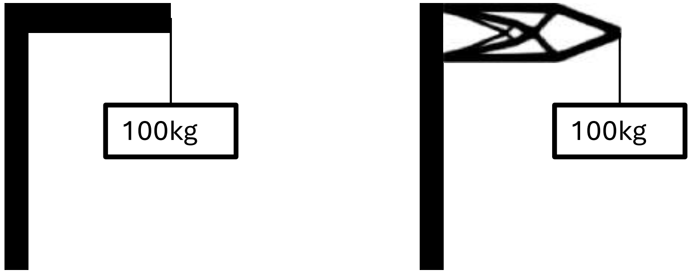
Ecodesign/Manufacturing

- Mass minimization of parts
  - And some additional constraints

(see Enrico’s PhD)

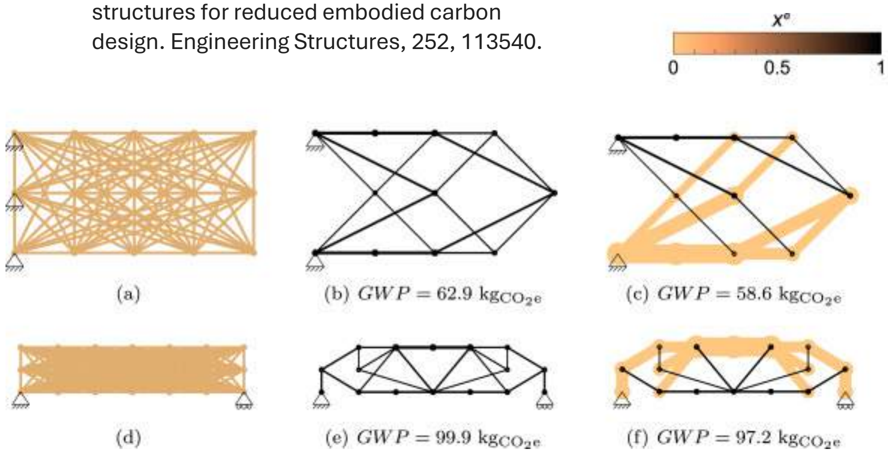
- Reparability
- Fail-safe design
- Reusability and robot for assembly (see NASA MADCAT)

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.



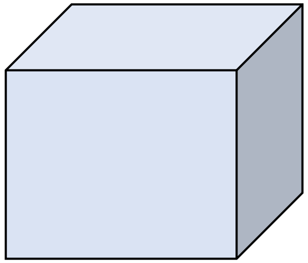
- Multimaterial
- GWP under stress

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

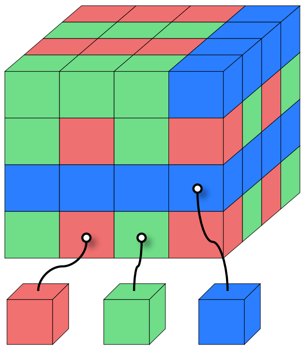


Example II: Mechanical Properties in Printing Microstructures

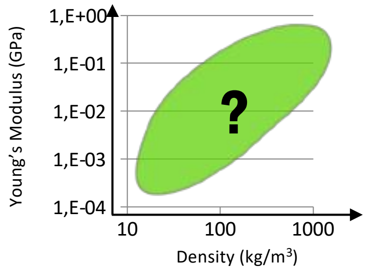
A unit microstructure cell



Heterogeneous material



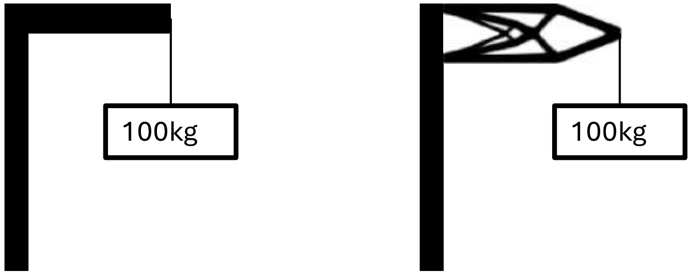
Base homogenous materials



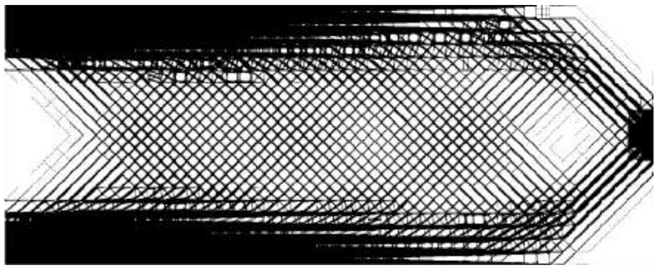
What physical properties can be achieved with microstructures?

Mass minimization of parts

- Redesign through topology optimization
  => same performance but lower mass

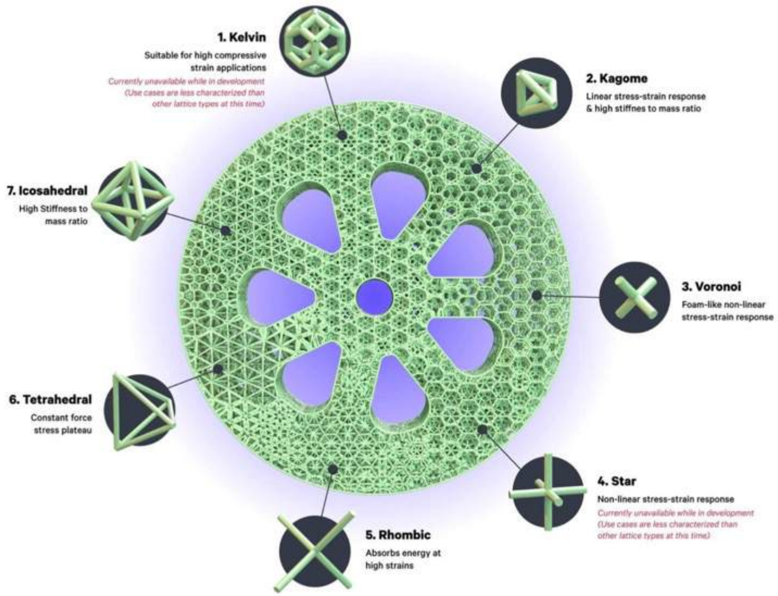


– One step further : multiscale topology optimization



Unit cell/material/process

Eco Material selection
Eco Process selection

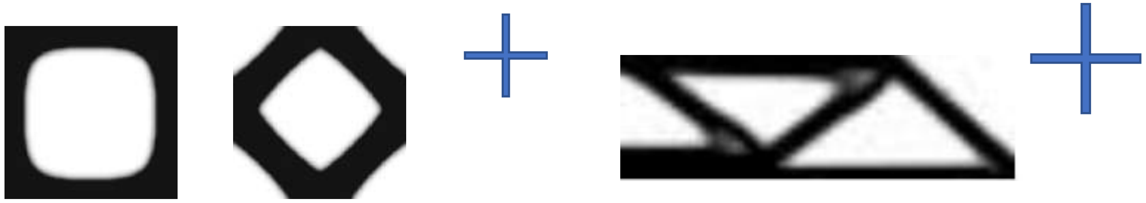


Unit cell design (anisotropy)

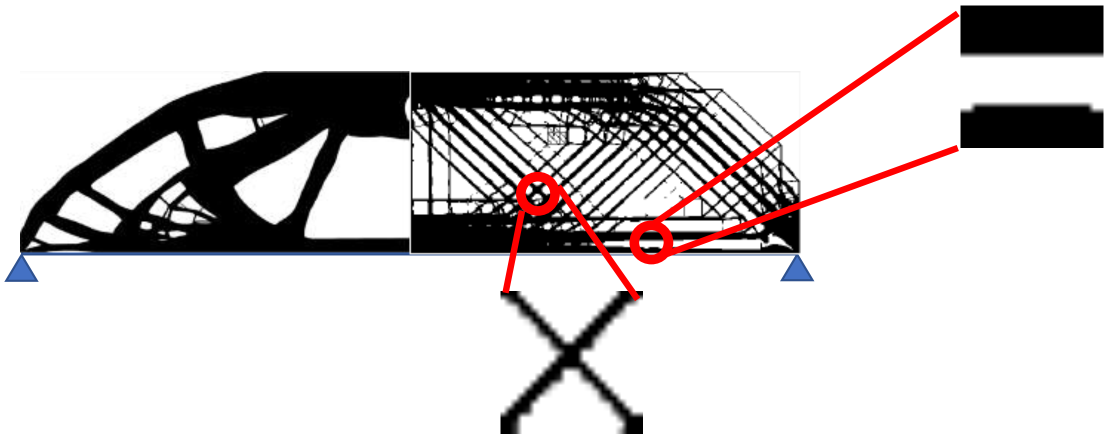
Digital materials as **new design variables** in Multidisciplinary Optimization

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

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

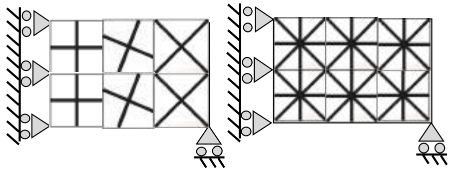


Thanks Edouard Duriez and co-authors

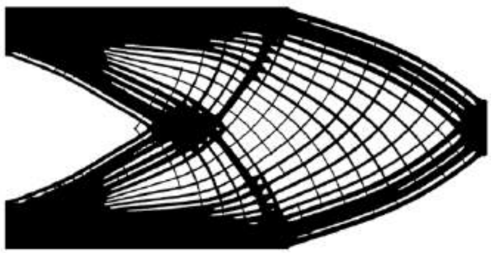


Xia L, Breitkopf P (2015) Design of materials using topology optimization and energy-based homogenization approach in Matlab. Struct Multidisc Optim 52(6):1229–1241.
Wu, Jun, Ole Sigmund, and Jeroen P. Groen. "Topology optimization of multi-scale structures: a review." Structural and Multidisciplinary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

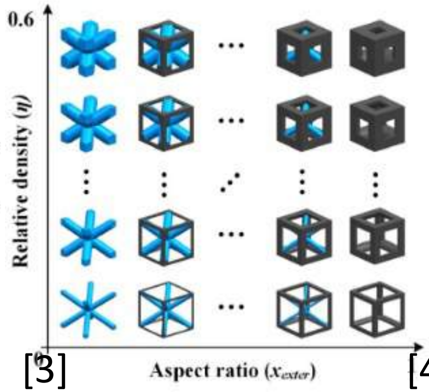
Main MTO methods



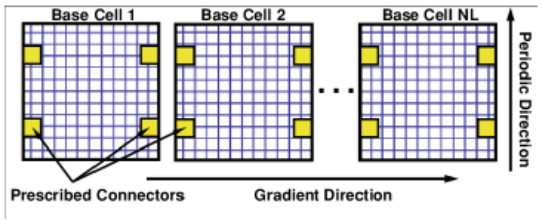
Approach	Examples	Connectivity	Locally adapted	Speed	Manufacturability
De-homogenization	[1],[2]				
Parametrized lattice	[3]				
Connectors	[4]				



[2]



[3]



[4]

[1] Grégoire Allaire, Perle Geoffroy-Donders et Olivier Pantz. « Topology optimization of modulated and oriented periodic microstructures by the homogenization method ». en. In : *Computers & Mathematics with Applications*.

[2] Groen, Jeroen P., and Ole Sigmund. "Homogenization-Based Topology Optimization for High-Resolution Manufacturable Microstructures." *International Journal for Numerical Methods in Engineering*

[3] Wang, Chuang, et al. "Concurrent Design of Hierarchical Structures with Three-Dimensional Parameterized Lattice Microstructures for Additive Manufacturing." *Structural and Multidisciplinary Optimization*

[4] Zhou S, Li Q (2008) Design of graded two-phase microstructures for tailored elasticity gradients. Journal of Materials Science

[5] Wu, Jun, et al. "Topology Optimization of Multi-Scale Structures: A Review." *Structural and Multidisciplinary Optimization*

Multiscale Topology Optimization

Macroscale Problem

need to solve

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

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

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

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

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

best unit cell per quad

Microscale Problem Unit cell with 3 properties

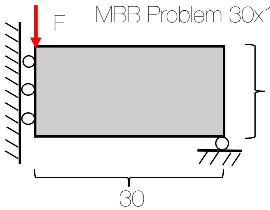
macro-density, angle, cubicity

$$\underset{\rho_{i,j}}{\text{minimize}} \quad c_i = E^{i\alpha}_{1111} \times \left(1 - \frac{x^i_{\text{cub}}}{2}\right) + E^{i\alpha}_{2222} \times \frac{x^i_{\text{cub}}}{2}$$

$$\text{subject to} \quad K_i u_i^{A(pq)} = f_i^{(pq)}$$

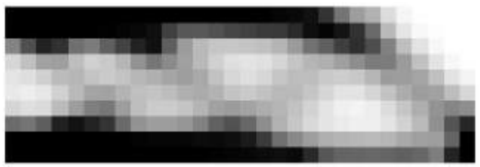
$$\sum_{j=1}^{m} \rho_{i,j} \leq m \times x^i_{\text{dens}}$$

MBB Problem 30x10 macro elements

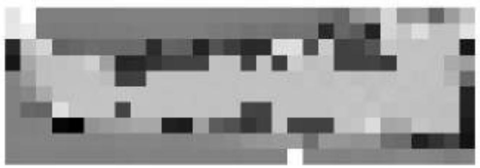


Theoretical compliance 192.7

Density of the cells

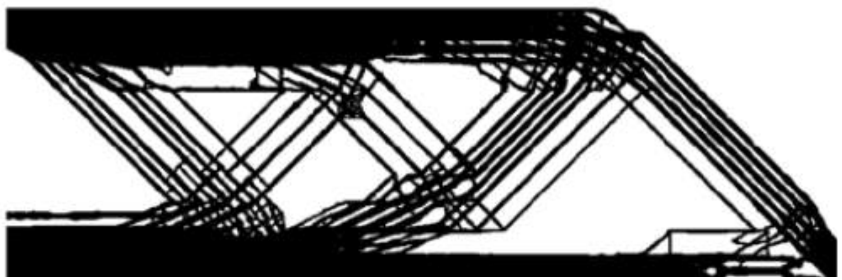


Orientation of the cells



Cubicity of the cells

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

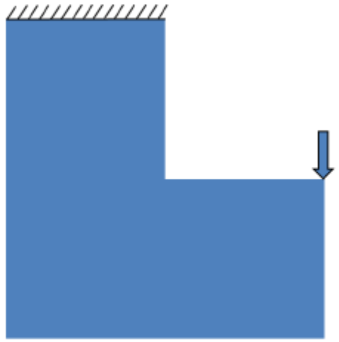


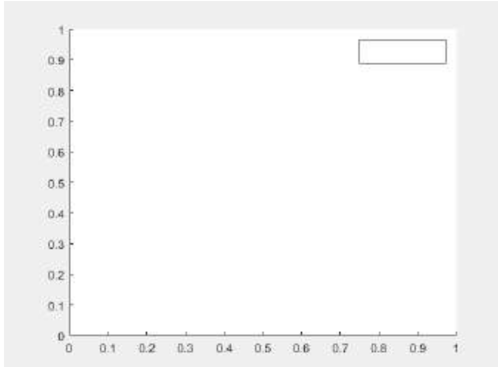
Comparison

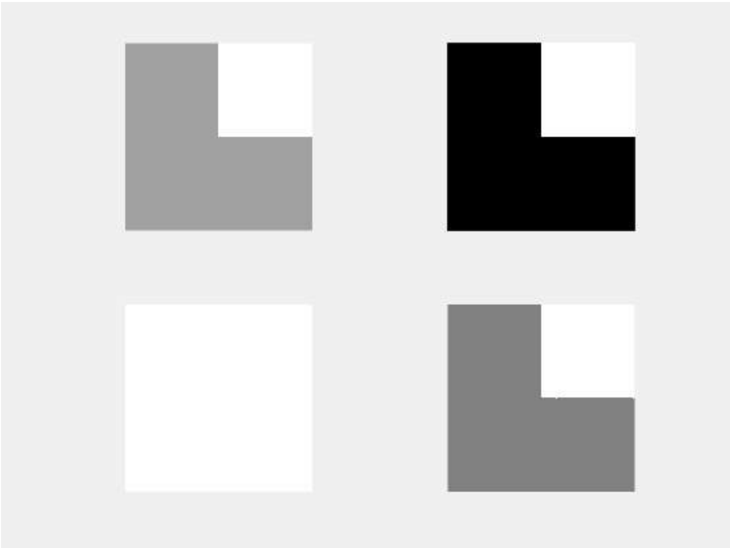
- Top88 versus EMTO

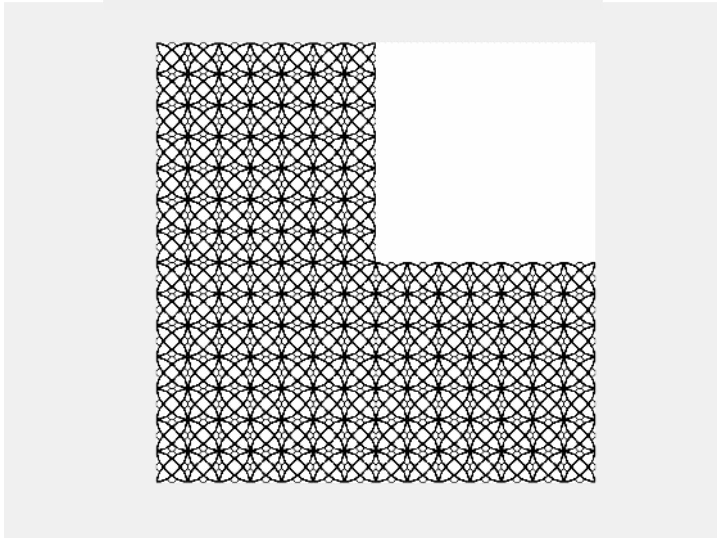
Result on classical test cases

- Validation on
 small grid
$\Rightarrow$ Evaluate
full-scale design



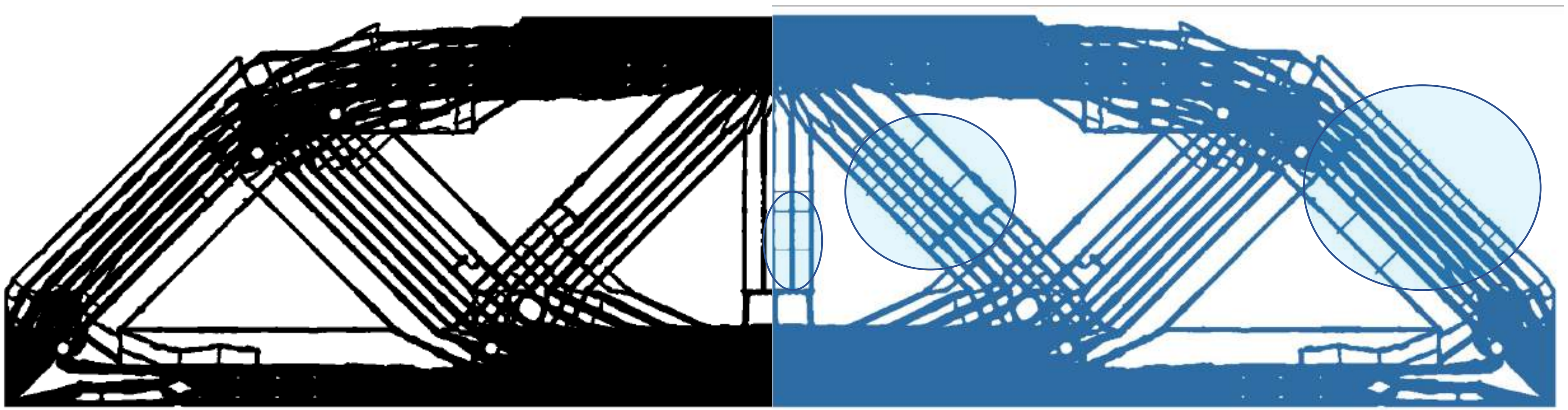




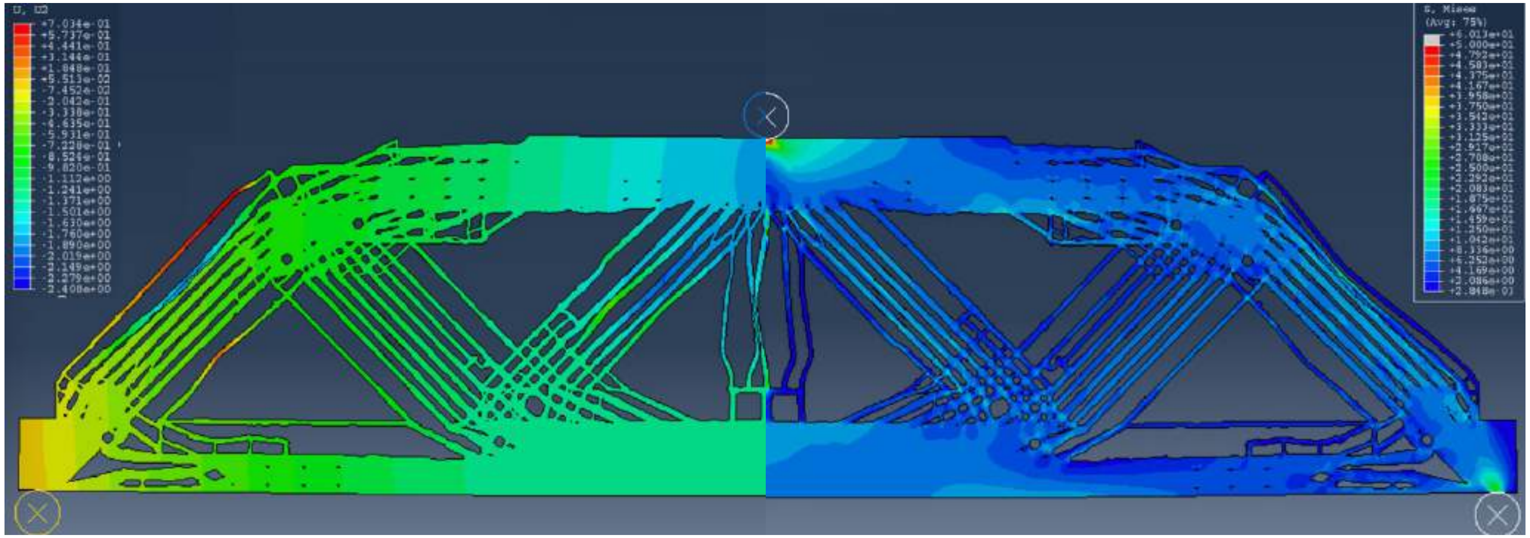


- 4x14*14 design variables;   stopping criteria : tolfun< 10^{-3}

Do you see a difference (Left2Right)?



EMTO 3pts bending (disp vs stress)

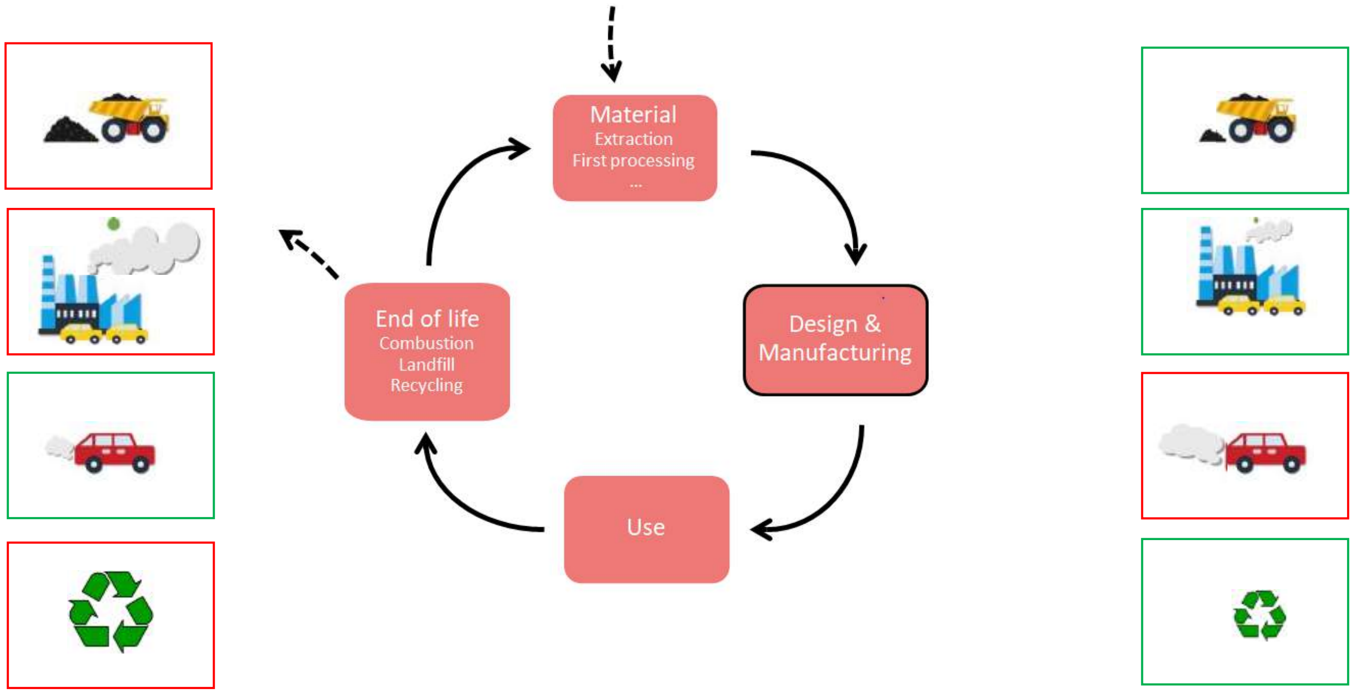


Selective Laser Melting (SLM)

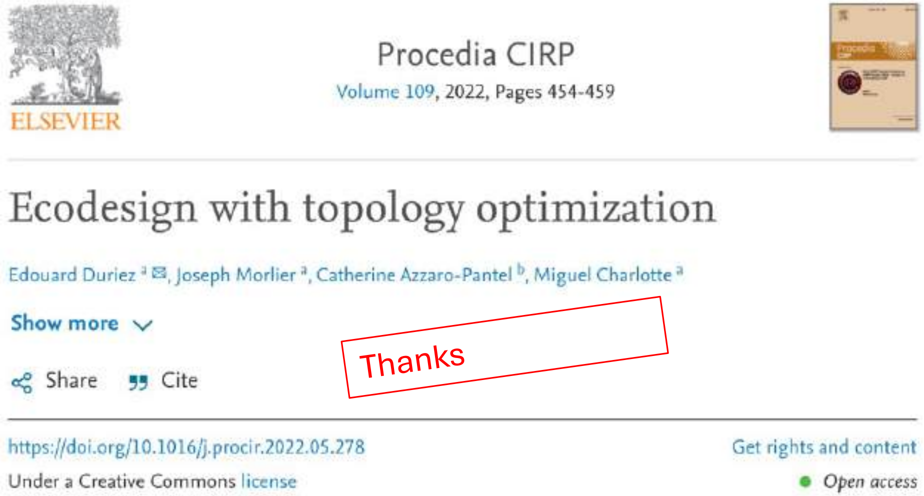
ABAQUS REANALYSE

Hypothesis 2

- CO_2 emissions minimization of parts
  - If material choice is **free** => more complicated



First zoom


ELSEVIER
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]

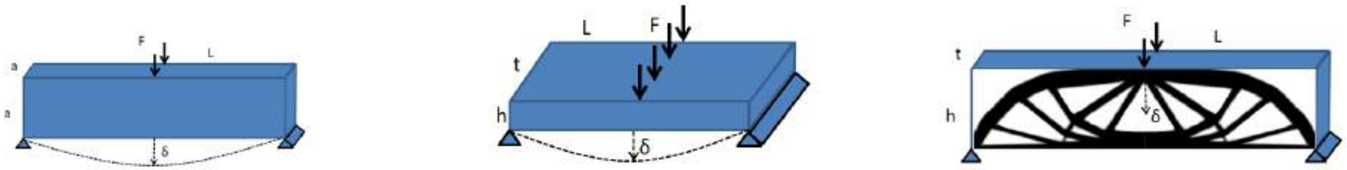
Show more

Share Cite

Thanks

https://doi.org/10.1016/j.procir.2022.05.278

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



To go deeper

ELSEVIER

Cleaner Environmental Systems
Volume 9, June 2023, 100114

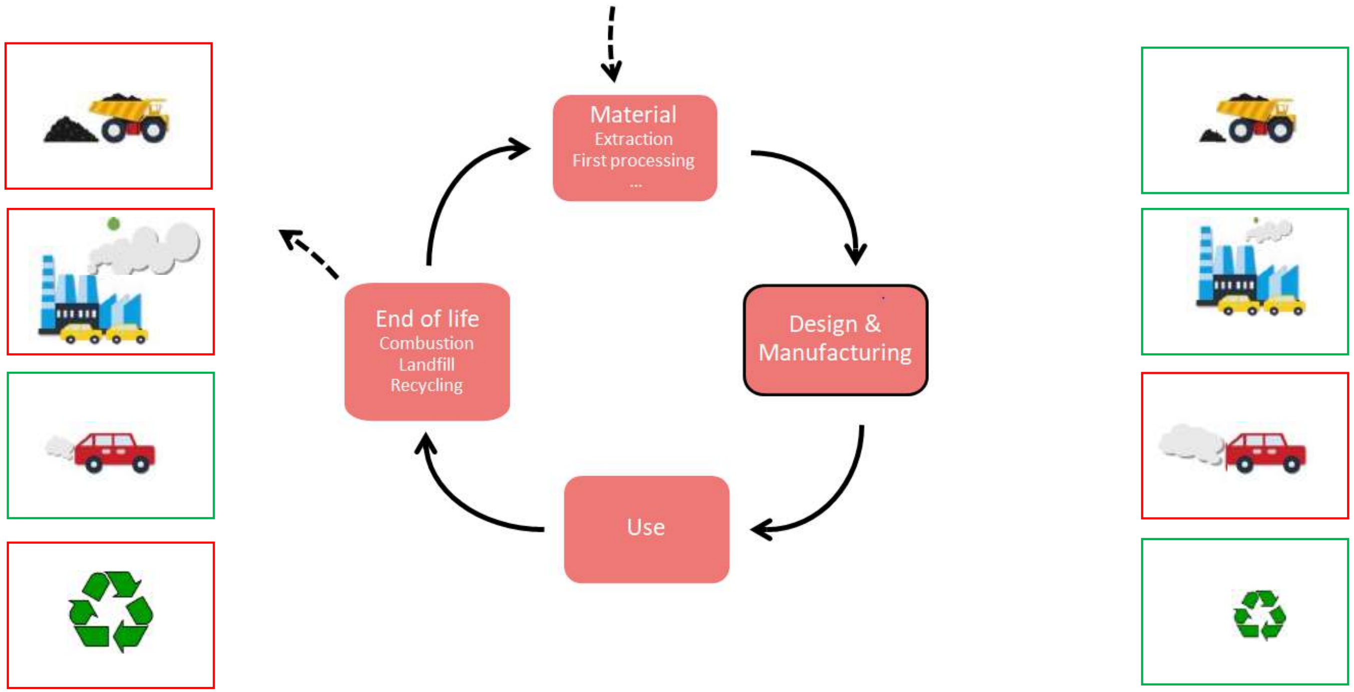
A fast method of material, design and process eco-selection via topology optimization, for additive manufactured structures

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}

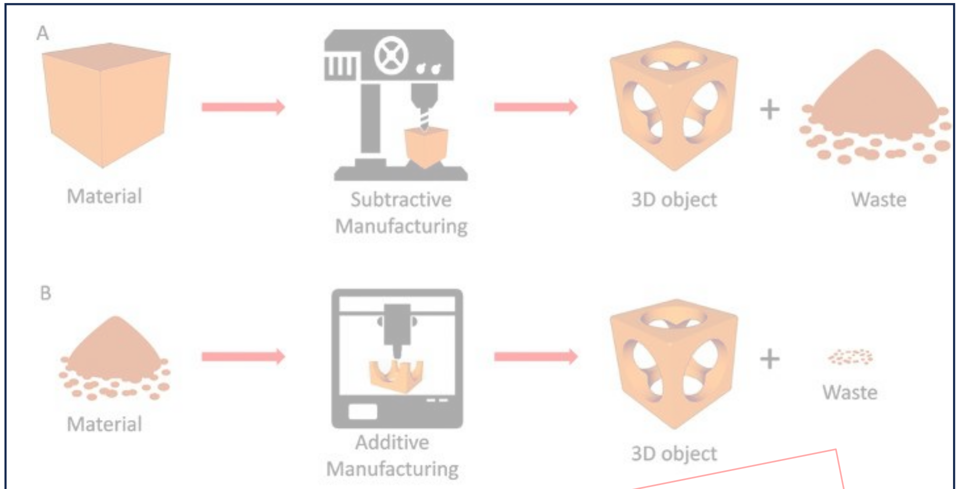
Hypothesis 2

- CO_2 emissions minimization of parts
  - If material choice is **free** => more complicated

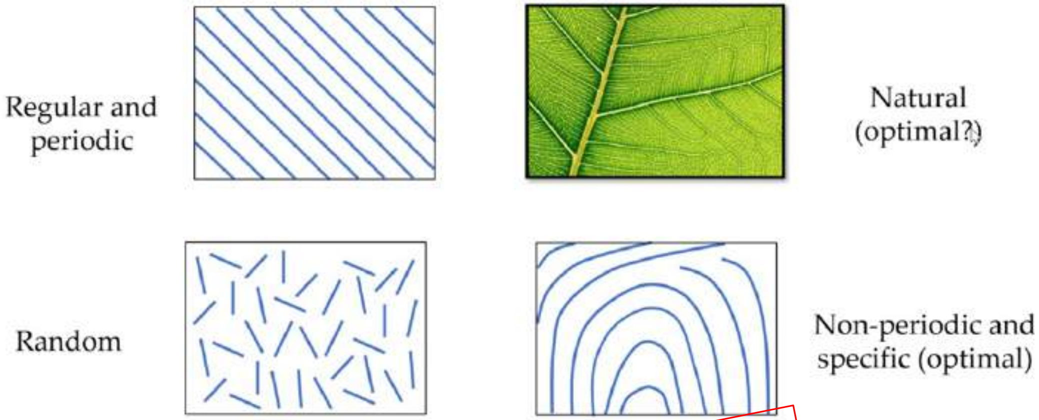


Process is AM, but WHY?

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



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

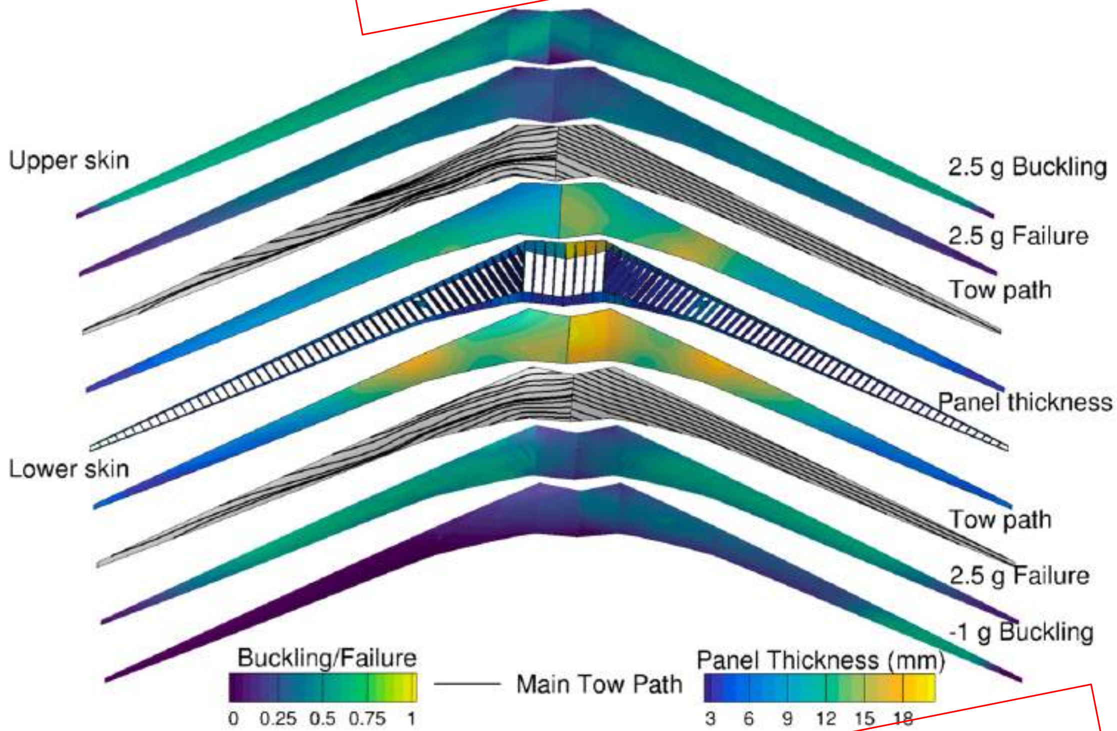


+ Automatic Fiber Placement + eco-fiber/resin selection
+Monitoring

Composites Fiber Placement as DVs

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

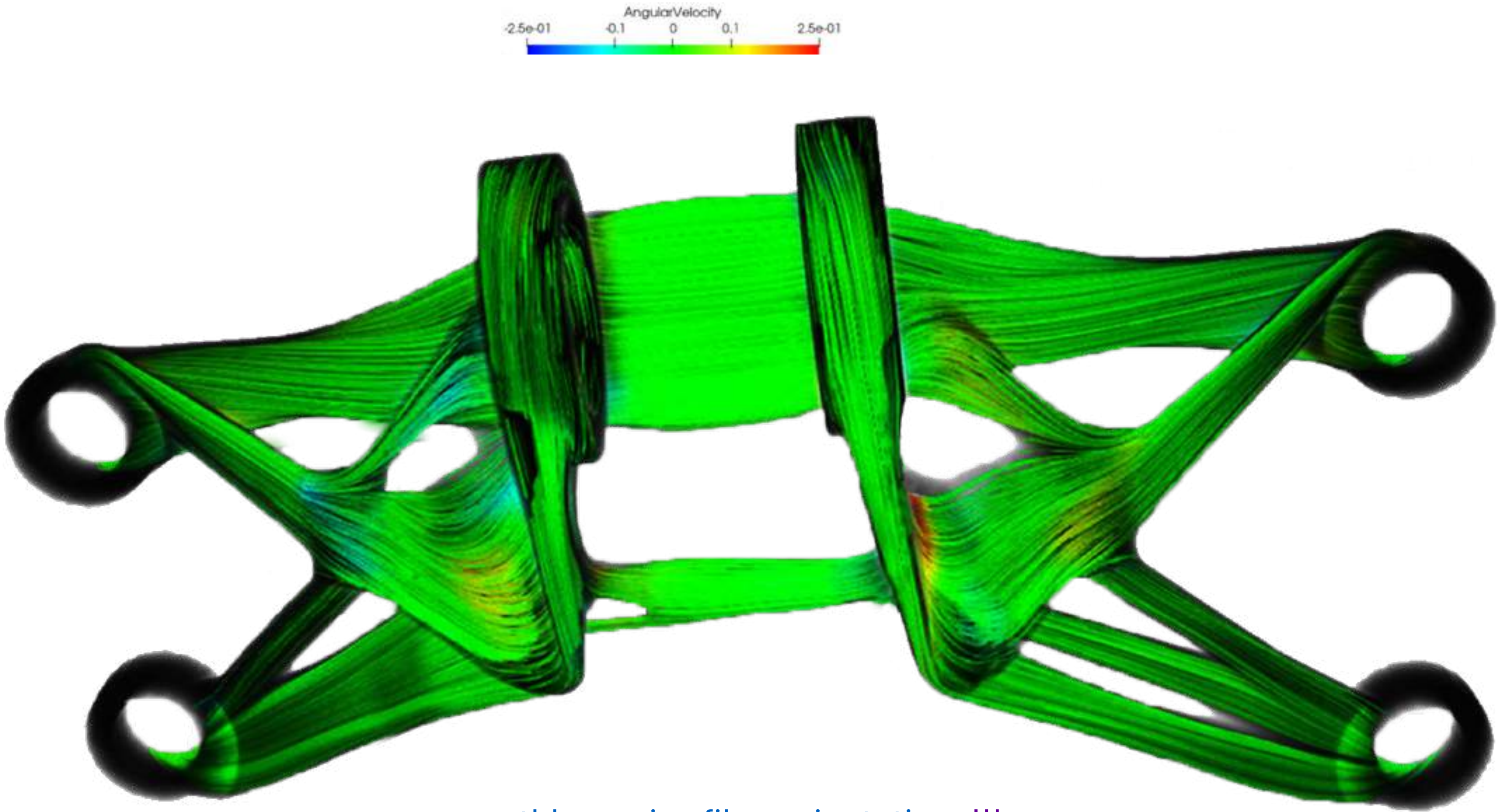
X* is a UHAR Wing ;)



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.

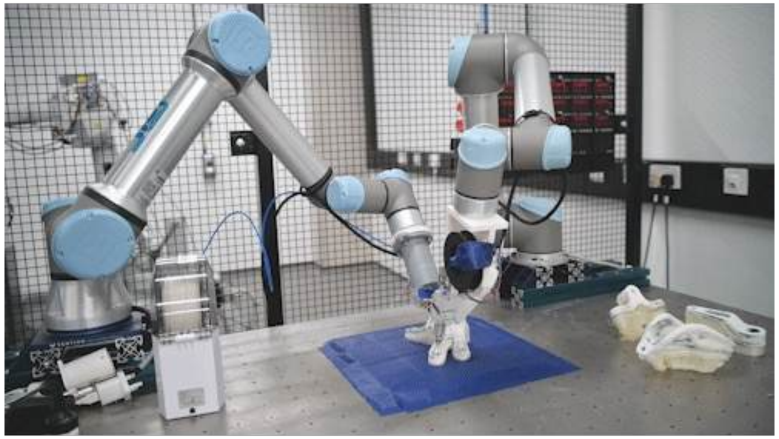
Lower wing mass,
Less fuel burn

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



smoothly varying fiber orientations!!!

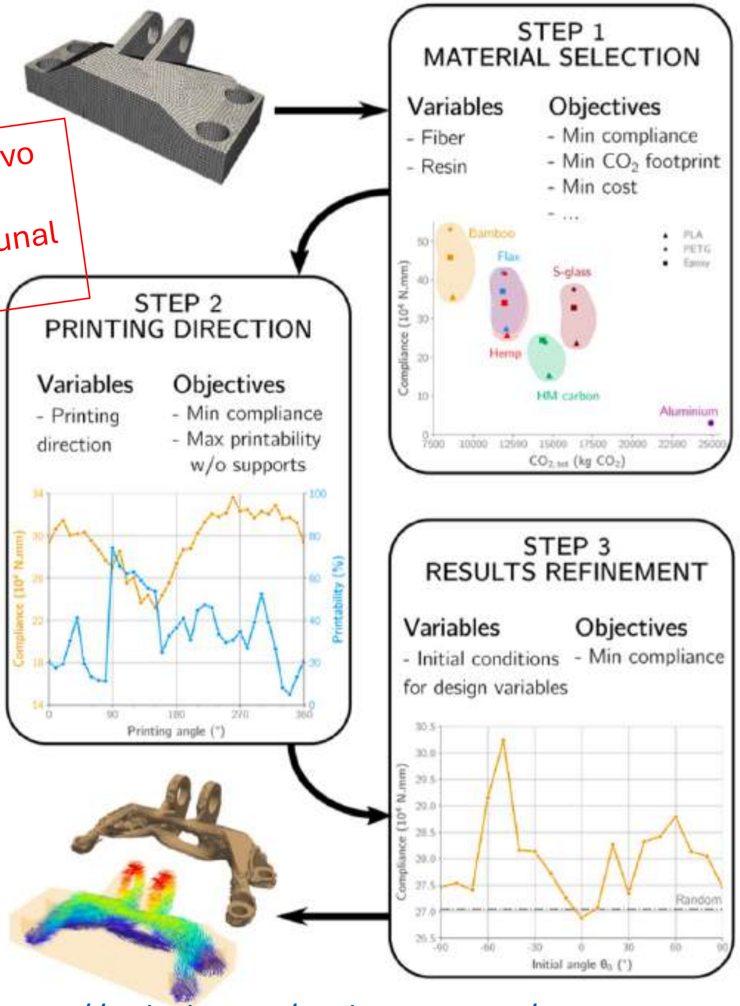
Inspired by spatial printing*



*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.

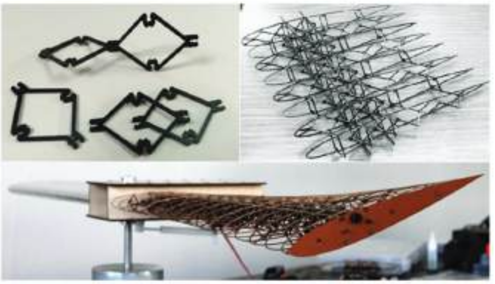
https://www.youtube.com/watch?v=7Jxyu9uRMLo

Thanks to Gustavo Asai, Frederic Lachaud and Kunal Masania

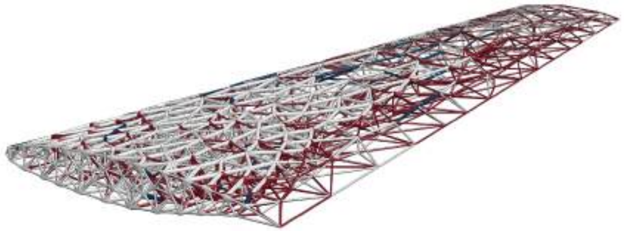


https://github.com/mid2SUPAERO/SOMP_Ansys

Full wingbox concept

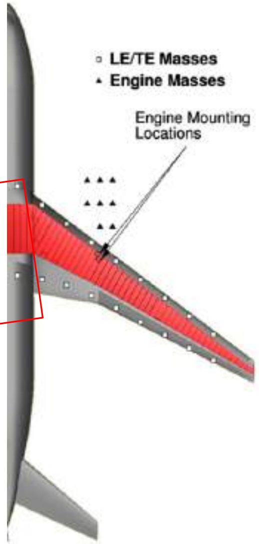


Jenett et al. (2017)



Opgenoord, M. M. and Willcox, K. E. (2018)

Cramer, N. B. et al. (2019)

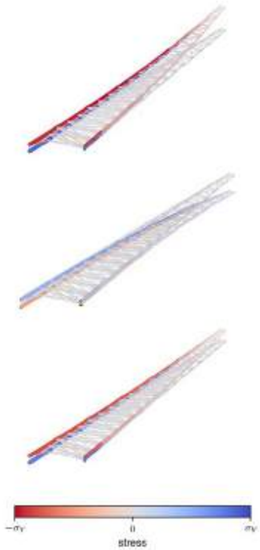


Thanks to Enrico Stragiotti and ONERA's

Wingspan, m : 58.76
MTOW, t : 297,55

3 load cases:

- +2.5 g manouver
- -1 g manouver
- Cruise with gust (+1.3 g)



Material	Aluminum alloy
E	69 GPa
σ_c	-270 MPa
σ_t	270 MPa
ρ	2.7 g/cm^3

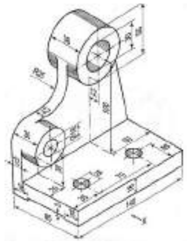
Optimized mass = 21.342 t

-27.01% compared to 29.238 t (Fakhimi et al., 2021)

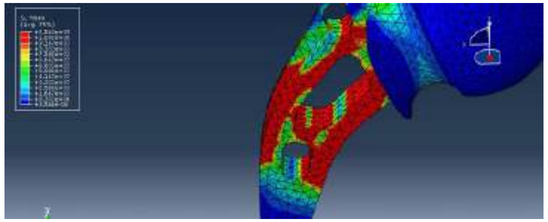
Practical Engineering Skills

CAD design

(engineering drawings)

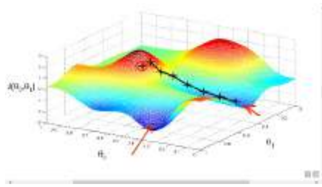


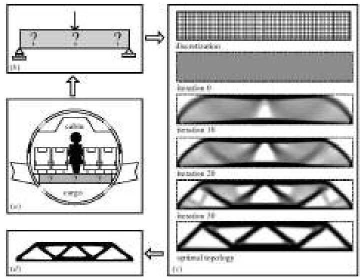
Finite Element Simulations

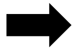


(stress analysis)

Gradient descent optimization
(TopOpt)







Additive Manufacturing
(future of industrial standards of manufacturing)

Mechanical Learning of Additive Manufacturing Parts

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

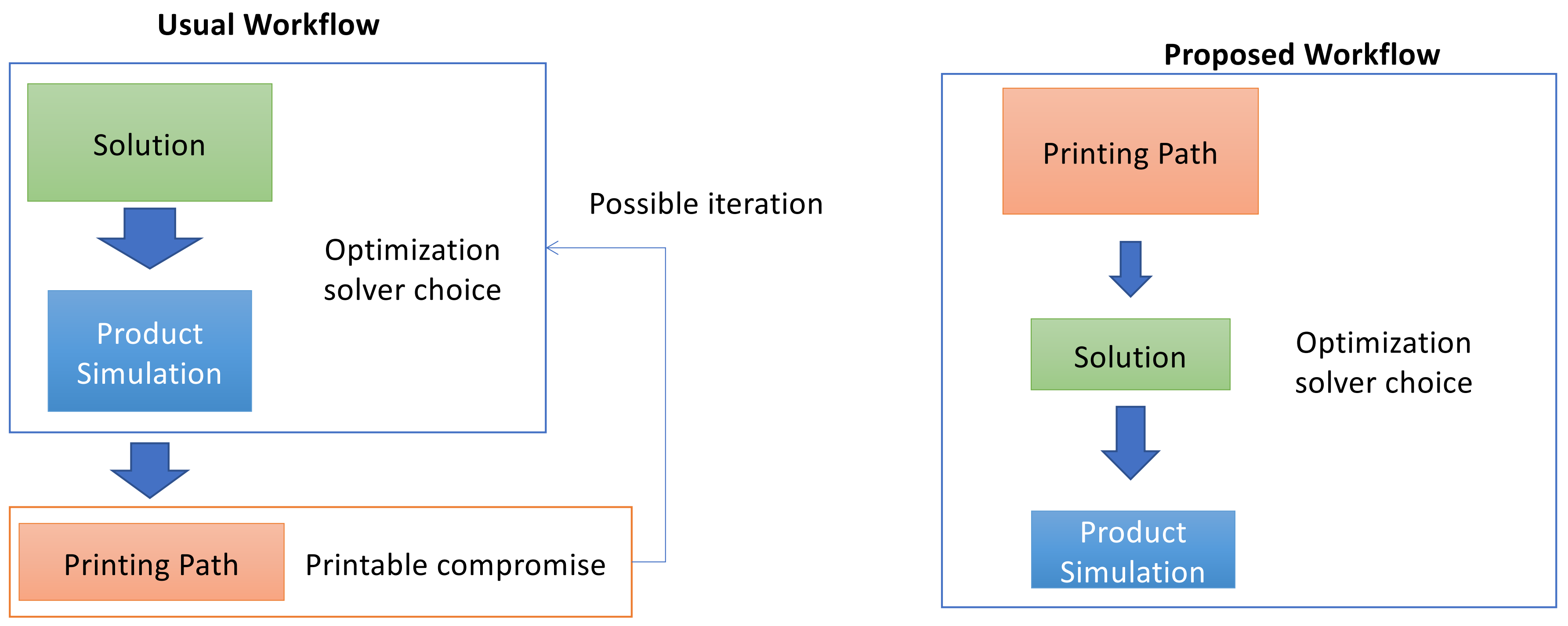
McMaster University

Example of 3D printed parts with different materials

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

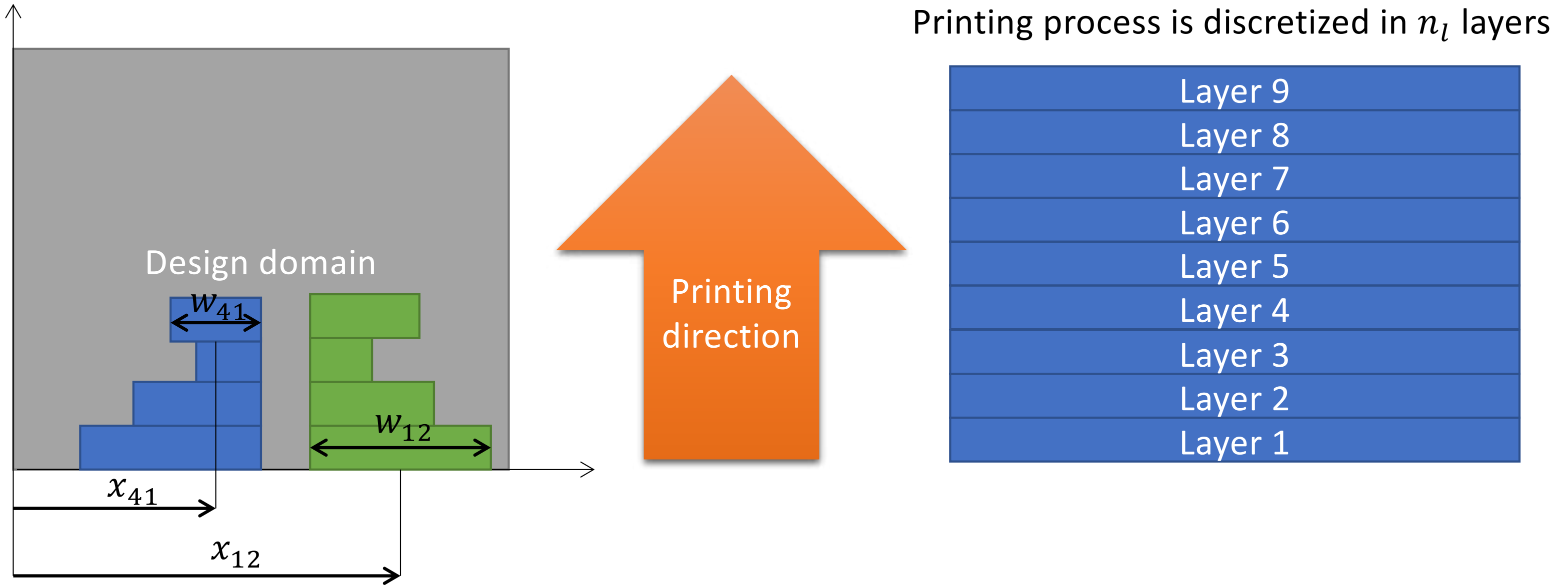
Sessional Instructor: Dr. Bosco (Hiu Ming) Yu, PhD
2018

ALM based projection



ALM based projection

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 projection

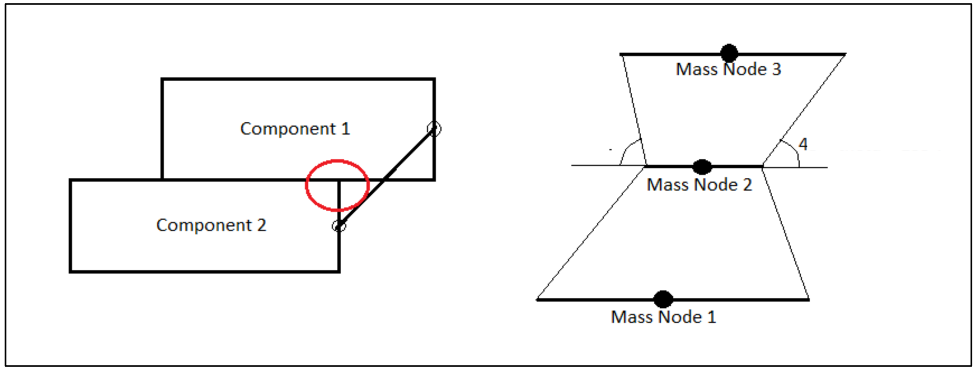
Optimization formulation

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

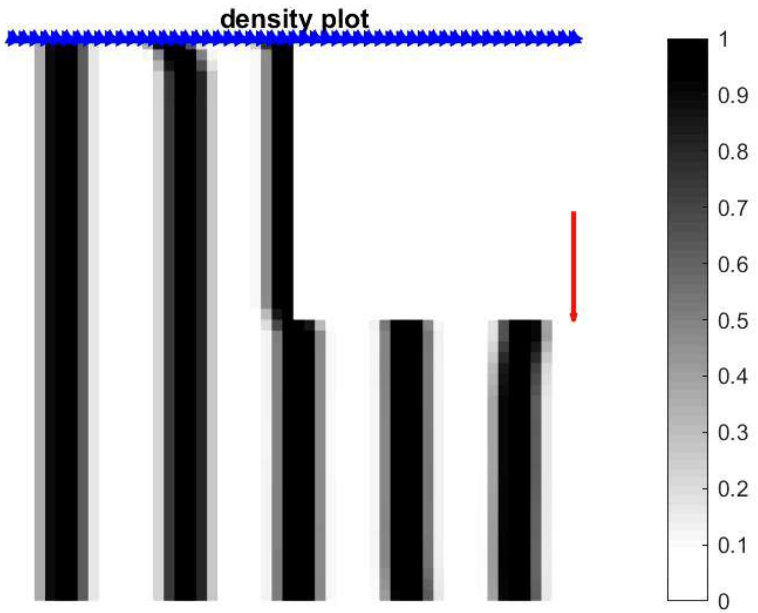
External forces work

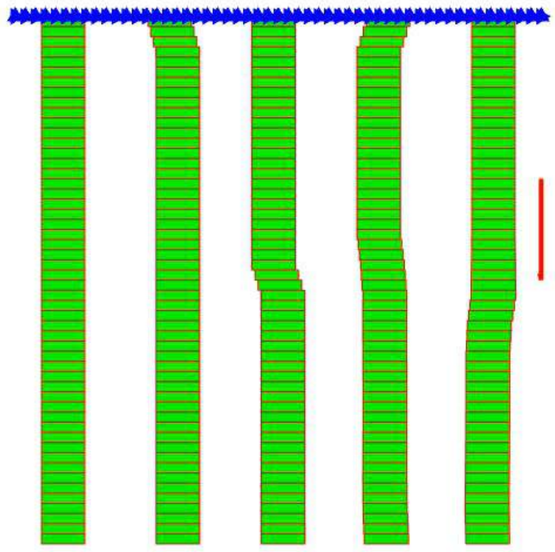
Mass constraint

Overhang angle constraint



ALM based projection





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

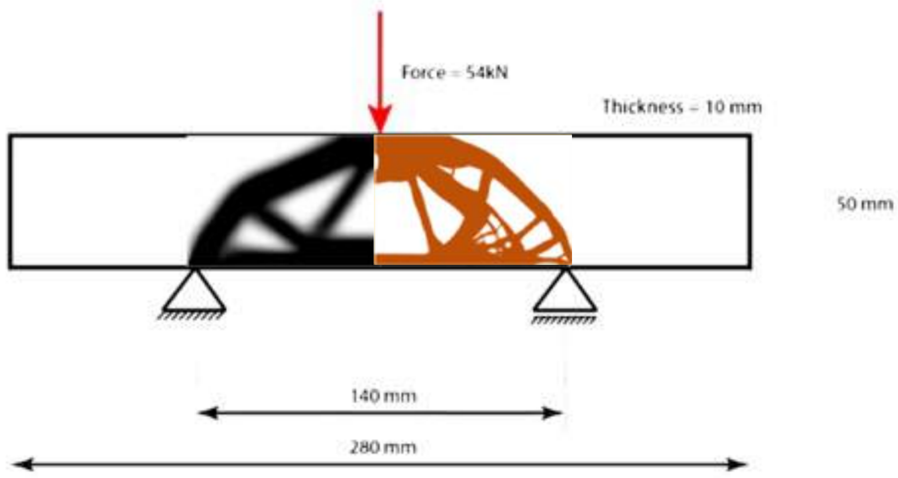
How to ECOdesign tomorrow's structures?

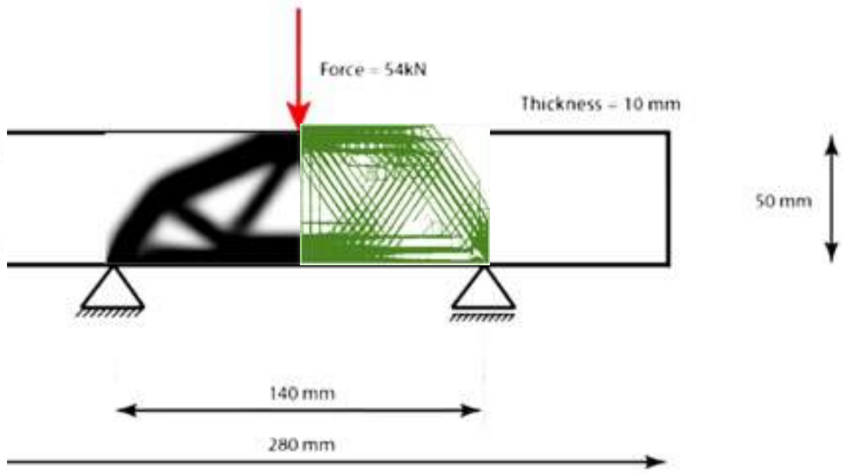
Prof. Joseph Morlier, Edouard Duriez, Miguel Charlotte, Catherine Azzaro-Pantel

#Our very First Results

#SIMP vs EMTO

Print it, test it



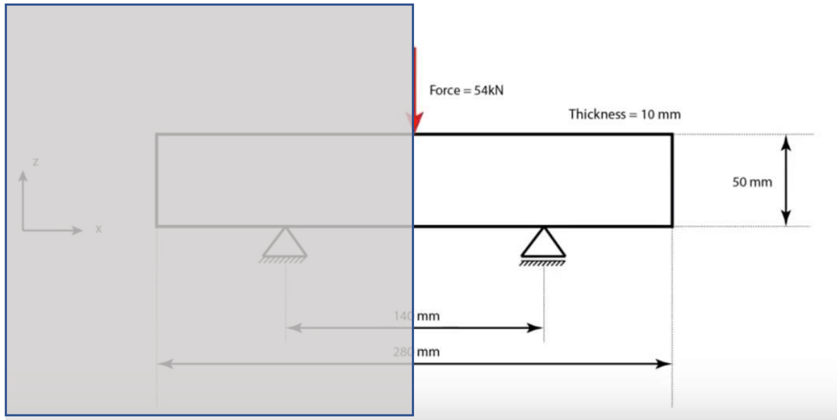


https://github.com/jomorlier/ALMcourse/tree/master/top88

SMALL EXERCICE using top88.m

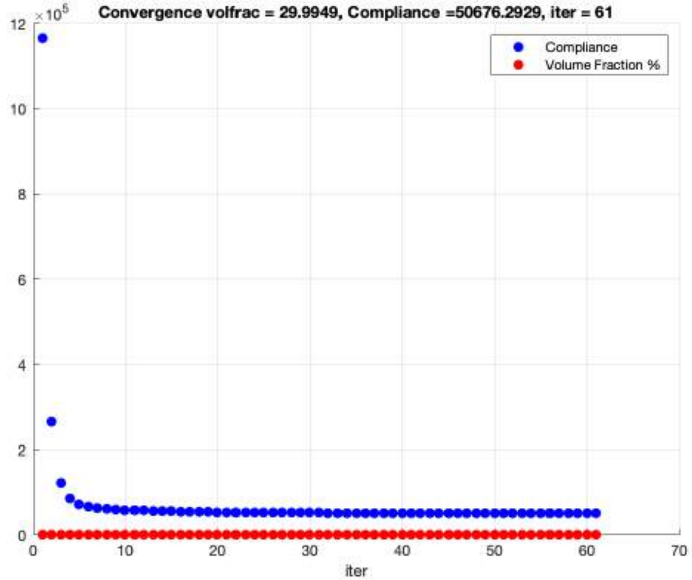
- Search the optimal 2D topology using symmetry

--> modify top88.m



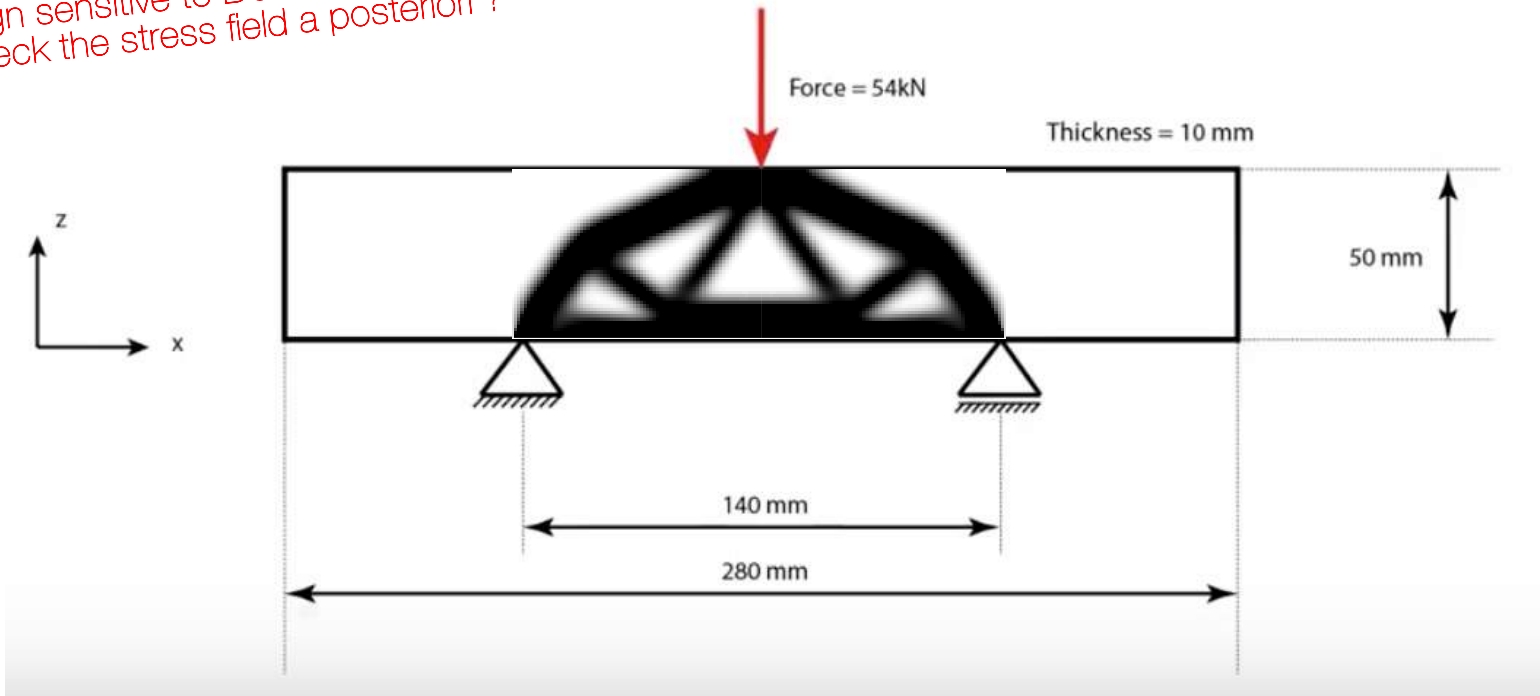
top88_ptBENDING(140, 50, 0.3, 3, 2, 2)

2 Outputs


Convergence volfrac = 29.9949, Compliance =50676.2929, iter = 61
×10^5
Compliance
Volume Fraction %
12
10
8
6
4
2
0
0
10
20
30
40
50
60
70
iter

Outputs

Need to add constraint max displacement ?
Need to produce a Pareto front design vs volfrac?
How do you experimentaly introduce the external force?
Is the design sensitive to BCs size ?
Do you check the stress field a posteriori ?



```
%%%% AN 88 LINE TOPOLOGY OPTIMIZATION CODE Nov, 2010 %%%%
function x=top88(nelx,nely,volfrac,penal,rmin,ft)
-
-
%% MATERIAL PROPERTIES
E0 = 1;
Emin = 1e-9;
nu = 0.3;
-
-
%% PREPARE FINITE ELEMENT ANALYSIS
A11 = [12  3 -6 -3;  3 12  3  0; -6  3 12 -3; -3  0 -3 12];
A12 = [-6 -3  0  3; -3 -6 -3 -6;  0 -3 -6  3;  3 -6  3 -6];
B11 = [-4  3 -2  9;  3 -4 -9  4; -2 -9 -4 -3;  9  4 -3 -4];
B12 = [ 2 -3  4 -9; -3  2  9 -2;  4  9  2  3; -9 -2  3  2];
KE = 1/(1-nu^2)/24*([A11 A12;A12' A11]+nu*[B11 B12;B12' B11]);
nodenrs = reshape(1:(1+nelx)*(1+nely),1+nely,1+nelx);
edofVec = reshape(2*nodenrs(1:end-1,1:end-1)+1,nelx*nely,1);
edofMat = repmat(edofVec,1,8)+repmat([0 1 2*nely+[2 3 0 1] -2 -1],nelx*nely,1);
iK = reshape(kron(edofMat,ones(8,1))',64*nelx*nely,1);
jK = reshape(kron(edofMat,ones(1,8))',64*nelx*nely,1);
% DEFINE LOADS AND SUPPORTS (HALF MBB-BEAM)
F = sparse(2,1,-1,2*(nely+1)*(nelx+1),1);
U = zeros(2*(nely+1)*(nelx+1),1);
fixeddofs = union([1:2:2*(nely+1)],[2*(nelx+1)*(nely+1)]);
alldofs = [1:2*(nely+1)*(nelx+1)];
freedofs = setdiff(alldofs,fixeddofs);
%% PREPARE FILTER
```

[58 unmodified lines hidden]

```
  %% PRINT RESULTS
  fprintf(' It.:%5i Obj.:%11.4f Vol.:%7.3f ch.:%7.3f\n',loop,c, ...
    mean(xPhys(:)),change);
-
-
-
-
-
-
-
-
-
  %% PLOT DENSITIES
-
  colormap(gray); imagesc(1-xPhys); caxis([0 1]); axis equal; axis off; drawnow;
-
end
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
. %%%% AN 88 LINE TOPOLOGY OPTIMIZATION CODE Nov, 2010 %%%%
x %example top88_joseph(140, 50, 0.3, 3, 2, 2)
> function x=top88_ptBENDING(nelx,nely,volfrac,penal,rmin,ft)
> close all
. %% MATERIAL PROPERTIES
x E0 = 210e3;
. Emin = 1e-9;
. nu = 0.3;
> thickness=10;
> Force_amplitude=54e3;
. %% PREPARE FINITE ELEMENT ANALYSIS
. A11 = [12  3 -6 -3;  3 12  3  0; -6  3 12 -3; -3  0 -3 12];
. A12 = [-6 -3  0  3; -3 -6 -3 -6;  0 -3 -6  3;  3 -6  3 -6];
. B11 = [-4  3 -2  9;  3 -4 -9  4; -2 -9 -4 -3;  9  4 -3 -4];
. B12 = [ 2 -3  4 -9; -3  2  9 -2;  4  9  2  3; -9 -2  3  2];
x KE = thickness*1/(1-nu^2)/24*([A11 A12;A12' A11]+nu*[B11 B12;B12' B11]);
. nodenrs = reshape(1:(1+nelx)*(1+nely),1+nely,1+nelx);
. edofVec = reshape(2*nodenrs(1:end-1,1:end-1)+1,nelx*nely,1);
. edofMat = repmat(edofVec,1,8)+repmat([0 1 2*nely+[2 3 0 1] -2 -1],nelx*nely,1);
. iK = reshape(kron(edofMat,ones(8,1))',64*nelx*nely,1);
. jK = reshape(kron(edofMat,ones(1,8))',64*nelx*nely,1);
. % DEFINE LOADS AND SUPPORTS (HALF MBB-BEAM)
x F = Force_amplitude*sparse(2,1,-1,2*(nely+1)*(nelx+1),1);
. U = zeros(2*(nely+1)*(nelx+1),1);
x fixeddofs = union([1:2:2*(nely+1)],[(nelx+2)*(nely+1)]);
. alldofs = [1:2*(nely+1)*(nelx+1)];
. freedofs = setdiff(alldofs,fixeddofs);
. %% PREPARE FILTER
```

[58 unmodified lines hidden]

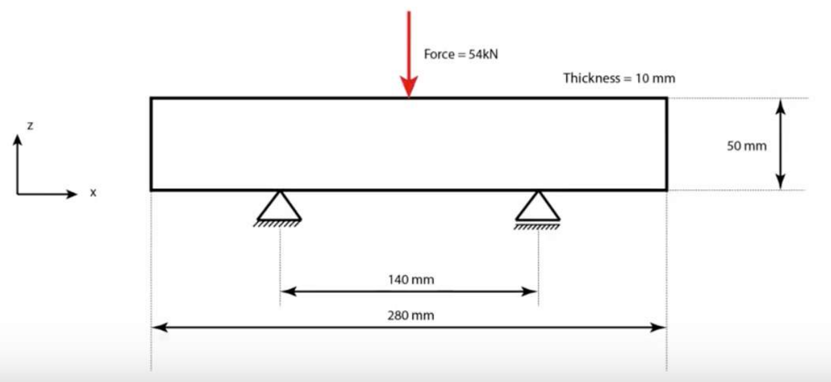
```
.   %% PRINT RESULTS
.   fprintf(' It.:%5i Obj.:%11.4f Vol.:%7.3f ch.:%7.3f\n',loop,c, ...
.     mean(xPhys(:)),change);
> figure(2)
> hold on
> plot(loop,c,'bo','MarkerFaceColor','b')
> plot(loop,mean(xPhys(:))*100,'ro','MarkerFaceColor','r')
> % plot(outeriter,(1+GKS1)*VM1,'ko','MarkerFaceColor','k')
> title(['Convergence volfrac = ',num2str(mean(xPhys(:))*100),', Compliance =',num
> grid on
> legend('Compliance','Volume Fraction %')
> xlabel('iter')
.   %% PLOT DENSITIES
>    figure(1)
.   colormap(gray); imagesc(1-xPhys); caxis([0 1]); axis equal; axis off; drawnow;
>   print(['DZ_it',num2str(loop,'%3d')],'-dpng')
. end
. %
. %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

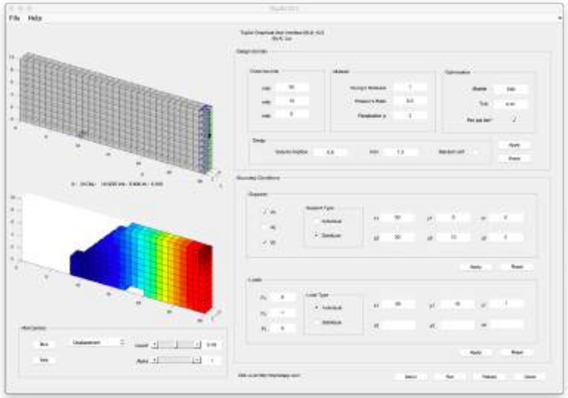
[26 unmodified lines hidden]

SAME EXERCISE using top3D

- https://top3dapp.com

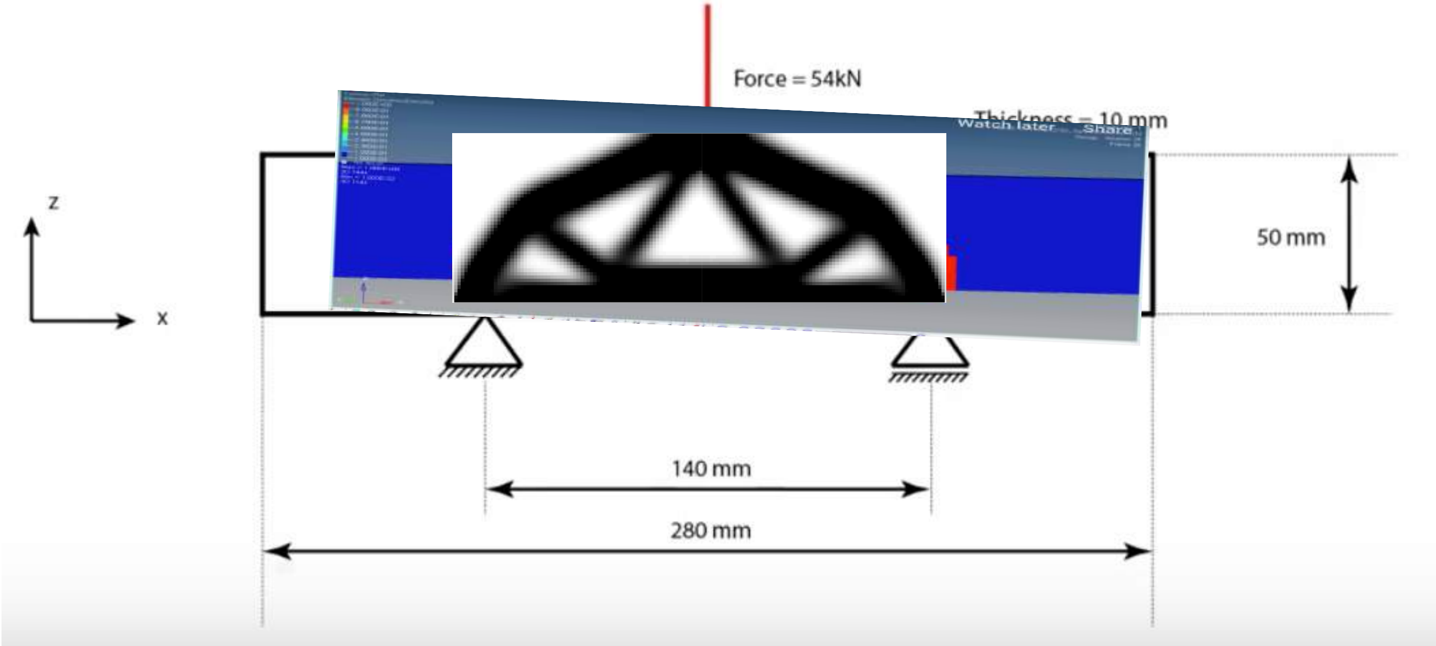
- Search the optimal 3D topology using symmetry

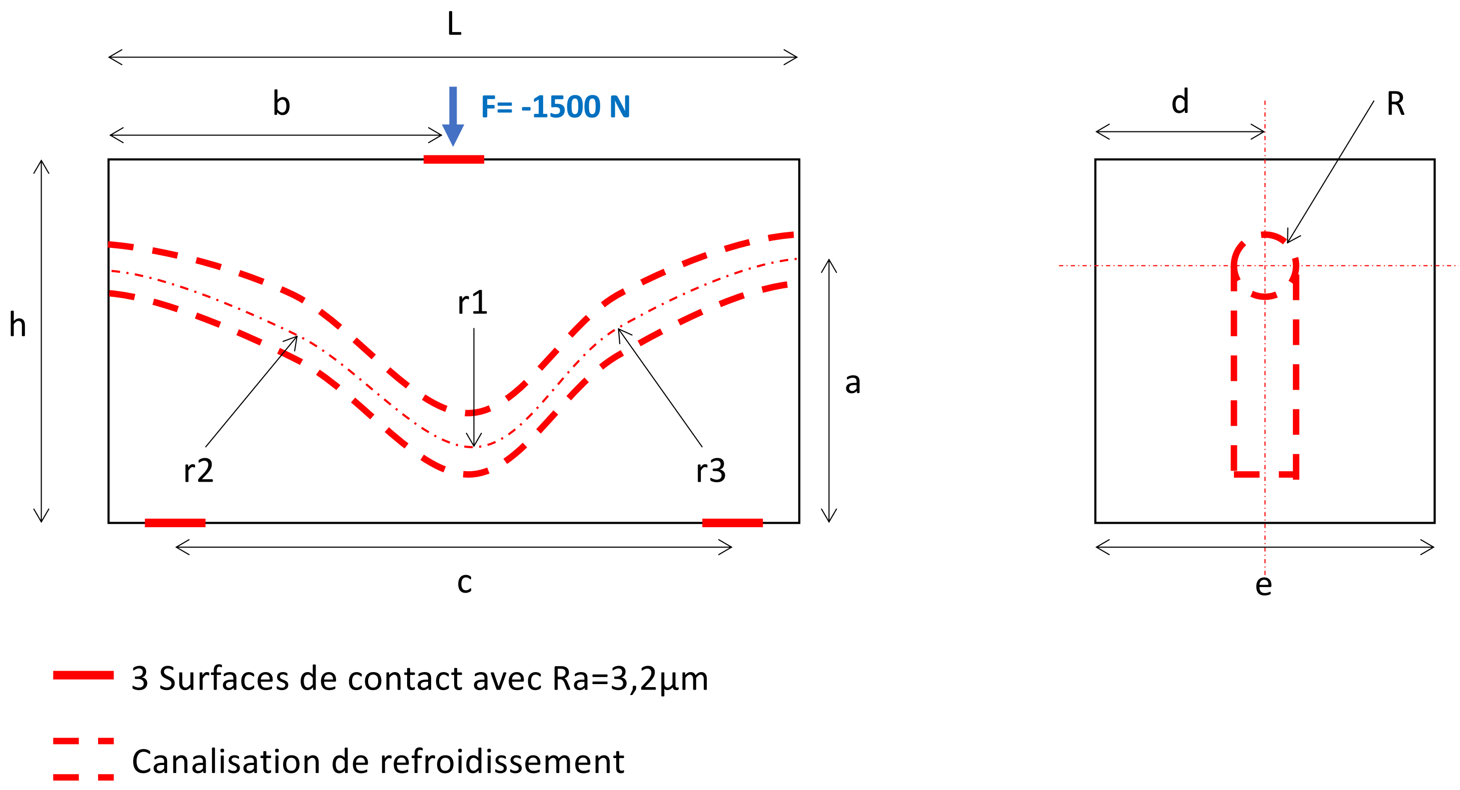




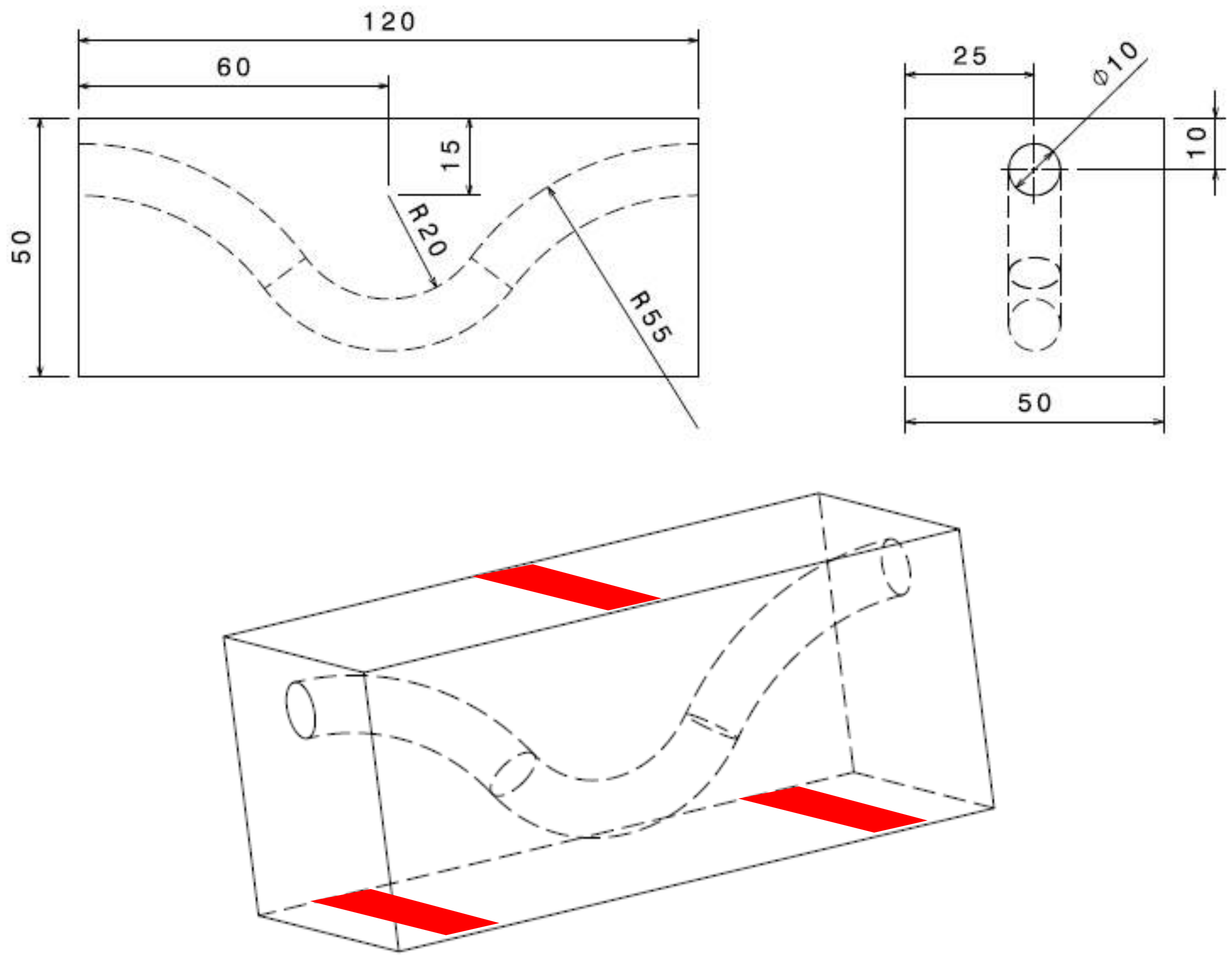
A regarder … avant les prochaines séances… OptiStruct

https://altairuniversity.com/13907-topology-optimization-tutorial-3-point-bending-of-a-beam-1d-2d-and-3d/#





Objectifs : déterminer une forme optimale qui minimise le rapport poids/résistance mécanique dans un volume défini tout en garantissant les surfaces de contact et la canalisation de refroidissement.


120
60
15
50
R20
R55
25
⌀10
10
50