Open Innovation Platform
University - Enterprise
Collaboration

Design for Additive Manufacturing

Uncover New Design Rules

Moscow – Vladimir Workshop
November 14-19, 2016

Laboratoire G-SCOP/Université Grenoble Alpes- Grenoble INP

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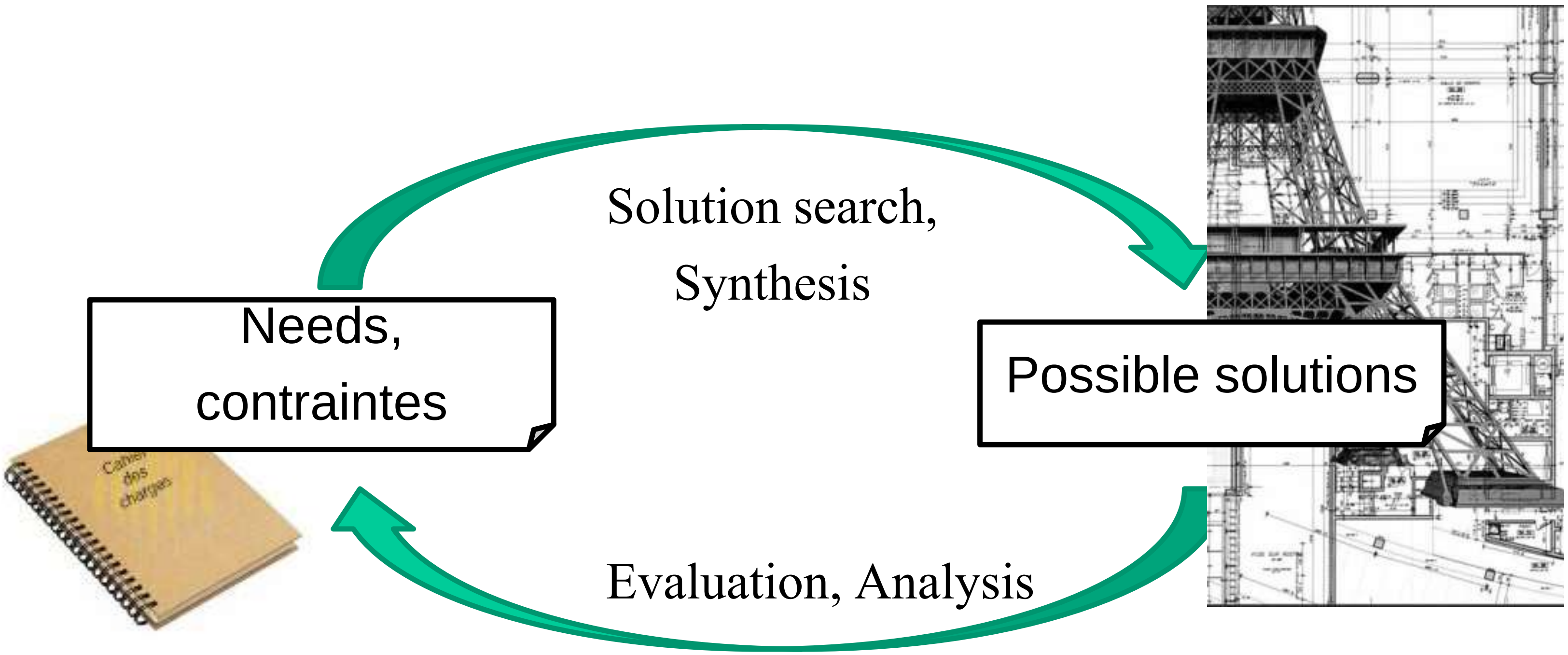
Design Process



Design for Additive Manufacturing

New design rules

New forms

Functional Materials

Form opportunities

Solution search, Synthesis

Needs, contraintes

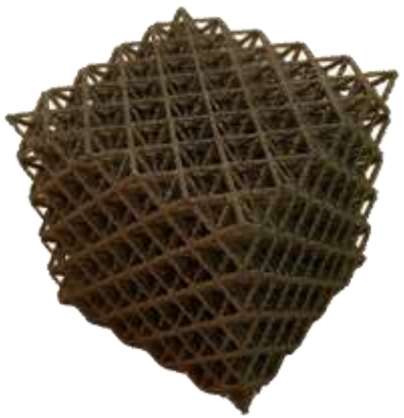
Possible solutions

Evaluation, Analysis

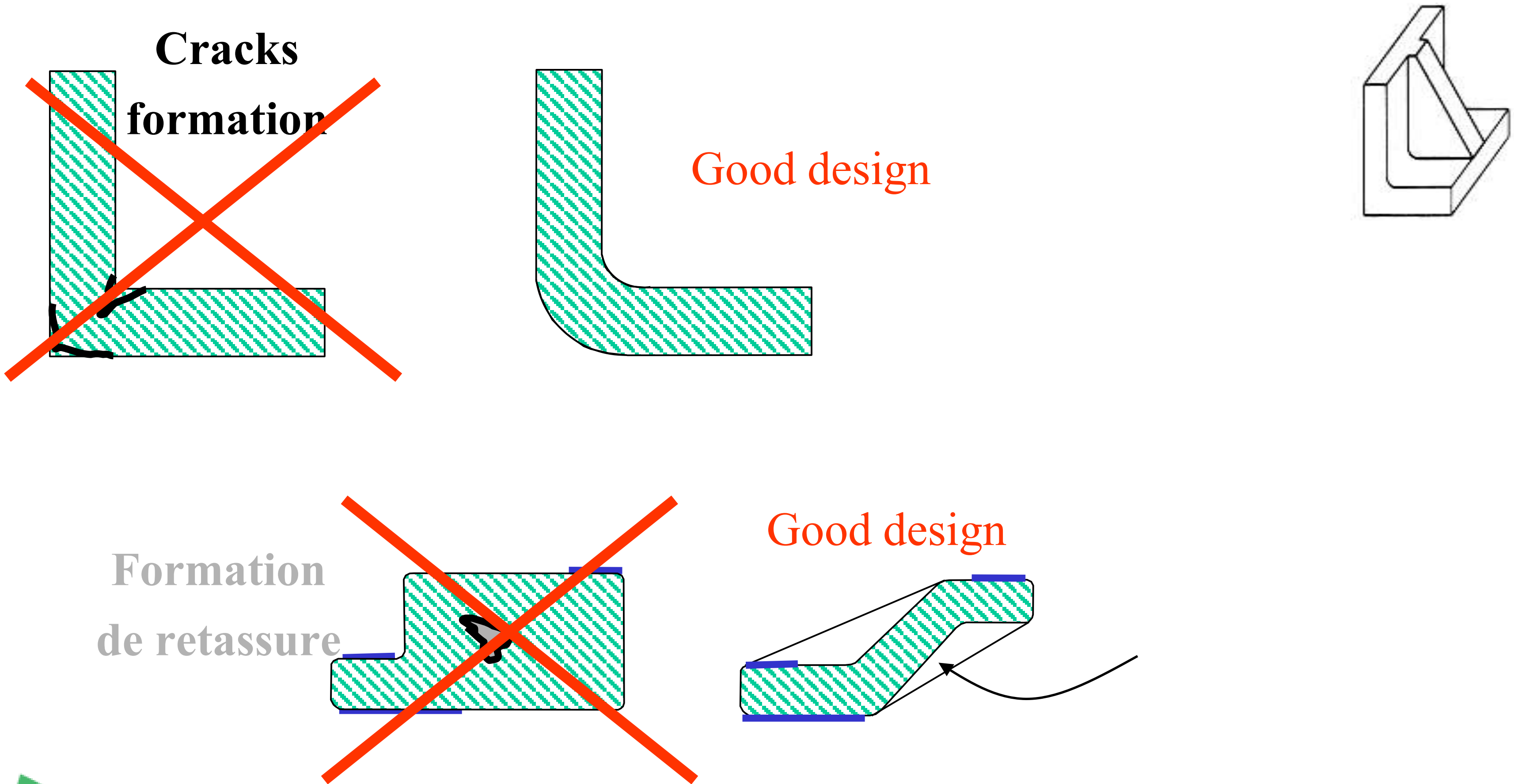
Prototyping opportunities

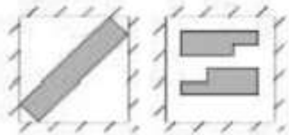
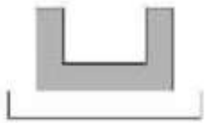
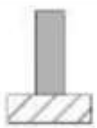
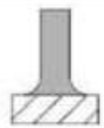
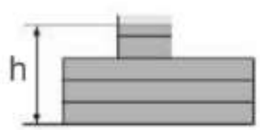
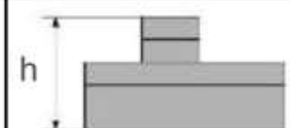
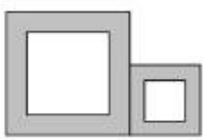
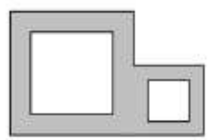
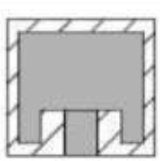
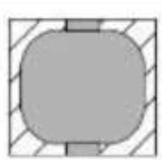
Form freedom

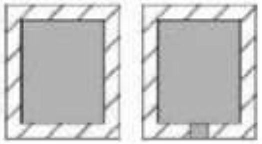
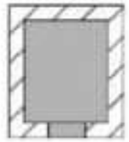
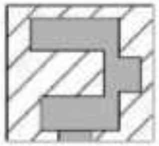
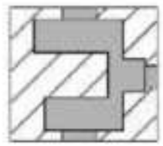
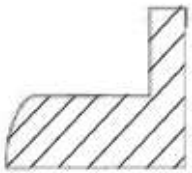
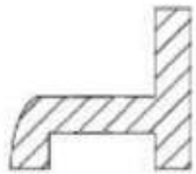
… Also induced constraints

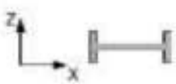


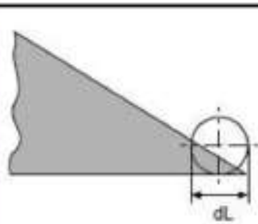
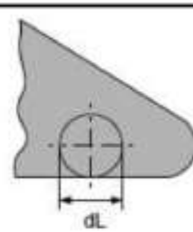
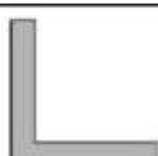
Molded parts design rules

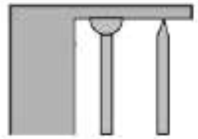
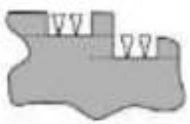
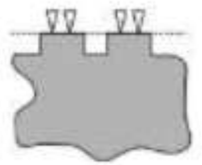
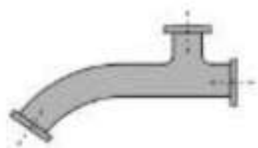
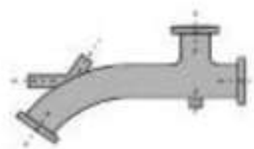
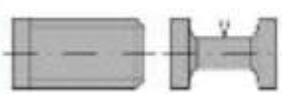
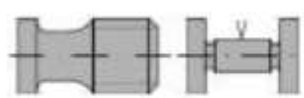
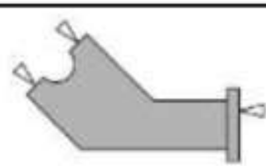
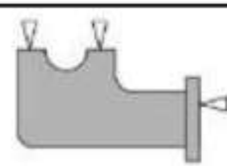
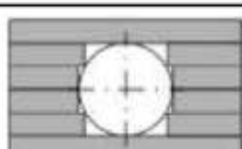
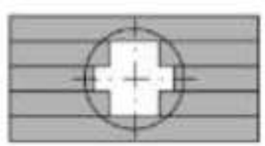


structure				unfavourable	favourable	explanation	restrictions and recommendations
Design Process – TiAl6V4	general geometry / part form	general part size	general			• part size must consider substrate plate dimensions • rotate, scale or separate parts if necessary	max. part dimensions incl. substrate plate: x = ca. 250 mm, y = ca. 250 mm, z = ca. 215 mm (see machine manufacturers for more information; larger machines available)
			inclusion of substrate platform			• integration of substrate platform into part possible • reduction of manufacturing time and costs • hybrid manufacturing approach	
						• radii at the interface part / substrate platform prevent part strip off during manufacturing process	• the larger the interfaces layer, the larger the radius should be • r=3-5 mm suitable for TiAl6V4
			height			• part heigth in build up direction should equal multiple layer thicknesses	layer thickness: 20 - 50 µm TiAl6V4: 30 µm (see manufacturing machine documentation)
		integration of functions				• prefere integral part design • reduction of manufacturing time	
		cavities	volume			• use cavities in order to reduce the part volume to be exposured • reduction of manufacturing time and cost	
			design			• avoid powder nesting by designing simple cavity geometries	

structure				unfavourable	favourable	explanation	restrictions and recommendations
Design Process – TiAl6V4	general geometry / part form	cavities	powder removal			• consider at least one opening • the larger the opening, the more easy the powder removal is	• 3 – 5 mm suitable for TiAl6V4
						• use multiple openings at complex parts	
		material distribution	accumulations			• avoid material accumulation • reduction of part volume reduces manufacturing time and costs	

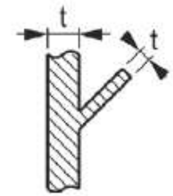
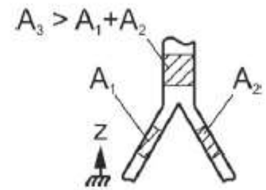
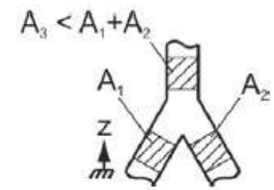
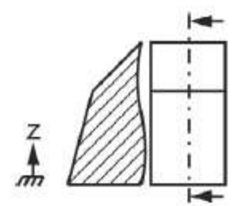
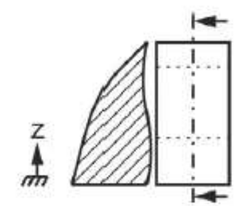
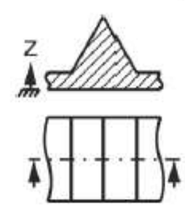
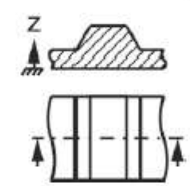
			horizontal segments	
				
					
					
						• avoid horizonically postioned part segments
						   • highest thermally induced stresses
						   • worst surface quality	

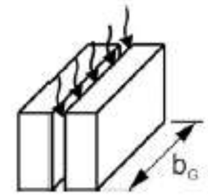
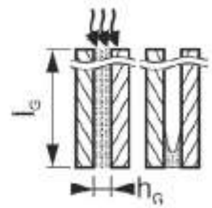
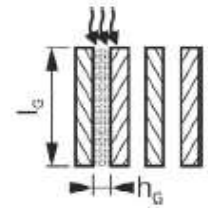
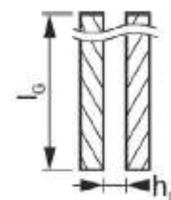
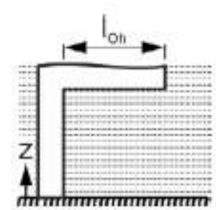
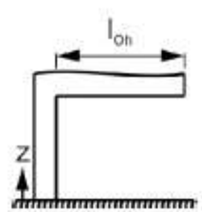
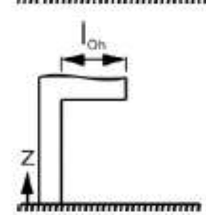
		walls	edges und corners	 	 	• focal diameter of laser limits resolution in manufacturing plane • sharp corners / edges not manufacturable	
						• thermally induced stresses can lead to part failure during build process • avoid notches in part design • prefere round material transitions	

structure				unfavourable	favourable	explanation
Design Process – TiAl6V4	gen. g	supports	massive supports			• consider massive supports for optimized heat flux and reduced part deformation during build up • consider breakage points for easy removal
	consider for part design: final machining	general	allowance			• consider adequate allowances in CAD design • necessary allowance highly depending on final machining
			position			• surfaces to be final machined should be lift from sourrounding part • surfaces to be machined should be placed in one plane
			tooling points			• span and positioning points should be incorporated in part design allowing safe spanning for final machining and low part deformation • place location loints in reference planes
		final machining	turning/ milling			• consider tooling run-outs and ensure accessibility as well as clearness
			milling			• prefere perpendicular alignment of planes to be final machined
			drilling			• design bore diameters smaller than necessary and drill out during final machining if high accuracy is needed

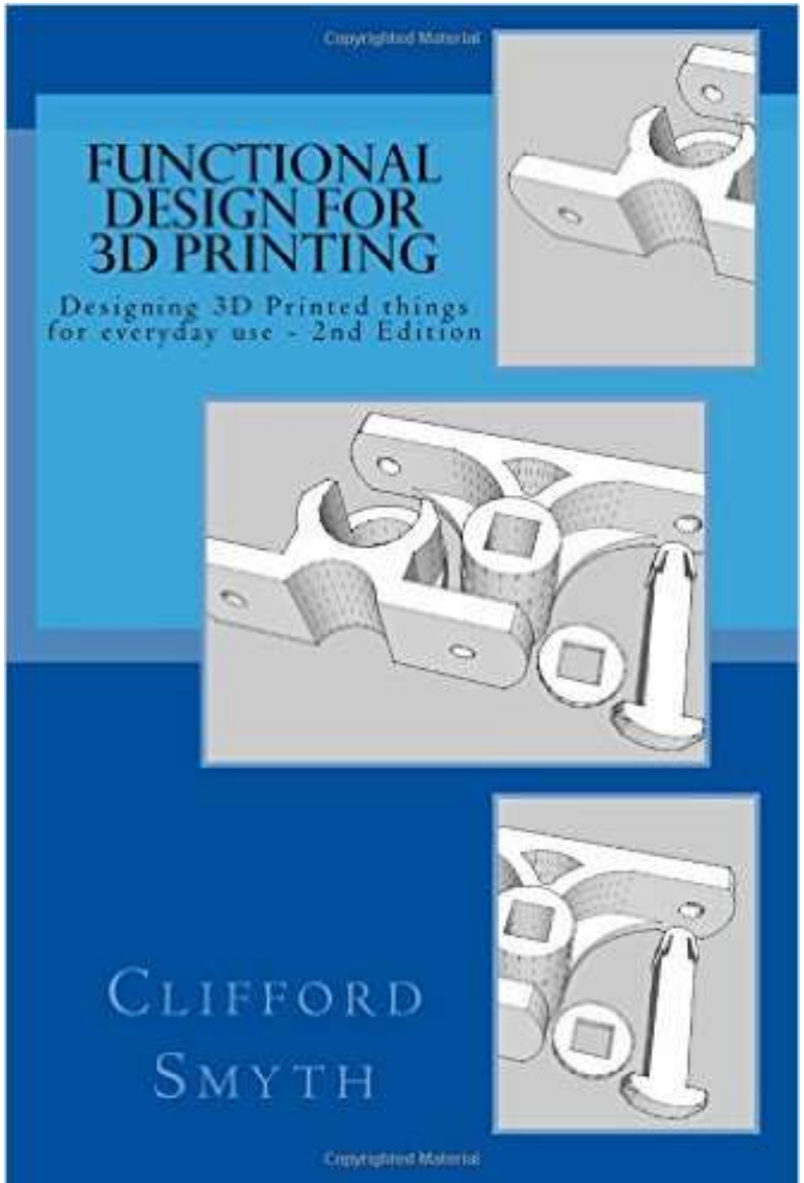
New Design Rules

Other design rules examples

Group	Typ	Attribute	Description Regular Special	Design for manufacturing Unsuitable	 Suitable	LS	LM	FDM
Element transitions	Firmly bonded elements	Thickness	Element transitions' thicknesses can be chosen freely as they do not influence element's form accuracies.			X	X	X
			Element transitions' thicknesses should be chosen so that the cross sectional areas in the building plane remain of the same size or become smaller.				X	
		Edge	Sharp (outer and inner) edges should be avoided. In order to receive better form accuracies edges should be rounded. The rounding radii correlate with the outer radii of simple-curved elements.			X	X	X
			Edges that form vertical extreme points should be blunted parallel to the building plane. The dimensions of the blunted areas should be larger than non-curved elements' thicknesses.			X	X	X

Group	Typ	Attribute	Description Regular Special	Design for manufacturing Unsuitable	 Suitable	LS	LM	FDM
Element transitions	Non-bonded elements	Gap width	If accessibility to the gap is given along the complete width, the gap width can be chosen freely.			X	X	X
		Gap length	Gaps' lengths need to be short enough to enable a robust removal of disperse support structures which are contained inside the gaps. LS: $l_G \leq 8.0\,mm$ ($h_G = 1.2$ mm) $l_G \leq 30.0\,mm$ ($h_G = 1.8$ mm) $l_G \leq 50.0\,mm$ ($h_G = 2.4\,mm$) (max. tested length) LM: $l_G \leq 50.0\,mm$ ($h_G = 0.2\,mm$) (max. tested length)			X	X	
			Gaps' lengths can be chosen freely because no disperse support structures are contained inside the gaps.					X
Aggregated structures	Overhang	Length	Overhangs' lengths can be selected freely because required stabilizations of the overhangs are provided by the disperse support structures.			X		
			Overhangs' lengths should be short enough to ensure a robust manufacturability given by part layers that do not bent out of the building plane (LM) or filaments that do not "fall off" their nominal positions (FDM). LM: $l_{Oh} \leq 2.0\,mm$ FDM: $l_{Oh} \leq 1.8\,mm$				X	X

New Design Rules



Think Out of the box…

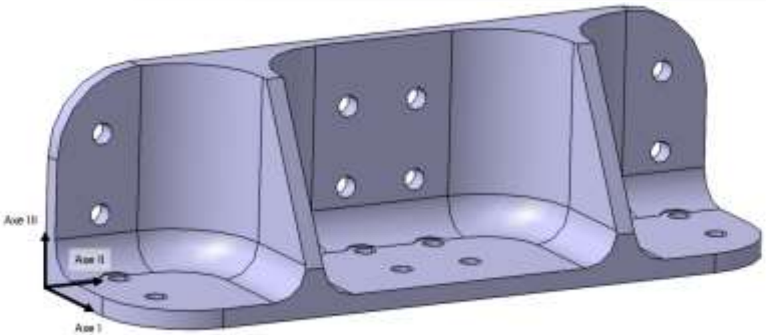
Psychological inertia :

- “we have always done like that”
- “we are not allowed to to that”
- “I usually do like that”
- “in this company we do it that way” …

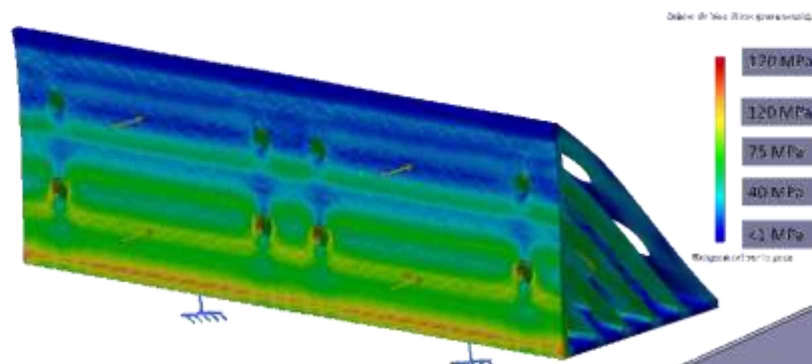
Optimized Forms

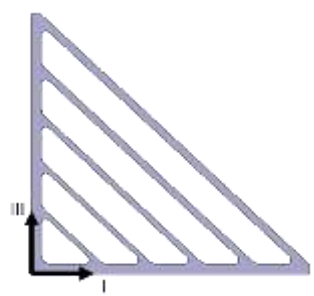
Solution 1: rely on experts knowledge

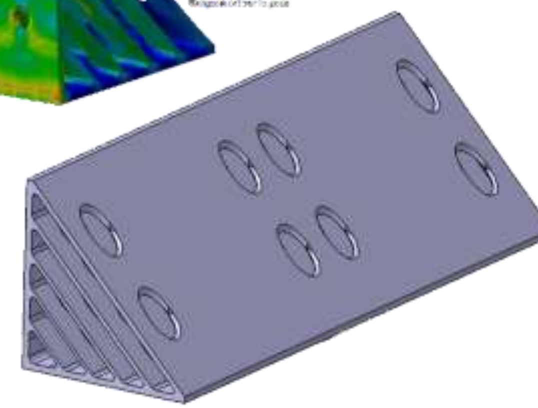
But they also have there cognitive limits …



Machined, Aluminium 7075, 52g



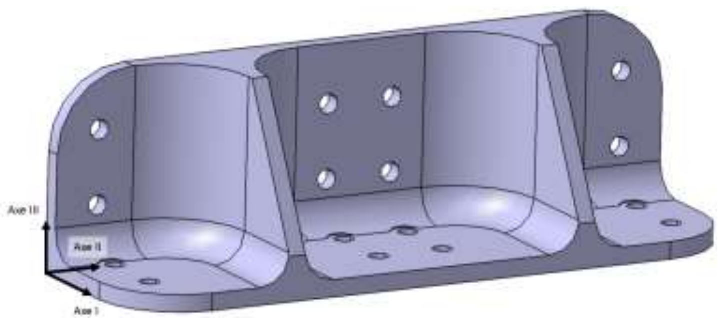




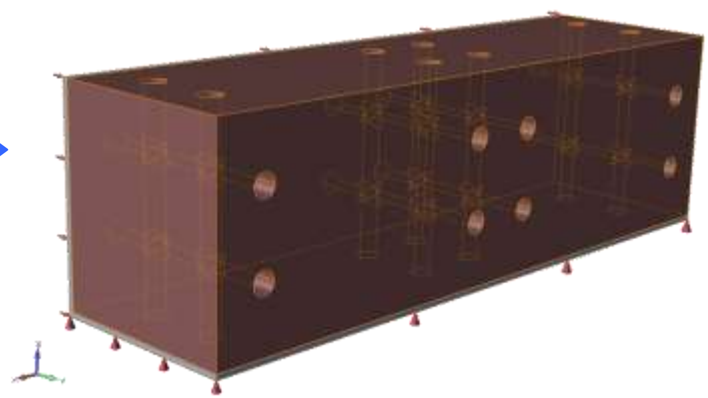
EBM, TA6V, 49g

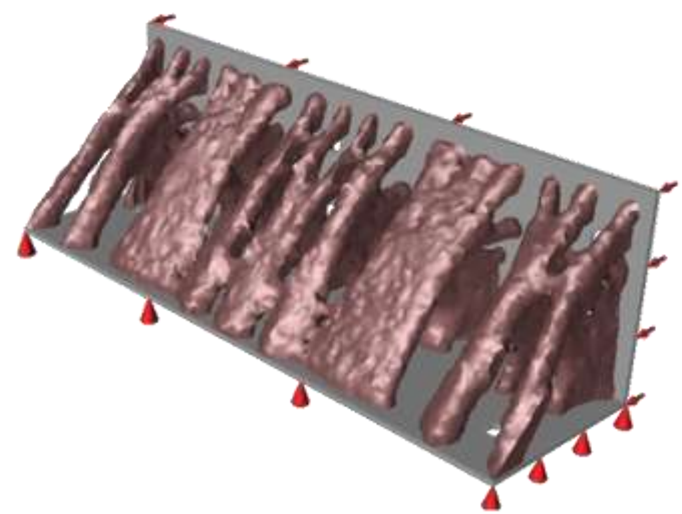
Optimized Forms

Solution 2: Topological optimisation



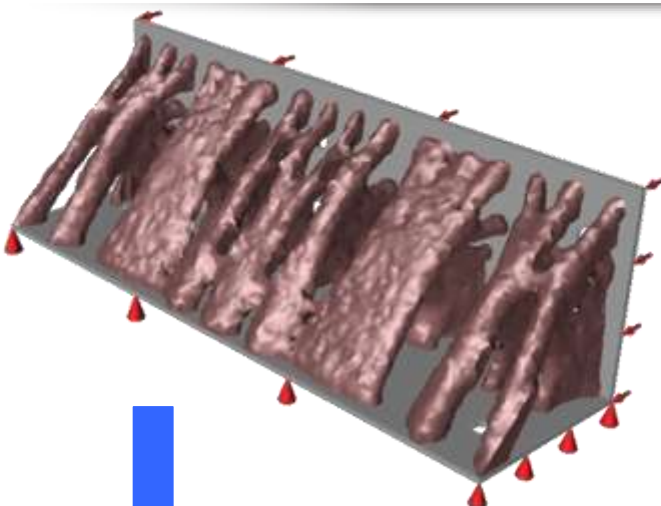
Machined, Aluminium 7075, 52g



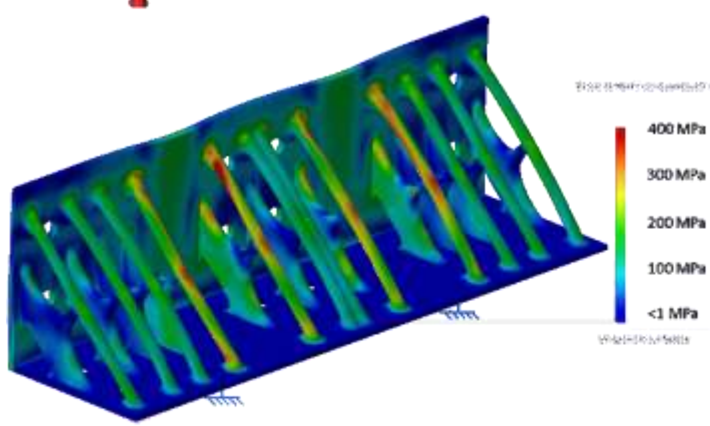


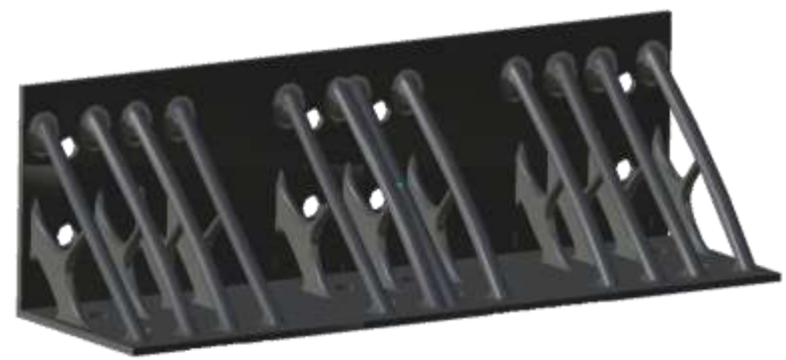
Optimized Forms

Solution 2: Topological optimisation



- Need a rebuild phase, verification, parametric optimisation …
- May be manufactured as is, but difficult to be accepted by people (psychological inertia again…)





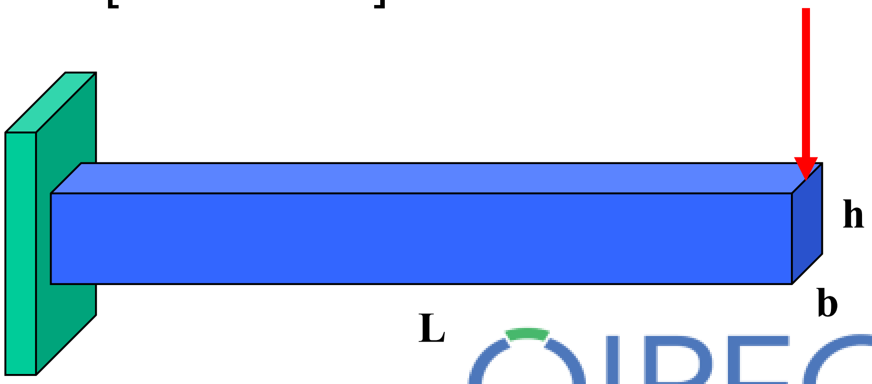
EBM, TA6V, 29g !

Optimized Forms

Optimisation

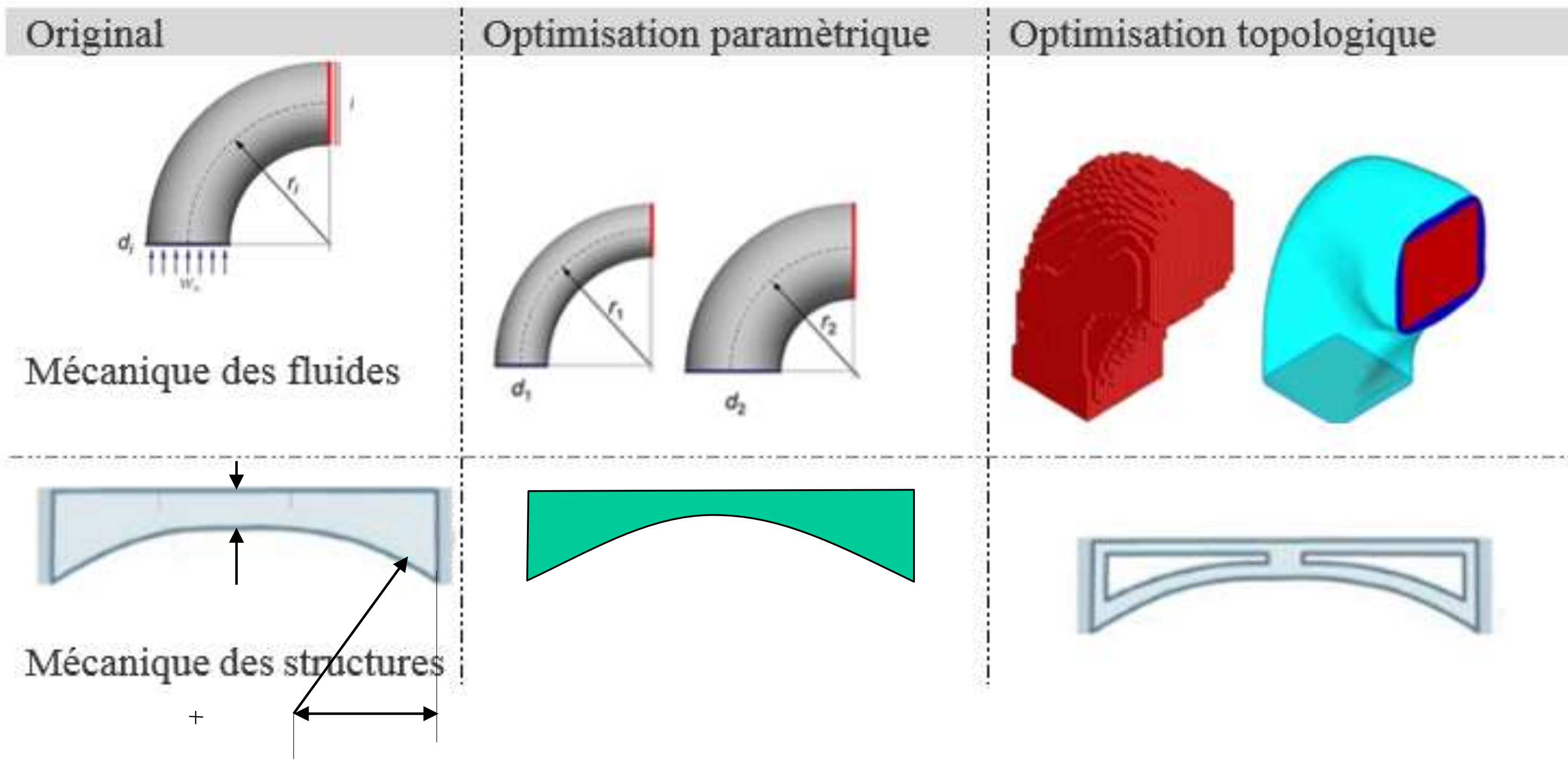
- **General principles**
  - To minimise a function (mass, cost, …) = objective fonction
  - Problem variables (and limit values). Dimensions for example
  - Constraintes = limitations of certain fonctions or its variables(s_{vm} < 200 MPa, T_{max} < 50°C…)

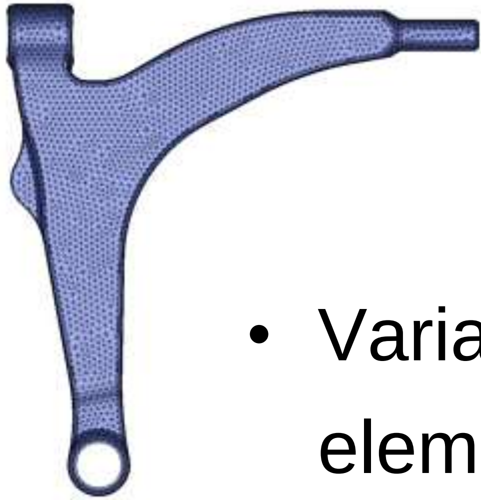
- **Mechanical example**
  - Minimise mass = f(b,h) = r.L.b.h
  - 2 variables b [10 - 30mm] et h [15 - 25mm]
  - d_{max} = 1 mm = g(b,h)



Optimized Forms

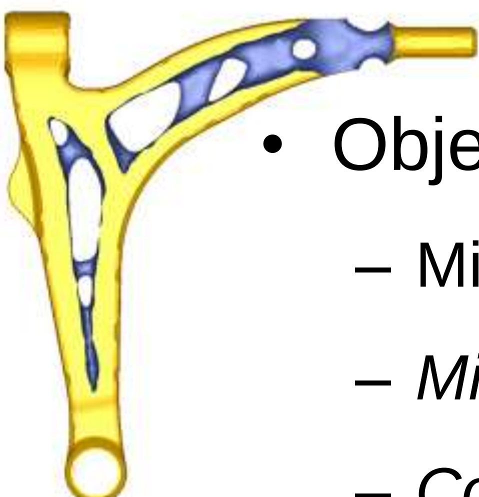
Parametric Optimisation vs. Topological Optimisation



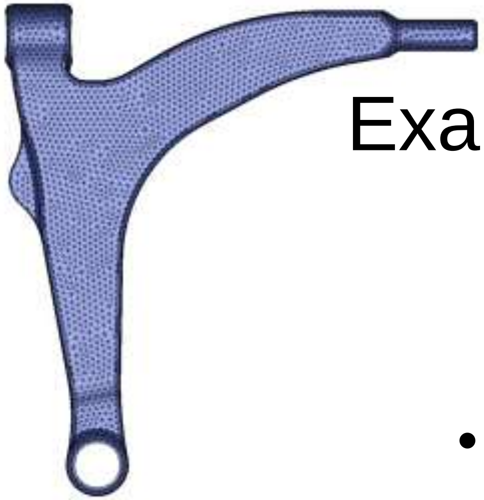


Topological Optimisation

- Variable -> material density ρ in each element of a FEM mesh

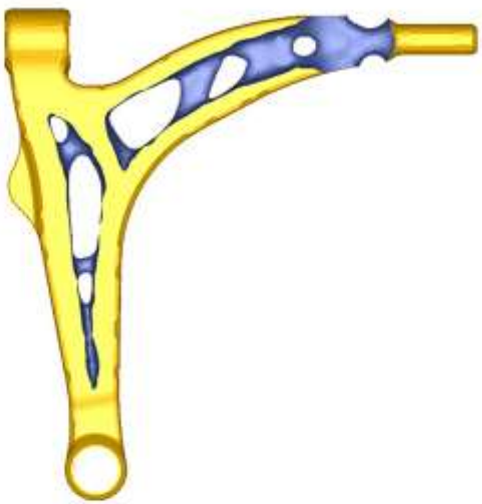


- Objective function ->
  - Mininimise mass -> $\int_V \rho .\, dV$
  - *Minimise compliance = energy ->* $\int_V \sigma.\epsilon\, dV$
  - *Compliance is expressed as a function of density : for example ->* $E=E_0 + \rho^n E_1$



Example of a formulation of a topological optimisation problem

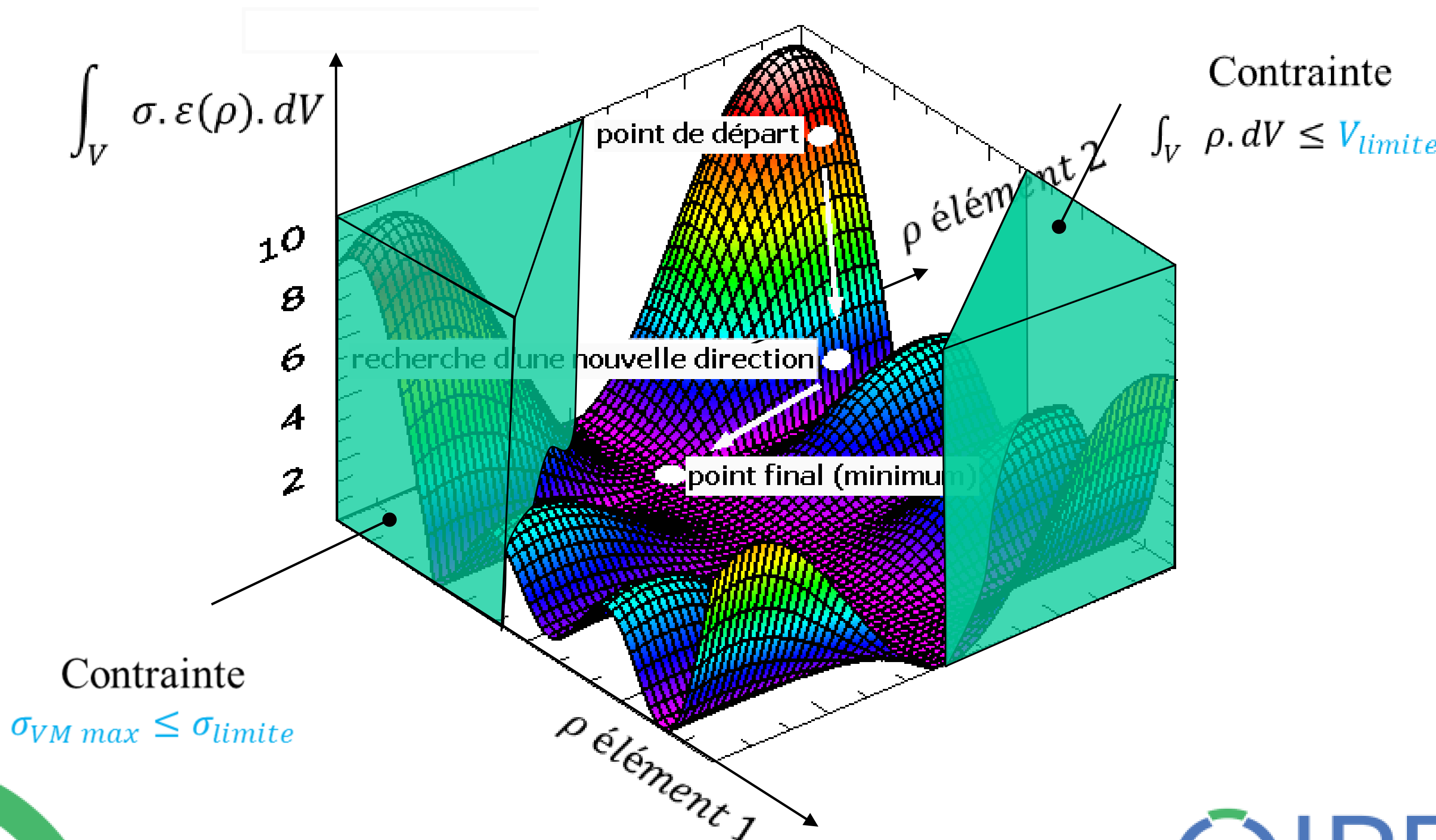
- Minimise compliance $\int_V \sigma.\epsilon(\rho)\, dV$
  - *With $\rho \in [0,1]$ for each element except BC where ρ=1*
    - $\int_V \rho.\, dV$
    - $\nabla\sigma + F = 0$
    - $\sigma = C.\varepsilon$
    - *Plus design constraints*



Optimized Forms

Find minimum compliance

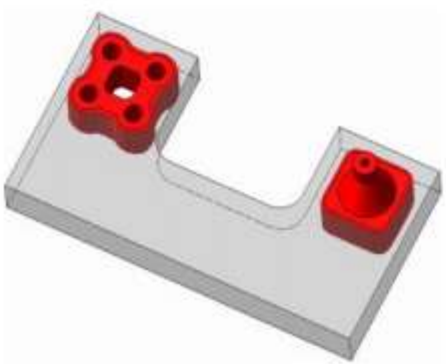
- Principle : example with 2 elements



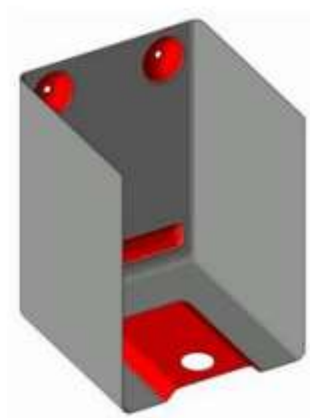
Topology Optimization

HyperWorks

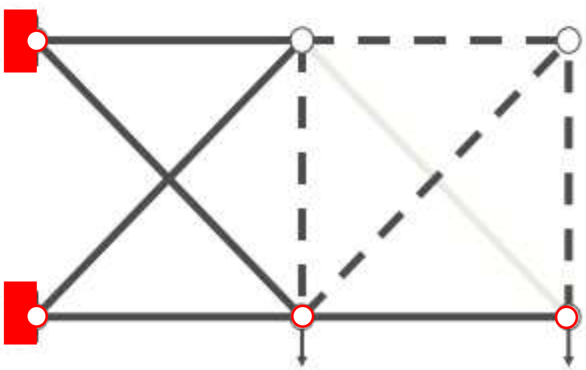
- **Method to find the optimum material distribution in a given design space**



3D ELEMENTS

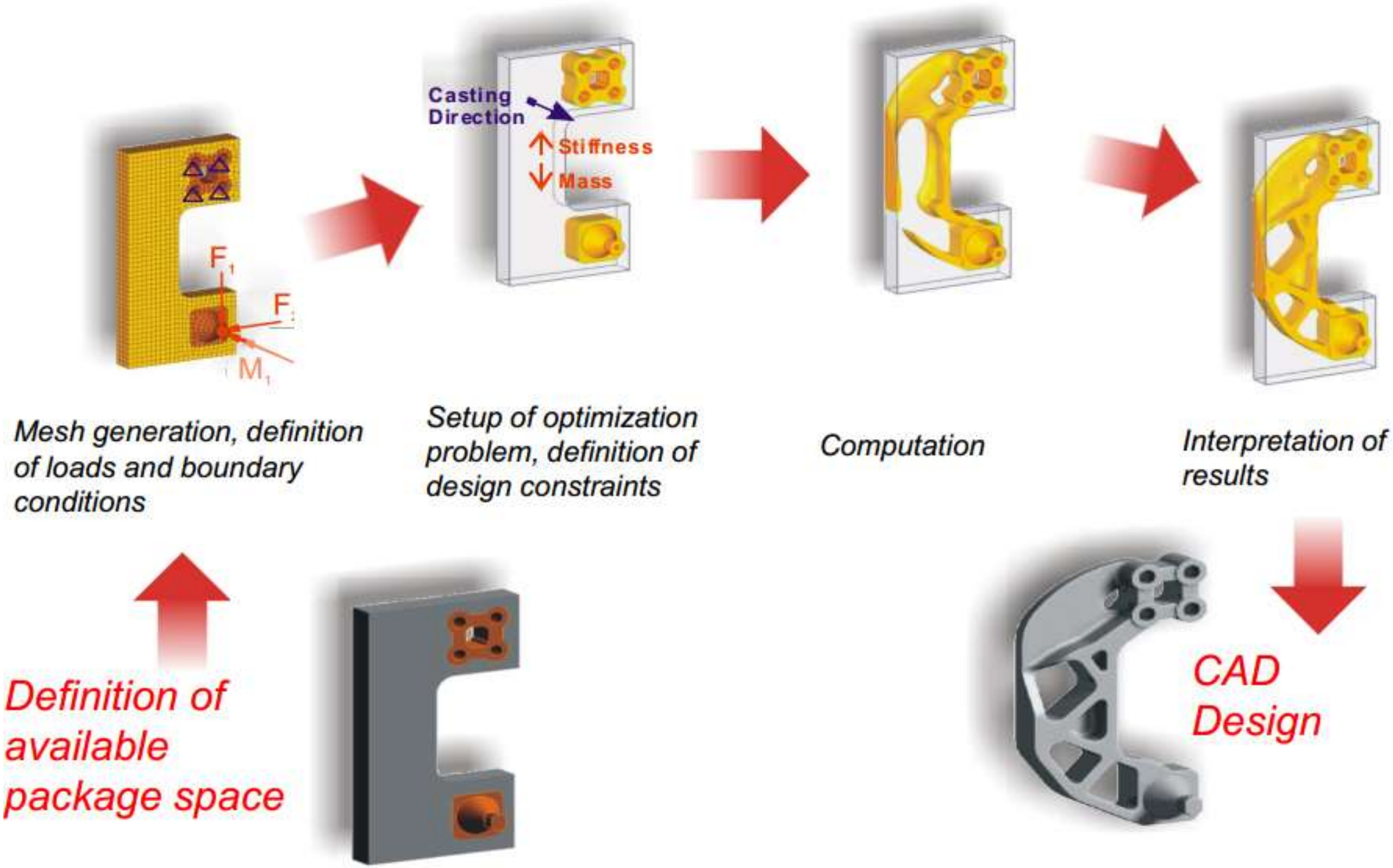


2D ELEMENTS



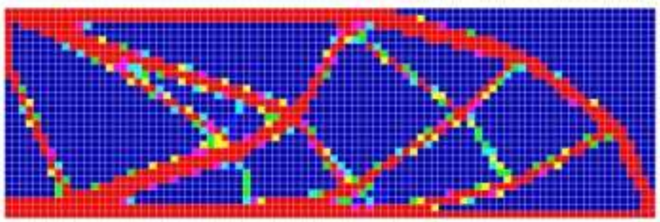
1D ELEMENTS

Topology Optimization Process in Altair OptiStruct



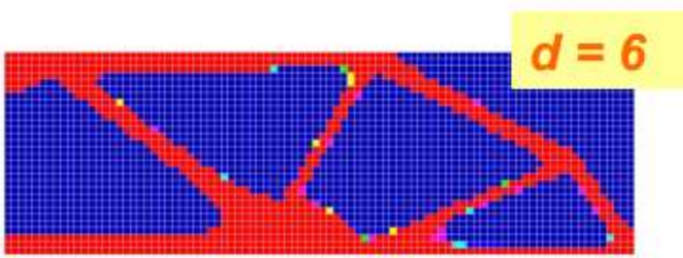
Manufacturing Constraints: Minimum Member Size Control

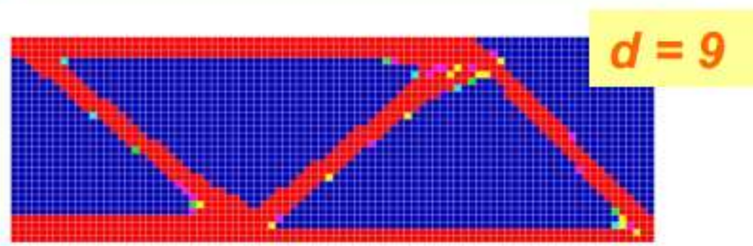
- Input: approximate minimum diameter *d* in two dimensions (SI units)
- Works in 2D and 3D
- Controls the size of small structural features
- Controls "checkerboarding"
- Easier interpretation of the resulting layout
- Higher computation cost



Without min member size

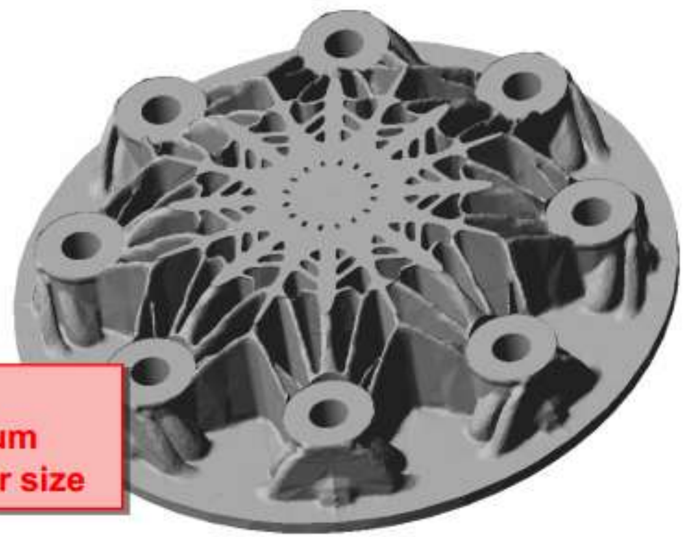
- *Difficult to manufacture due to micro structures*
- *Results are mesh dependent*





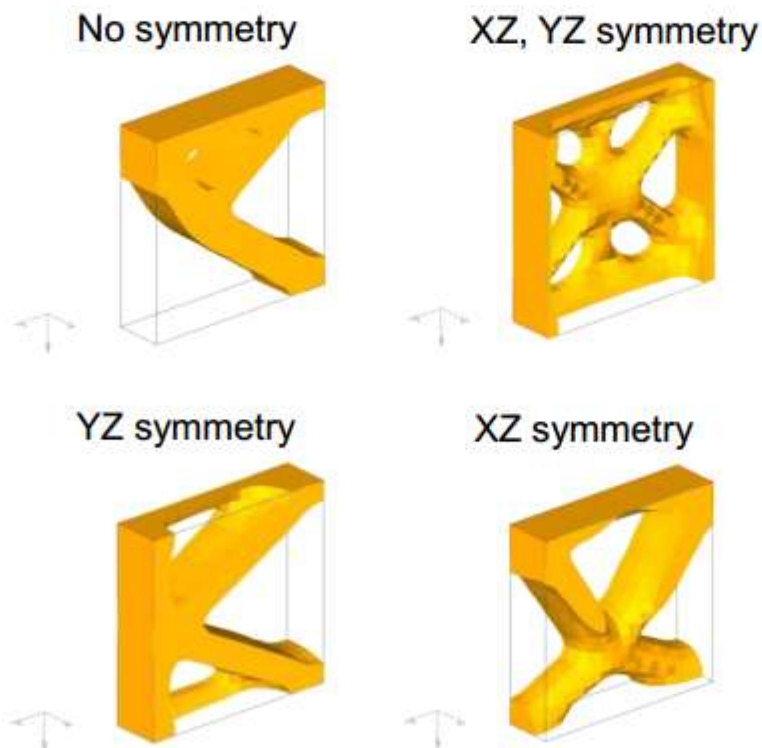
Manufacturing Constraints: Maximum Member Size Control

- Definition of maximum allowable structural member size
- Eliminates material concentrations
- Mesh considerations
  - Shell and solid elements
  - Tetrahedral and hexhedral
  - Min member > 3 X mesh size
  - Max member > 2 X min size

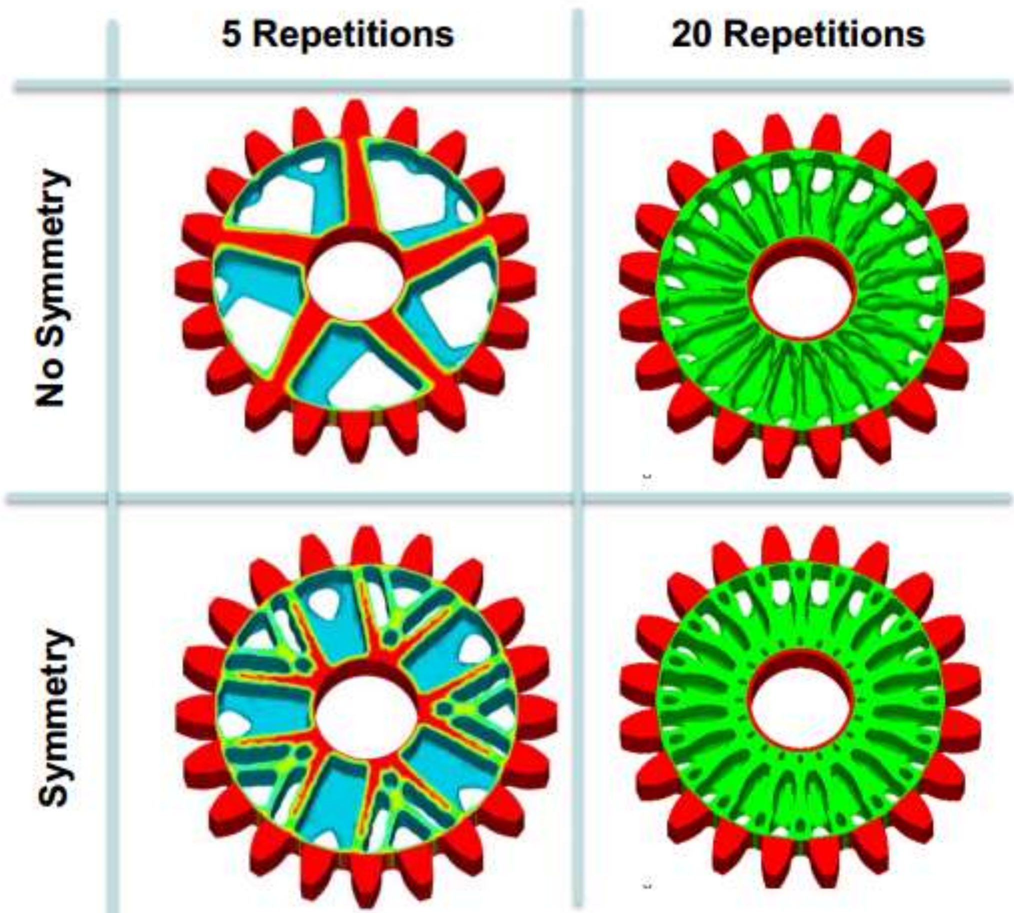


Manufacturing Constraints: Symmetry

- Load independent
- Mesh independent
- Geometry independent

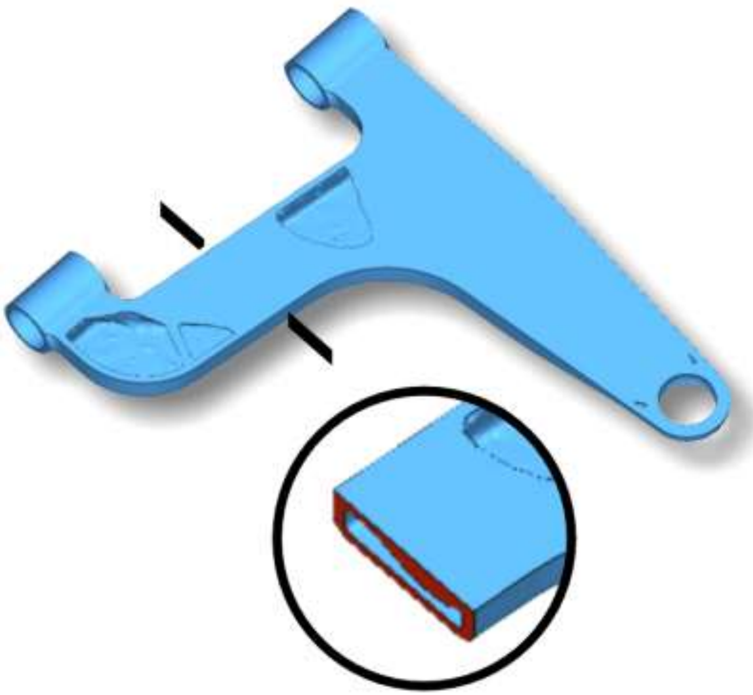


Manufacturing Constraints: Pattern Repetition

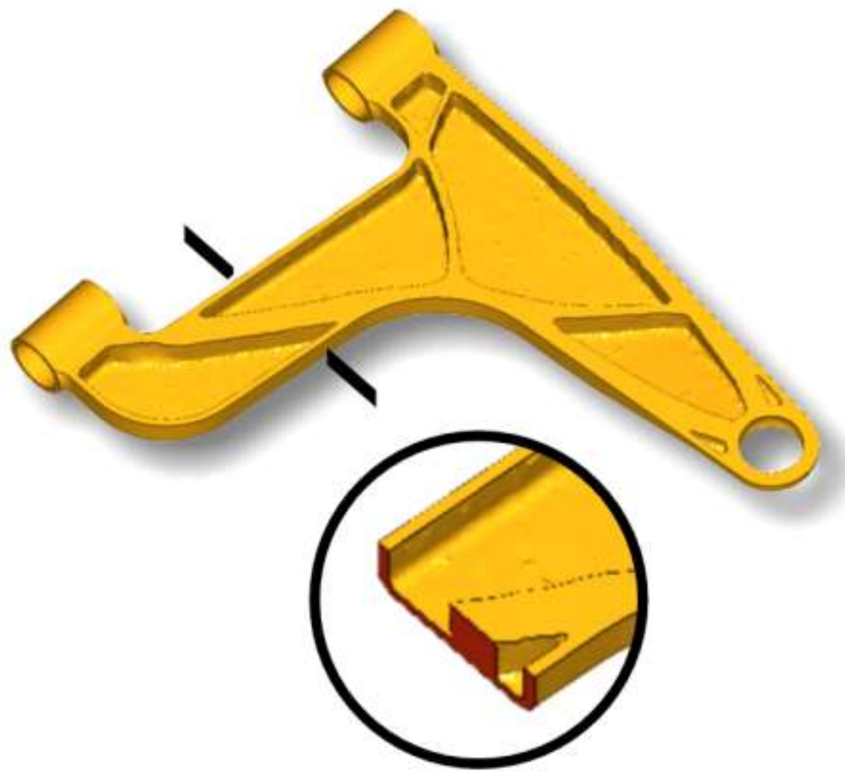


Draw Direction Constraint

Example: Optimum Rib Pattern of a Control Arm



Without Draw Direction

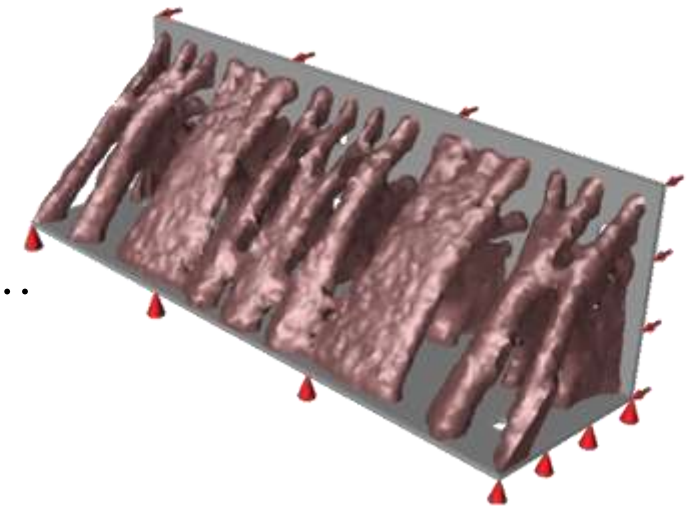


With Draw Direction

Optimized Forms

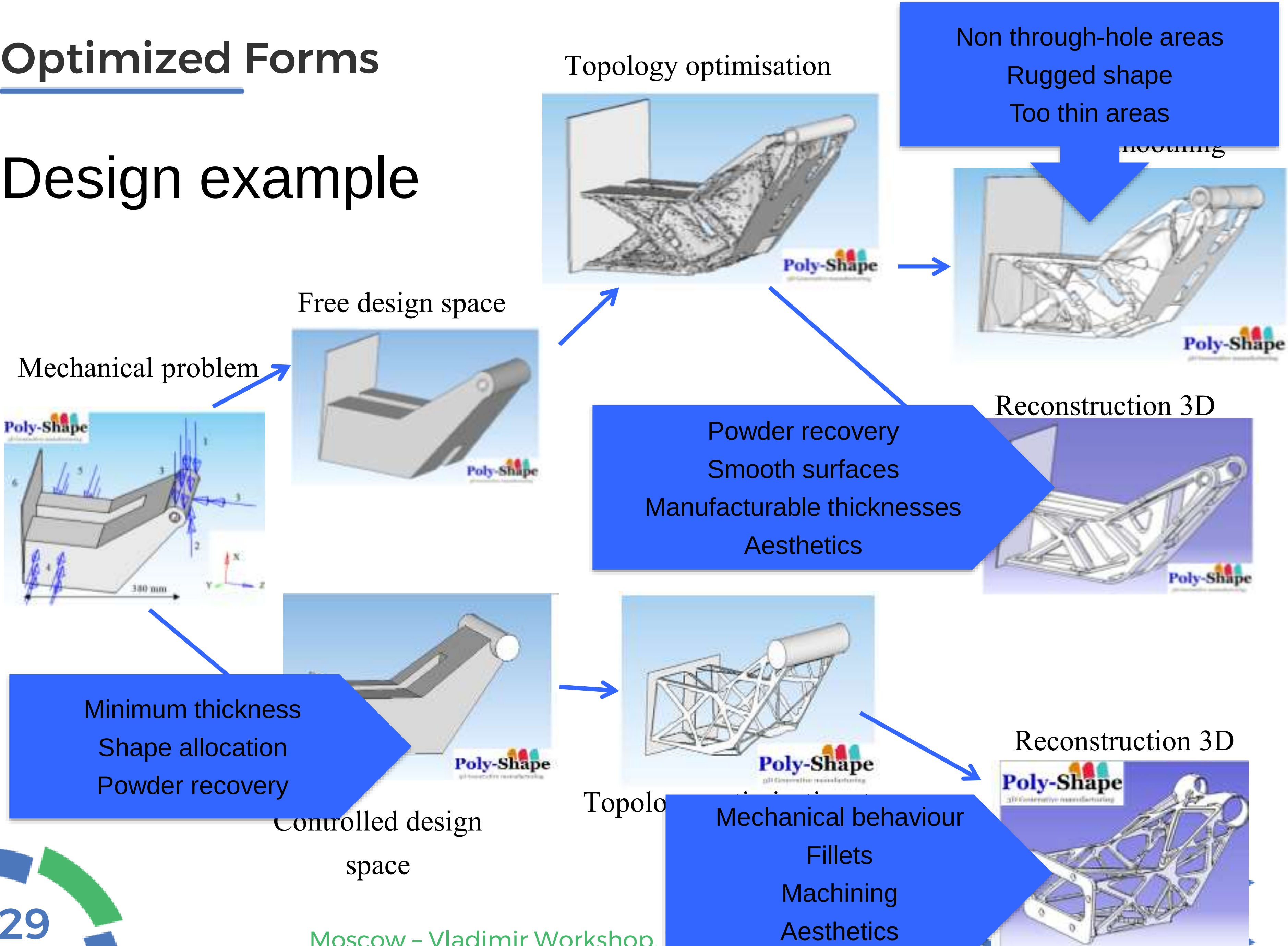
Manufacturing

- Can we print directly an SO result?
  - Yes… but not relevant most of the time
- Simplification and cleaning is often necessary…
- …And some verification/modification as well.
  - Will the final shape acceptable by the client?
  - Shall we be able to remove the supports?
  - Shal we be able to remove all the unused powder?
  - Will there be some weak points?



Optimized Forms

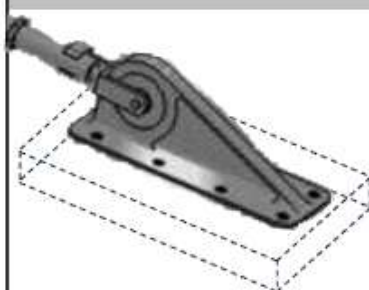
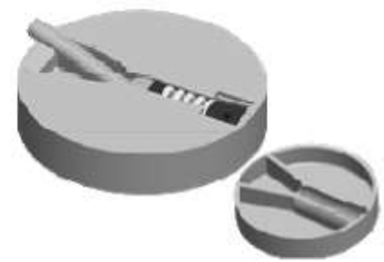
Design example



4 criteria to select AM candidates (Klahn et al. 2014)

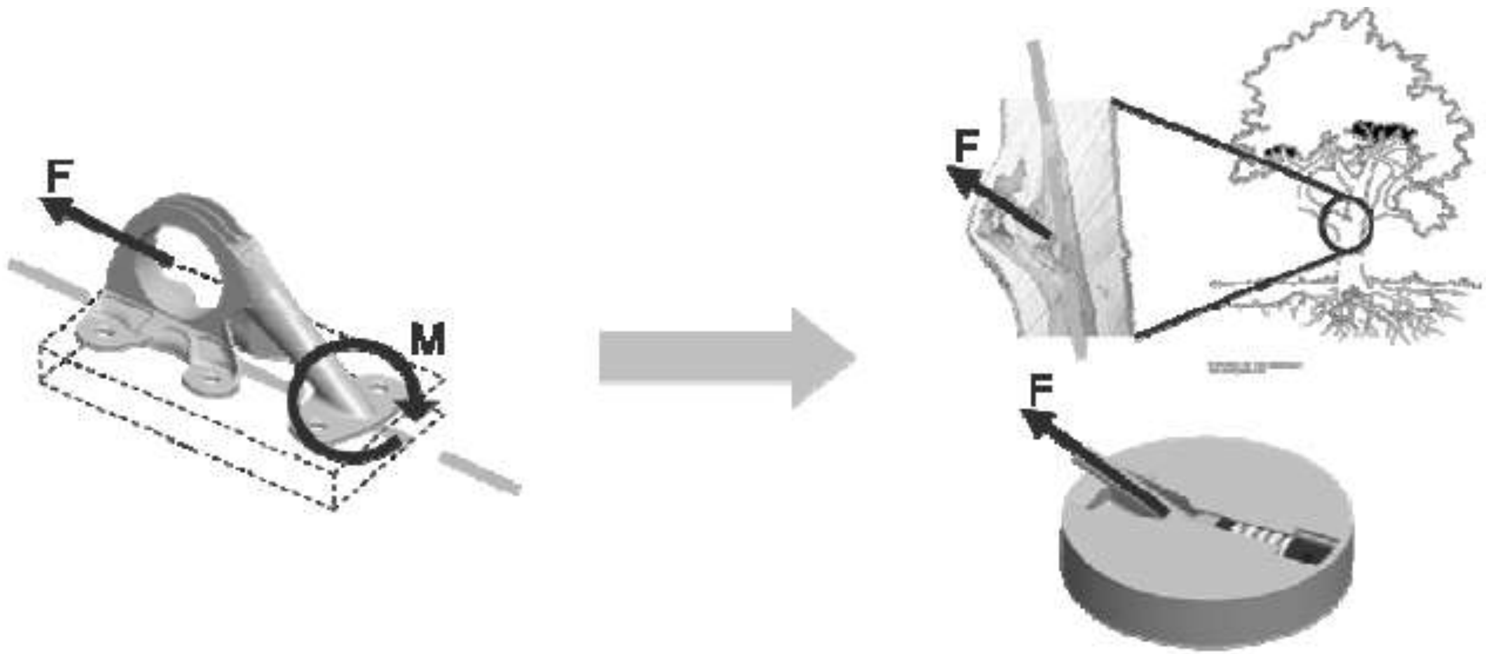
1- « Integrated design »

Identify groups of parts that can be combined in one single part

	original design	bionic design	integrated design* ("bracket" directly glued into honeycomb)
			
bracket weight	330 g	195 g	0 g
assembly weight	1.400 g incl. fiber mount and HiLocks	1.265 g incl. fiber mount and HiLocks	300 g
dimensioning load case	35 kN	35 kN	35 kN
weight saving		**135 g** per bracket **- 41%**	**1.100 g** per assembly **> - 80%**

Example (Emmelmann et al. 2012)

4 criteria to select AM candidates (Klahn et al. 2014)



4 criteria to select AM candidates (Klahn et al. 2014)

2- « Individualization » : Complex part with high variability (often interface parts)

4 criteria to select AM candidates (Klahn et al. 2014)

3 - « Lightweight Design » : Complex mobile parts

Bracket airbus A380 (EOS)

4 criteria to select AM candidates (Klahn et al. 2014)

4 - « Efficient Design » : Part participating to mass, energy transmission or conversion

Heat exchanger (EOS)

4 criteria to select AM candidates (Klahn et al. 2014)

1. « Integrated design » : Identify groups of parts that can be combined in one single part
2. « Individualization » : Complex part with high variability (often interface parts)
3. « Lightweight Design » : Complex mobile parts
4. « Efficient Design » : Part participating to mass, energy transmission or conversion

The Materials in Additive Manufacturing

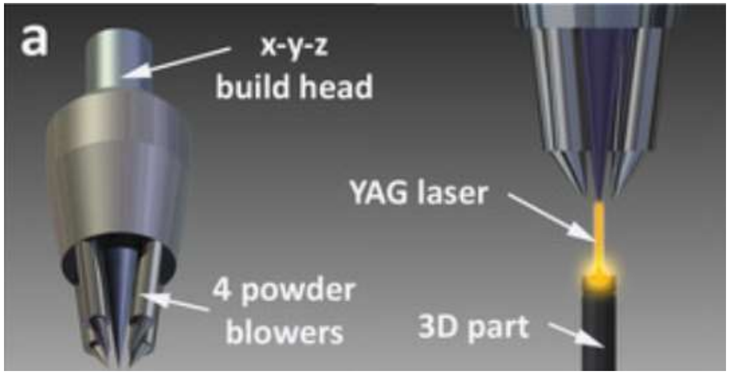
- The material is « built » at the same time as the part

=> Tight connexion product-material-process

- Multi materials opportunities

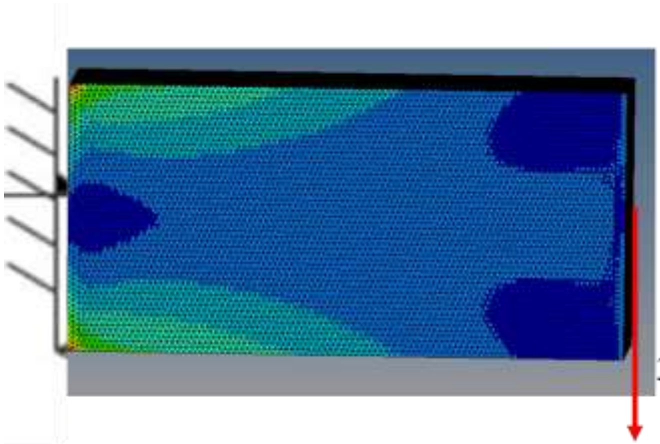
=> alternate, and blend materials and filament

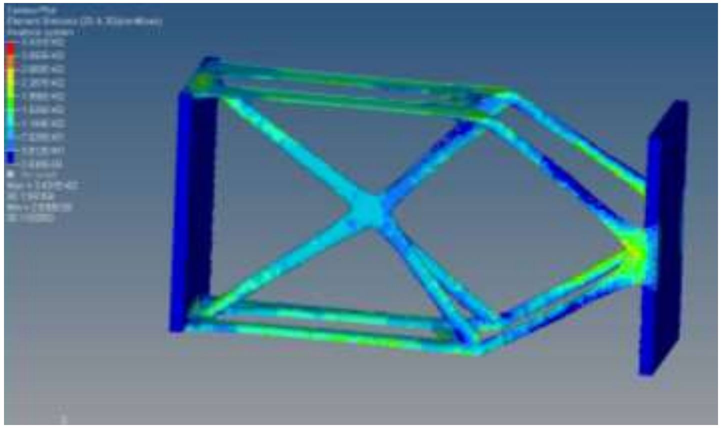
credit: NASA-JPL/Caltech



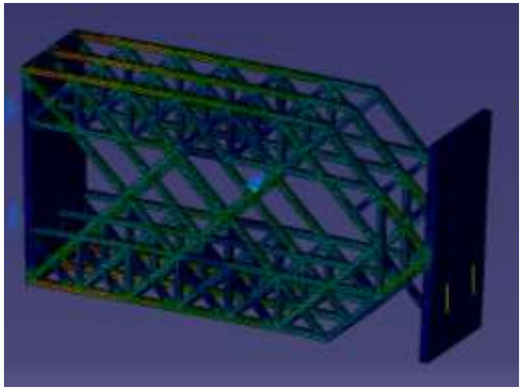
Architectured materials

- Best ratio mass/resistance





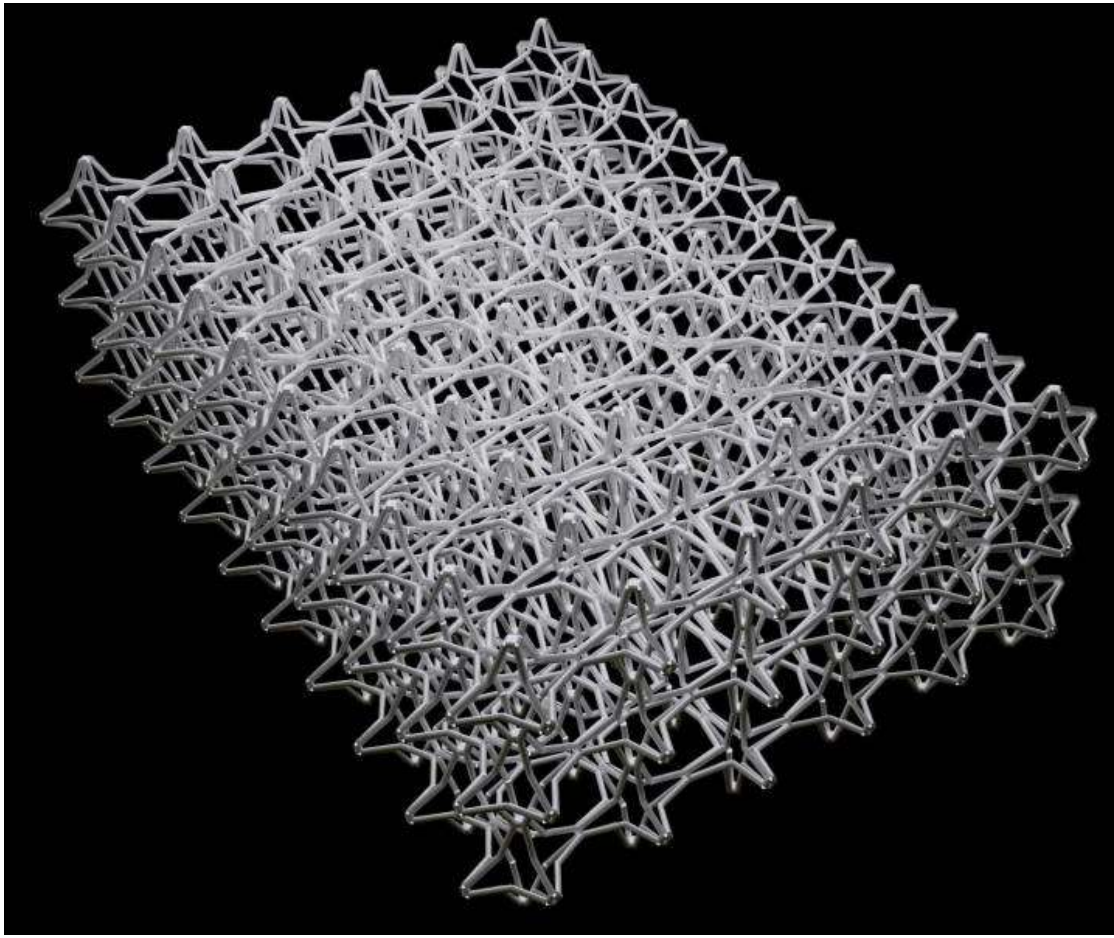
343 Mpa, 7,2 g



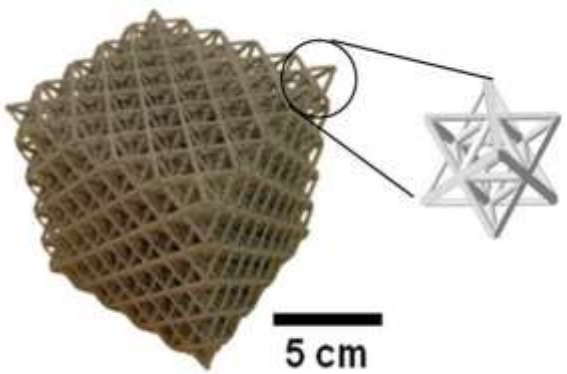
328 Mpa, 6,1 g

Architectured material

- Specific and « designed » properties
- Complex behavior (negative poisson ratio)



Architectured materials



Lighten structures

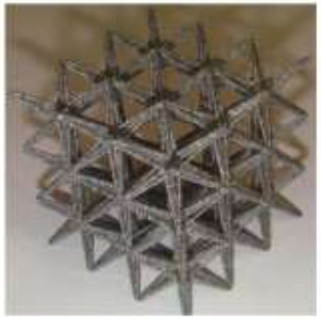
Porosity gradient

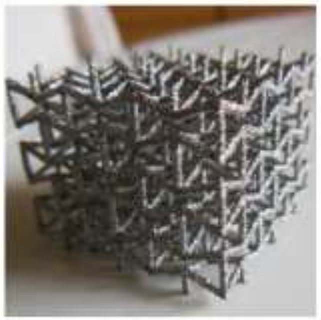
Scaffolds for
Bones developmement

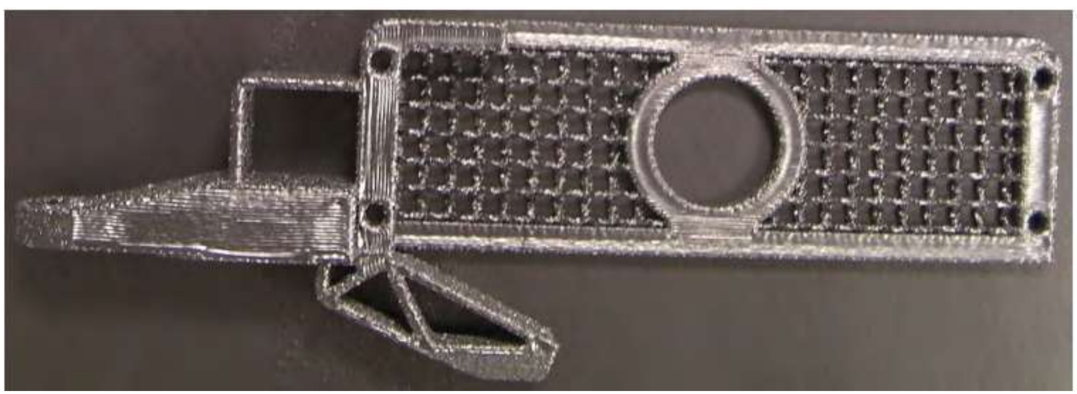
Credit SIMAP - Grenoble

Materials Dimension

Lattice structures







Materials Dimension

Insert lattice structures in blind zones of topology optimisation

http://www.3ders.org/articles/20140915-futurist-christopher-barnatt-report-london-2014-3d-printshow.html

Materials Dimension

Design FOR
Additive Manufacturing

New design rules

New forms

Functional Materials

Form opportunities

Solution search, Synthesis

Needs, contraintes

Possible solutions

Evaluation, Analysis

Prototyping opportunities

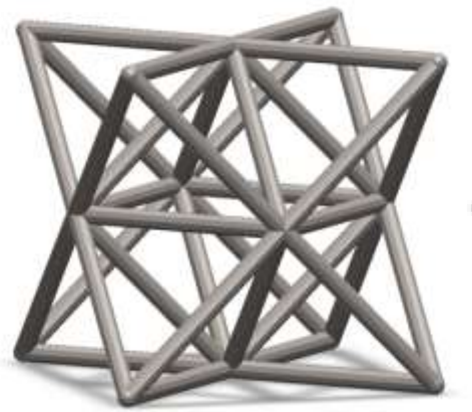
Complexity of numerical simulation

- Material modeling
- Importance of CL
- Geometric Singularities
- Many details
- Geometric uncertainties …

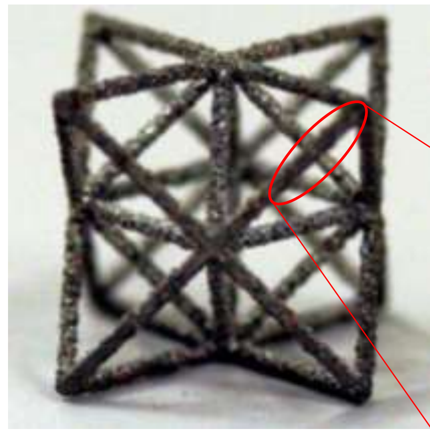
Some Manufacturing Issues

Architectured materials

Do we build what we calculate?



1mm strut
Circular cross-section



How far from the ideal ?

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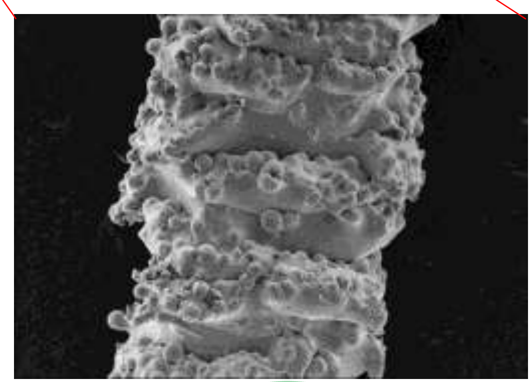
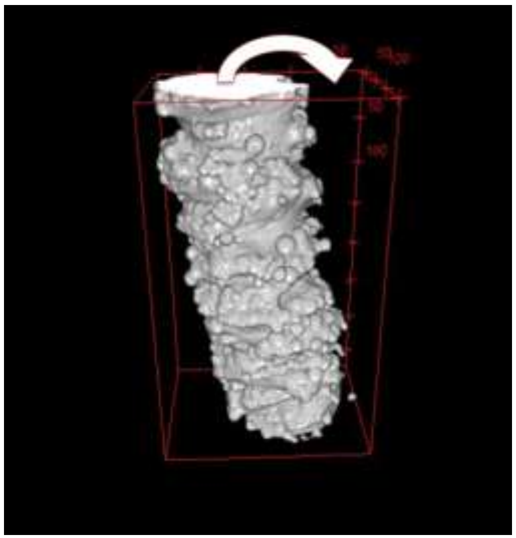
SEM micrograph

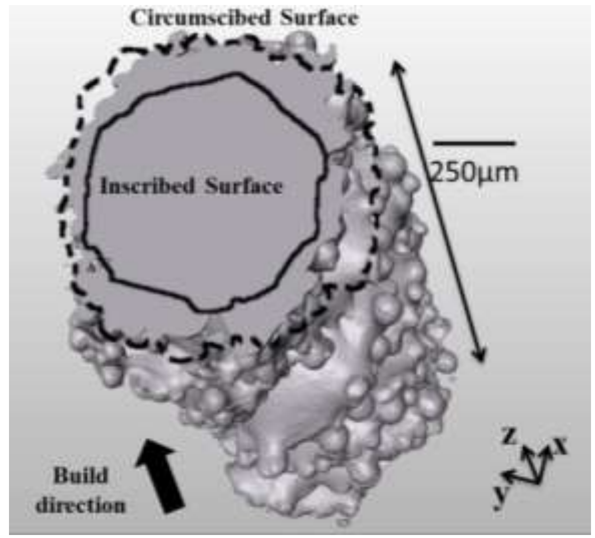


Some Manufacturing Issues

Geometry correction

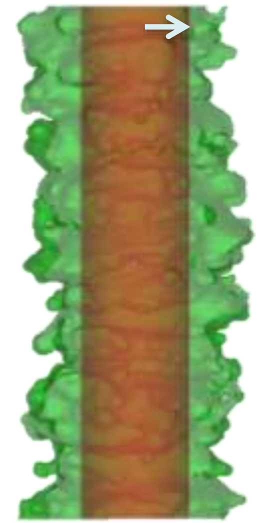


Alignement of neutral axis of strut with vertical



Projection of pixel along the strut.

R_{EQ}^{GEOM}



Inscribed cylinder: circular cylinder of same area than the inscribed surface

R_{EQ}^{GEOM}=radius of inscribed cylinder

Inscribed cylinder→ Mechanical properties

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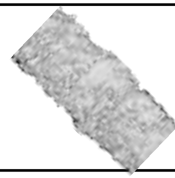
Equivalent diameter

Influence of orientation (EBM)

Build direction

Build orientation	$\mathrm{R}_{\mathrm{EQ}}^{\mathrm{NUM}} / R_{CAD}$
	71%
	58.1%
	57.6%

- Horizontal strut :
  Larger cross-section due to over-melting→Higher stiffness
- No change in stiffness for vertical and 45° strut

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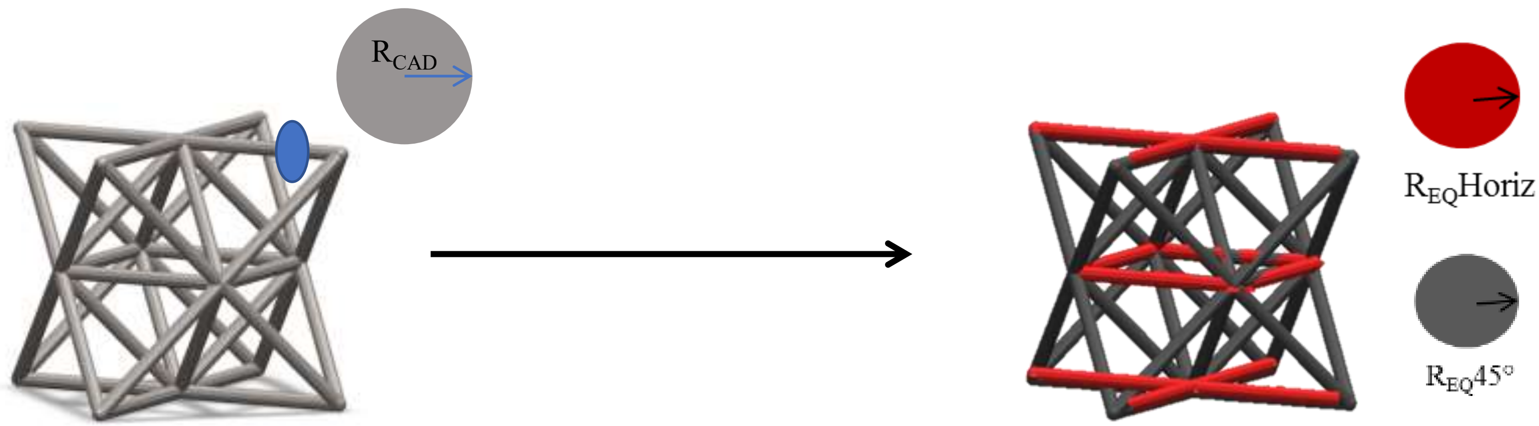
Equivalent diameter

structures



Different orientations

R_{EQ} depends on:
- fabrication direction
- CAD size
- Process parameter

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Conclusion

Take advantage of the form freedom offered by AM:

- Uncover new design rules
- Topoligical optimisation used
  - Optimisation require expertise
- Topological optimisatin + architectured materials = promising results
- Rapid access to prototyping even when simulation is complex

Design FOR
Additive Manufacturing

New design rules

New forms

Functional Materials

Form opportunities

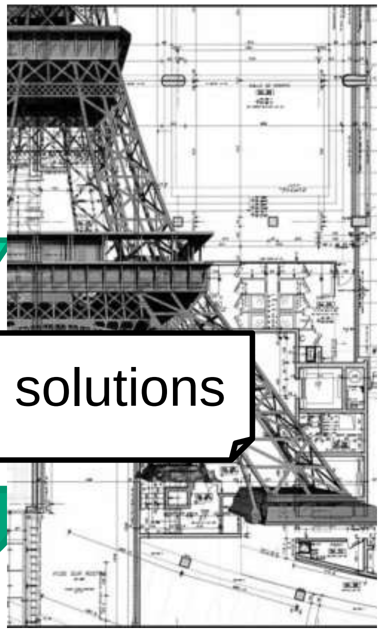
Solution search,

Synthesis

Needs,

contraintes

Possible solutions



Evaluation, Analysis

Prototyping opportunities

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Thank you