Modélisation numérique des problèmes de l'ingénieur

CALCUL ELMENTS FINIS ET OPTIMISATION DE FORME DANS LES STRUCTURES AEROSPATIALES

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Rabat

En quelques mots …

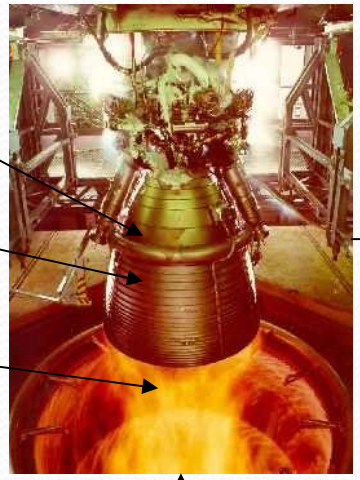
Objectif : Contrôle des calculs par la Méthode des éléments Finis

Fournir des outils dédiés pour la résolution informatique des phénomènes physiques et Optimiser la forme des pièces Mécaniques (Légèreté / Résistance)

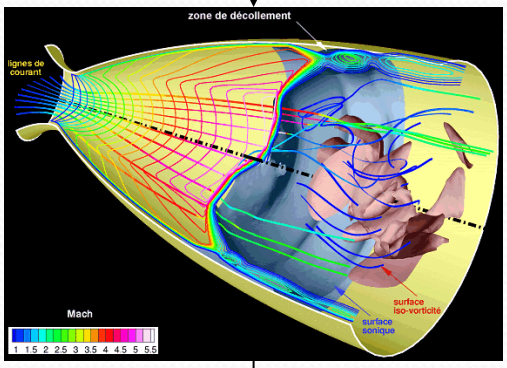
Structure

Thermique

Fluide



Source : technoscience



Source : ONERA

Modèle réel

Modèle numérique

Intérêts « industriels »

www.dt.insu.cnrs.fr

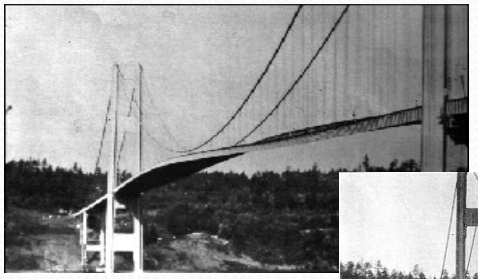
Aéronautique/ Aérospatial
Vibration - acoustique

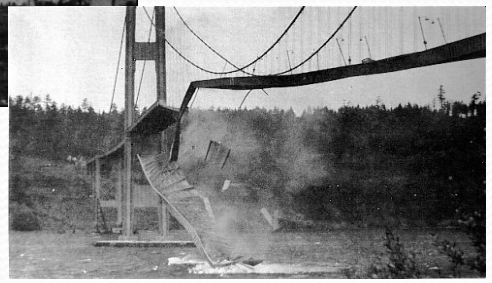
www.otua.org/acier/seisme/

Protection séisme

www.cnes.fr

Couplage fluide-structure





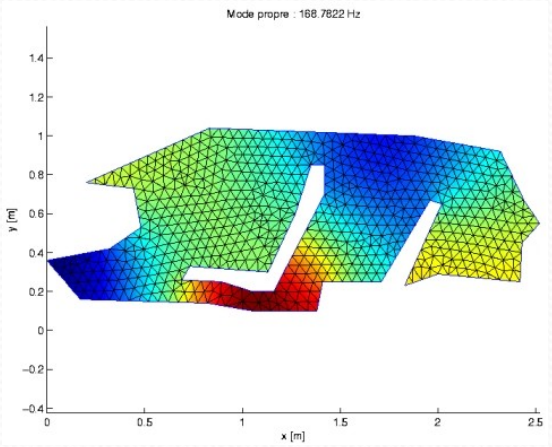
«Tacoma narrows bridge »

Ouvrage génie civil

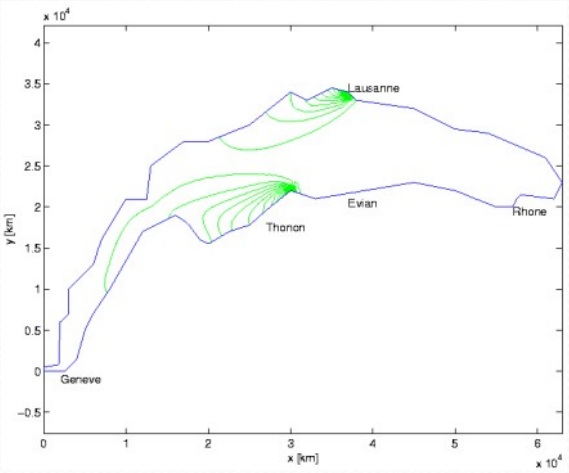
...

Pourquoi EF?

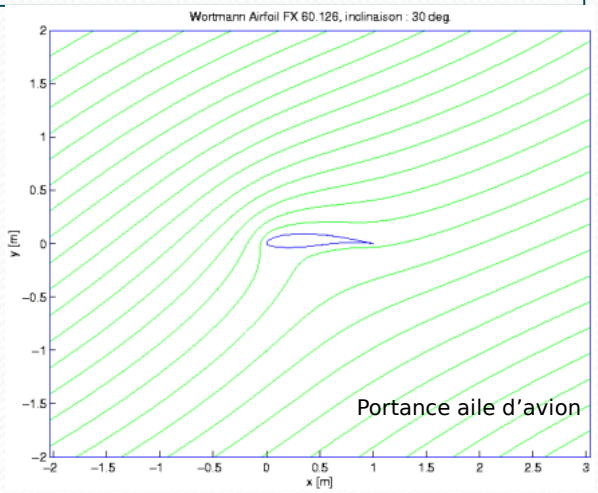
- Passage incontournable dans la boucle de conception d'un produit industriel
  - Automobile, aéronautique, acoustique, génie civil …
  - Un ingénieur sur Trois concerné par le numérique
- 99 % de la physique sous la forme d'E.D.P.
- « Outils » mathématiques classiques (fondamentales) valables pour moins de 1 % des cas !!



Acoustique automobile



Pollution d'un lac



Bagages nécessaires …

- Mathématique :
  - Équations différentielles ordinaires
  - Techniques d'intégration standard
  - Opérations matricielles de base
  - Notion d'interpolation
  - Interpolations (Courbes, Surfaces, Topologie,…)
- Physique : ?
- Ingénieur : développer le bon Sens et un esprit critique
- Informatique : (C++, Fortran, Matlab, …)

Complexité : Multi compétences

Intérieur:
- Capacité transport
- Confort passagers
- …

Fluide:
- Aérodynamique
- Traînée
- Acoustique
- …

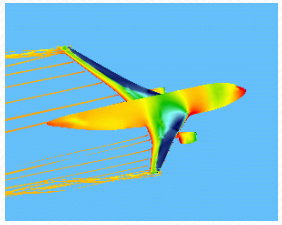
Structure:
- Tenue
- Fatigue
- Aéroélasticité
- Fréquences
- …

Moteurs:
- Combustion
- Poussée
- Acoustique environmentale
- …

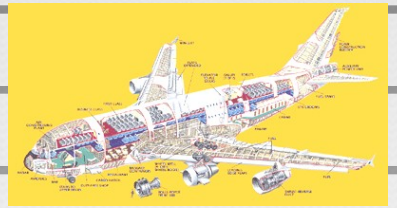
Electronique / Automatisme:
- Automatisme
- Contrôle
- Asservissement
- Commandes
- …

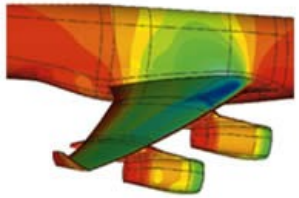
Source : futura-sciences

Chaîne de conception « industrielle »

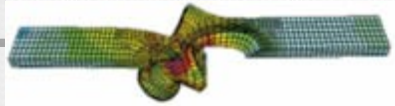


Aérodynamique





Aéroélasticité



Tenue mécanique

Simulation
Optimisation

Conception

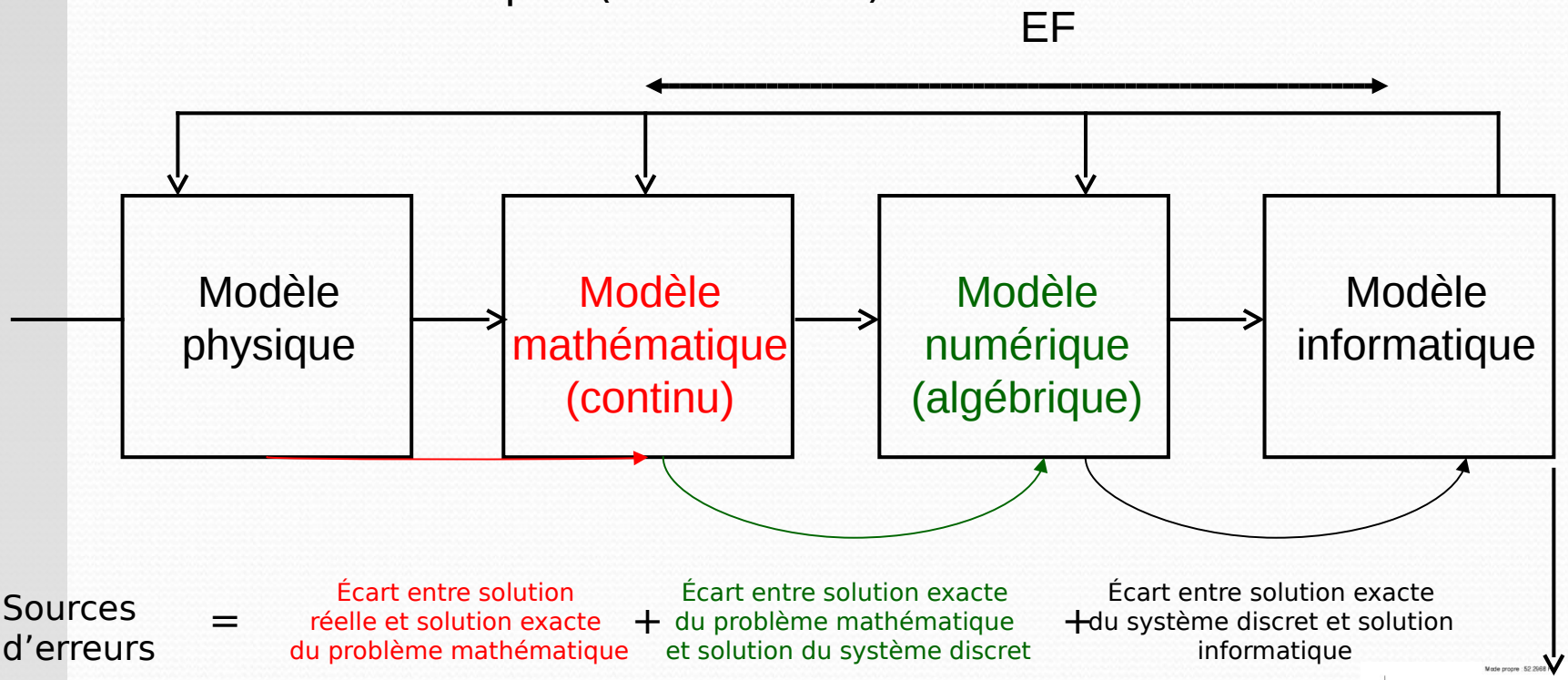
Expérimental

Production

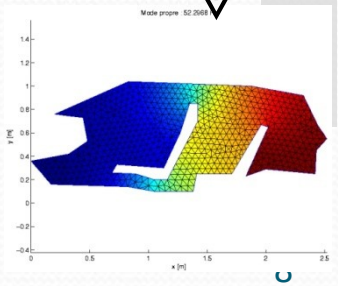
Sources : engineering.swan
ONERA

« Boucle de Modélisation »

Démarche en 4 étapes (ou modèles) distinctes :

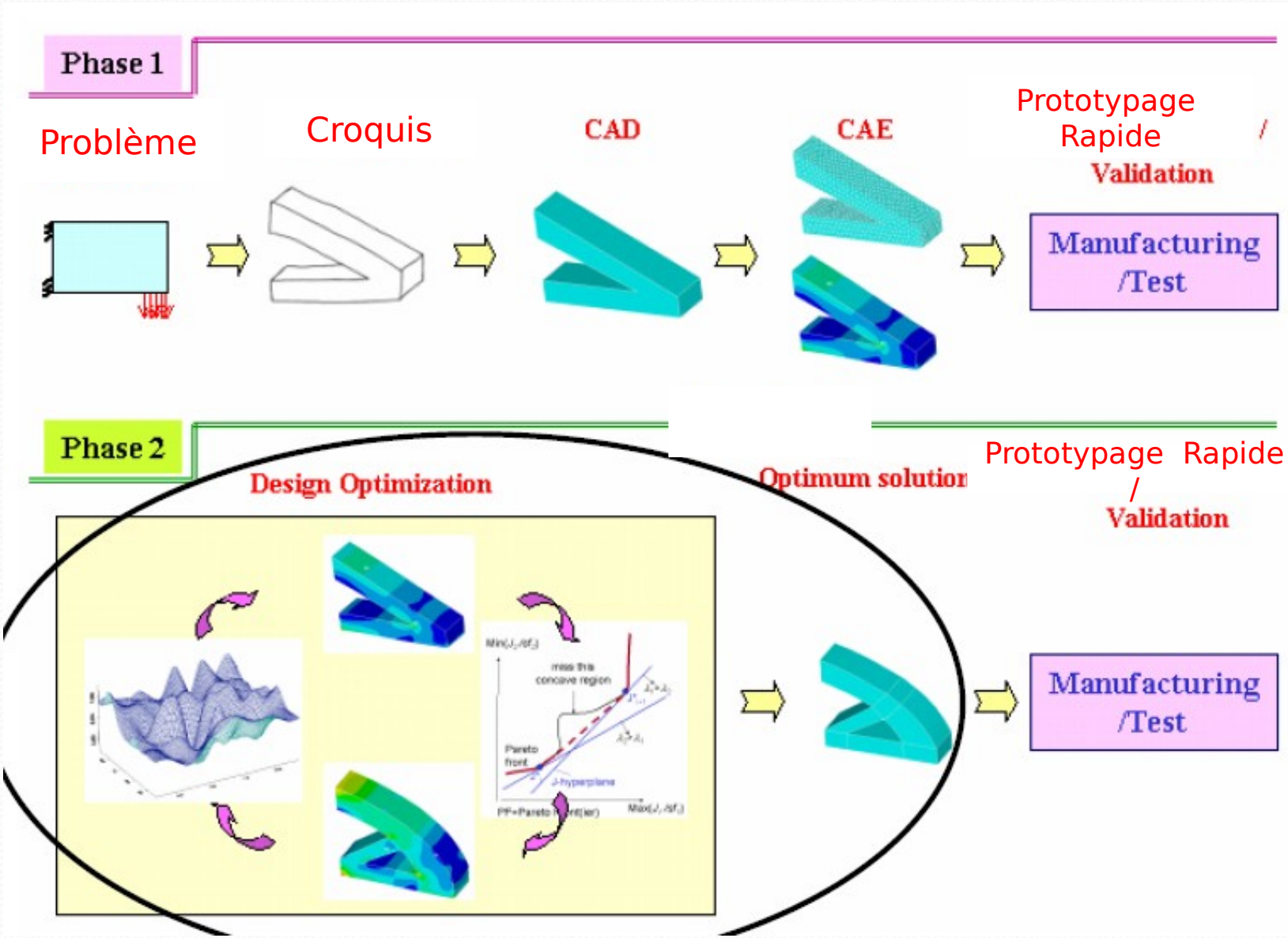


Sources d'erreurs = Écart entre solution réelle et solution exacte du problème mathématique + Écart entre solution exacte du problème mathématique et solution du système discret + Écart entre solution exacte du système discret et solution informatique

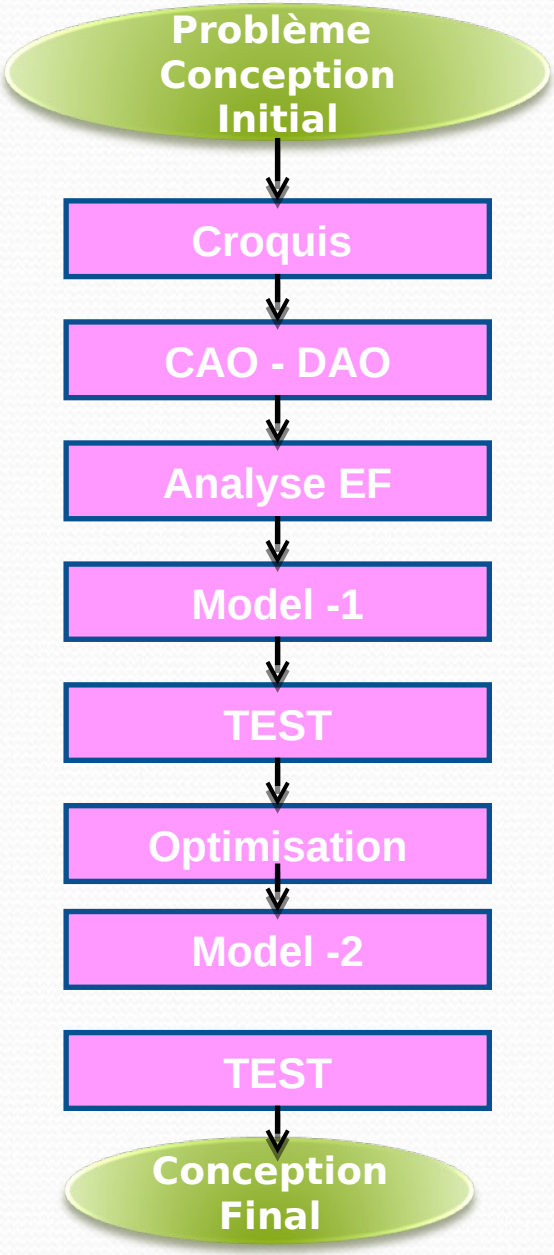


OPTIMISATION DES STRUCTURES AEROSPATIALES

PHASES D'OPTIMISATION



PHASES D'OPTIMISATION



PHASES D'OPTIMISATION

QUESTIONS : Quelle est la meilleure Conception « Meilleur Design » ?

1- Quel est le critère de choix de la meilleure conception → Fonction Objectif

2- Principes → Contraintes, Spécifications techniques

3- Comment décrire les différentes conceptions → Variables de conception

FORMULATION D'UN PROBLEME D'OPTIMISATION

$$\text{Minimize} \quad f(\mathbf{x})$$

$$\text{Subject to} \quad g(\mathbf{x}) \leq 0$$

$$h(\mathbf{x}) = 0$$

CONTRAINTES

2. Requirements

Manufacturing Cost (C):	C ≤ 3.6$ /part
Performance (δ_1, δ_2, f_1):	Displacement $\delta_1 \leq 0.078$ mm Displacement $\delta_2 \leq 0.012$ mm First natural frequency $f_1 \geq 195$ Hz
Mass (m):	m ≤ 0.27 lbs
Surface Quality (Q):	Q ≥ 2
Load Case (F):	F1 = 50 lbs / F2 = 50 lbs / F3 = 100 lbs

The part has to conform to the interface requirements and geometrical boundary conditions shown on page 2 of this document. This requirement cannot be waived.

3. Priorities

Low manufacturing cost is the first priority for this product. Next, the customer cares about light-weighting (low mass) and thirdly, structural performance should be as high as possible. These priorities are shown in the Ishii-matrix below:

Attribute	Constrain	Optimize	Accept
Cost	■		
Performance			■
Mass		■	

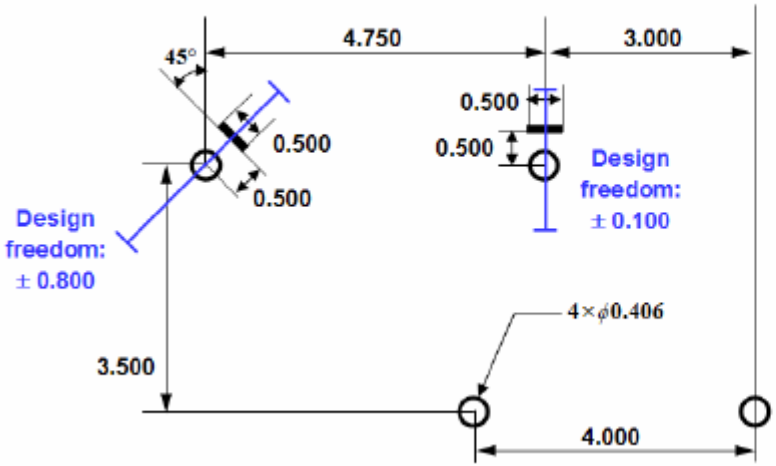
Contraintes Qualitatives

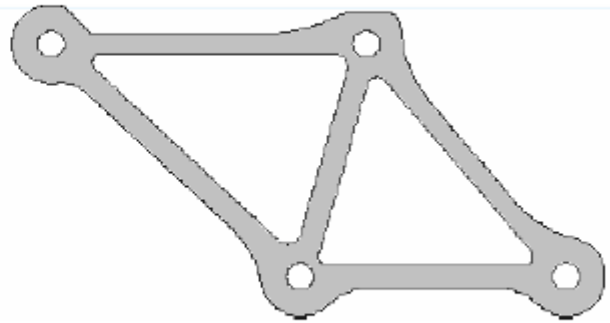
Contraintes Quantitatives
Fonction Objectifs

VARIABLES DE CONCEPTION

PARAMETRES CHOISIS POUR DEFINIR LA CONCEPTION DU SYSTEME

Variables de conception contrôlés par le concepteur





Ici la position et diamètres des trous

PHASES D'OPTIMISATION

For computational design optimization,

⇨ **Objective function and constraints must be expressed as a function of design variables (or design vector X)**

Objective function: $f(\mathbf{x})$ Constraints: $g(\mathbf{x}), h(\mathbf{x})$

Cost = f(design)

Displacement = f(design)

Natural frequency = f(design)

Mass = f(design)

What is "f" for each case?

FORMULATION

$$\text{Minimize} \quad f(\mathbf{x})$$

$$\textit{Subject to} \quad g(\mathbf{x}) \leq 0$$

$$h(\mathbf{x}) = 0$$

$f(\mathbf{x})$: Objective function to be minimized

$g(\mathbf{x})$: Inequality constraints

$h(\mathbf{x})$: Equality constraints

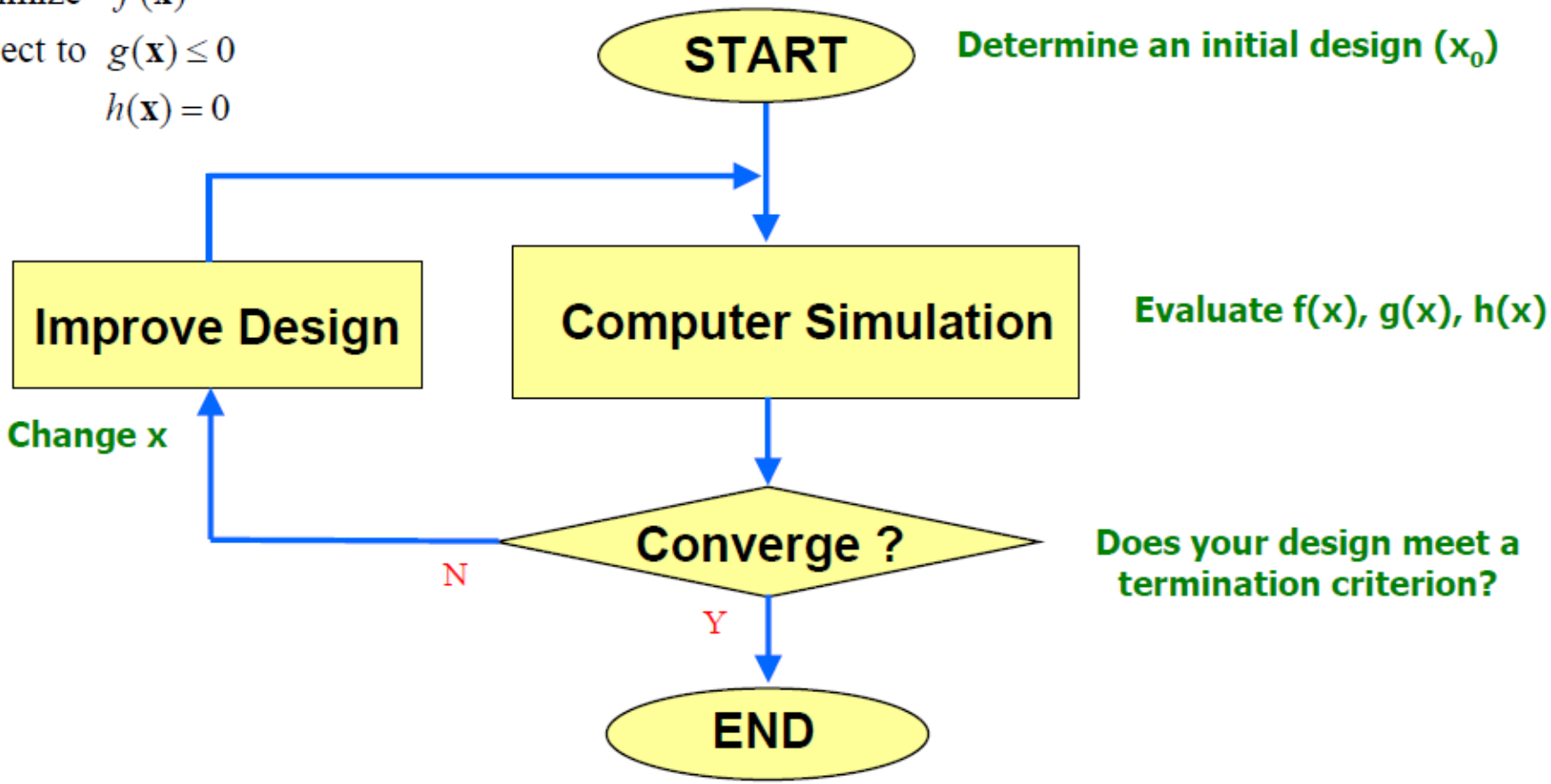
$\mathbf{x}$: Design variables

PROCEDURE D'OPTIMISATION

Minimize $f(\mathbf{x})$

Subject to $g(\mathbf{x}) \leq 0$

$h(\mathbf{x}) = 0$



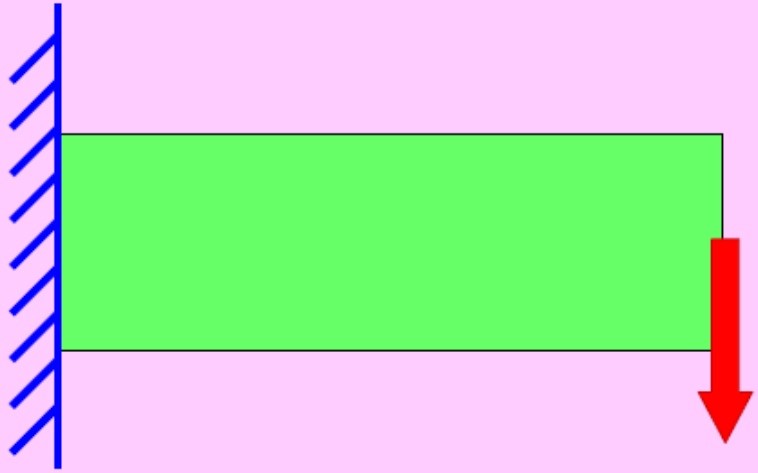
METHODES D'OPTIMISATION

Selecting the best "structural" design

- Size Optimization
- Shape Optimization
- Topology Optimization

OPTIMISATION STRUCTURELLE

$$\text{minimize} \quad f(\mathbf{x})$$
$$\text{subject to} \quad g(\mathbf{x}) \leq 0$$
$$h(\mathbf{x}) = 0$$

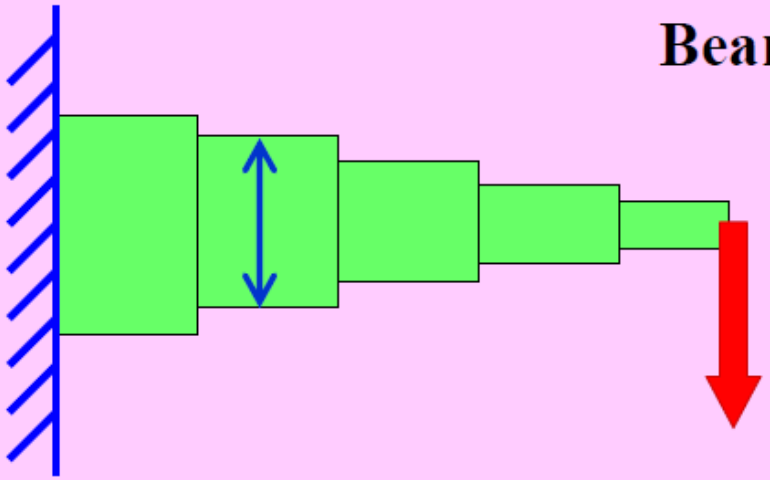


1. To make the structure strong
   e.g. Minimize displacement at the tip
   ➡ $Min.\ f(\mathbf{x})$

2. Total mass $\leq M_c$
   ➡ $g(\mathbf{x}) \leq 0$

OPTIMISATION DE FORME (TAILLE DE LA STRUCTURE)

$$\begin{aligned} \text{minimize} \quad & f(\mathbf{x}) \\ \text{subject to} \quad & g(\mathbf{x}) \leq 0 \\ & h(\mathbf{x}) = 0 \end{aligned}$$



Design variables (x)

x : thickness of each beam

Number of design variables (ndv)

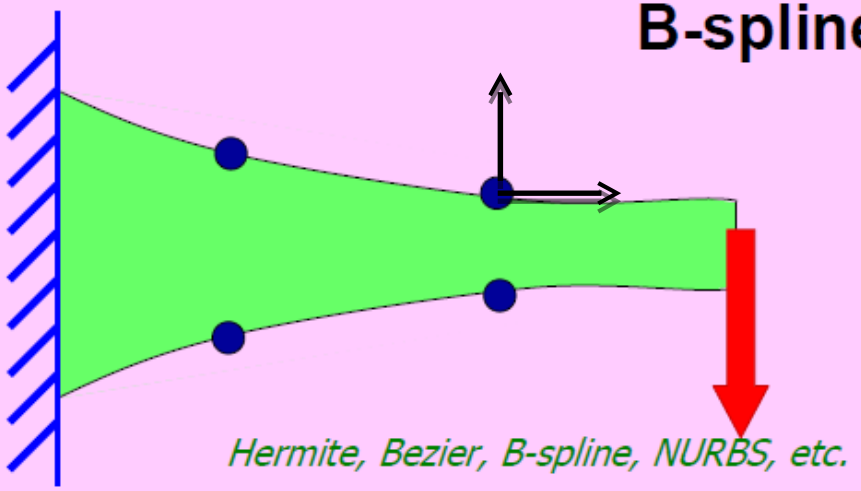
ndv = 5

f(x) : compliance

g(x) : mass

OPTIMISATION DE FORME (FORME DE LA STRUCTURE)

$$\begin{aligned} \text{minimize} \quad & f(\mathbf{x}) \\ \text{subject to} \quad & g(\mathbf{x}) \leq 0 \\ & h(\mathbf{x}) = 0 \end{aligned}$$



Design variables (x)

x : control points of the B-spline

(position of each control point)

Number of design variables (ndv)

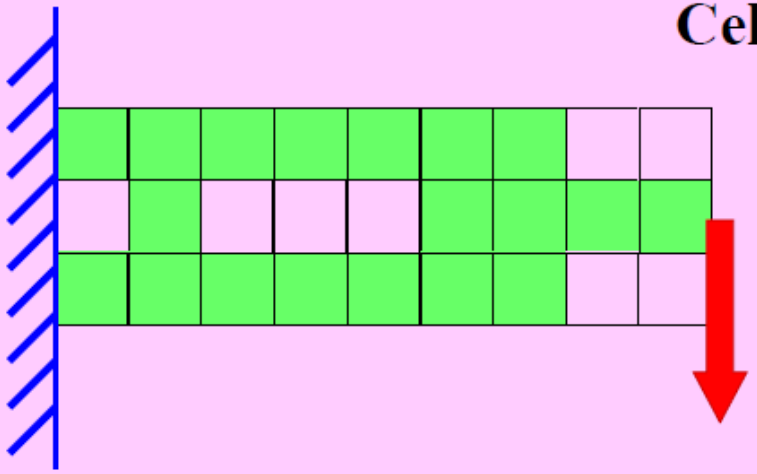
ndv = 8

***f*(x) : compliance**

***g*(x) : mass**

OPTIMISATION TOPOLOGIQUE

$$\begin{aligned} \text{minimize} \quad & f(\mathbf{x}) \\ \text{subject to} \quad & g(\mathbf{x}) \leq 0 \\ & h(\mathbf{x}) = 0 \end{aligned}$$



Design variables (x)

x : density of each cell

Number of design variables (ndv)

ndv = 27

***f*(x) : compliance**

***g*(x) : mass**

OPTIMISATION DE FORME (FORME DE LA STRUCTURE)

Multiobjective & Multidisciplinary Shape Optimization

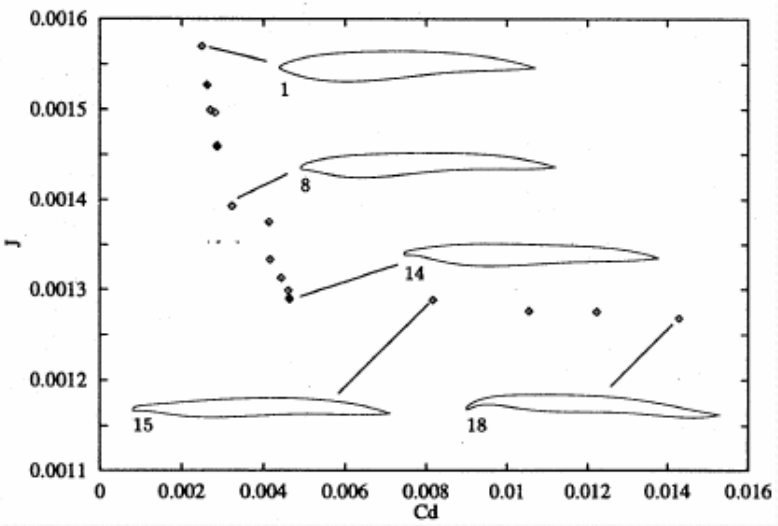
Objective function

1. Drag coefficient, 2. Amplitude of backscattered wave

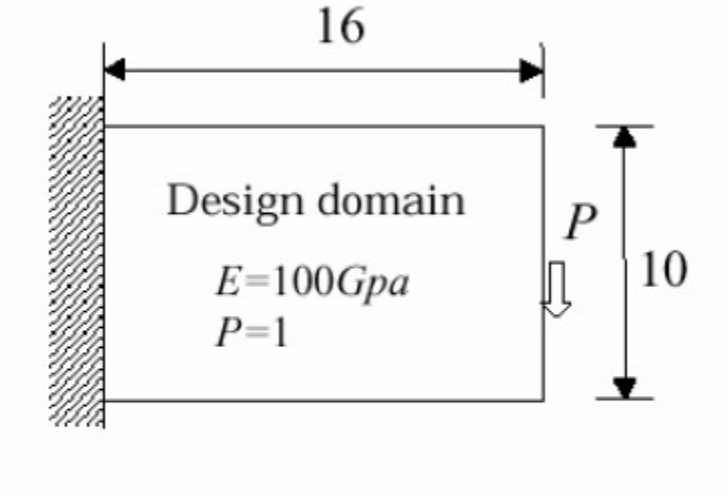
Analysis

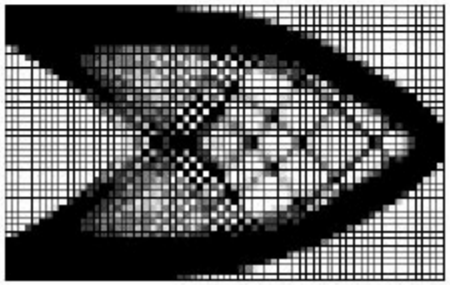
1. Computational Fluid Dynamics Analysis
2. Computational Electromagnetic Wave Field Analysis

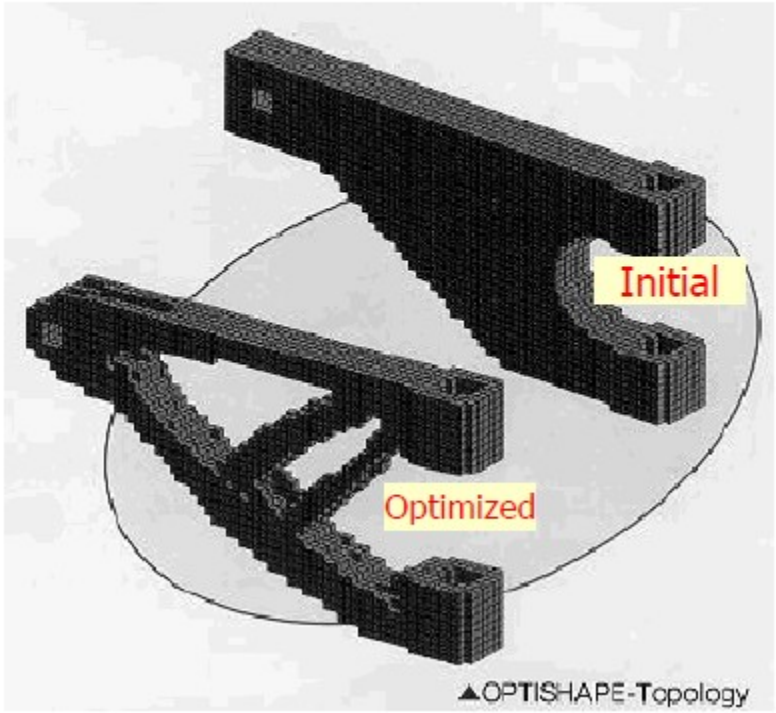
Obtain Pareto Front



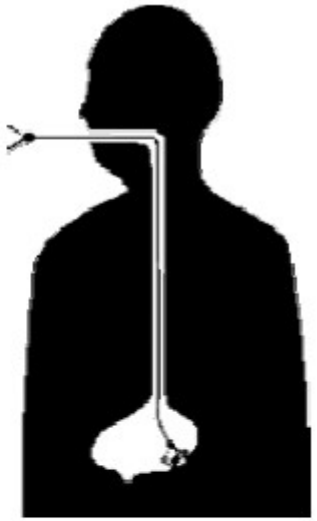
Short Cantilever problem

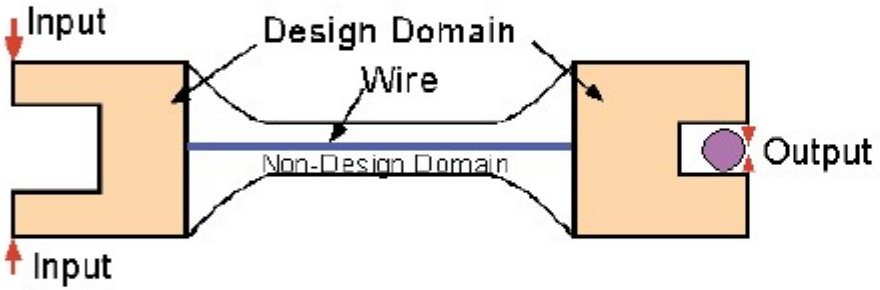


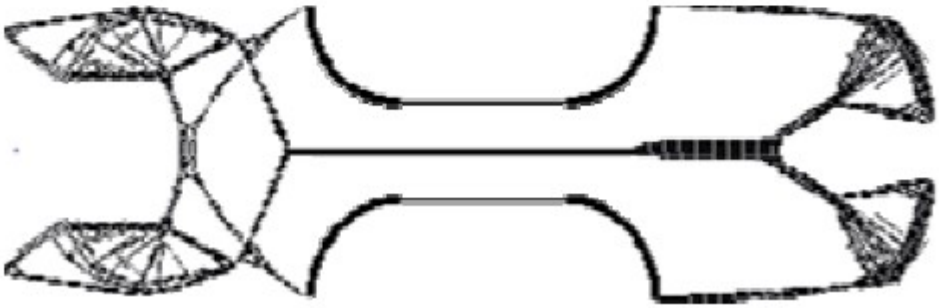




OPTIMISATION TOPOLOGIQUE

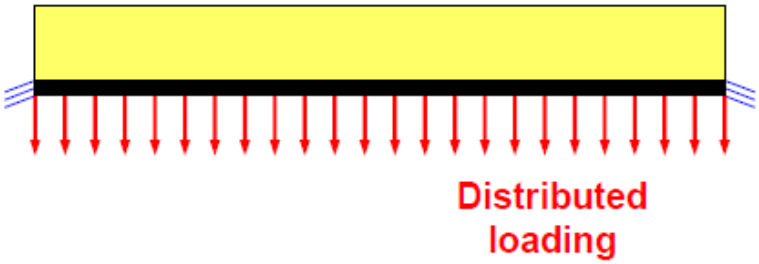






OPTIMISATION TOPOLOGIQUE

Bridge problem

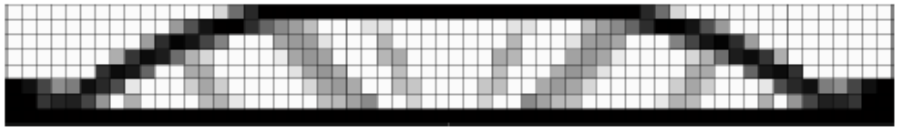


$$\text{Minimize} \quad \int_{\Gamma} F^i z^i d\Gamma,$$

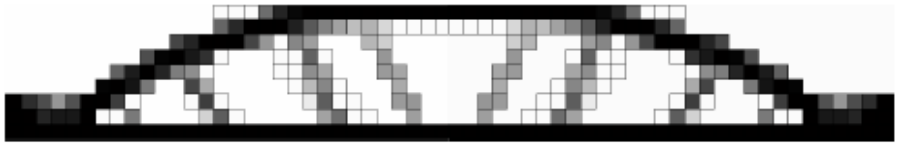
$$\text{Subject to} \quad \int_{\Omega} \rho(x) d\Omega \le M_o,$$

$$0 \le \rho(x) \le 1$$

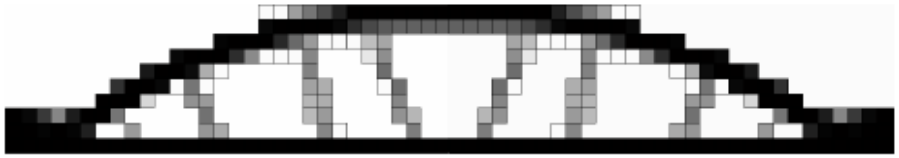
Mass constraints: 35%



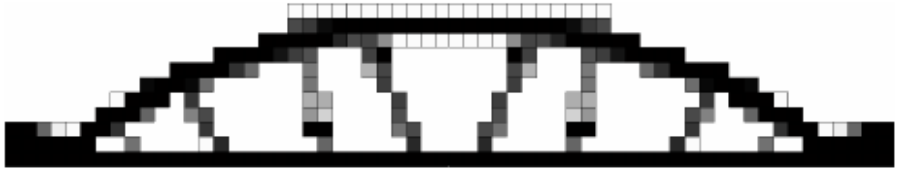
Obj = 4.16×10^5



Obj = 3.29×10^5

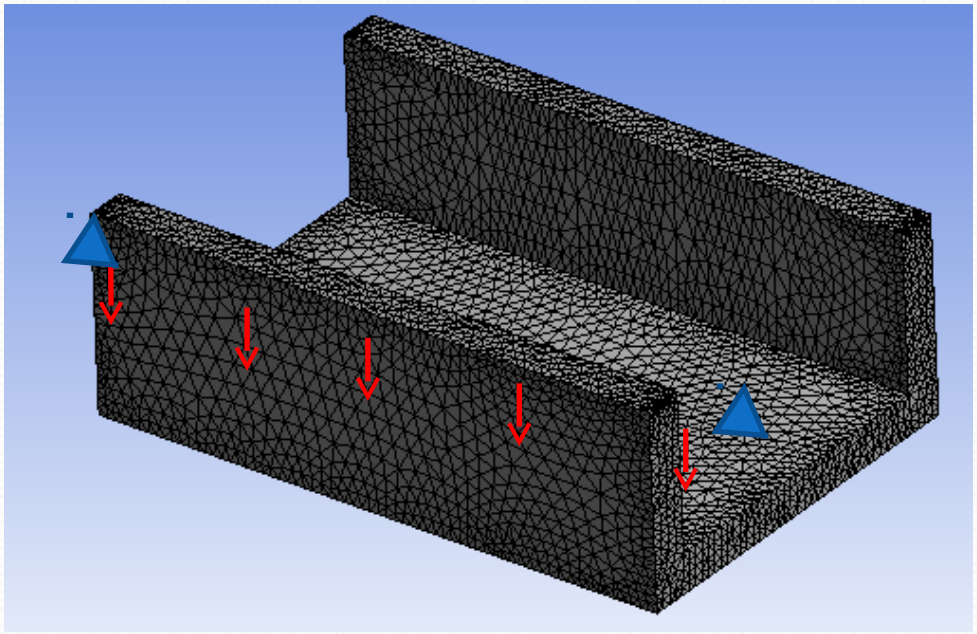


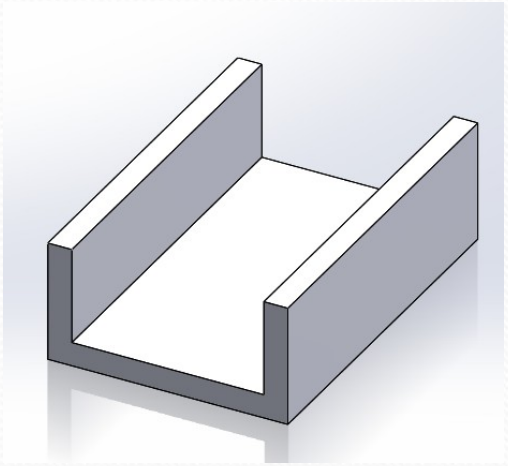
Obj = 2.88×10^5



Obj = 2.73×10^5

OPTIMISATION TOPOLOGIQUE





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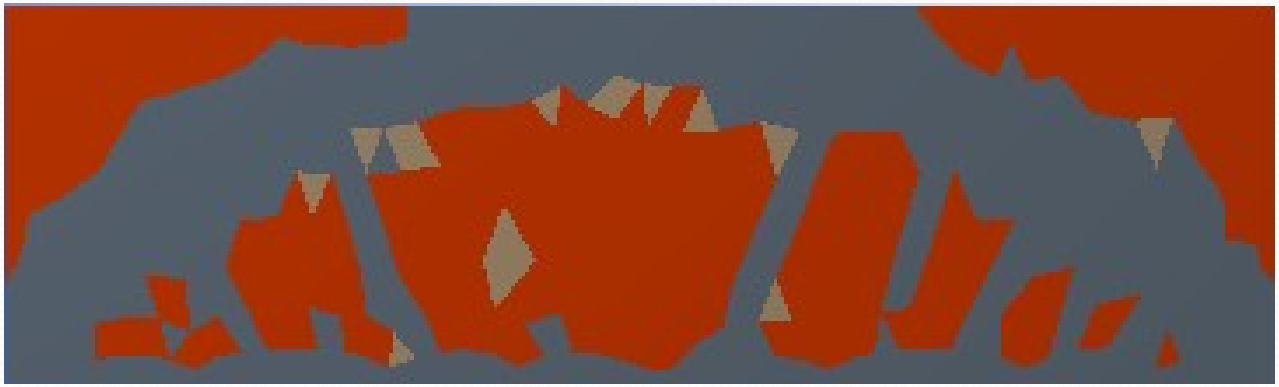
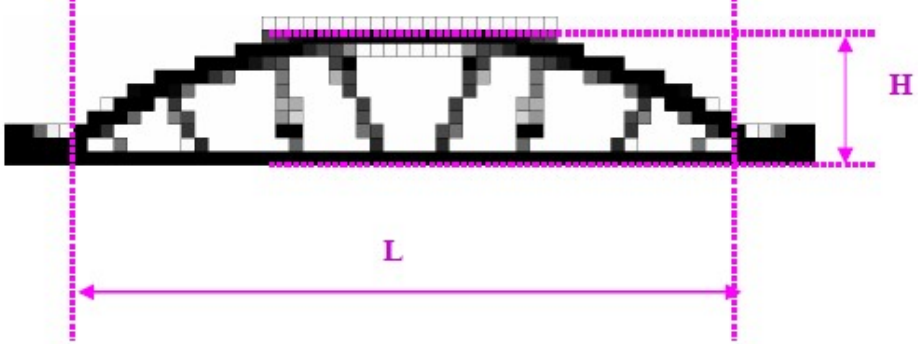
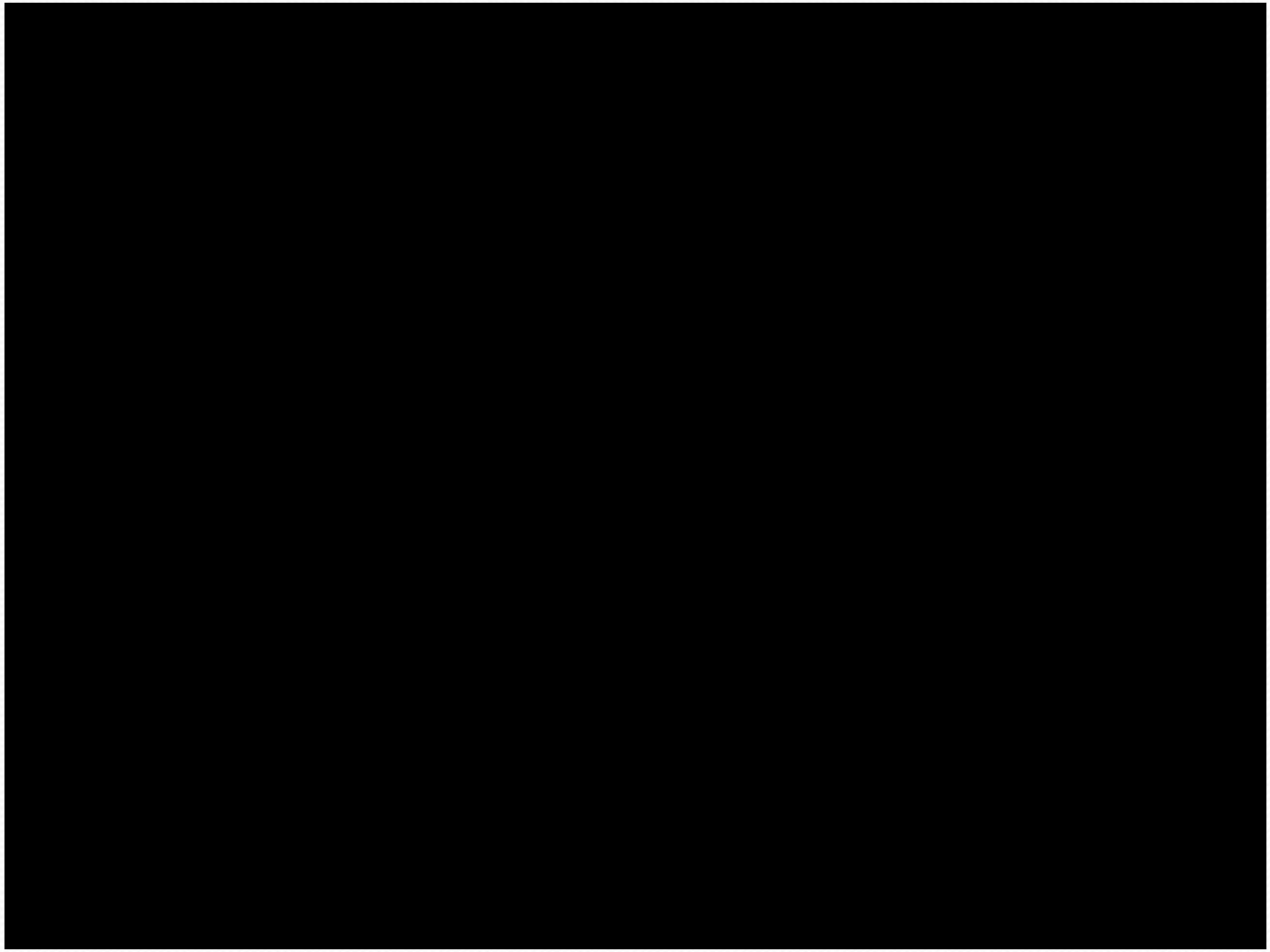
A garder



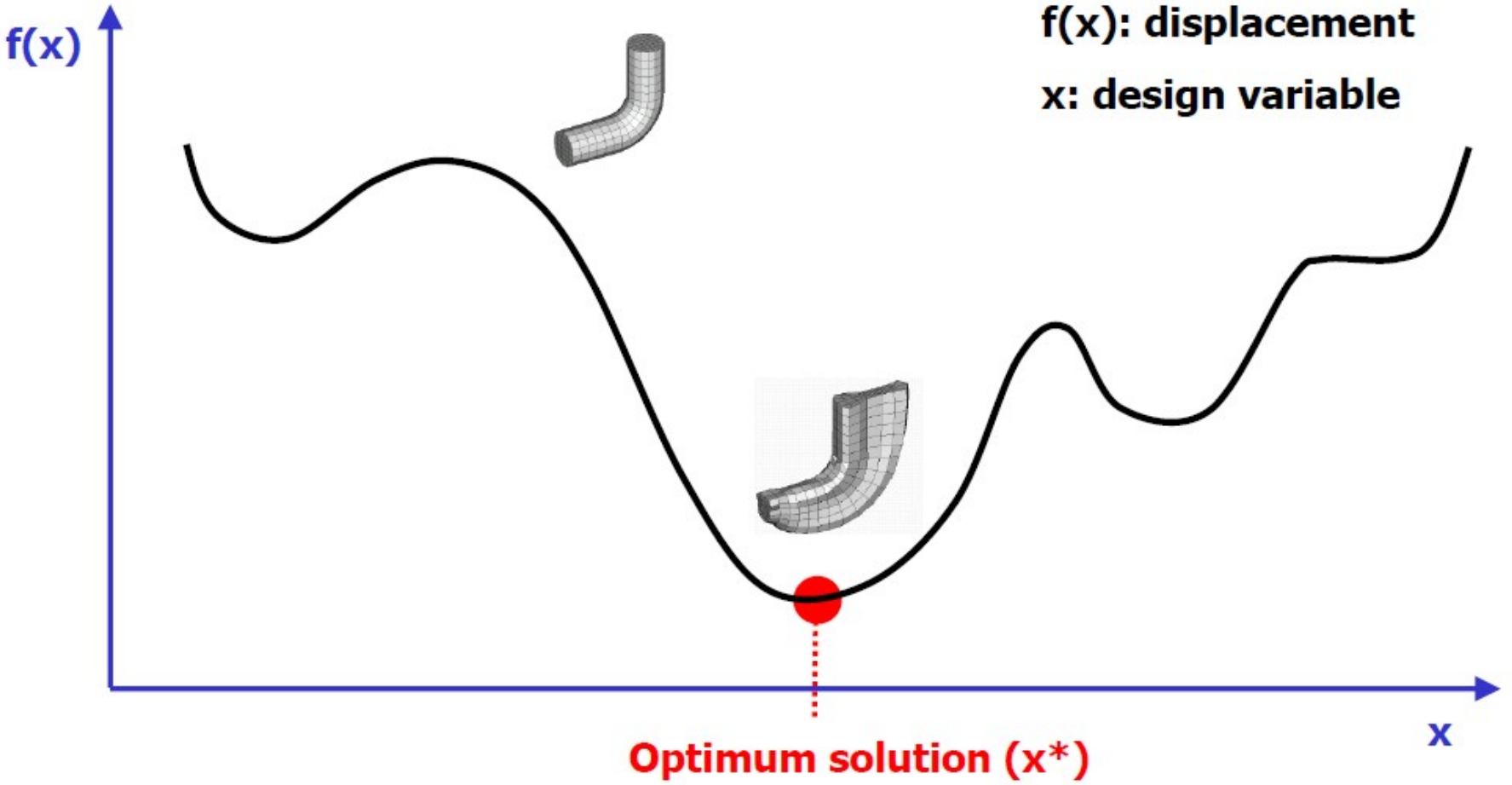
OPTIMISATION TOPOLOGIQUE
Ex : PONT



OPTIMISATION TOPOLOGIQUE
Ex : PONT



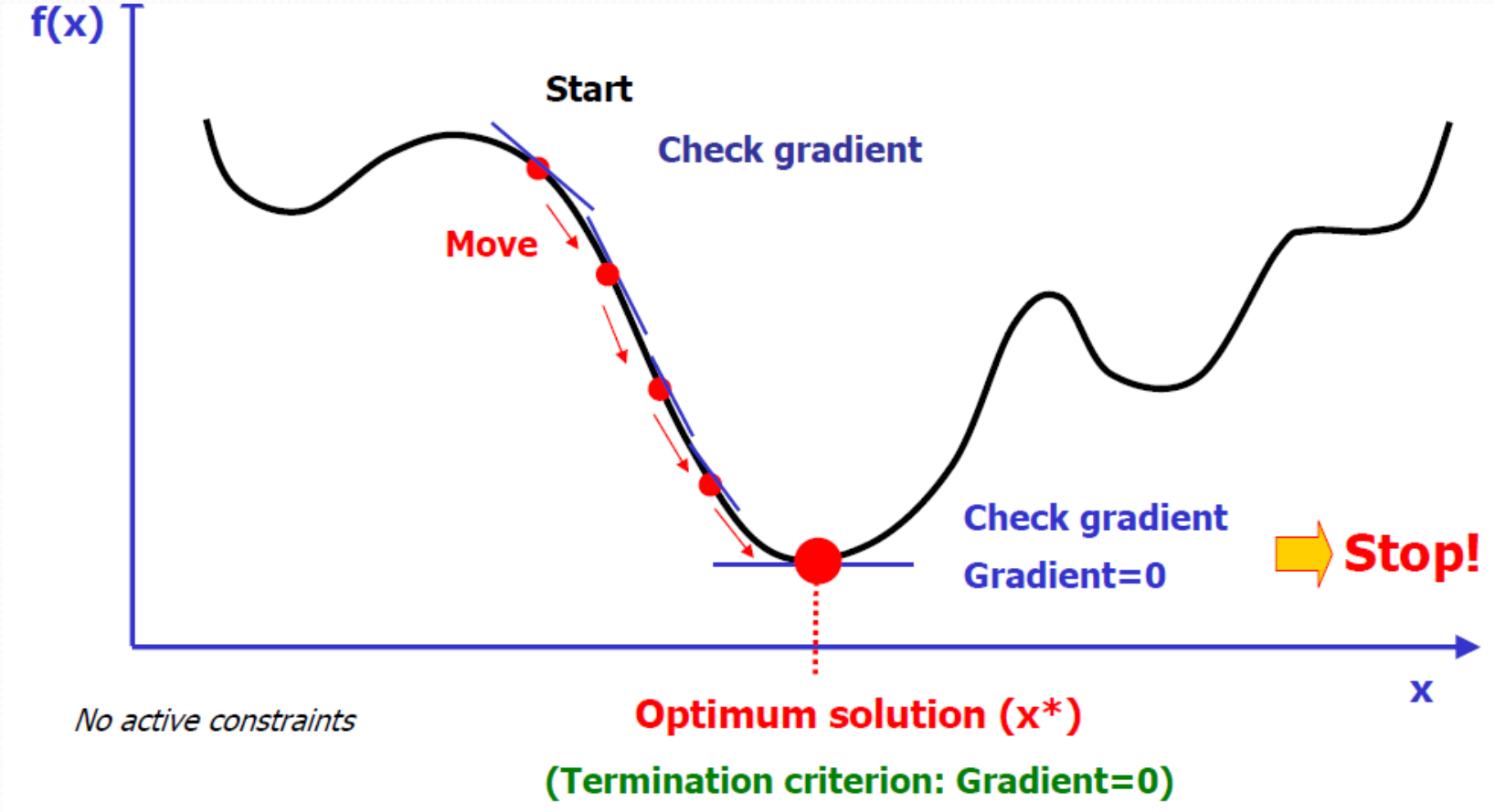
OPTIMISATION STRUCTURELLE : Représentation Graphique
SOLUTION OPTIMALE



Deux Méthodes d'optimisation :

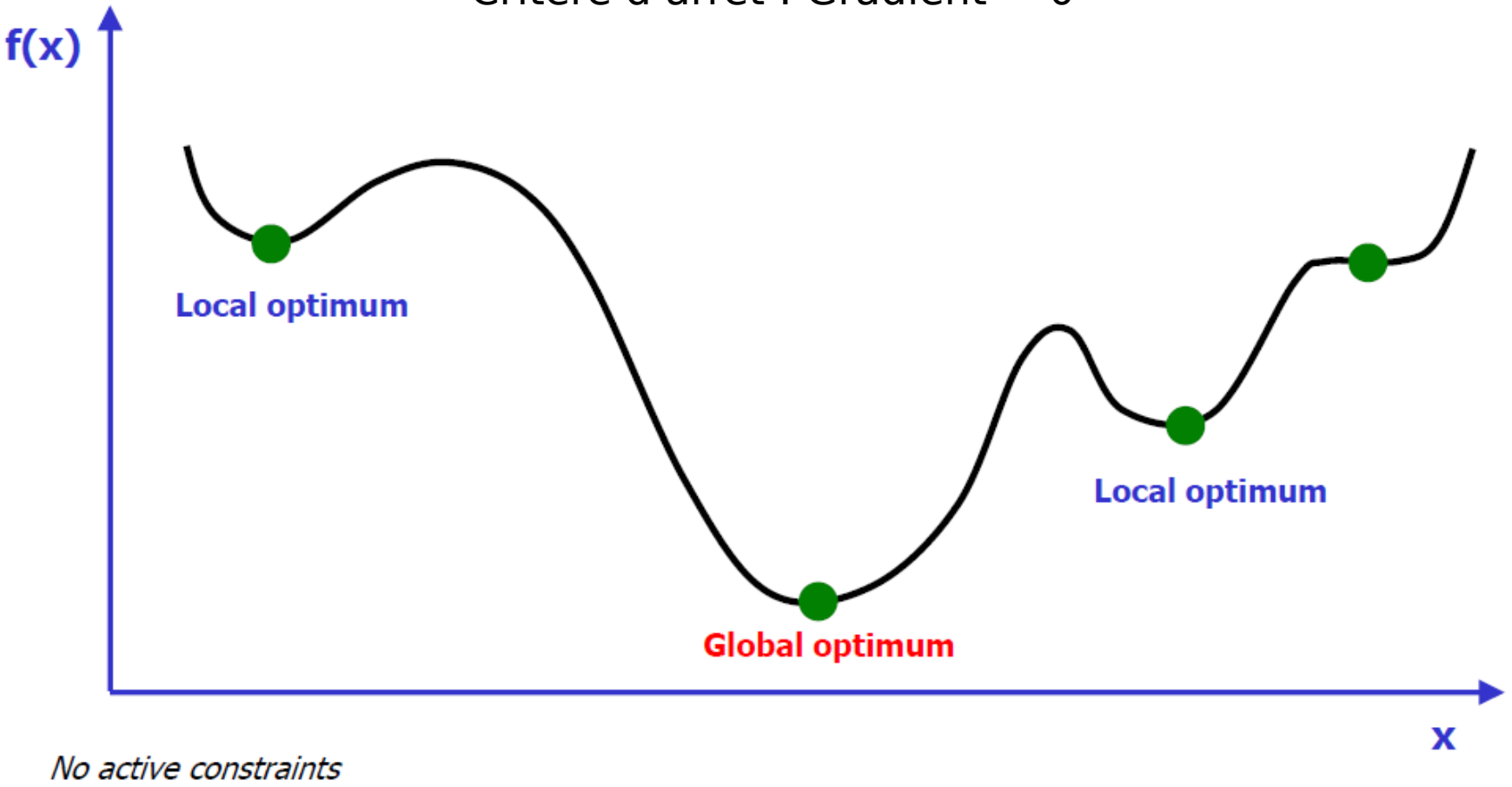
- Méthodes basées sur le Gradient
- Méthodes Heuristics

METHODES D'OPTIMISATION : METHODES BASEES SUR LE GRADIENT



METHODES BASEES SUR LE GRADIENT

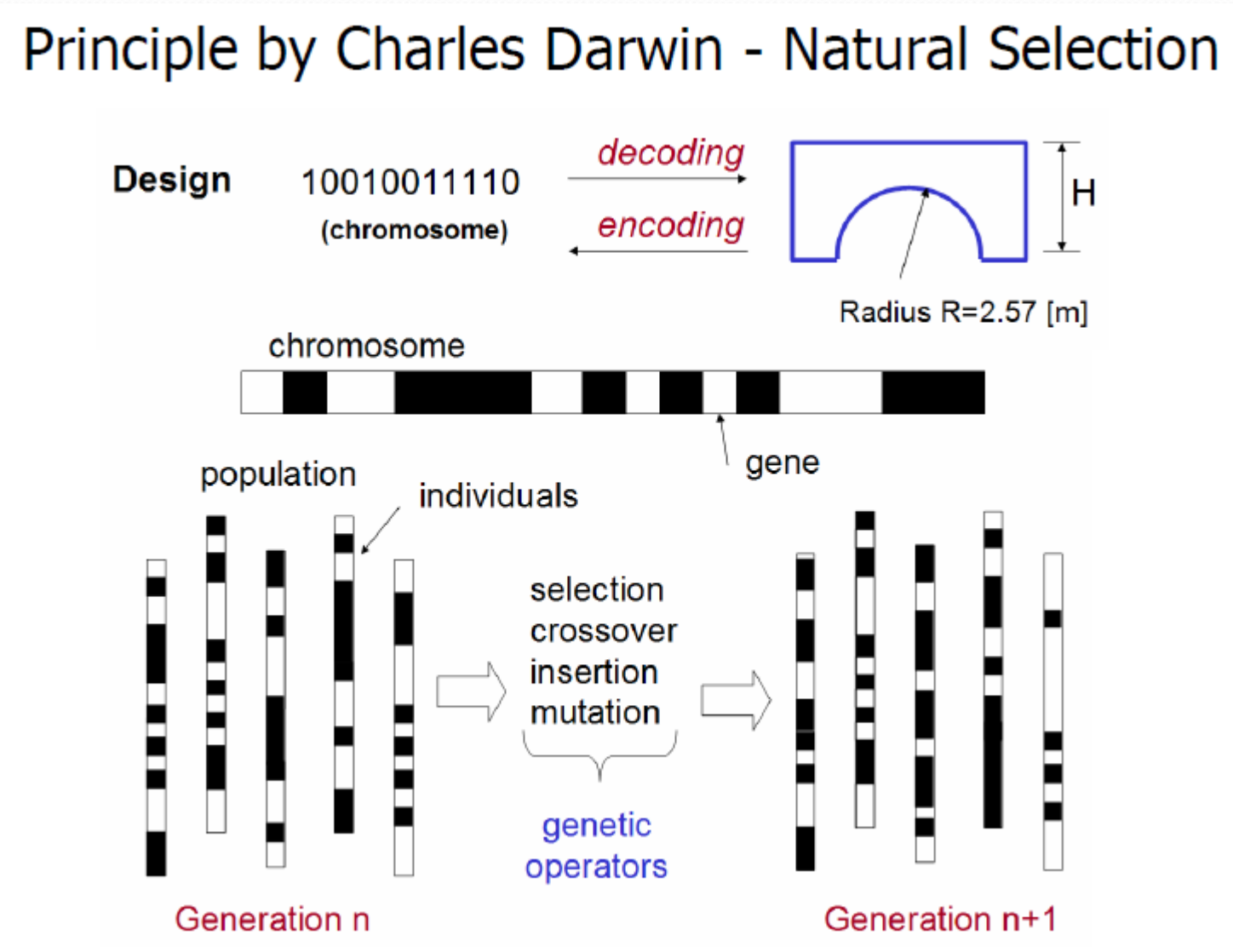
Critère d'arrêt : Gradient = 0



METHODES HEURISTICS

- A Heuristic is simply a rule of thumb that hopefully will find a good answer.
- Why use a Heuristic?
  - Heuristics are typically used to solve complex optimization problems that are difficult to solve to optimality.
- Heuristics are good at dealing with local optima without getting stuck in them while searching for the global optimum.

LES ALGORITHMES GENETIQUES



METHODES HEURISTICS

- Heuristics Often Incorporate Randomization

- **3 Most Common Heuristic Techniques**
  - Genetic Algorithms
  - Simulated Annealing
  - Tabu Search

LOGICIELS D'OPTIMISATION TOPOLOGIQUE

ANSYS

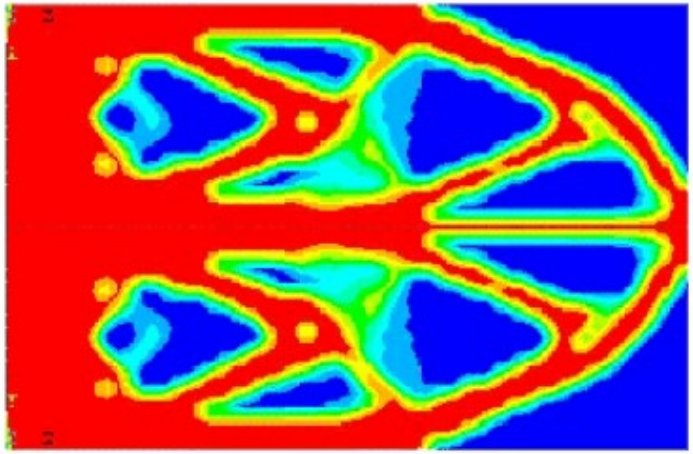
Static Topology Optimization

Dynamic Topology Optimization

Electromagnetic Topology Optimization

Subproblem Approximation Method

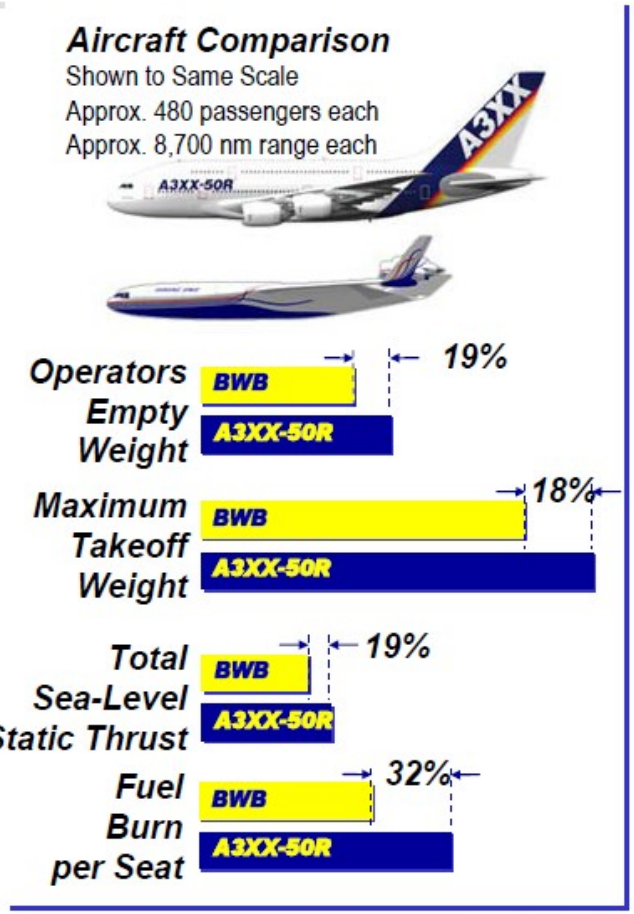
First Order Method



Multidisciplinary Design Optimization
MDO

Boeing Blended Wing Body Concept

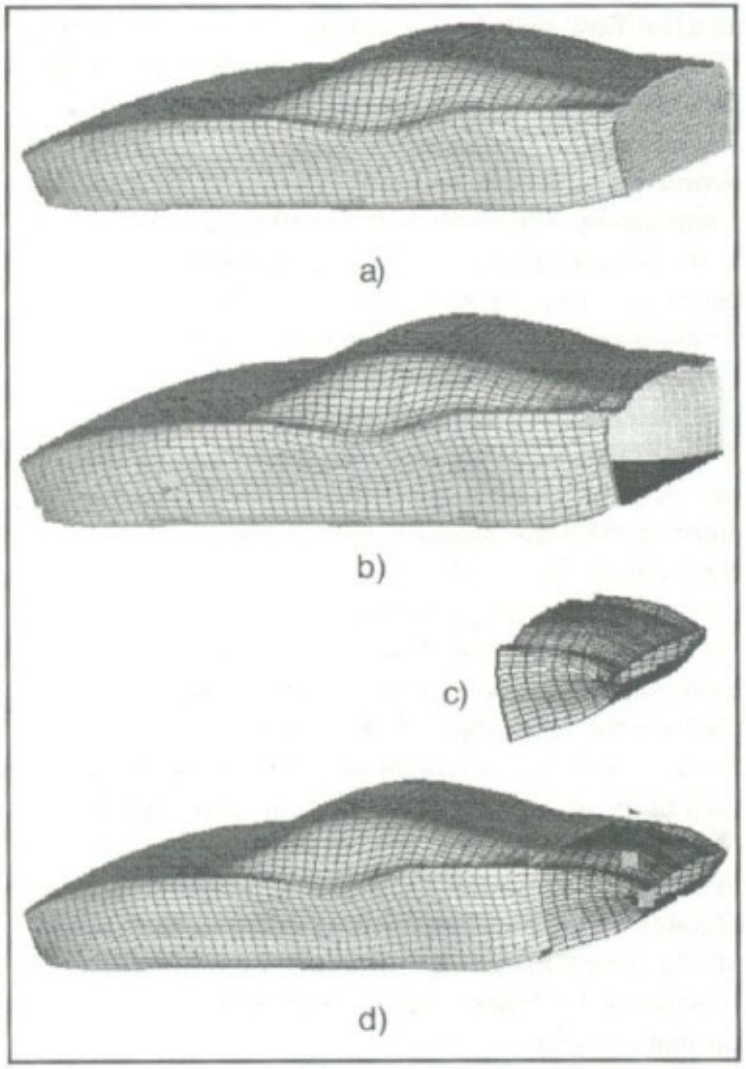
Goal: Find a design for a family of blended wing aircraft that will combine aerodynamics, structures, propulsion and controls such that a competitive system emerges - as measured by a set of operator metrics.



Multidisciplinary Design Optimization
MDO

Ferrari 360 Spider

Goal: High end vehicle shape optimization while improving car safety for fixed performance level and given geometric constraints



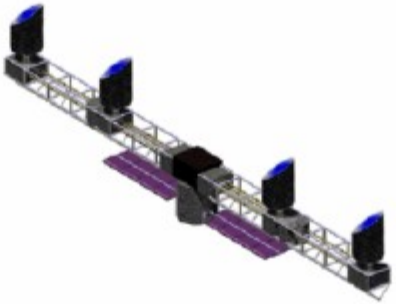
Reference: G. Lombardi, A. Vicere, H. Paap, G. Manacorda, "Optimized Aerodynamic Design for High Performance Cars", AIAA-98-4789, MAO Conference, St. Louis, 1998

Multidisciplinary Design Optimization
MDO

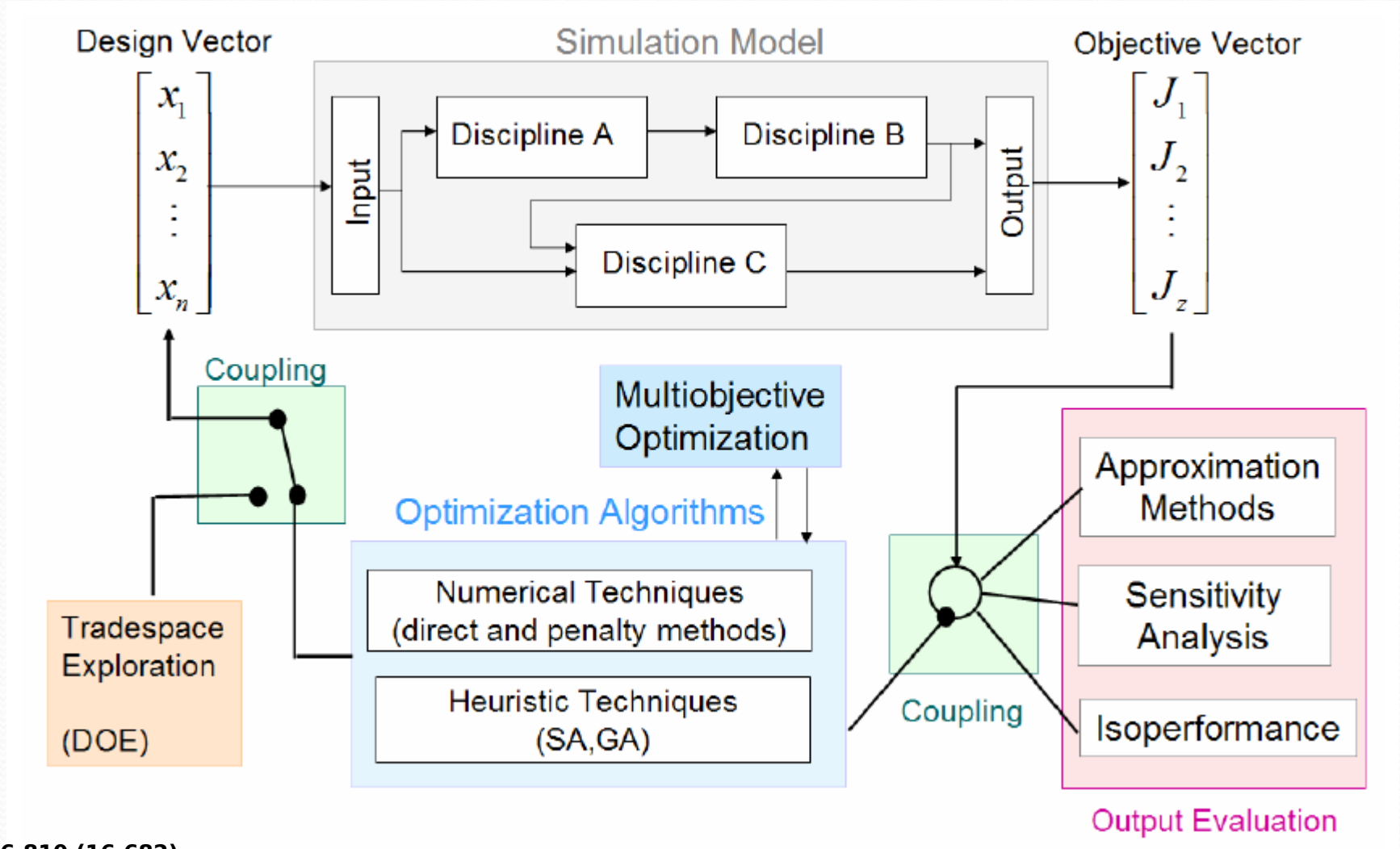
Aircraft:
Aerodynamics
Propulsion
Structures
Controls
Avionics/Software
Manufacturing
others

Spacecraft:
Astrodynamics
Thermodynamics
Communications
Payload & Sensor
Structures
Optics
Guidance & Control

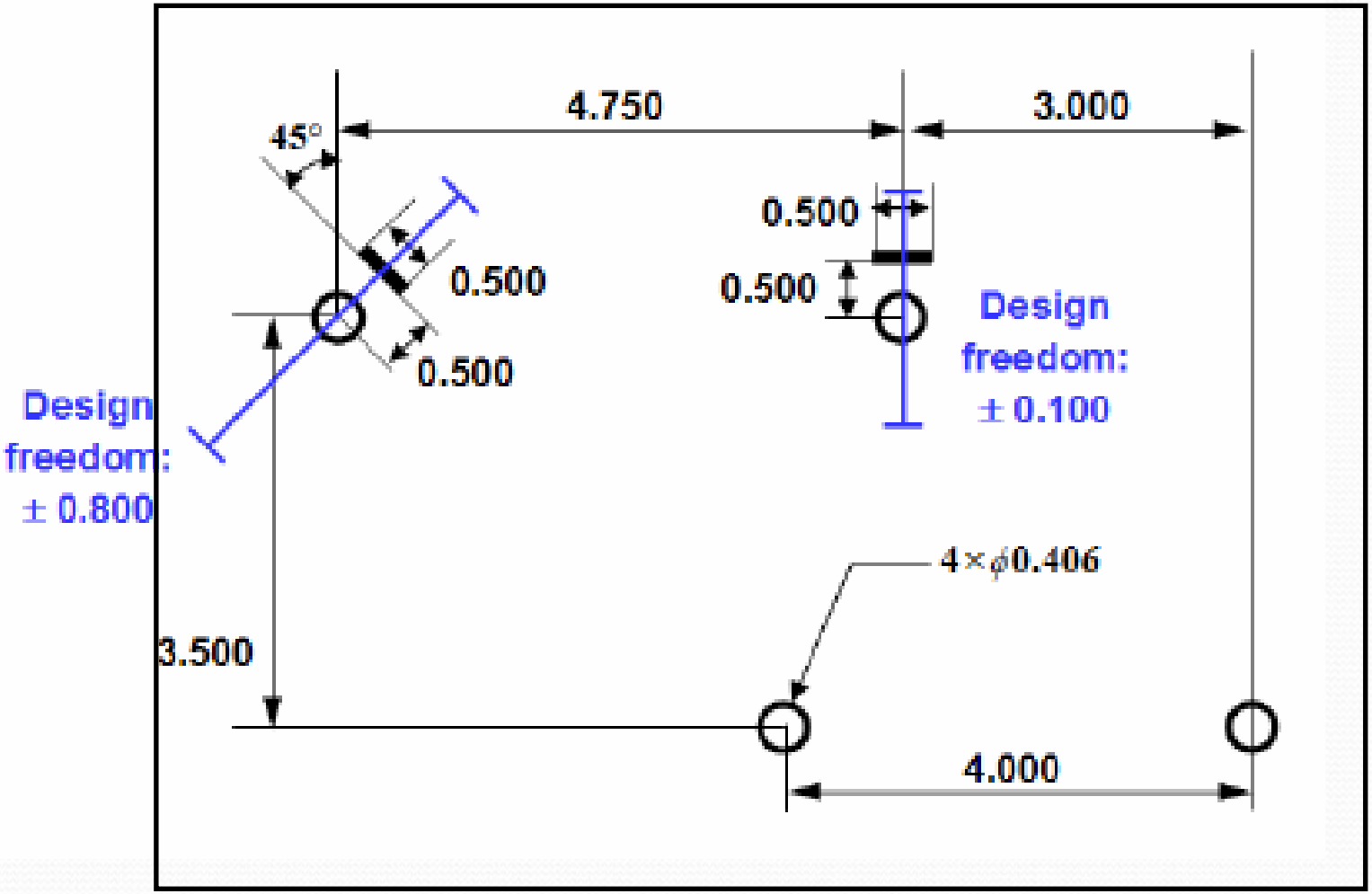
Automobiles:
Engines
Body/chassis
Aerodynamics
Electronics
Hydraulics
Industrial design
others



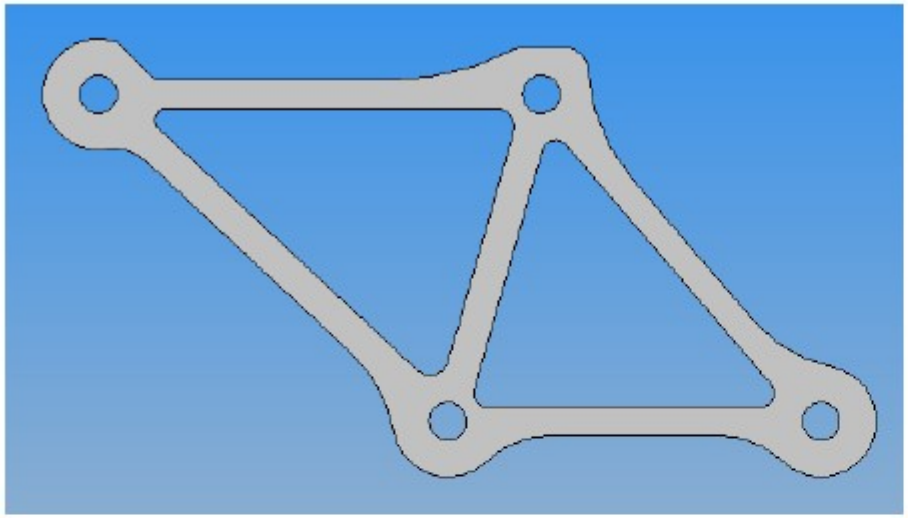
Multidisciplinary Design Optimization
MDO

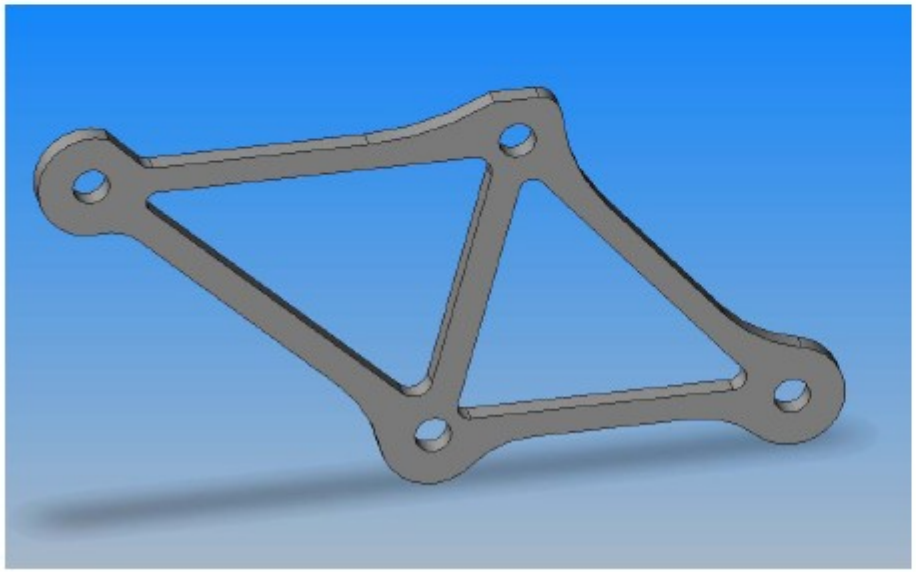


EXEMPLES


4.750
3.000
45°
0.500
0.500
0.500
0.500
Design freedom: ± 0.100
Design freedom: ± 0.800
4×ϕ0.406
3.500
4.000

EXEMPLES





Performance and cost

$$\delta_1 = 0.070\ mm$$

$$\delta_2 = 0.011\ mm$$

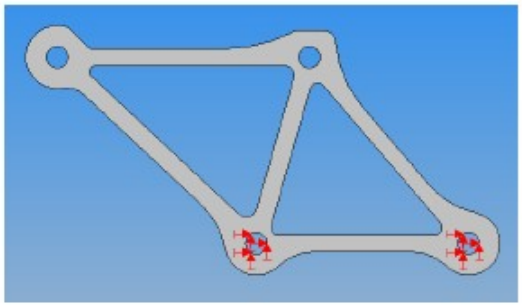
$$f = 245\ Hz$$

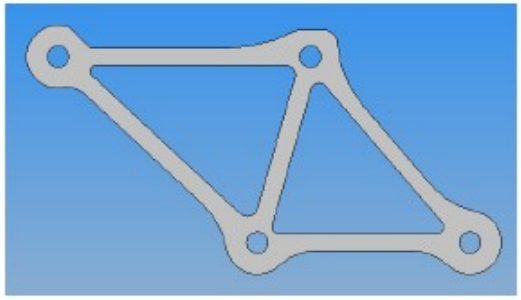
$$m = 0.224\ lbs$$

$$C = 5.16\ \$$$

EXEMPLES

245 Hz



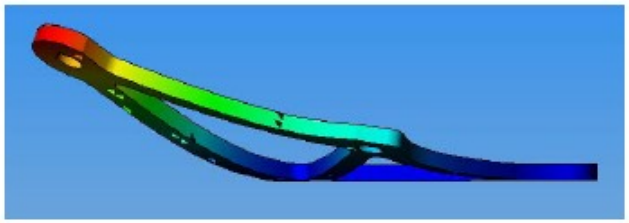


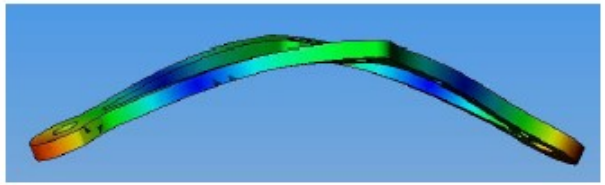
421 Hz

f1=245 Hz

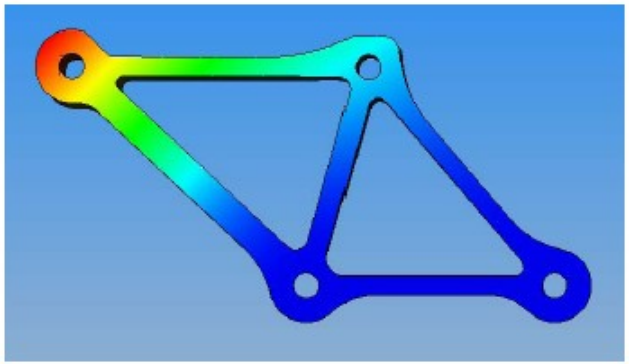
f2=490 Hz

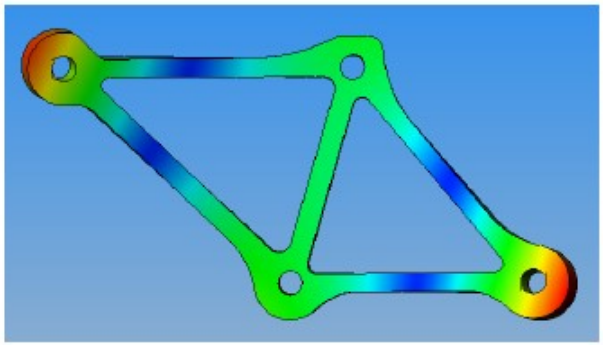
f3=1656 Hz





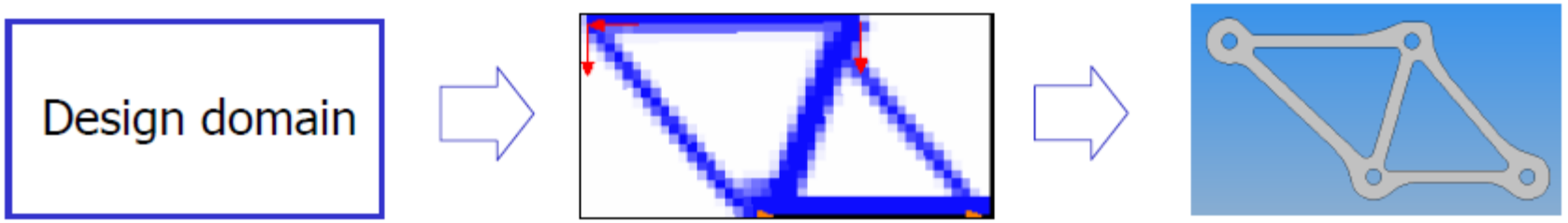
f1=0
f2=0
f3=0
f4=0
f5=0
f6=0
f7=421 Hz
f8=1284 Hz
f9=1310 Hz



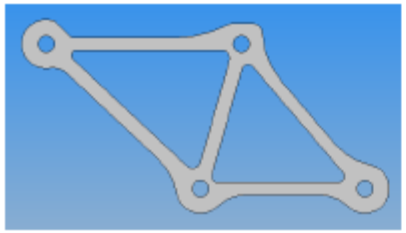


EXEMPLES

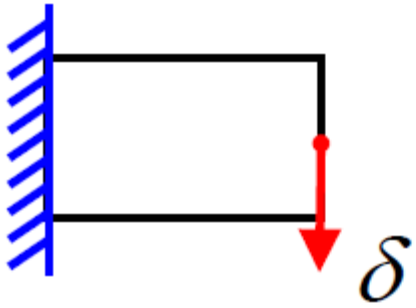
Topology optimization



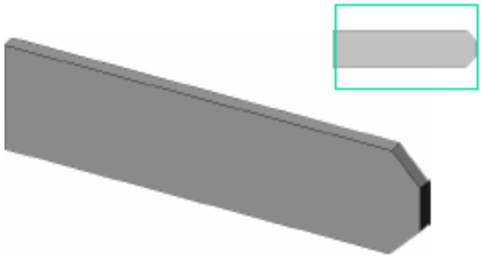
Shape optimization



EXEMPLES

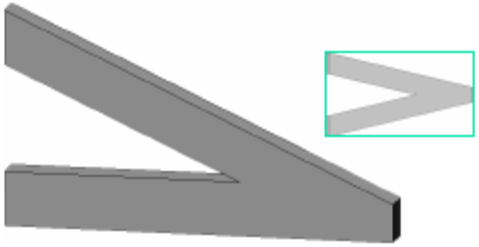


1 bar



$\delta = 2.50\ mm$

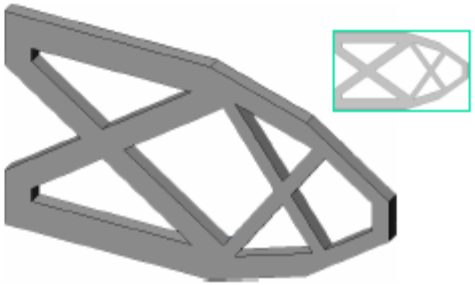
2 bars



$\delta = 0.80\ mm$

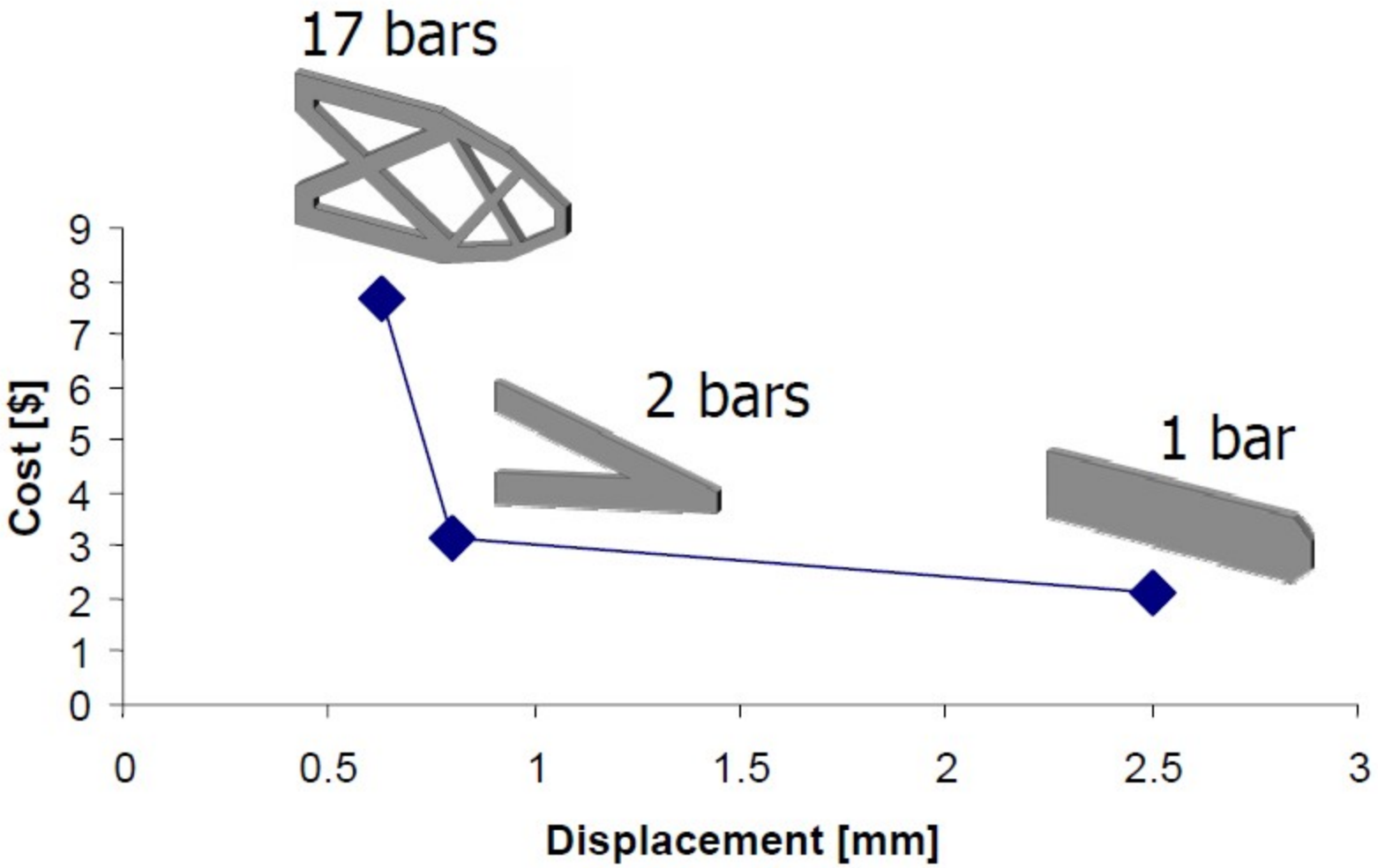
Volume is the same.

17 bars

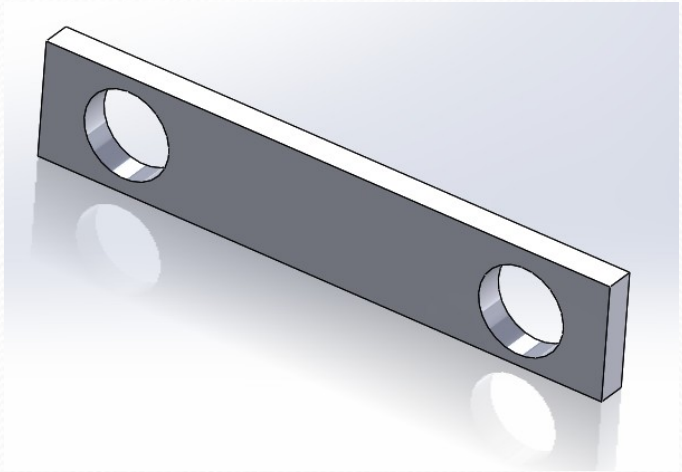


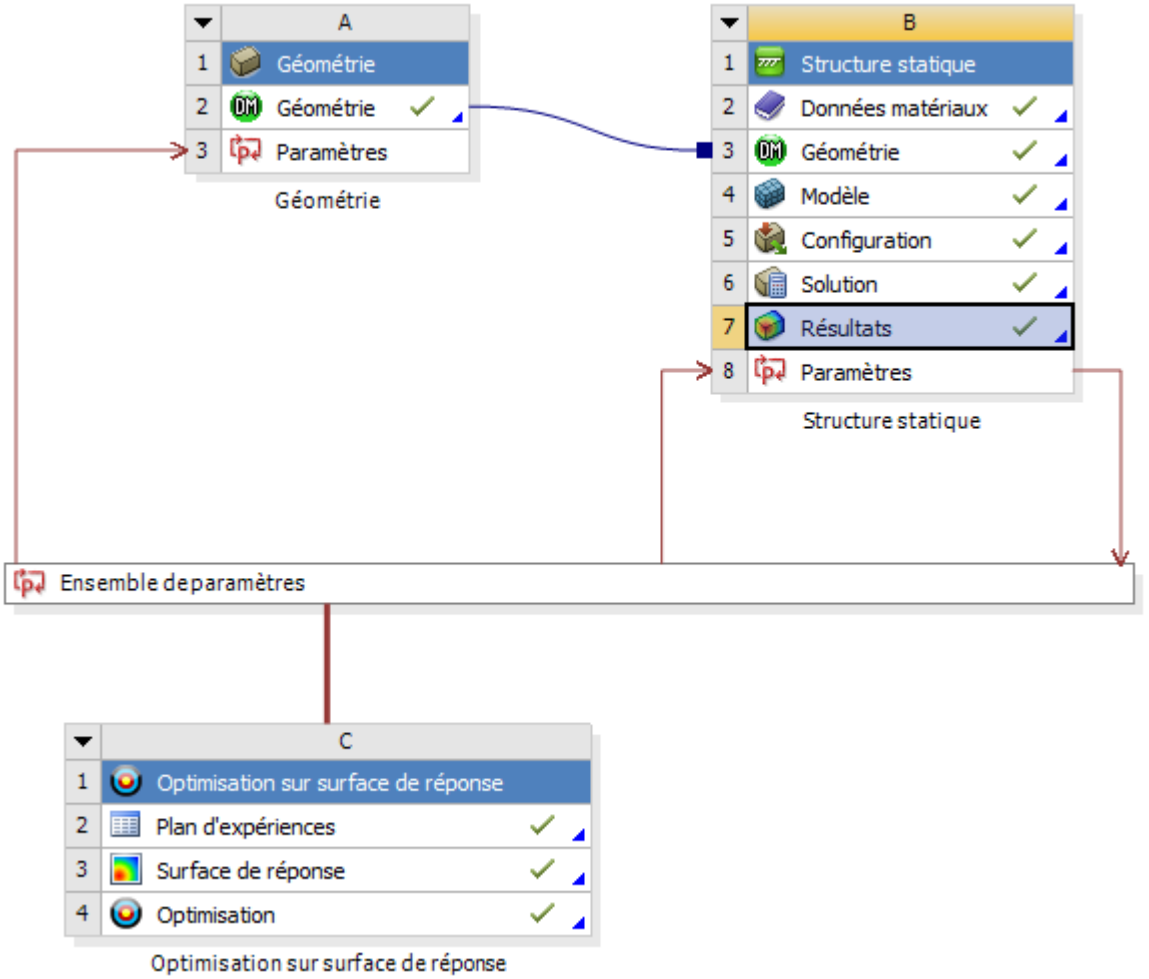
$\delta = 0.63\ mm$

EXEMPLES

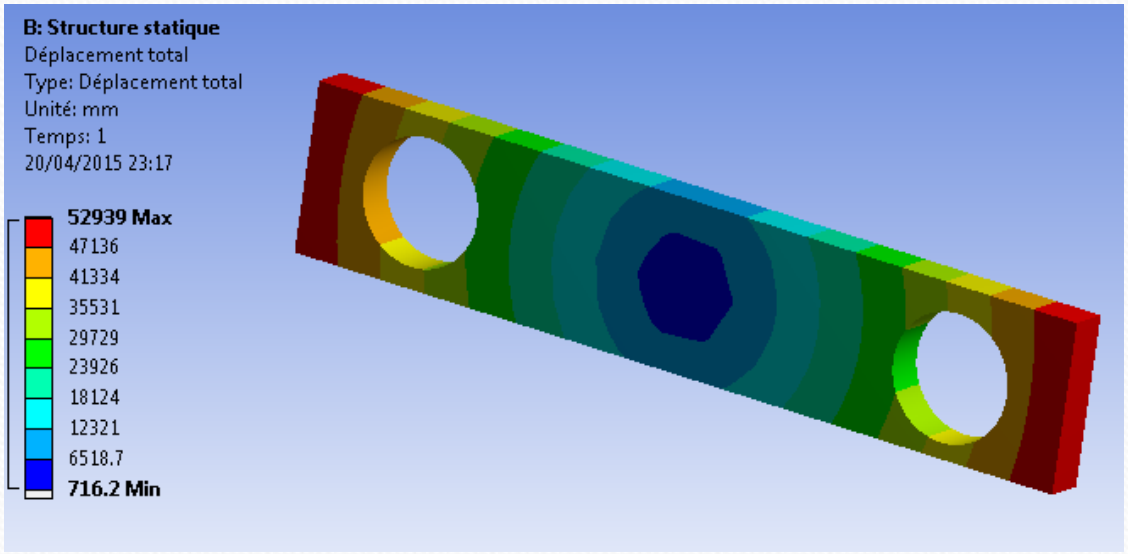

17 bars
2 bars
1 bar
Cost [$]
0
1
2
3
4
5
6
7
8
9
0
0.5
1
1.5
2
2.5
3
Displacement [mm]

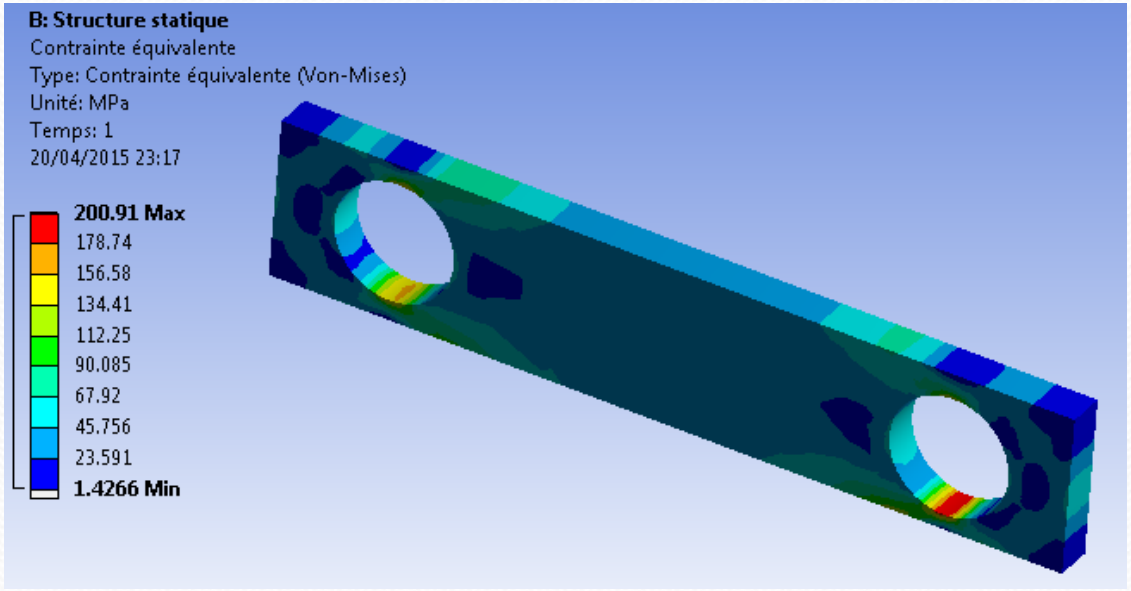
EXEMPLES



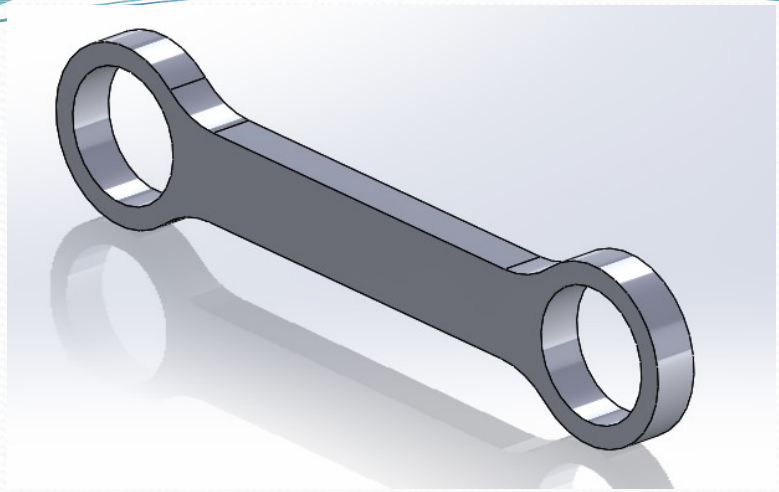

A
1 Géométrie
2 Géométrie
3 Paramètres
Géométrie
B
1 Structure statique
2 Données matériaux
3 Géométrie
4 Modèle
5 Configuration
6 Solution
7 Résultats
8 Paramètres
Structure statique
Ensemble de paramètres
C
1 Optimisation sur surface de réponse
2 Plan d'expériences
3 Surface de réponse
4 Optimisation
Optimisation sur surface de réponse

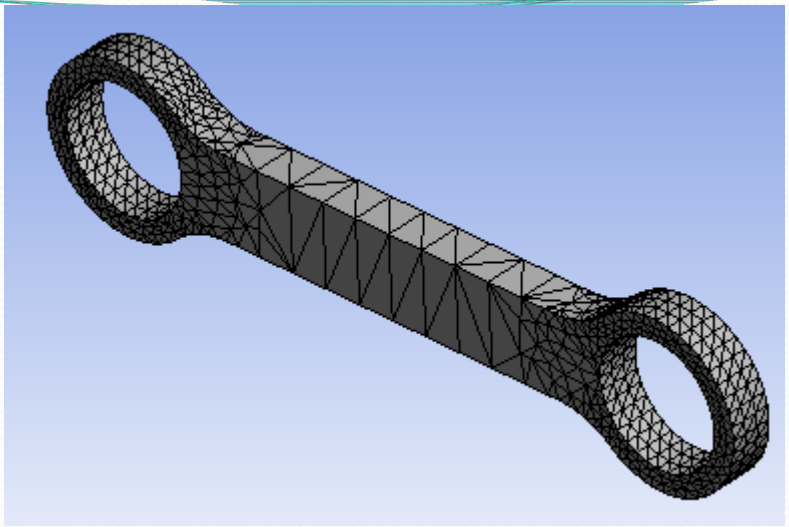
EXEMPLES

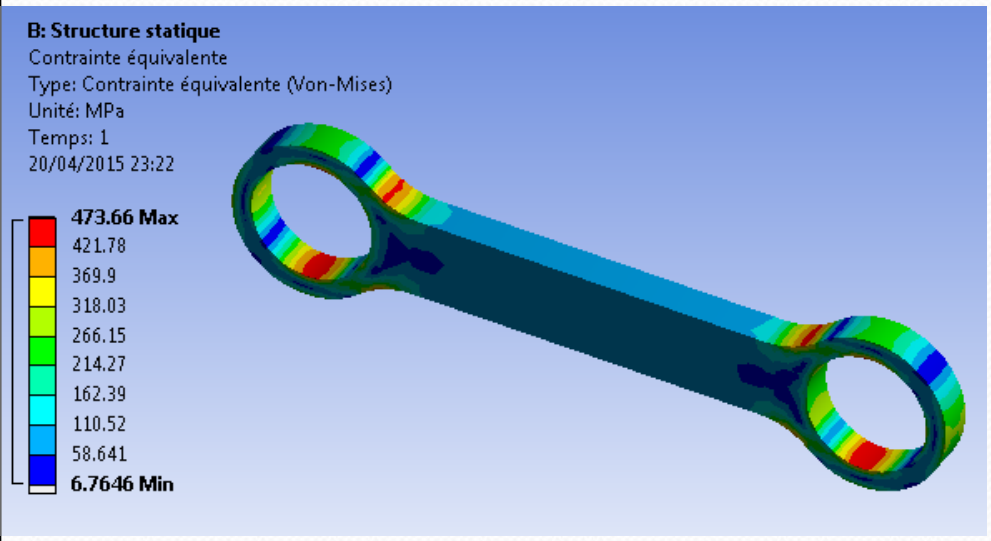

B: Structure statique
Déplacement total
Type: Déplacement total
Unité: mm
Temps: 1
20/04/2015 23:17
52939 Max
47136
41334
35531
29729
23926
18124
12321
6518.7
716.2 Min

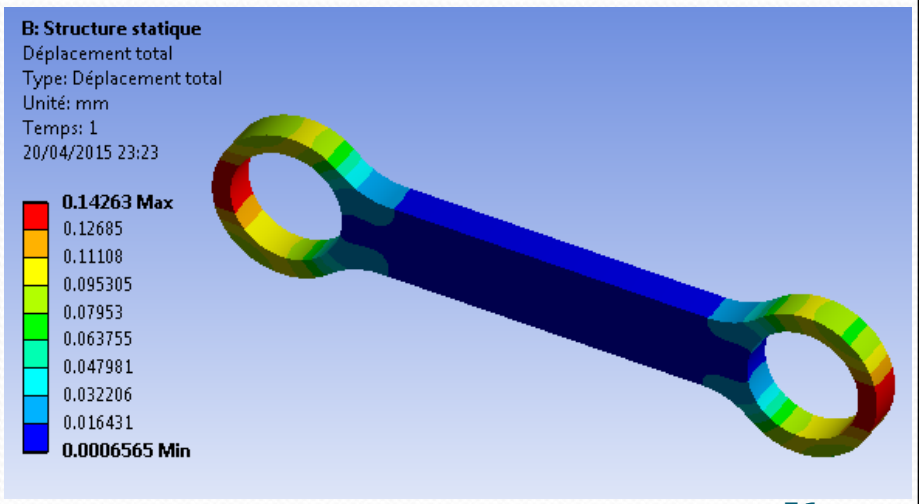

B: Structure statique
Contrainte équivalente
Type: Contrainte équivalente (Von-Mises)
Unité: MPa
Temps: 1
20/04/2015 23:17
200.91 Max
178.74
156.58
134.41
112.25
90.085
67.92
45.756
23.591
1.4266 Min

EXEMPLES

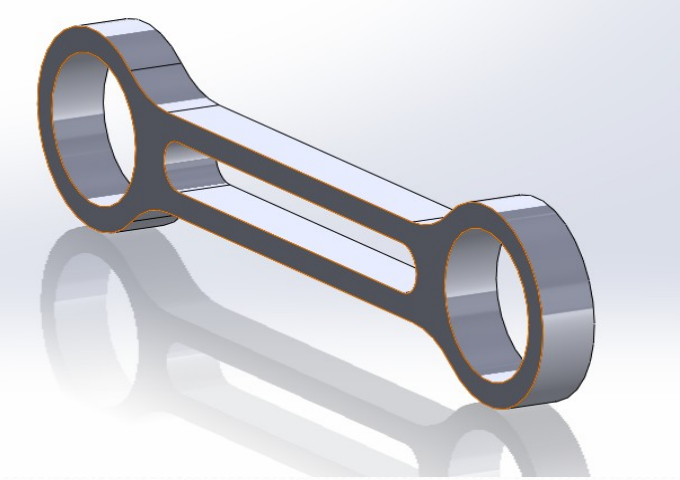


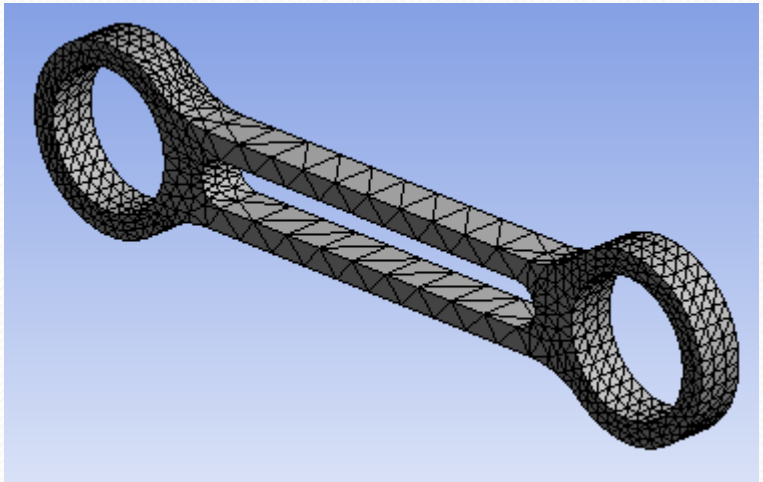


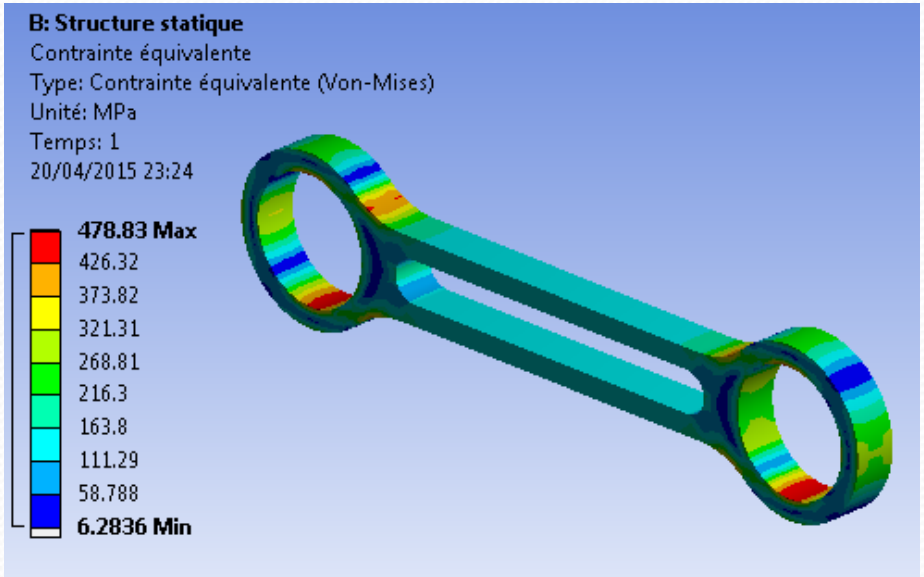

B: Structure statique
Contrainte équivalente
Type: Contrainte équivalente (Von-Mises)
Unité: MPa
Temps: 1
20/04/2015 23:22
473.66 Max
421.78
369.9
318.03
266.15
214.27
162.39
110.52
58.641
6.7646 Min

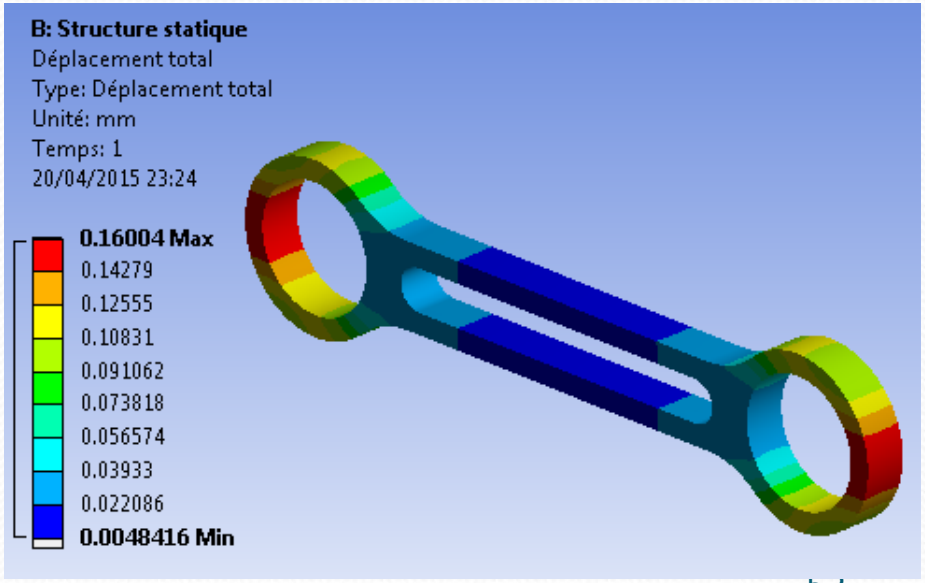

B: Structure statique
Déplacement total
Type: Déplacement total
Unité: mm
Temps: 1
20/04/2015 23:23
0.14263 Max
0.12685
0.11108
0.095305
0.07953
0.063755
0.047981
0.032206
0.016431
0.0006565 Min

EXEMPLES



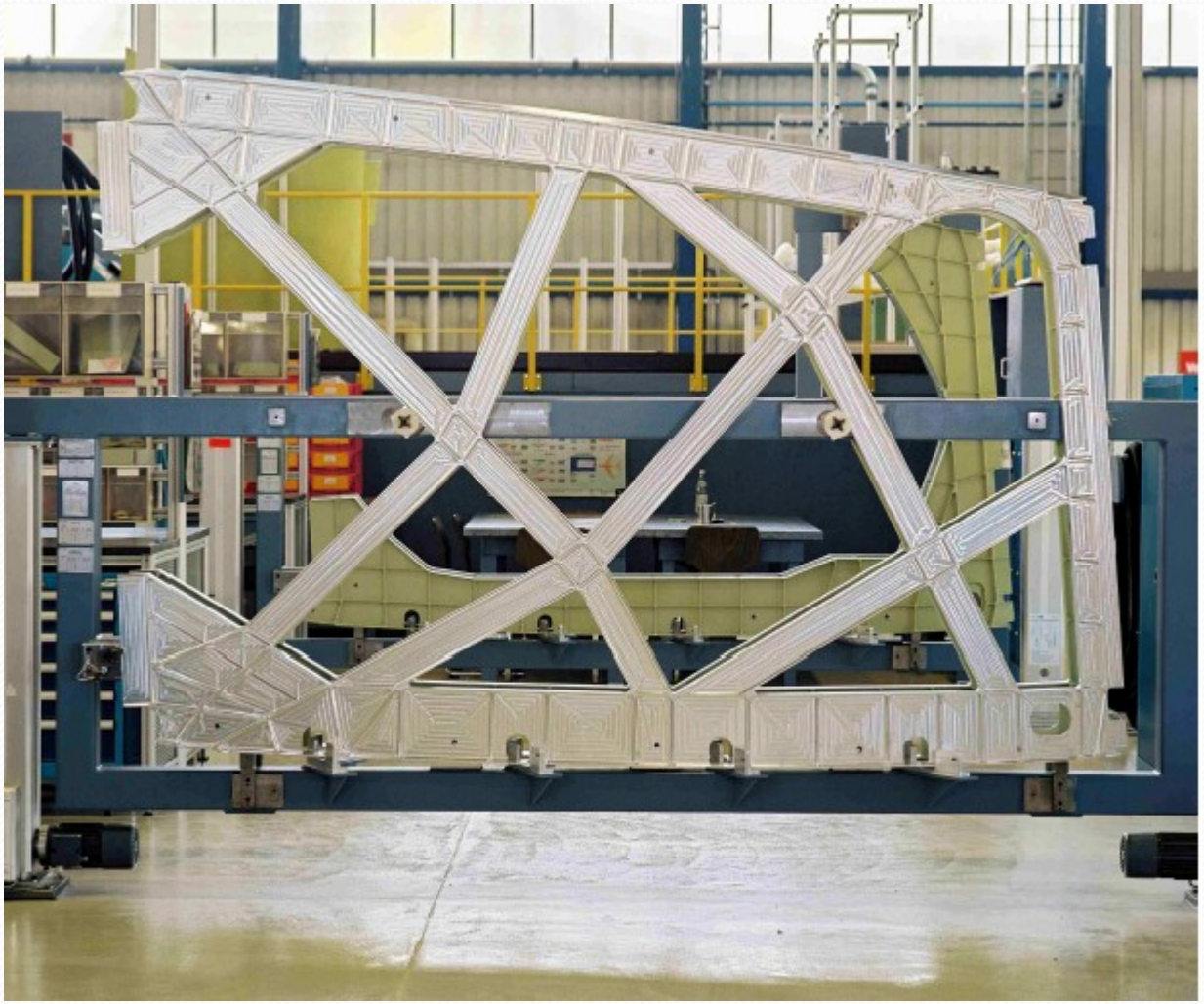



B: Structure statique
Contrainte équivalente
Type: Contrainte équivalente (Von-Mises)
Unité: MPa
Temps: 1
20/04/2015 23:24
478.83 Max
426.32
373.82
321.31
268.81
216.3
163.8
111.29
58.788
6.2836 Min


B: Structure statique
Déplacement total
Type: Déplacement total
Unité: mm
Temps: 1
20/04/2015 23:24
0.16004 Max
0.14279
0.12555
0.10831
0.091062
0.073818
0.056574
0.03933
0.022086
0.0048416 Min

EXEMPLES

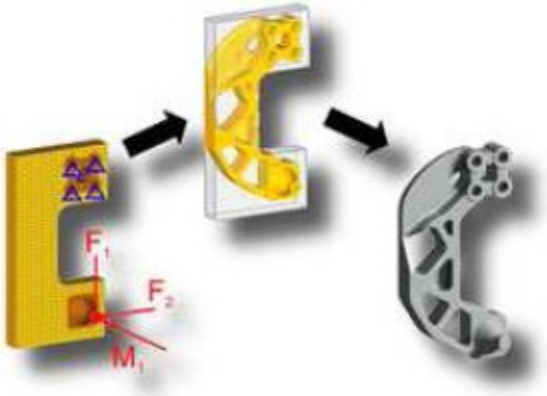
EXEMPLES

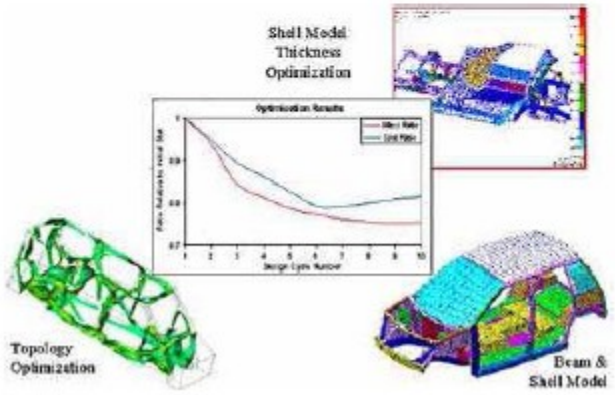


EXEMPLES

Logiciels industriels

Optistruct, Ansys DesignSpace, Genesis, MSC-Nastran, Tosca, devDept...





MERCI

Pr. BOUDI M.
EMI