Opening the design space by removing constraints with Additive Manufacturing and Topology Optimization

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The Micro and Nanoscale Design (MnD) Group

- NTNU- Department of Mechanical and Industrial Engineering
- 6 PhD/ 6 Master Students
- Publications (2017-2020): 44 Journal Articles/ 1 Patent
- 1 Frinatek grant (similar to FWF Start), 1 ERC grant
- Supported by Stanford University and TU Wien

NanoNetwork

The Research Council of Norway

ENGINEERING

erc European Research Council

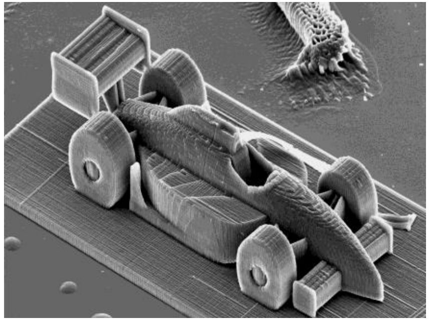
SIU

New possibilities through AM

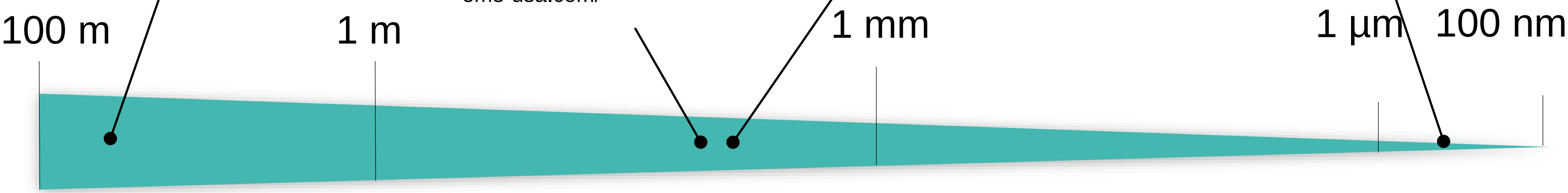
mx3D.com

ems-usa.com/

Stratasys.com



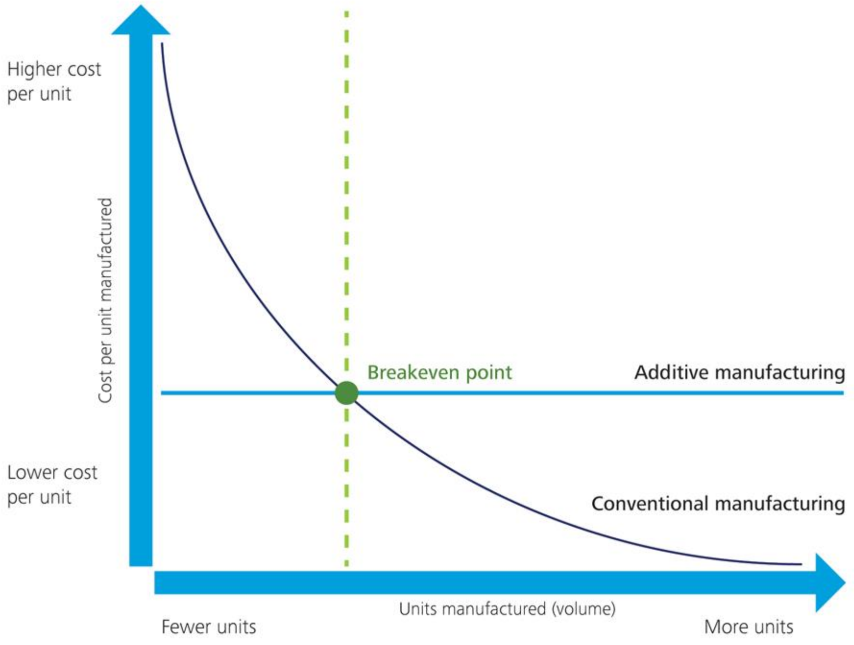
TU Wien 2012



New possibilities through AM

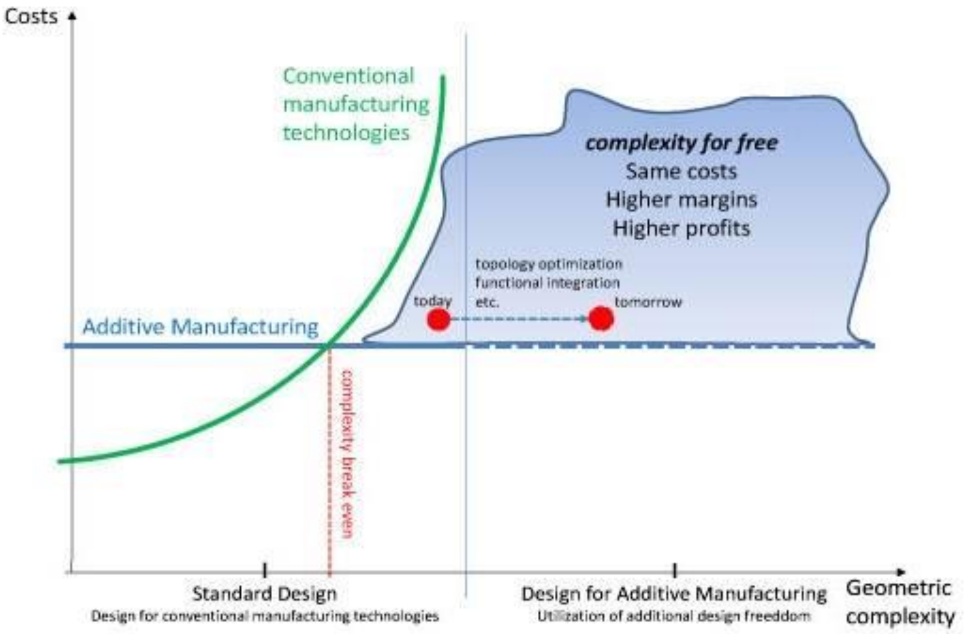
https://www.youtube.com/watch?v=GUdnrtnjT5Q

Possibilities in design through additive production



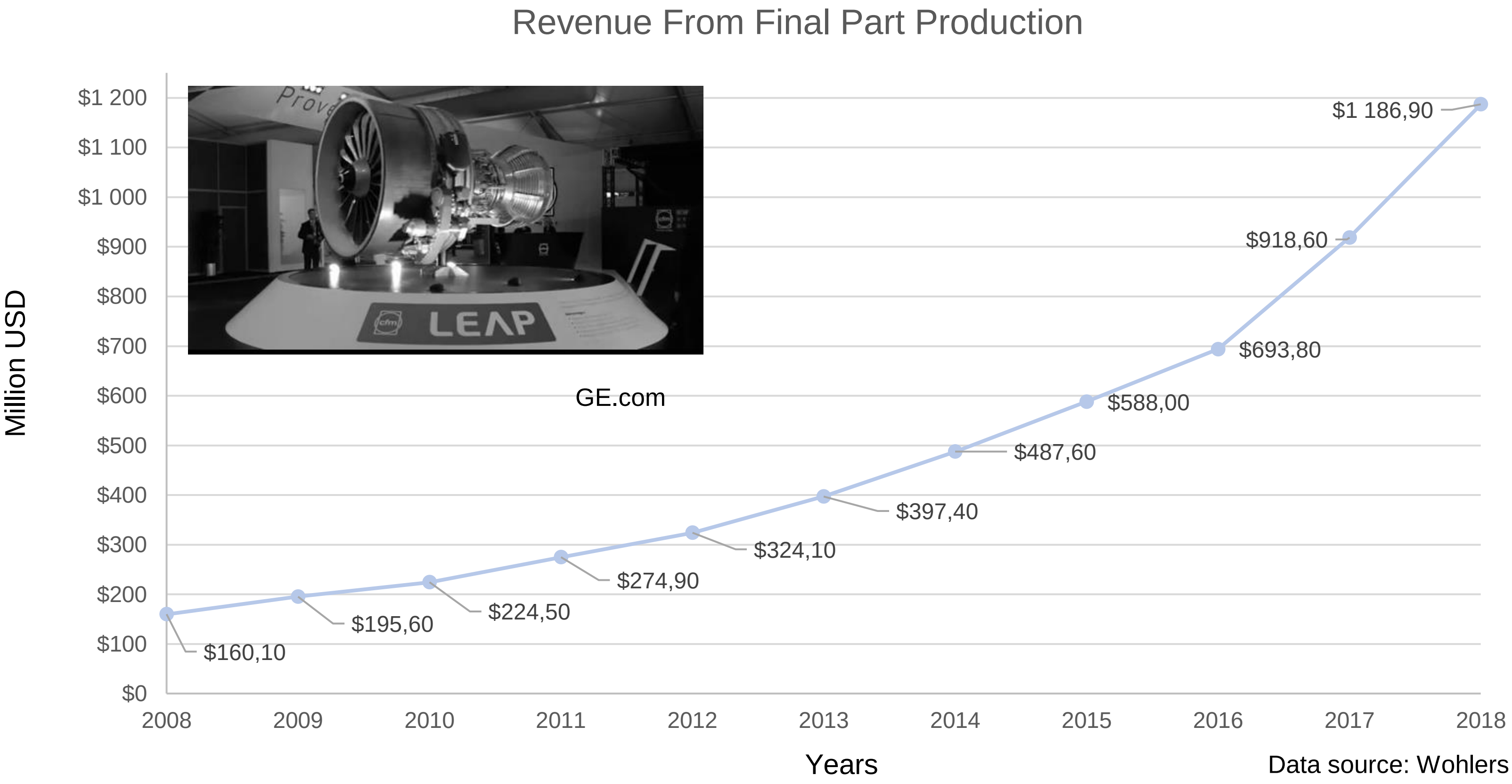
Source: Mark Cotteleer and Jim Joyce, *3D opportunity: Additive manufacturing paths to performance, innovation, and growth*, Deloitte University Press, http://dupress.com/articles/dr14-3d-opportunity/, accessed March 17, 2015.

Graphic: Deloitte University Press | DUPress.com



Farina.com

Possibilities in design through additive production



Data source: Wohlers Associates, Inc.

AM and Data Driven Design

Additive Manufacturing

- No tools
- Minimal material waste
- Low manufacturing constraints
- Production time dependent on material used

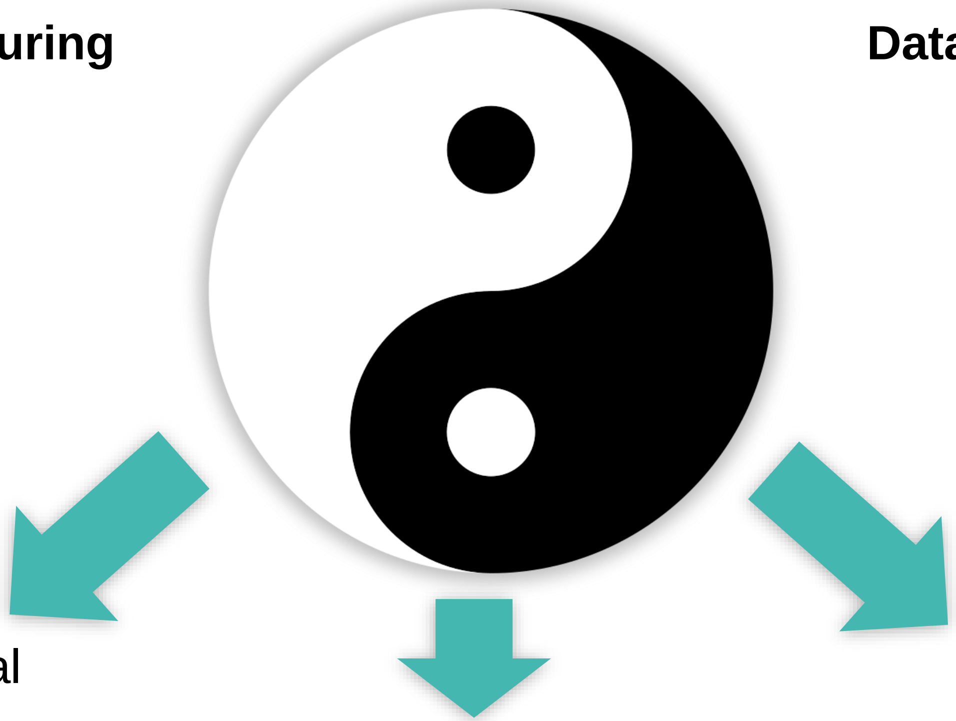
Data Driven Design

- Less design restrictions lead to an extended solution space
- Among more solutions there is always a «better» one

Design to…

Additive Manufacturing

Data Driven Design



Save Material

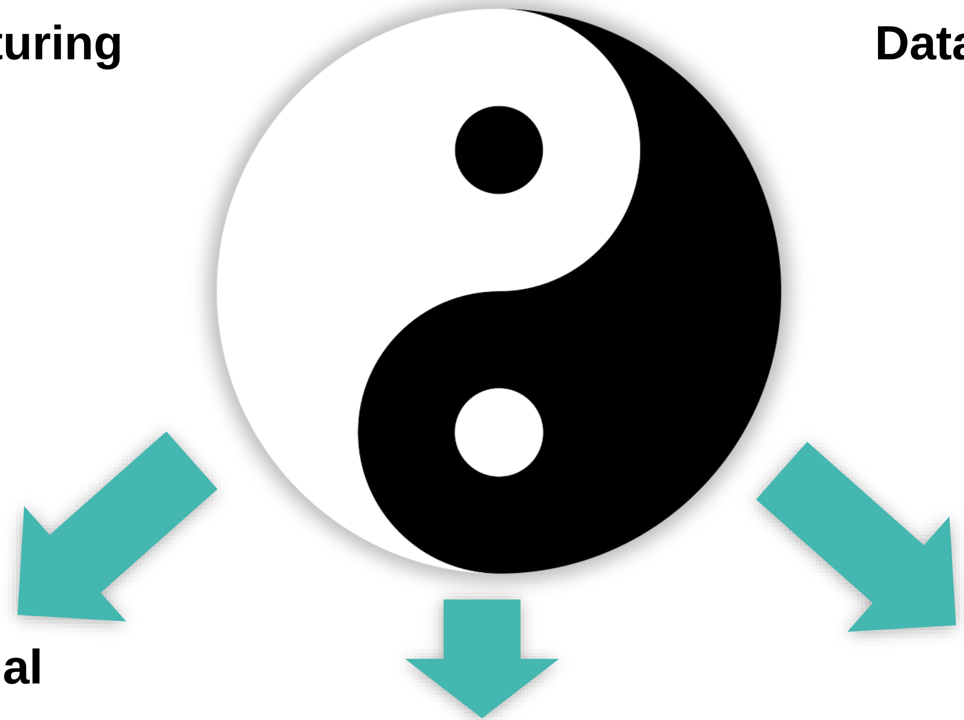
Gain performance

Reuse

Design to…

Additive Manufacturing

Data Driven Design



Save Material

Gain performance

Reuse

Materials Saving- Near Net Shape

Norsk Titanium Høynefoss

norsktitanium.com

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Materials Saving- Near Net Shape

Part build size: 900mm x 600mm x 300mm

Layer dimensions: H = 3–4 mm; W = 8–12 mm

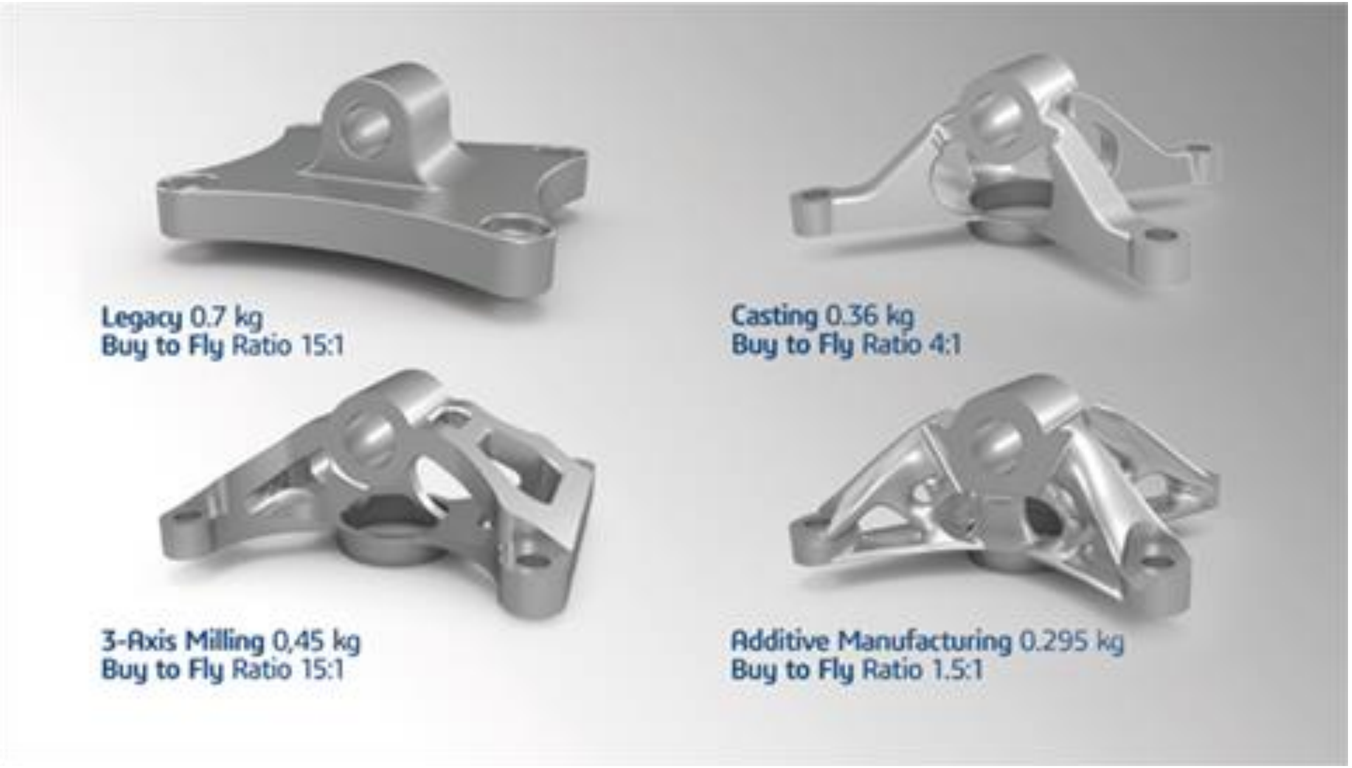
Deposition rate: 5–10 kg/hour

Titanium, Nickel Alloys, Tool Steel, Stainless Steel

High Volume Production: 10-20 metric tons annually

http://www.norsktitanium.com/

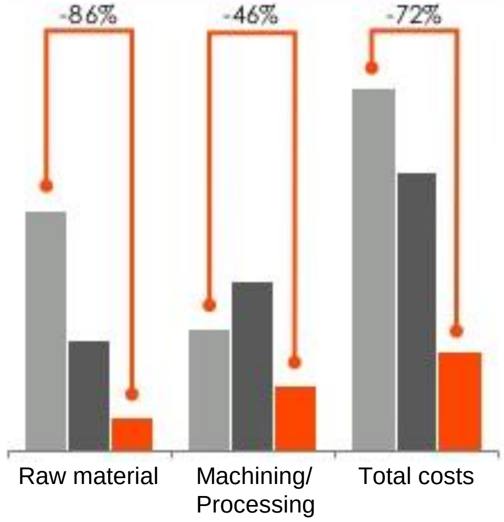
Materials Saving- Near Net Shape



3ds.com

Materials Saving- Near Net Shape

Unit cost
USD/kg



	Forged block Quoted	Die forging Quoted	DMD Estimated
Raw material cost (USD/kg)	~55	~88	~65*
Buy-to-fly ratio	16:1	6:1	1.5:1
Weight (kg)	~210	~82	~20

» **Specifications for sample unit used for comparison:**

- Component produced in low volume (40 components/year)
- Dimensions: 406 x 508 x 229 mm
- **Finished product weight: ~13 kg**

* Assumed cost for wire

Slide 22

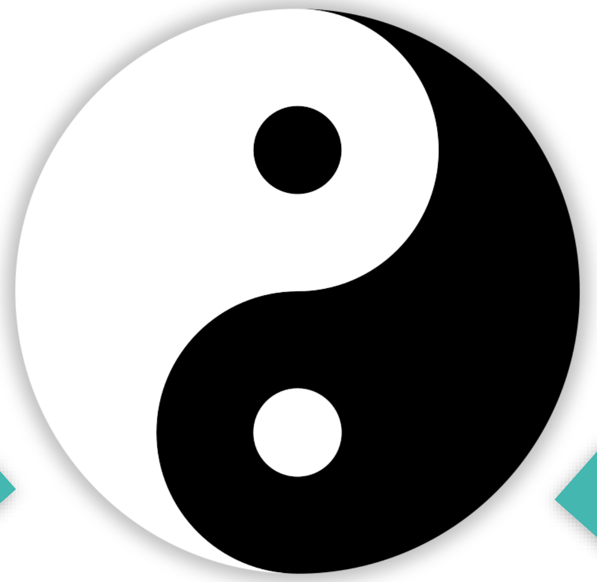
Norsk Titanium

Courtesy of Norsk Titanium

Design to…

Additive Manufacturing

Topology Optimization



Save Material

Gain performance

Reuse

High Stiffness/ Low Weight

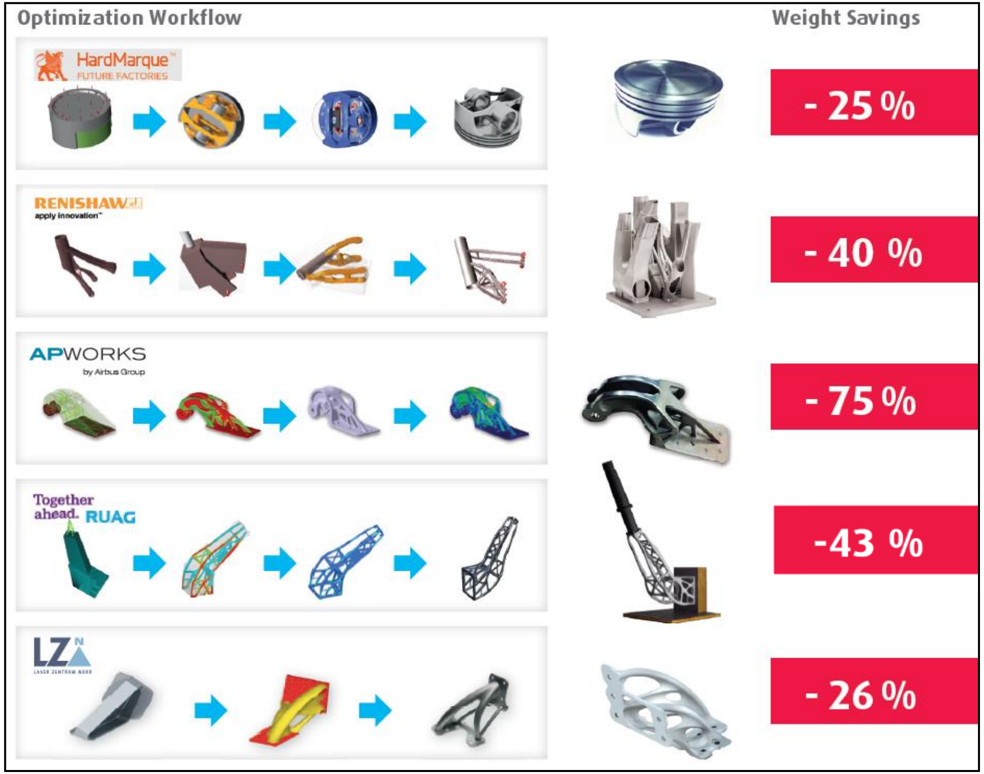
<20k $/kg

<1k $/kg

<100 $/kg

<5 $/kg

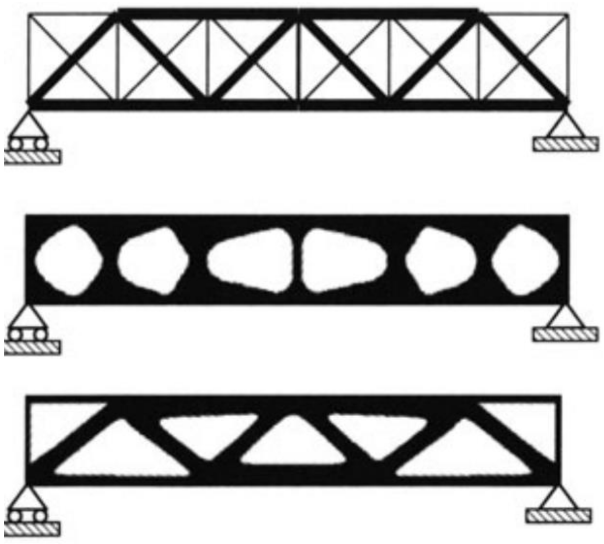
High Stiffness/ Low Weight

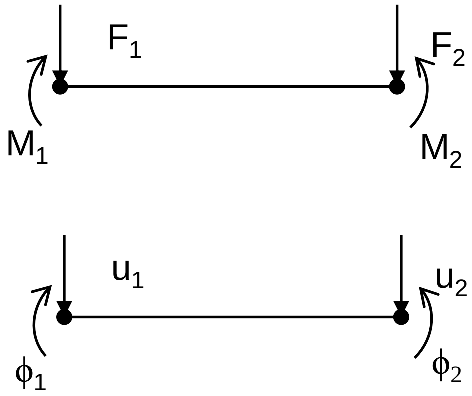


Courtesy of Jürgen Stampfl, TU Wien

Structural Optimizatioon- Overview

- The Design Domain
- Objective Function
- Boundary Conditions
- Homogenization of Stress Level
- Minimum Compliance





What is Topology Optimization?

Design variable

State variable

Thickness

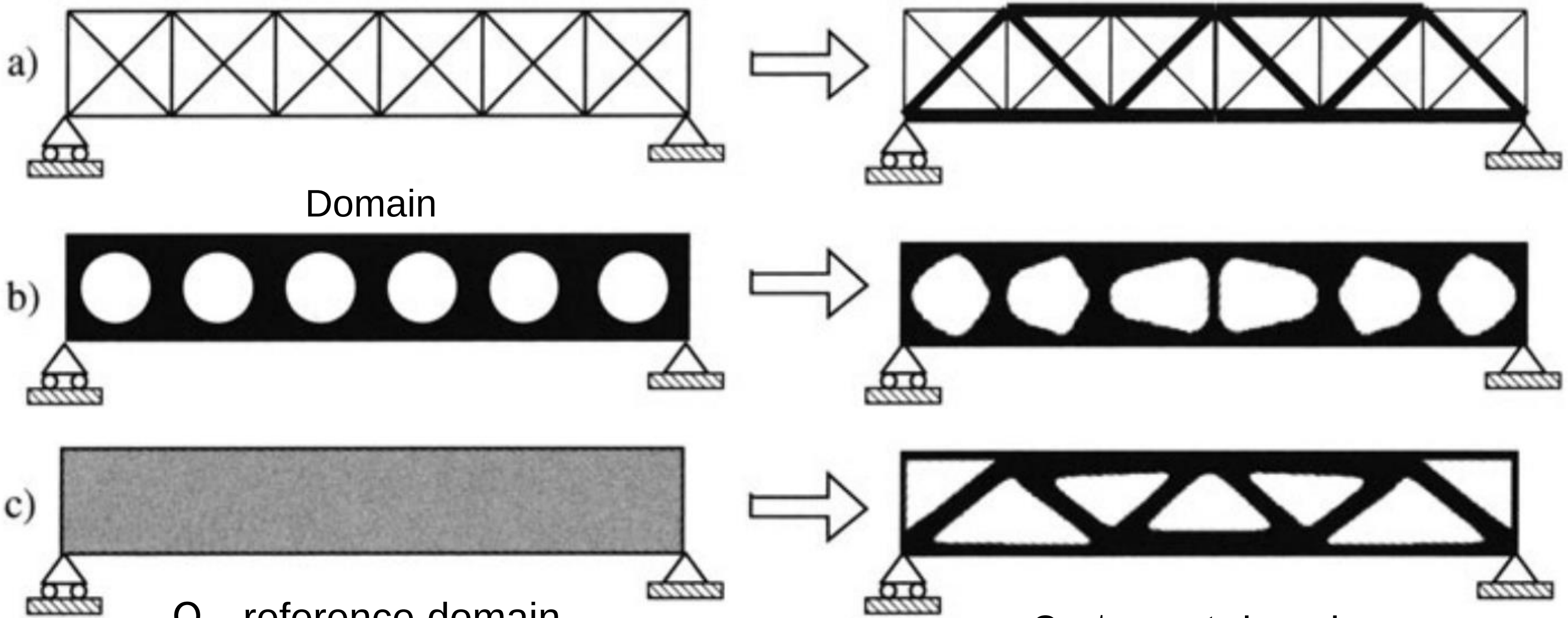
Deflection

Sizing

Domain

Shape-Optimization

Topology-Optimization



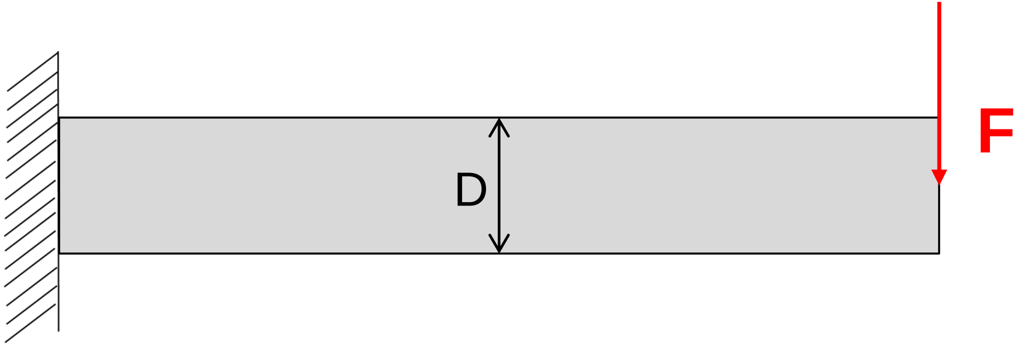
Ω…reference domain

Ω^{mat}…part domain

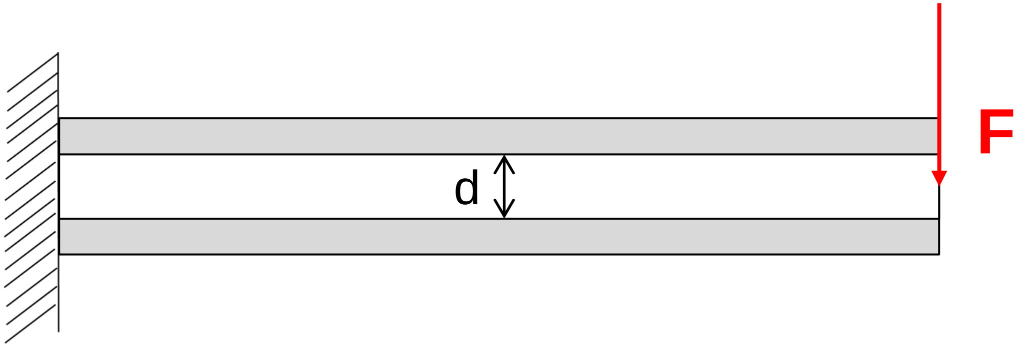
Bendsoe, Sigmund- Springer 2004

What is Topology Optimization?

Sizing

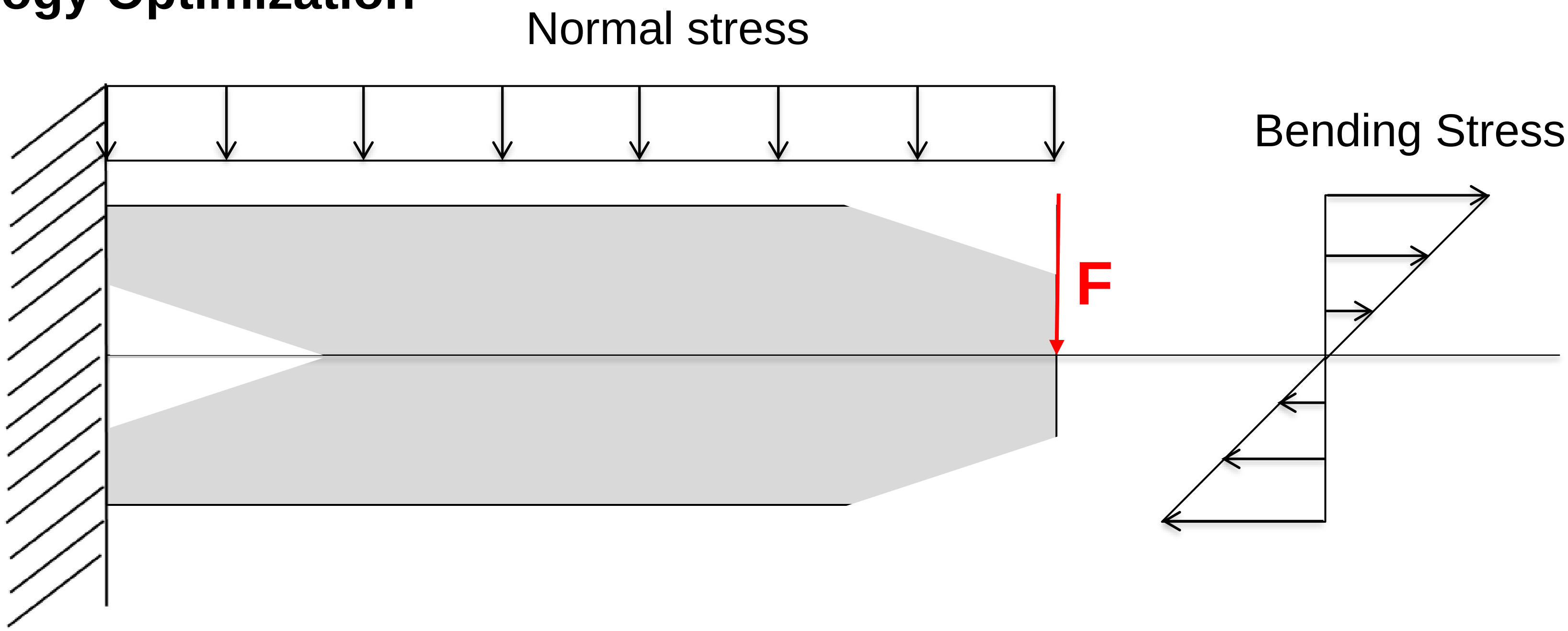


Shaping



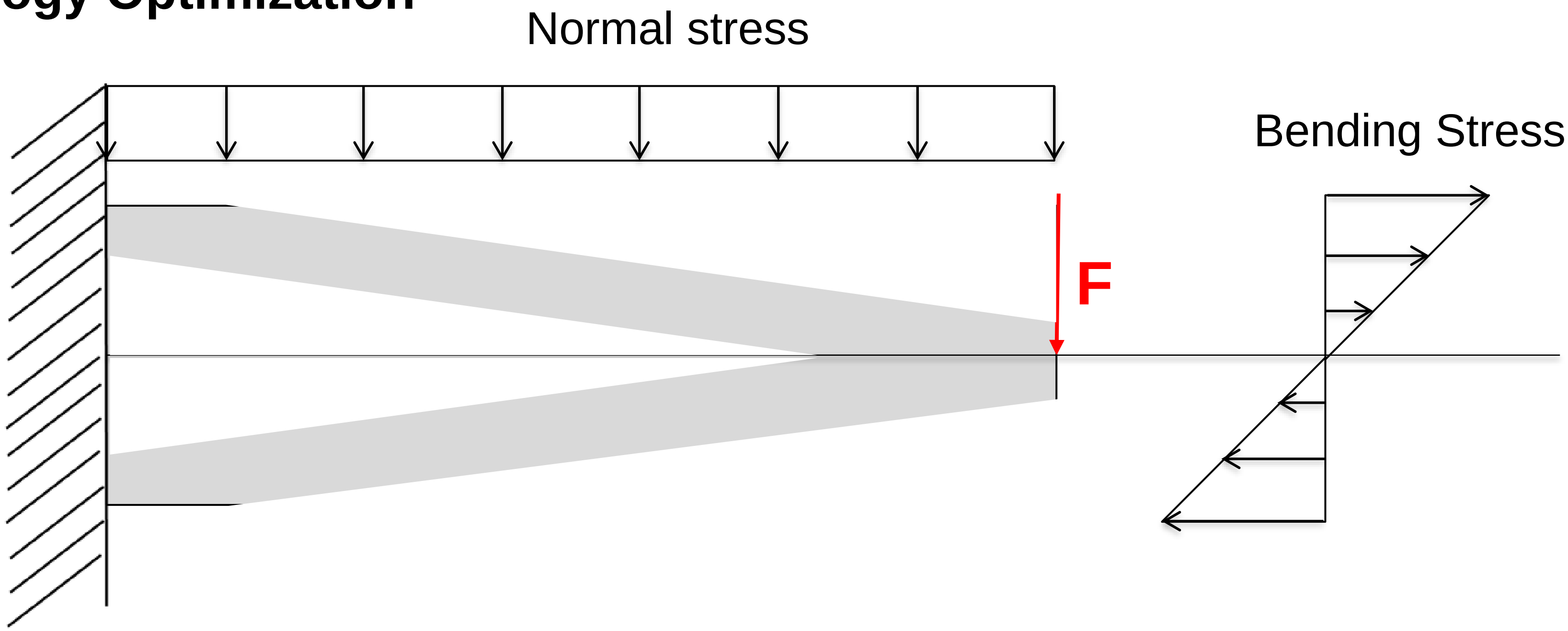
What is Topology Optimization?

Topology Optimization



What is Topology Optimization?

Topology Optimization



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Stress-strain relationship and stiffness matrix for isotropic material

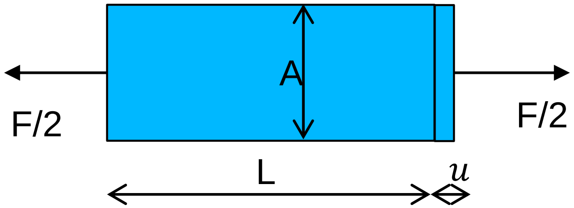
Hooke's law

$$\sigma = \frac{F}{A}$$

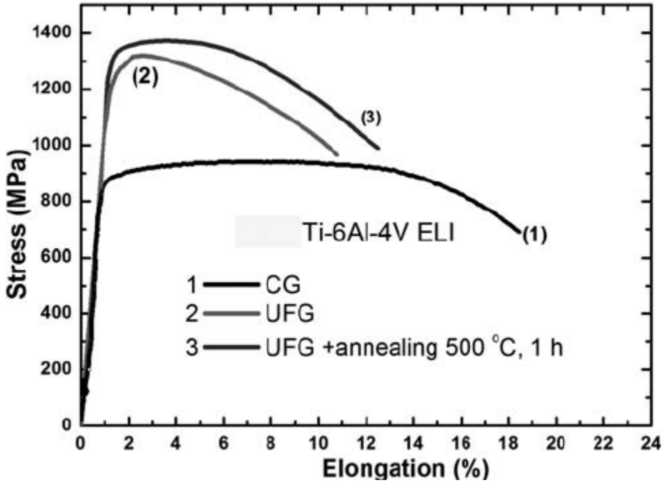
$$\epsilon = \frac{\delta}{L}$$

$$\varepsilon = \frac{\sigma}{E} = \frac{F}{AE}$$

$$u = \epsilon L = \frac{FL}{AE}$$



σ…Normal stress
F…Applied load
ε…Normal strain
δ…Change in length
L…Original length
E…Elastic modulus



Semenova et al.-Int. J. o. Materials Research, 2009

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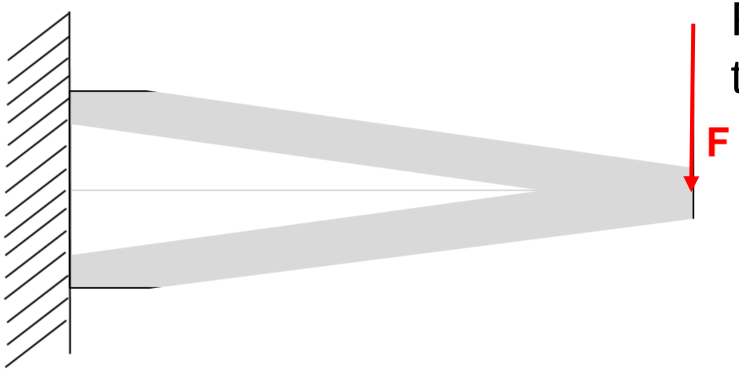
What is Stiffness?



F and l are defined by product function and can therefore usually not be changed

$$\delta_{max} = \frac{Fl^3}{3EI}$$

Stiffer Material?

E/ρ? Steel: 25.5 Ti: 25.5 Al: 26 [10^6 m^2/s^2]

Steel: 10x10 → 650xl → Aluminium: 16.5x16.5

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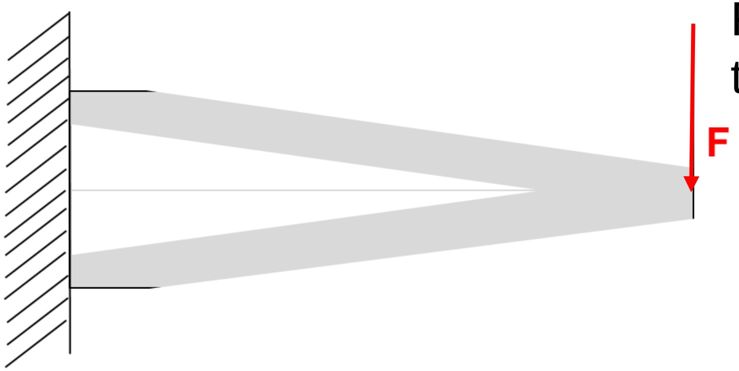
What is Stiffness?



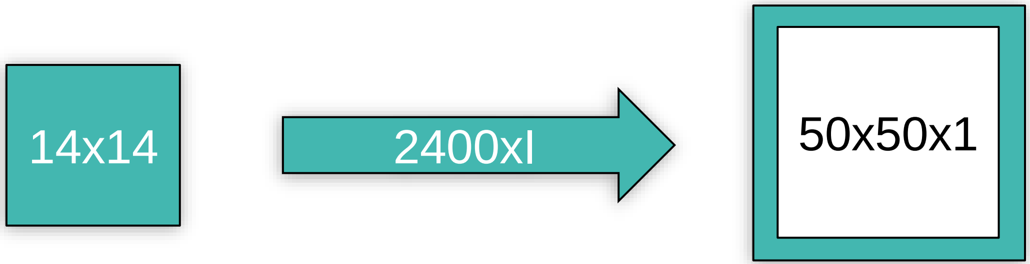
F and l is defined by product function and can therefore usually not be changed

$$\delta_{max} = \frac{Fl^3}{3EI}$$

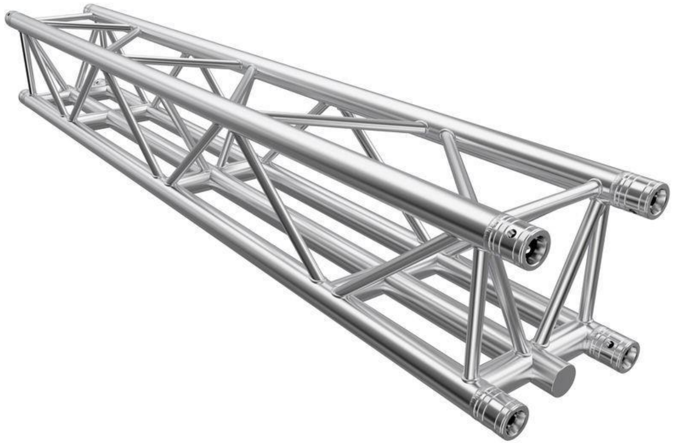
More utilization of design domain?

Stiffer Material?

Hollow structure:



What is Stiffness?



Truss: High directional stiffness geometrically simple

Shell: High global stiffness, high eigenfrequencies

What is Stiffness?

Key Takeaways

- Use the largest design domain possible
- Use a low density material to maximize I
- Optimization of material cross section important

Stress-strain relationship and stiffness matrix for isotropic material

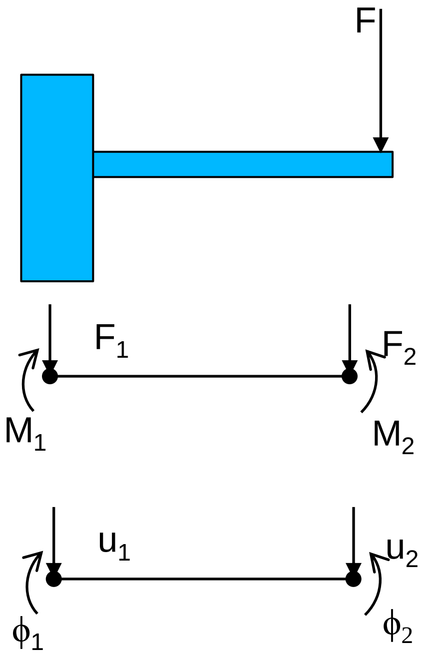
f…Load vector
u…Displacement vector
k…Stiffness tensor

Tensor Form

$$f_s = k u$$

$$\begin{bmatrix} F_1 \\ M_1 \\ F_2 \\ M_2 \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} \\ k_{21} & k_{22} & k_{23} & k_{24} \\ k_{31} & k_{32} & k_{33} & k_{34} \\ k_{41} & k_{42} & k_{43} & k_{44} \end{bmatrix} \begin{bmatrix} u_1 \\ \phi_1 \\ u_2 \\ \phi_2 \end{bmatrix}$$

Force — Stiffness tensor — Displacement



Equivalet Stress- Von Mises Stress

$$\sigma_{vm} = \sqrt[2]{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2}$$

Stress homogenization based Structural Optimization

Objective Function

Volume — Relative density — Volume of element

(1) $$V = \sum_{i=1}^{N} x_i * v_i$$

Elements in the design domain

Boundary Conditions

Von mises stress

(2) $$\frac{\sigma_e^{vm}}{\sigma_{yield}} < RRi$$

Current rejection ratio

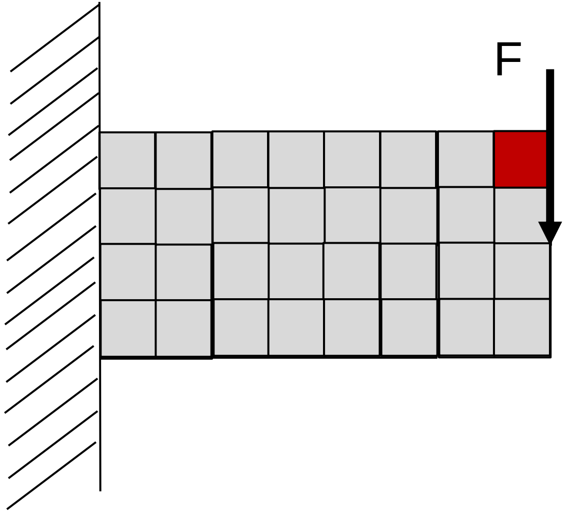
Yield strength

Global stiffness matrix

(3) $$KU = \mathrm{F}$$

Global force

Global displacement vector



(4) $$x_i \begin{cases} 1 \in \Omega_{mat}/\Omega \\ 0 \notin \Omega_{mat}/\Omega \end{cases}$$

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Stress homogenization based Structural Optimization

Michell Type Structure

“*a frame (today called truss) (is optimal) attains the limit of economy of material possible in any frame-structure under the same applied forces, if the space occupied by it can be subjected to an appropriate small deformation, such that the strains in all the bars of the frame are increased by equal fractions of their lengths, not less than the fractional change of length of any element of the space*.” (Michell 1904)

Maxwell load-path theorem

Tension value in any tension element of length lp

$$\sum l_p f_p - \sum l_q f_q = C$$

Constant based on external loads/ supports

Compression value in any compression element of length lq

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Stress homogenization based Structural Optimization

Gradually removing inefficient material from the structure

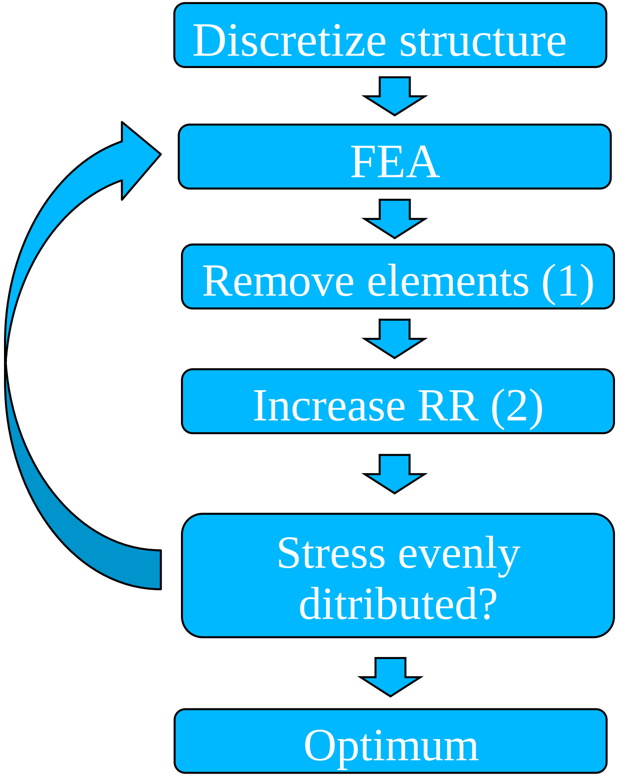
- Inefficiencies- low values of stress/strain
- Black and white rendering
- Reference domain Ω in R^2

(1) $$\frac{\sigma_e^{vm}}{\sigma_{max}^{vm}} \leq RR_i$$

- σ_e^{vm} — Von Mises stress of element
- RR_i — Current rejection ratio
- σ_{max}^{vm} — Maximum van Mises stress of whole structure

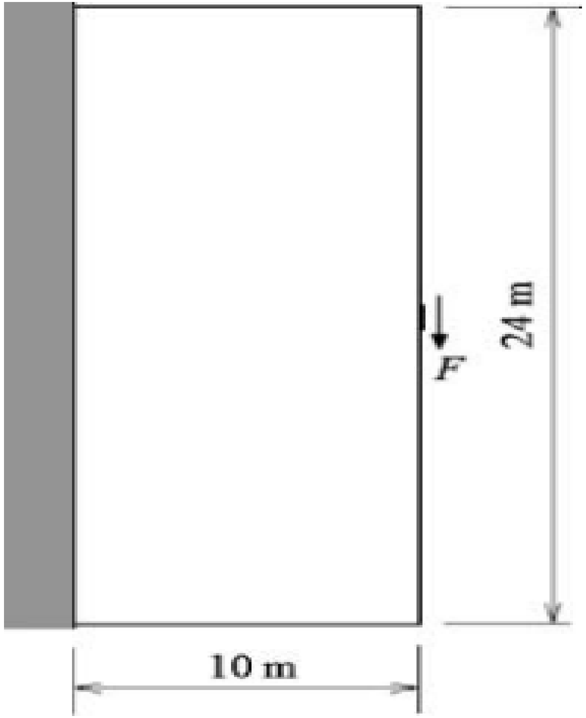
(2) $$RR_{i+1} = RR_i + ER$$

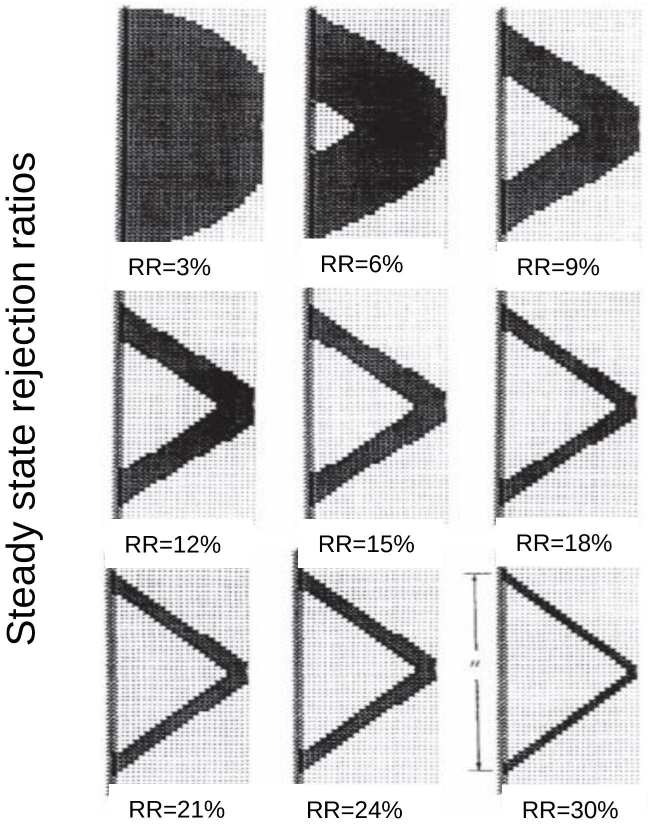
- ER — Evolutionary rate



Stress homogenization based Structural Optimization

Michell Type Structure





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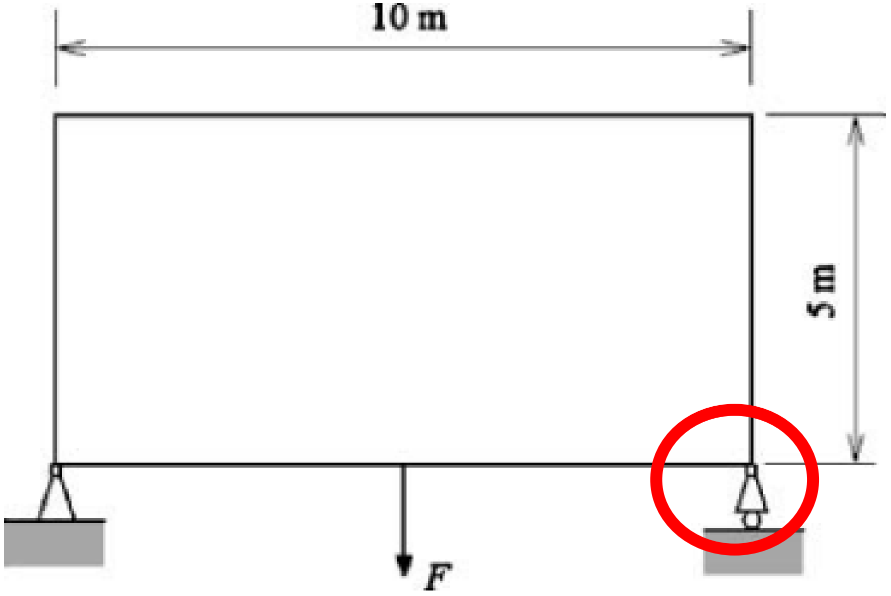
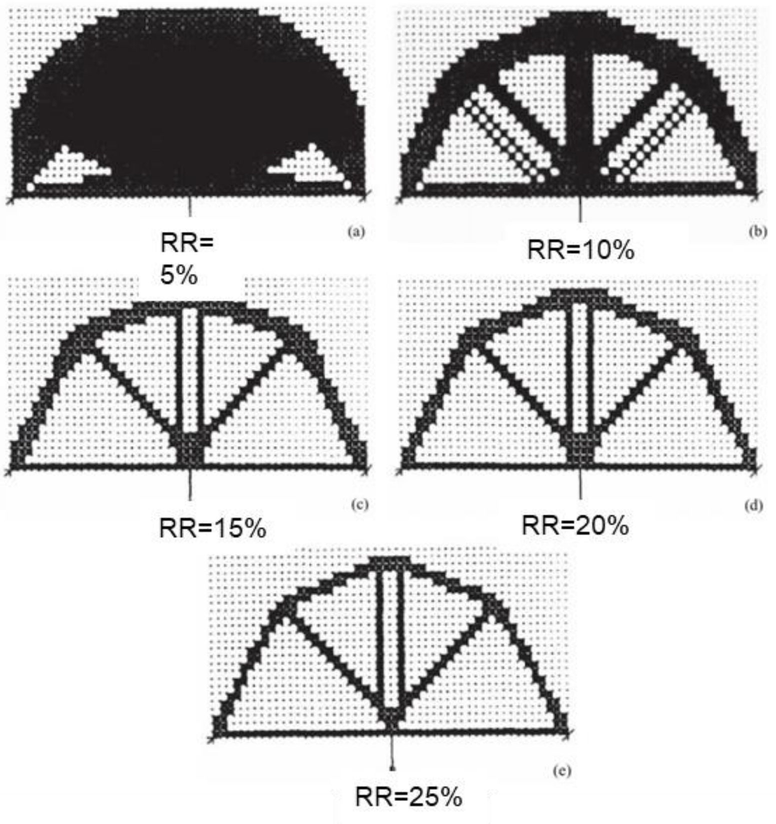
Stress homogenization based Structural Optimization

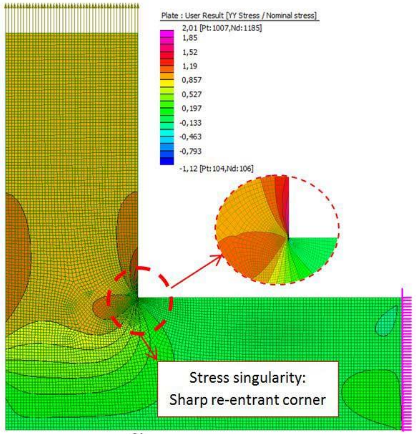
Support Condition

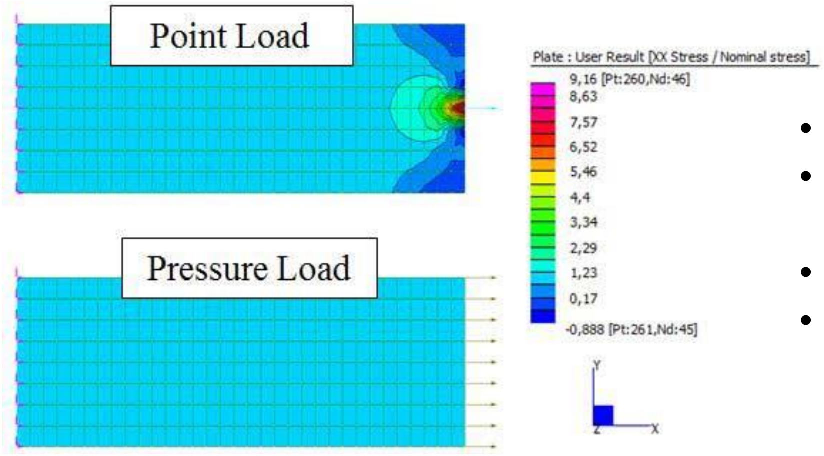




Stress homogenization based Structural Optimization

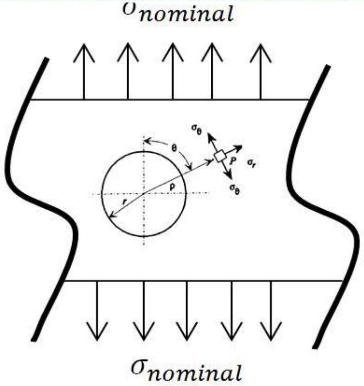
Stress Singularities





- Point load
- Sharp re-entrant corners
- Corners of bodies
- Point restraints

Stress Concentrators



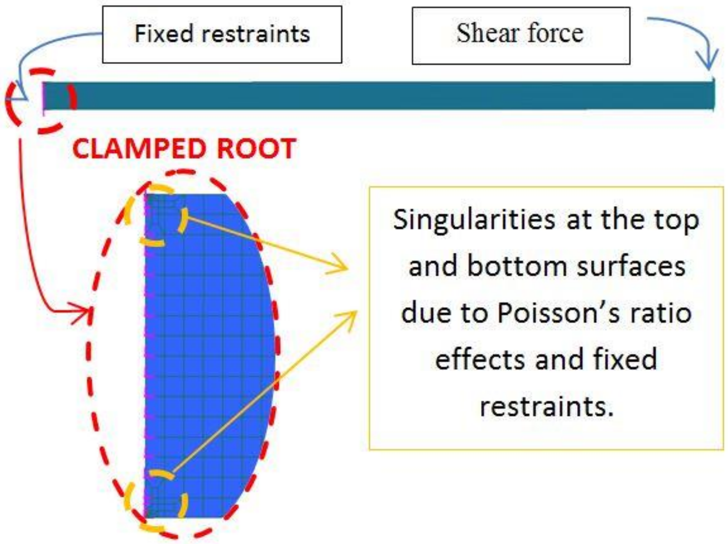
- Manufacturing produces fillet radiuses
- Finite stress value
- Hole in plate mesh, fillet corners, change of cross section,…

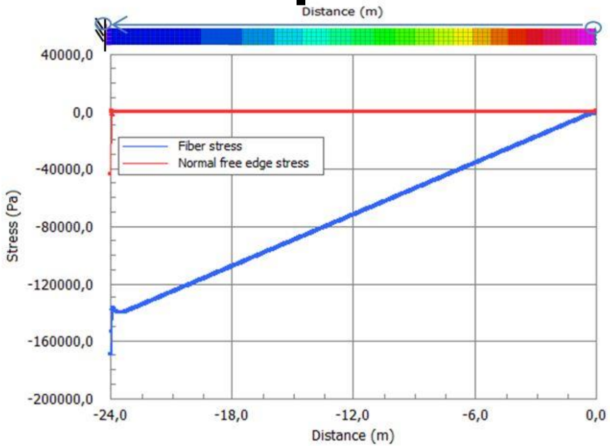
$$K_t = \frac{\sigma_{max}}{\sigma_{nom}} = 3$$

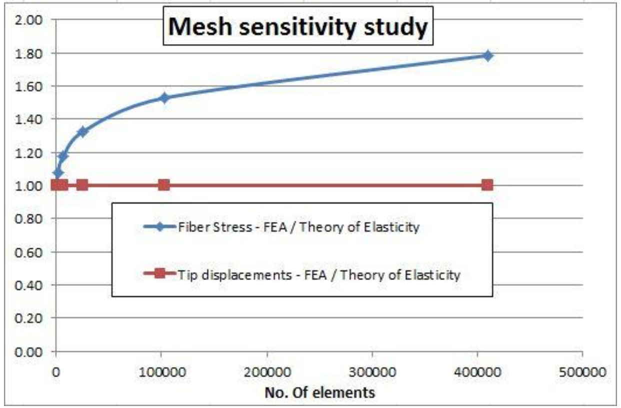
Shimels et al- IOP Conf. Ser.: Mater. Sci. Eng. 2017

Stress homogenization based Structural Optimization

- Stress singularities do not affect displacement results
- Occur at supports when displacement and stress conditions are mixed







Shimels et al- IOP Conf. Ser.: Mater. Sci. Eng. 2017

The Minimum Compliance Model

Mean Compliance C

Displacement Vector

$$C = \frac{1}{2} f^T u$$

Force Vector

$$f = Ku$$

Global Stiffness Matrix

Stiffness Matrix of the i^th element

$$\Delta K = K^* - K = -K_i$$

Stiffness Matrix of the resulting structure

$$\Delta u = -K^{-1} \Delta f = -K^{-1} \Delta K u$$

$$\Delta C = \frac{1}{2} f^T \Delta u = -\frac{1}{2} f^T K^{-1} \Delta K u = \frac{1}{2} u_i^T K_i u_i$$

Displacement Vector of the i^th element

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The Minimum Compliance Model

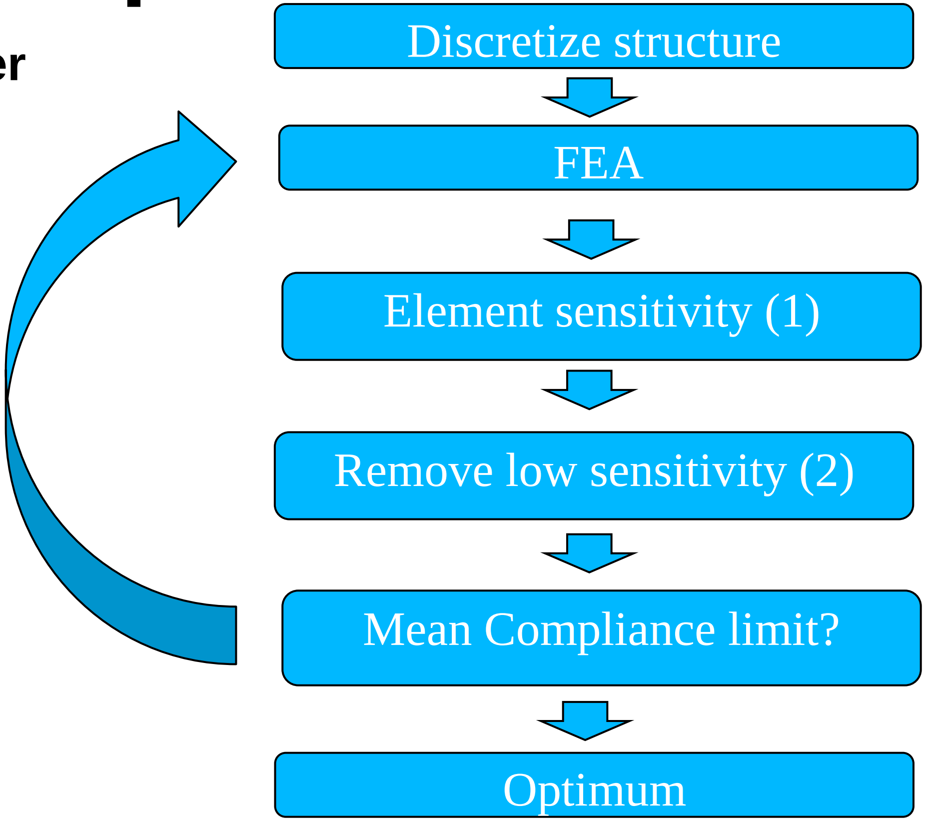
Mean Compliance C- Sensitivity number

$$\alpha_i^e = \frac{1}{2} u_i^T K_i u_i \qquad (1)$$

Elemental removal ratio

$$ERR = \frac{\#elements\ removed}{\#total\ elements} \qquad (2)$$

No steady state!



The Minimum Compliance Model

Objective Function

Number of elements

Relative density

Elemental stiffness matrix

(1) $C(x) = \sum_{i=1}^{N} x_i * u_i^T k_i u_i$

Elemental displacement

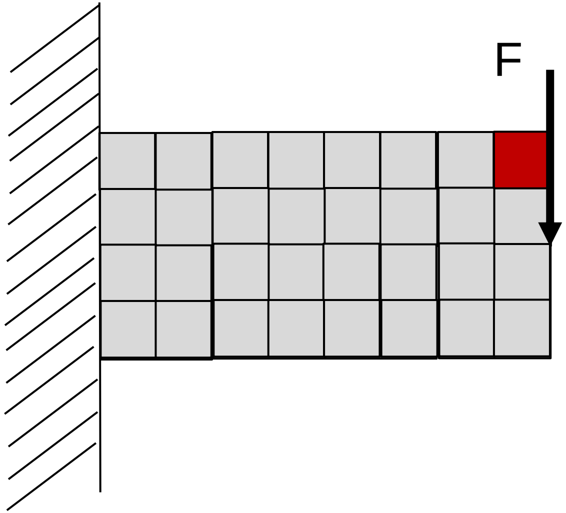
Elements in the design domain

Boundary Conditions

Material domain volume

(2) $\frac{\Omega^{mat}}{\Omega} < \text{volfrac}$ — Desired volume

Design domain volume



Global stiffness matrix

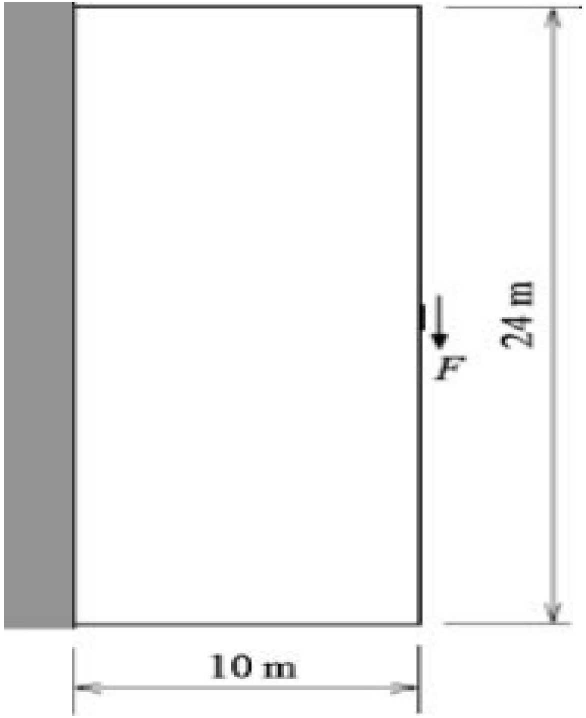
(3) $KU = \text{F}$ — Global force

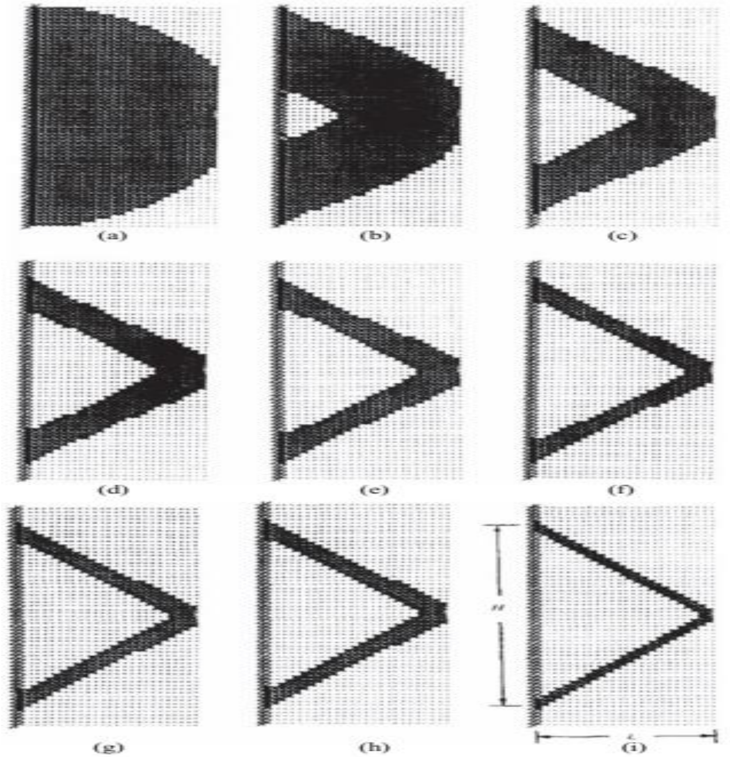
Global displacement vector

(4) $x_i \begin{cases} 1 \in \Omega_{mat}/\Omega \\ 0 \notin \Omega_{mat}/\Omega \end{cases}$

The Minimum Compliance Model

Example: Short Cantilever

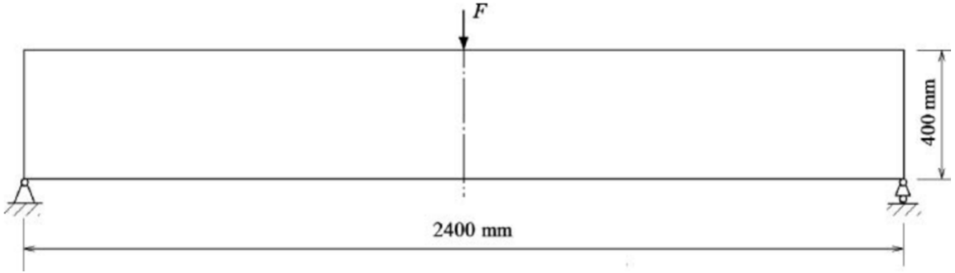




32x20 four node (hxahedral) elements

The Minimum Compliance Model

Example: Beam structure



- Half of structure modelled (symmetry)
- 60x20 four node (hexahedral) elements

ERR=1%; V=50%

ERR=2%; V=52%

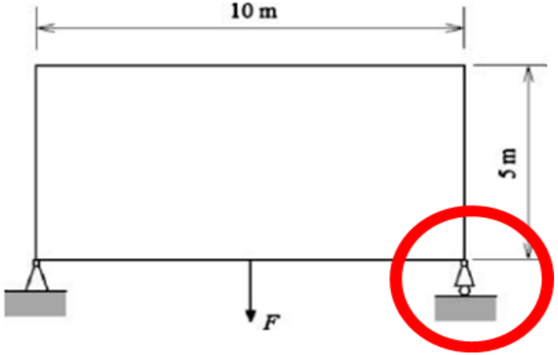
ERR=4%; V=54%

Minimum Compliance vs. Stress Homogenization

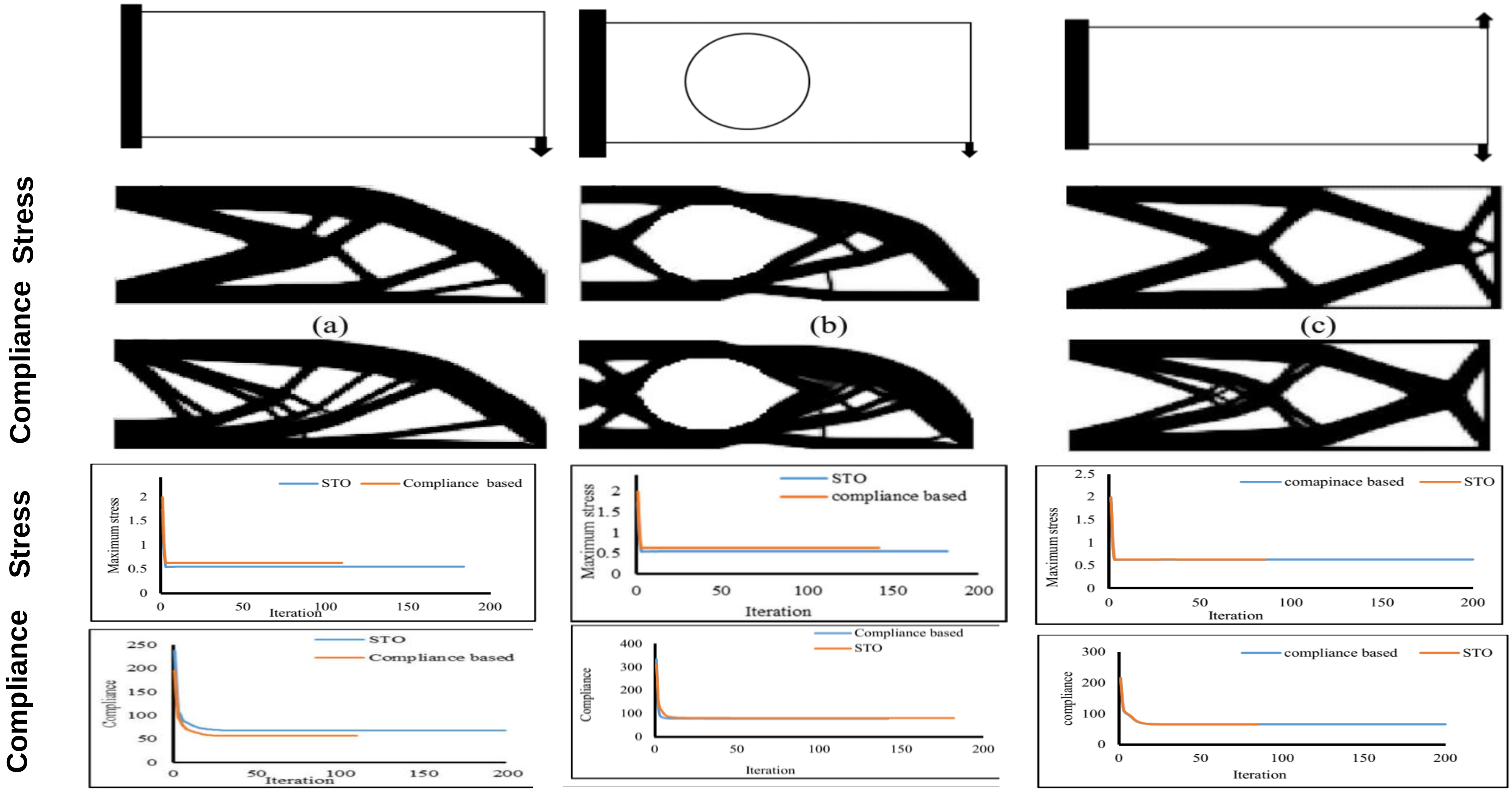
Stress level

Compliance based

120 x48 elements
E= 1 Mpa
Volfrac= 0,3



Shimels et al- IOP Conf. Ser.: Mater. Sci. Eng. 2017


Stress
Compliance
Stress
Compliance
(a)
(b)
(c)
STO
Compliance based
Maximum stress
Iteration
Compliance
compliance based
comapinace based
compliance
0
0.5
1
1.5
2
2.5
50
100
150
200
250
300
400

Minimum Compliance vs. Stress Homogenization

Stress level

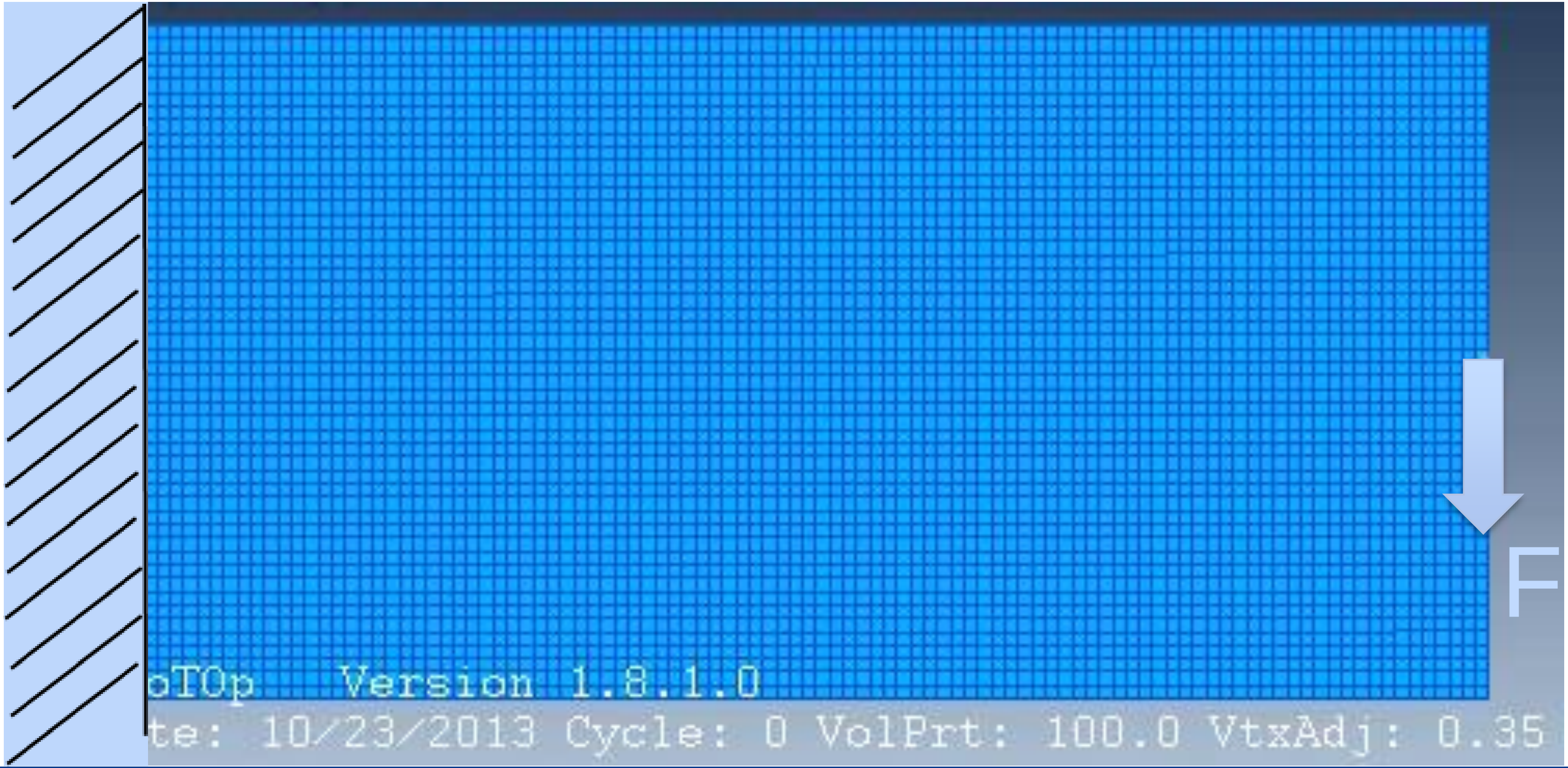
- Material distributed to sustain loads
- Subject to defined boundary and load conditions
- Simpler structures
- Higher computational efforts
- Layout favors failure criterion and not material to be distributed
- More realistic
- Definition of stress constraint at element level difficult (singularity, local nature, nonlinear behavior)
- Less popular

Compliance minimization

- Optimal volume fraction bounday condition
- Optimal material distributions and induced stress are result of volume fraction
- Complex layout
- Depndent on the amount of material to be distributed
- Not exact in predicting stress and displacements
- Robust
- Lower computational effort
- Most common

Shimels et al- IOP Conf. Ser.: Mater. Sci. Eng. 2017

The Minimum Compliance Model



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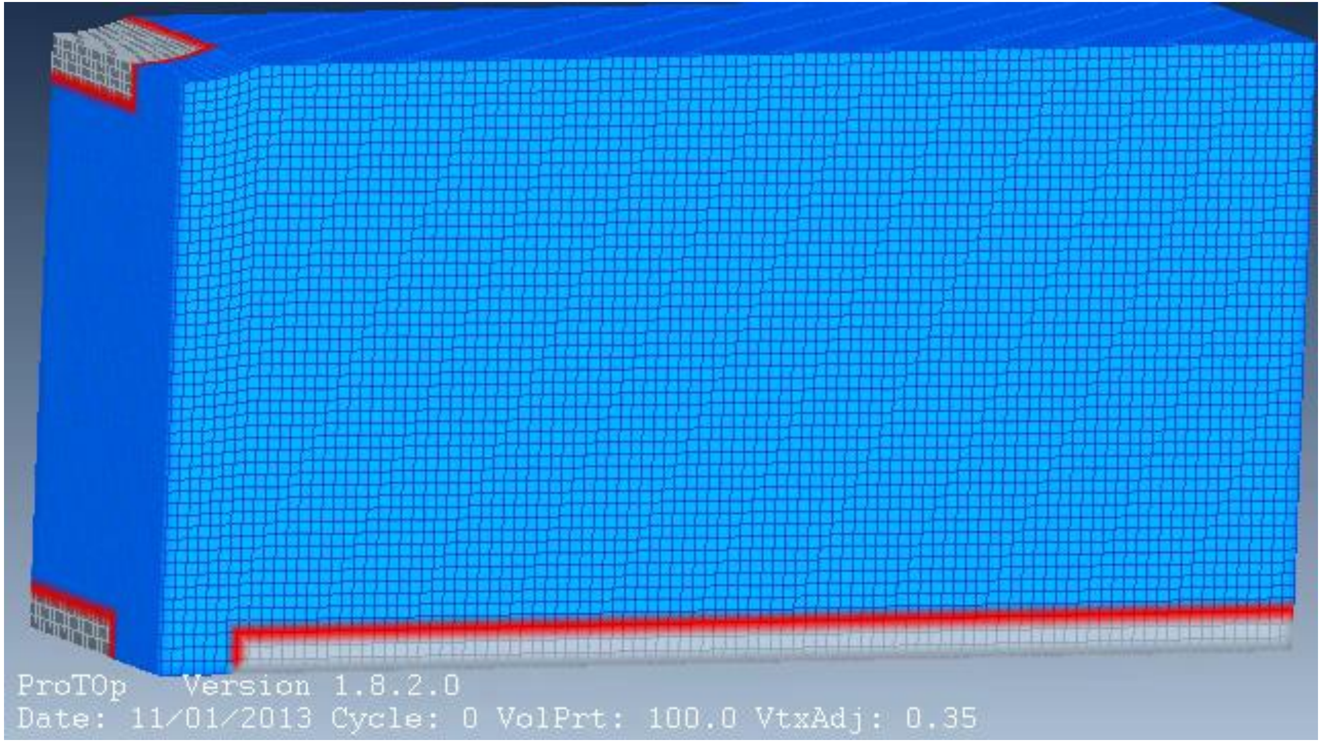
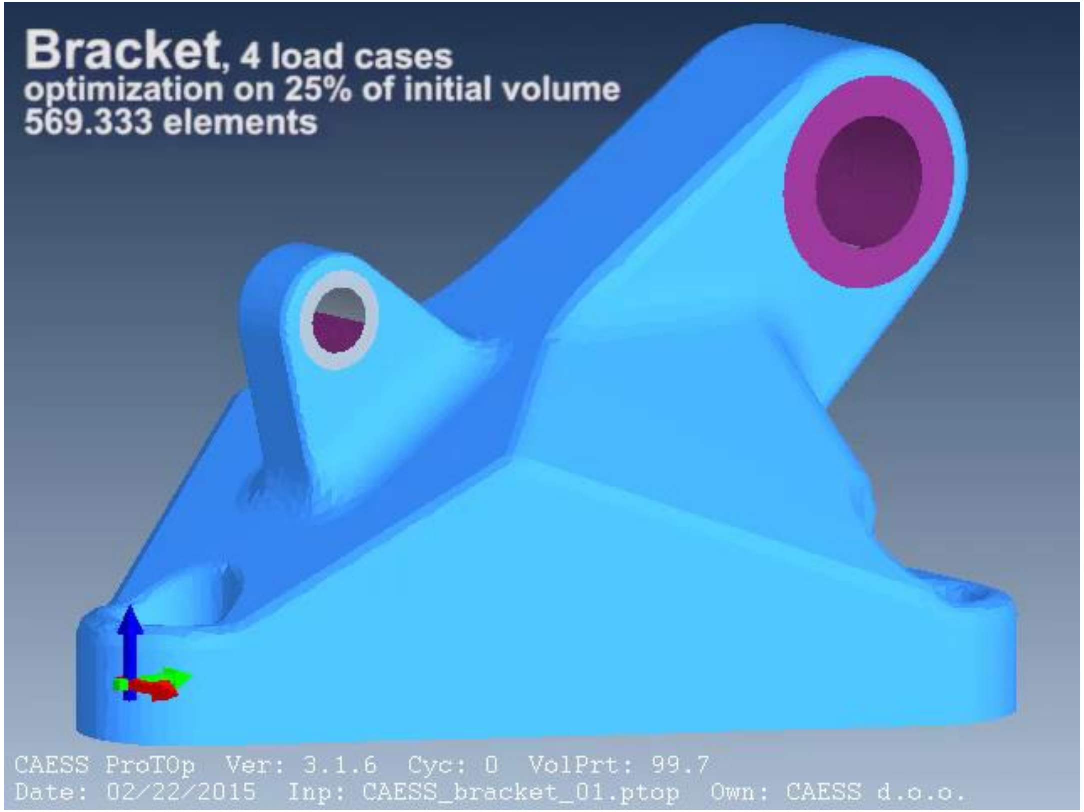


http://caess.eu/site/anim/anim2/Anim.html

The Minimum Compliance Model

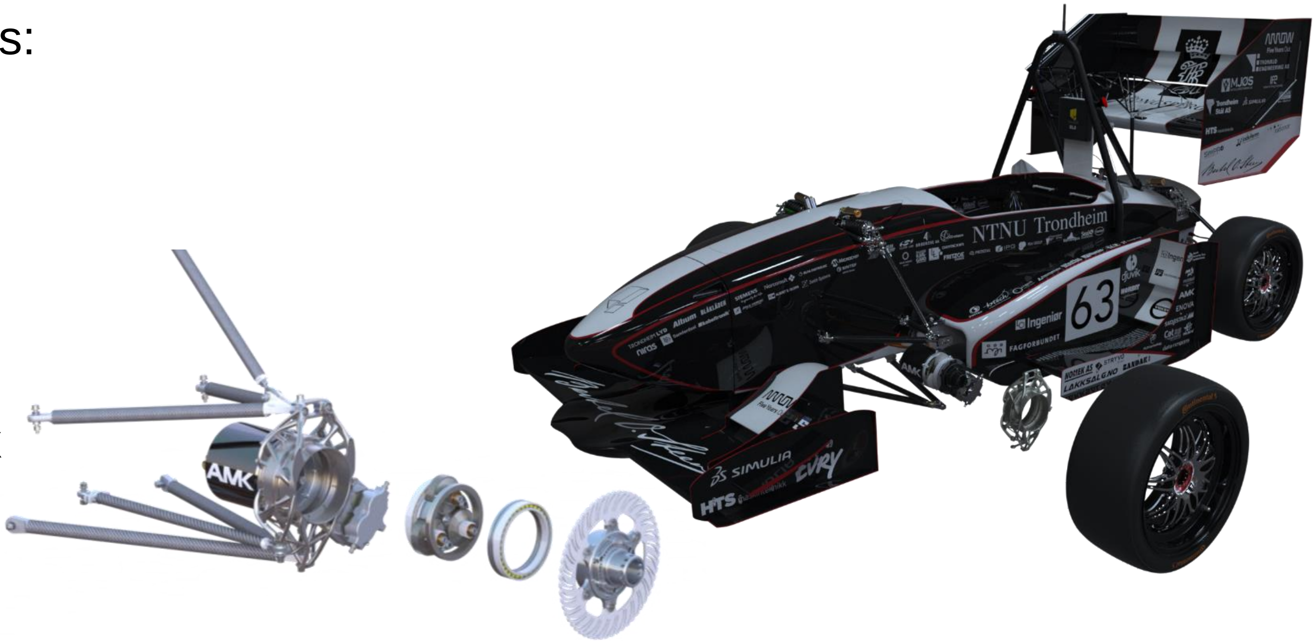


Compliance Model- An example

General requirements:
- Stiffness
- Weight
- Multi-purpose use

Housing:
- Wheel bearings
- Planetary gearbox

Connecting:
- Suspension arms
- Brakes
- Electrical motor



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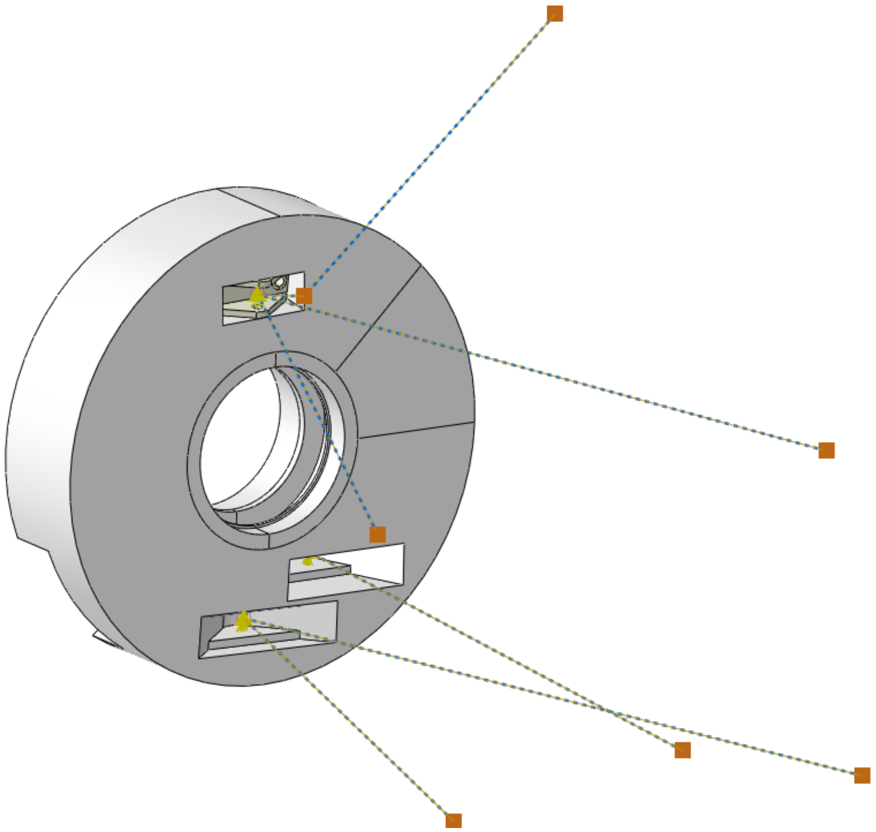
NTNU 2017

The Workflow

1. **Design domain**
2. Properties
3. Mesh
4. Interactions
5. Loads and boundary conditions
6. Optimization setup
7. Pre-processing
8. CAD regeneration
9. FE Validation
10. AM support generation



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The Workflow

1. Design domain
2. **Properties**
   - **Ti6Al4V**
   - **Density**
   - **Elastic Modulus**
3. Mesh
4. Interactions
5. Loads and boundary conditions
6. Optimization setup
7. Pre-processing
8. CAD regeneration
9. FE Validation
10. AM support generation

Material data sheet

Mechanical properties of parts

	As built	Heat treated [6]
Tensile strength [5]		
- in horizontal direction (XY)	typ. 1230 ± 50 MPa typ. 178 ± 7 ksi	min. 930 MPa (134.8 ksi) typ. 1050 ± 20 MPa (152 ± 3 ksi)
- in vertical direction (Z)	typ. 1200 ± 50 MPa typ. 174 ± 7 ksi	min. 930 MPa (134.8 ksi) typ. 1060 ± 20 MPa (154 ± 3 ksi)
Yield strength ($R_{p0.2}$) [5]		
- in horizontal direction (XY)	typ. 1060 ± 50 MPa typ. 154 ± 7 ksi	min. 860 MPa (124.7 ksi) typ. 1000 ± 20 MPa (145 ± 3 ksi)
- in vertical direction (Z)	typ. 1070 ± 50 MPa typ. 155 ± 7 ksi	min. 860 MPa (124.7 ksi) typ. 1000 ± 20 MPa (145 ± 3 ksi)
Elongation at break [5]		
- in horizontal direction (XY)	typ. (10 ± 2) %	min. 10 % typ. (14 ± 1 %)
- in vertical direction (Z)	typ. (11 ± 3) %	min. 10 % typ. (15 ± 1 %)
Modulus of elasticity [5]		
- in horizontal direction (XY)	typ. 110 ± 10 GPa typ. 16 ± 1.5 Msi	typ. 116 ± 10 GPa typ. 17 ± 1.5 Msi
- in vertical direction (Z)	typ. 110 ± 10 GPa typ. 16 ± 1.5 Msi	typ. 114 ± 10 GPa typ. 17 ± 1.5 Msi
Hardness [7]	typ. 320 ± 12 HV5	

[5] Tensile testing according to ISO 6892-1:2009 (B) Annex D, proportional test pieces, diameter of the neck area 5 mm (0.2 inch), original gauge length 25 mm (1 inch).

[6] Specimens were treated at 800 °C (1470 °F) for 4 hours in argon inert atmosphere. Mechanical properties are expressed as minimum values to indicate that mechanical properties exceed the minimum requirements of material specification standards. ASTM F1472-08. By fulfilling these minimum values, also the specifications of standards ASTM B348-09 and ISO 5832-3:2000 are meet.

[7] Vickers hardness measurement (HV) according to EN ISO 6507-1 on polished surface. Note that measured hardness can vary significantly depending on how the specimen has been prepared.

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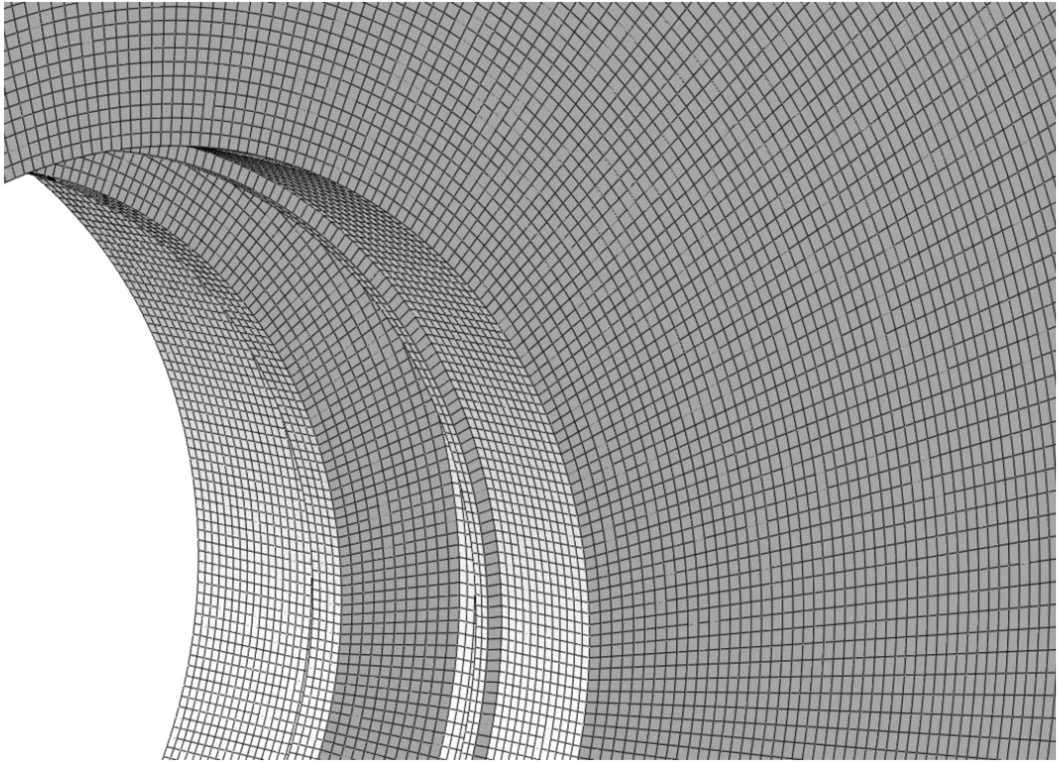
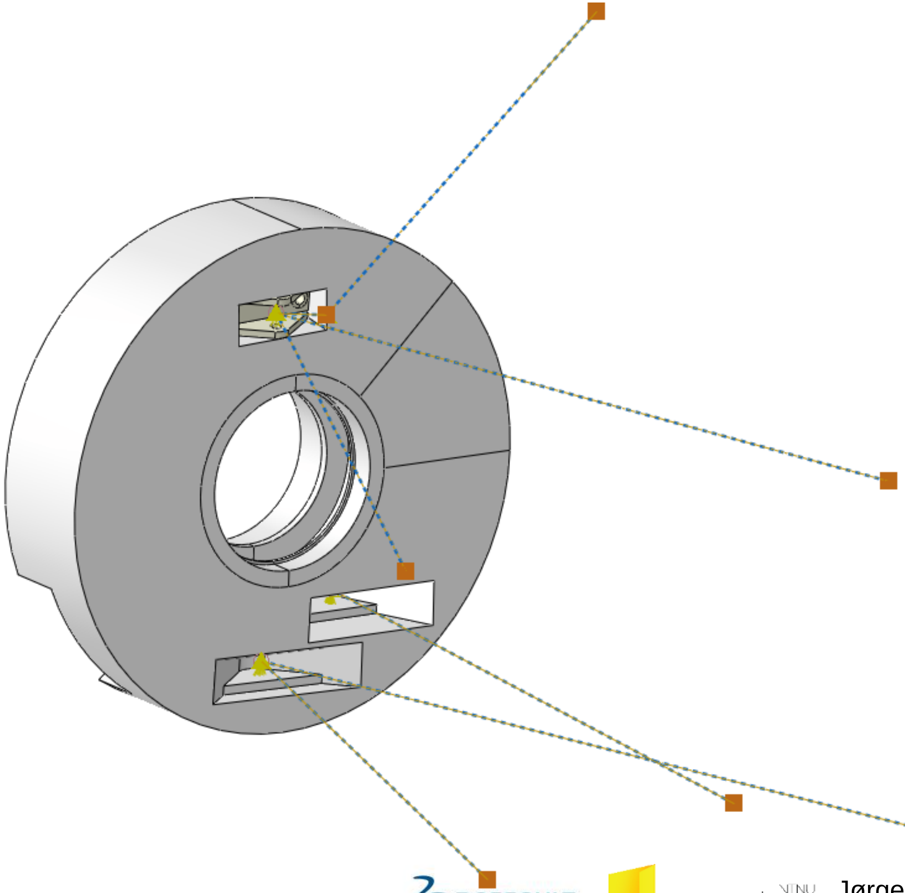
The Workflow

1. Design domain
2. Properties
3. **Mesh**
   - **Structured Hexahedral elements**
   - **1 070 000 elements**
4. Interactions
5. Loads and boundary conditions
6. Optimization setup
7. Pre-processing
8. CAD regeneration
9. FE Validation
10. AM support generation



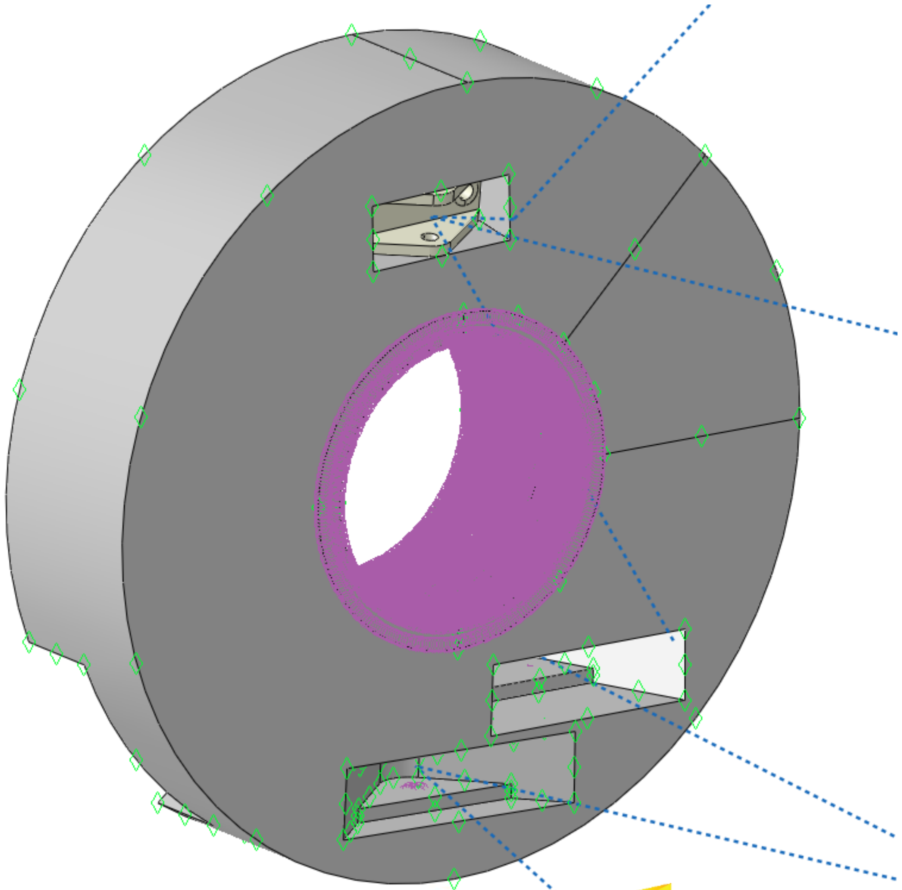
The Workflow

1. Design domain
2. Properties
3. Mesh
4. **Interactions**
   - **Suspension points**
   - **Mounting bracket**
   - **Brake caliper**
5. Loads and boundary conditions
6. Optimization setup
7. Pre-processing
8. CAD regeneration
9. FE Validation
10. AM support generation



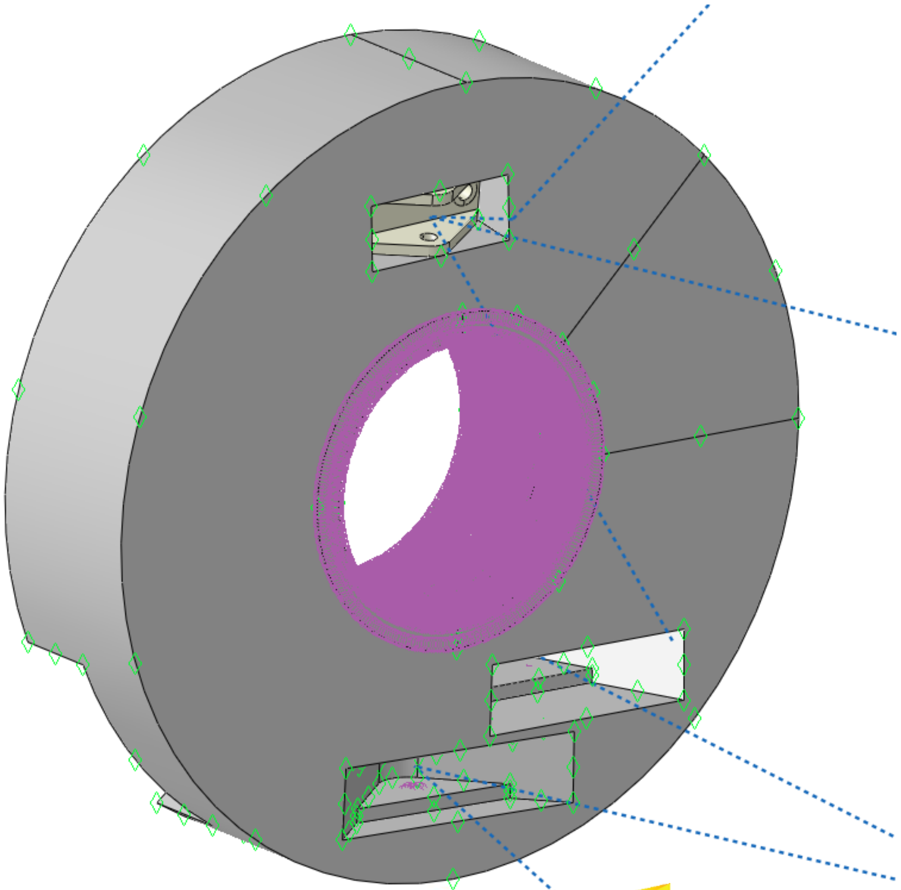
The Workflow

1. Design domain
2. Properties
3. Mesh
4. Interactions
5. **Loads and boundary conditions**
    - **Wheel bearing reaction forces**
    - **Mapped analytical fields**
    - **Four quasi-static scenarios**
6. Optimization setup
7. Pre-processing
8. CAD regeneration
9. FE Validation
10. AM support generation



The Workflow

1. Design domain
2. Properties
3. Mesh
4. Interactions
5. Loads and boundary conditions
6. **Optimization setup**
   - **Sensitivity-based algorithm**
   - **Minimum Compliance problem**
   - **Weight target**
7. Pre-processing
8. CAD regeneration
9. FE Validation
10. AM support generation



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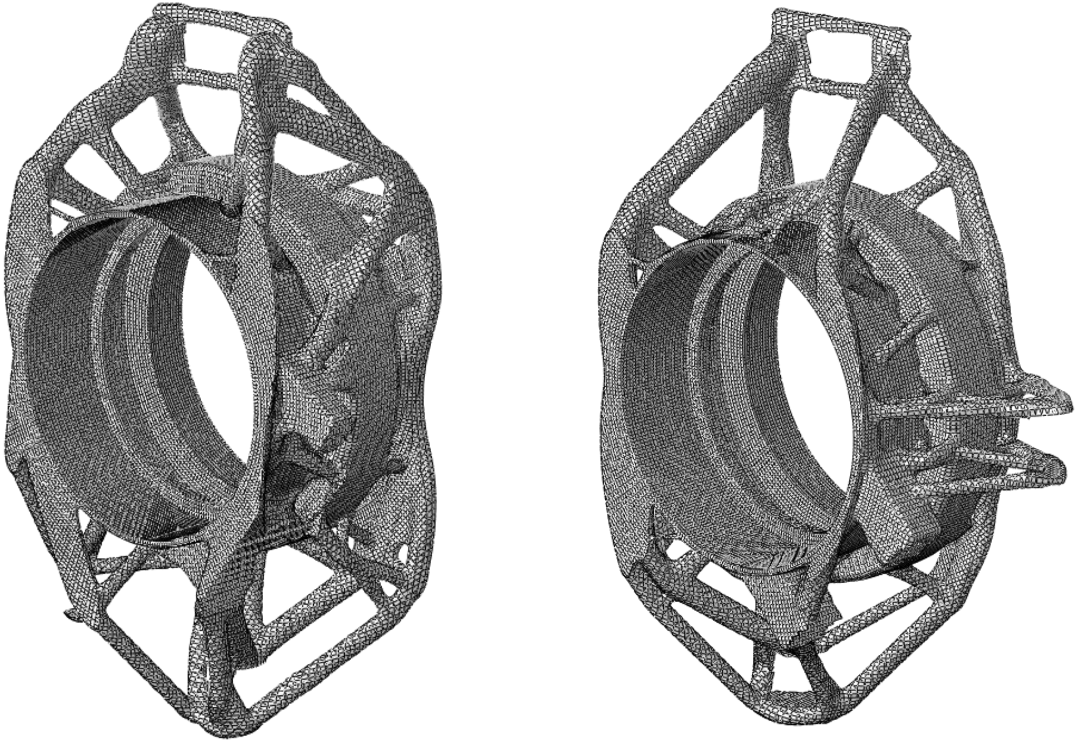
The Workflow

1. **Design domain**
2. **Properties**
3. **Mesh**
4. Interactions
5. Loads and boundary conditions
6. Optimization setup
7. **Pre-processing**
    - **Filtering**
    - **Smoothing**
8. CAD regeneration
9. FE Validation
10. AM support generation



Front

Rear

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NTNU 2017

The Workflow

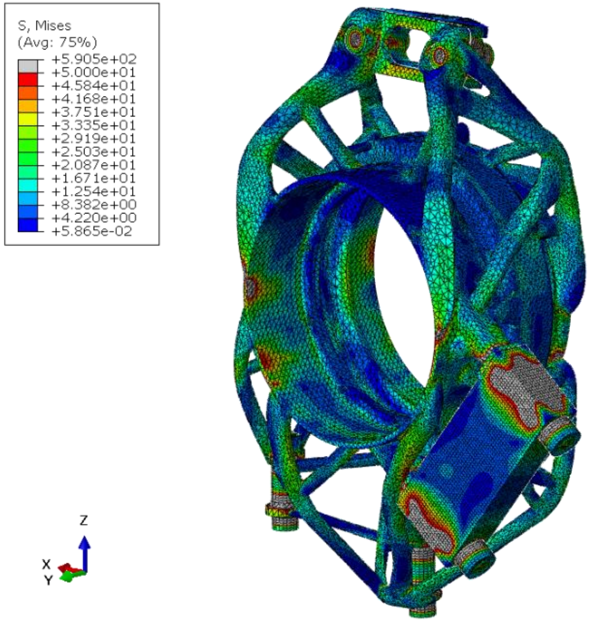
1. Design domain
2. Properties
3. Mesh
4. Interactions
5. Loads and boundary conditions
6. Optimization setup
7. Pre-processing
8. **CAD regeneration**
    - **Modifications for mounting holes**
    - **Inclusion of additional details (motor mount, seal slots,…)**
9. FE Validation
10. AM support generation

Front Rear

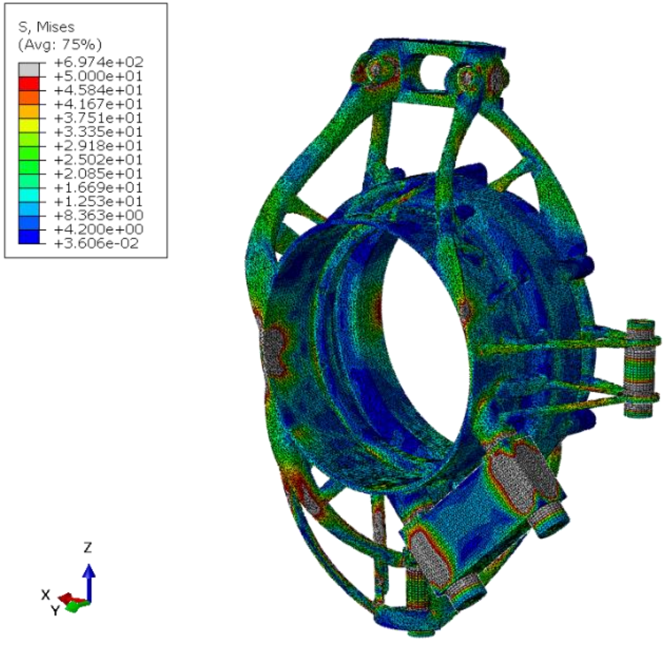
Jørgen Eliassen
NTNU 2017

The Workflow

1. **Design domain**
2. **Properties**
3. **Mesh**
4. Interactions
5. Loads and boundary conditions
6. Optimization setup
7. Pre-processing
8. CAD regeneration
9. **FE Validation**
    - Dimensioning load scenario
    - Extreme load scenario
    - Non-linearites (contact, pretension)
10. AM support generation



Front



Rear

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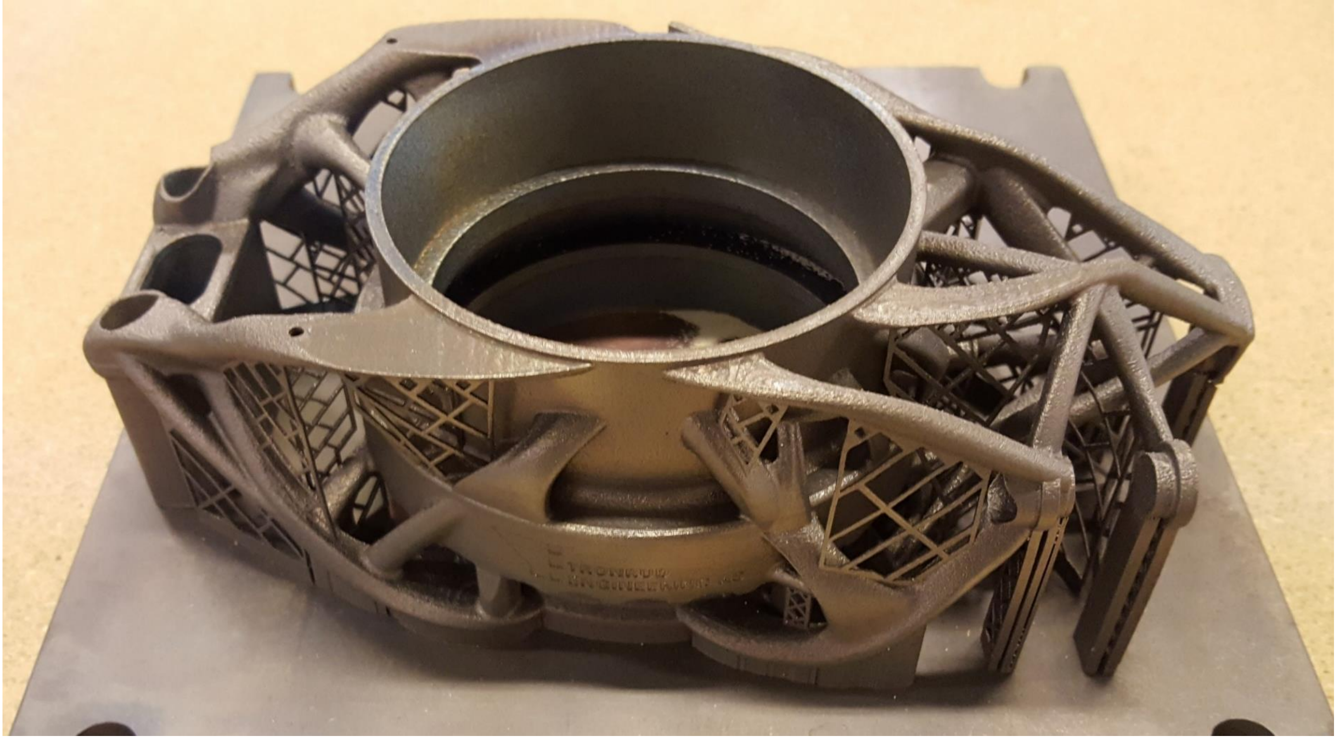
The Workflow



The Workflow

Front upright post CNC-machining

Rear upright post CNC-machining

The Workflow

Compliance Model- An example

Dynamic wheel loads

- Tire-track interaction
- Weight transfer

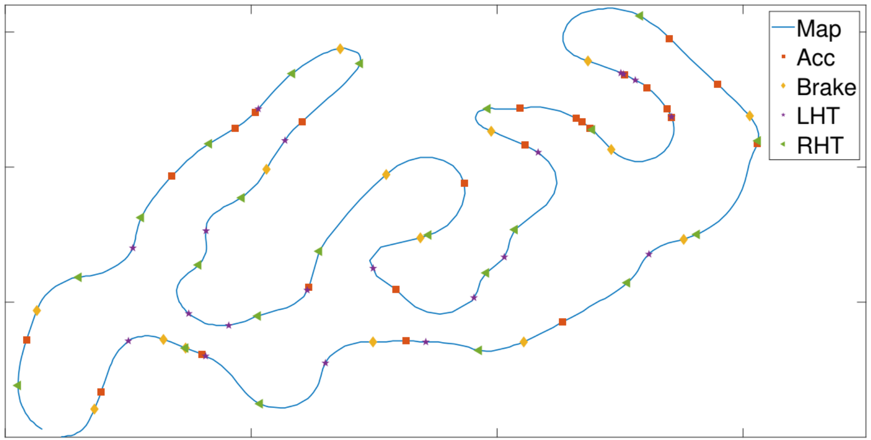


Figure 3.1: Load scenarios during FSG, longitude and latitude data from INS plotted. The car drives in the clockwise direction. Acc = Acceleration, LHT = Left Hand Turn, RHT = Right Hand Turn

Truls Skoglund
NTNU 2019

Compliance Model- An example

Material: EOS Ti6Al4V/ EOS Al10MgSi

Discretization
- Element type: Structured hexahedral
- Mesh method: Top-down combined with bottom-up

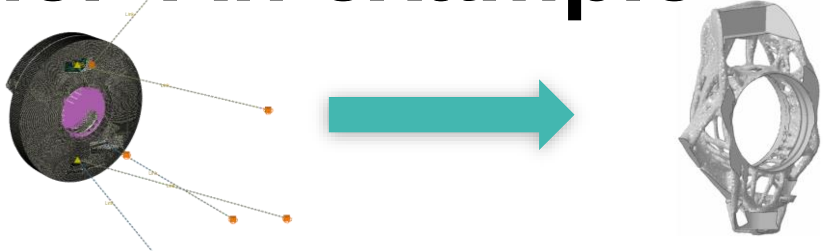
Loads: From tire tests – wheel bearing reaction forces used in optimization is calculated in collaboration with SKF

Abaqus load definition: 4 independent quasi-static load scenarios defined with linear perturbation steps

Design responses: Strain energy (all steps)
Weight

Objective function: Minimum compliance

Constraint: Weight target 350g



Upright	Iterations	Total iteration time [h]	TO raw weight [g]	Weight after regeration [g]
Front left	72	95.2	374.6	577.9
Rear left	56	59.4	323.6	532.7
Rear right	49	46.3	324.2	524.5

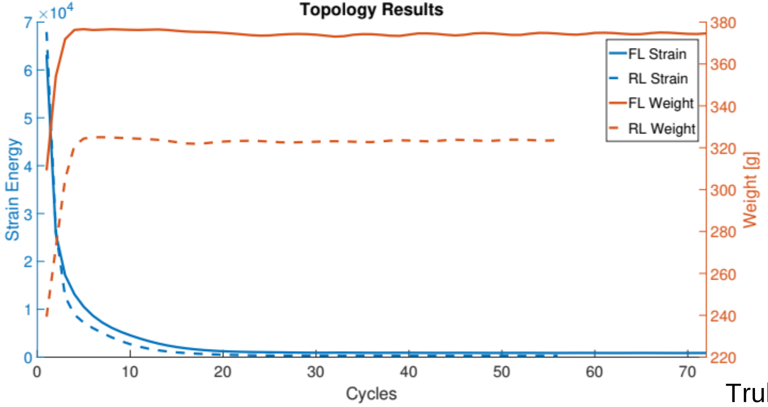


Figure 4.1: Results from Tosca Structure for front left and rear right upright

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Compliance Model- Material Selection

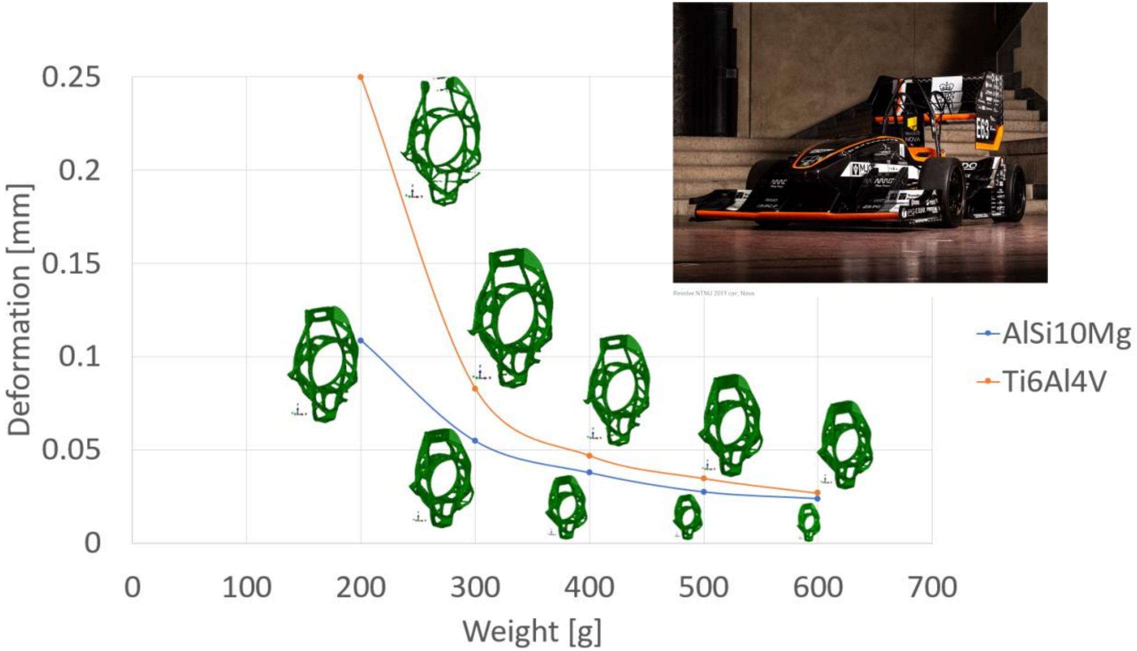

Figure 2.6: Comparison between upright in AlSi10Mg and Ti6Al4V, Skoglund (2019)

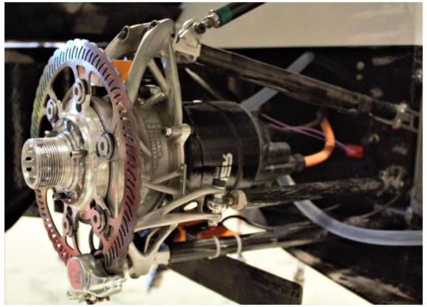

Figure 4.11: Rear left upright

Figure 4.12: Rear right upright

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What is performance?- the objective

Efficiency

Flow resistance

Material used

Stiffness/ Weight

Corrosion resistance

Dissassembly

Conductance

Manufacturing complexity

Surface area

Power

Number of parts

Eigenfrequency

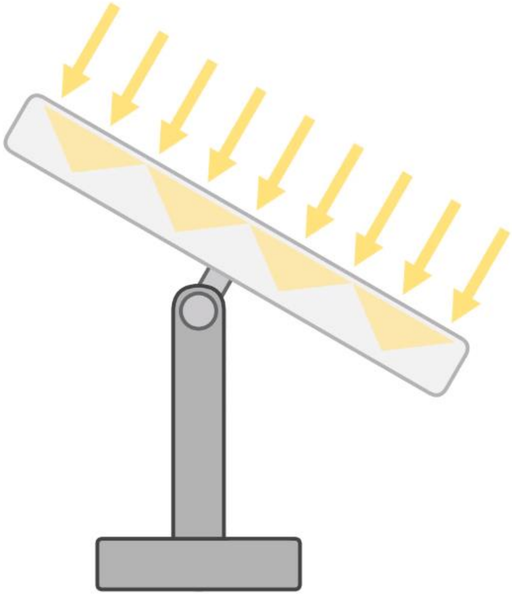
Transmittance

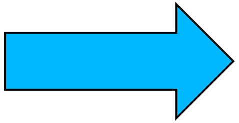
Cost

Accessibility

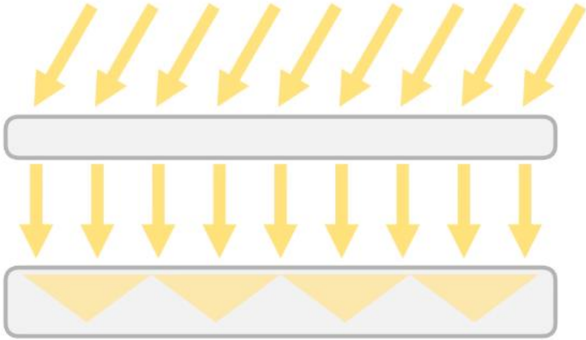
Beyond stiffness- Solar Concentrator

Common tracker





Tracking integration with beam steering lens array



- No Rotation
- Low Physical Footprint
- Low Power, Fast, Accurate Tracking

Johnsen et al.- Optics Express 2020

Solar concentration with BSLAs

Objective Function

(1) Maximize efficiency in redirecting sunlight ↑η

Ingoing/ Outgoing intensity

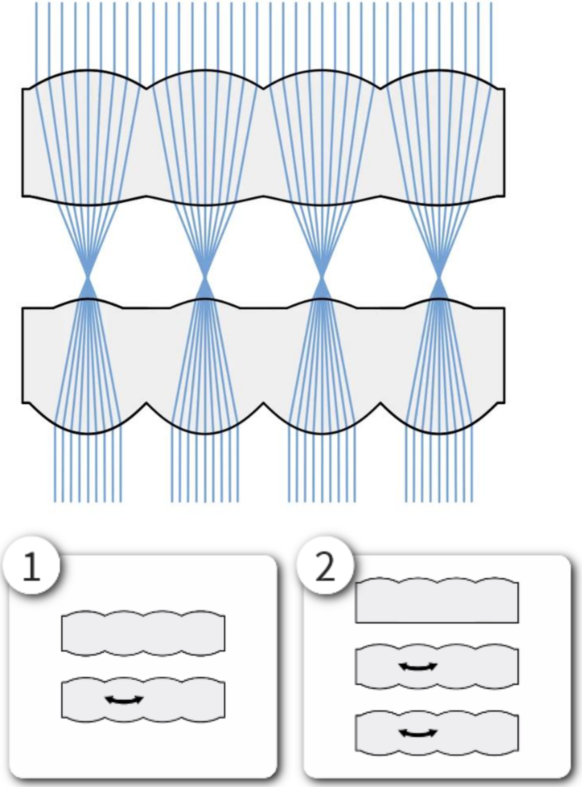
Boundary Conditions

(2) At a set divergence angle ↓Θ_{max}

Deviation of outgoing rays from surface normal

(3) At a set cost/complexity of the system ↓$

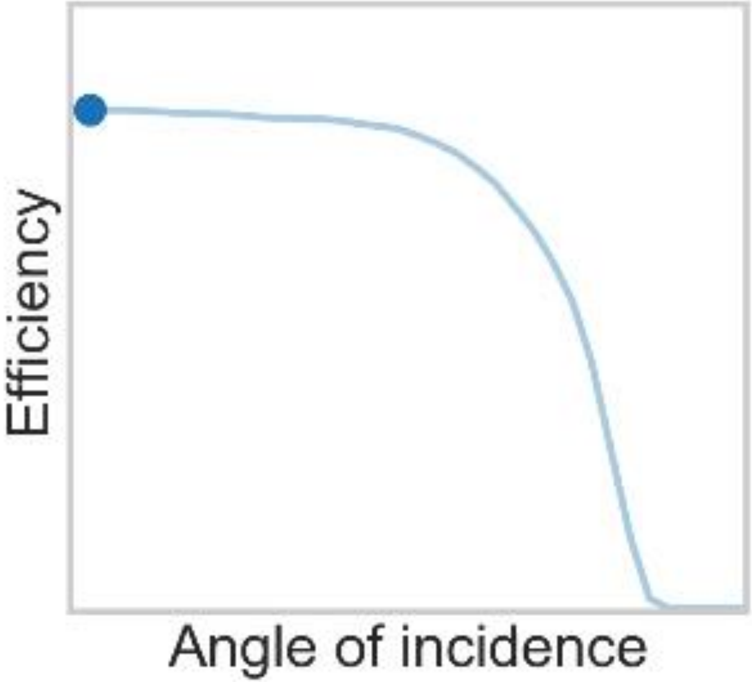
 # Parts/ Complexity of movement

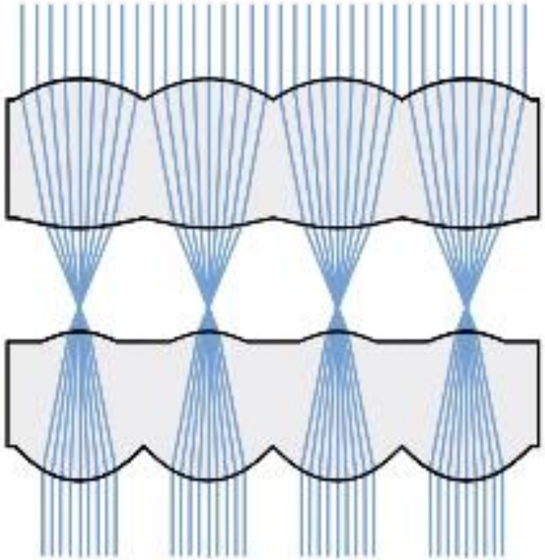


Johnsen et al.- Optics Express 2020

Solar concentration with BSLAs

Maximize efficiency in redirecting sunlight ↑η

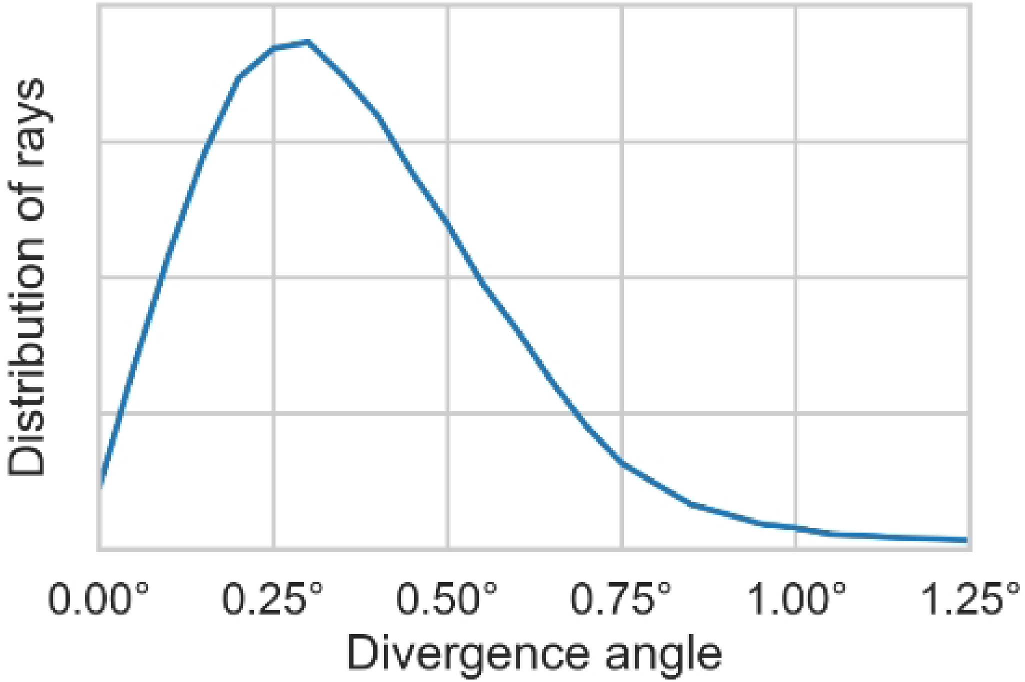




Johnsen et al.- Optics Express 2020

Solar concentration with BSLAs

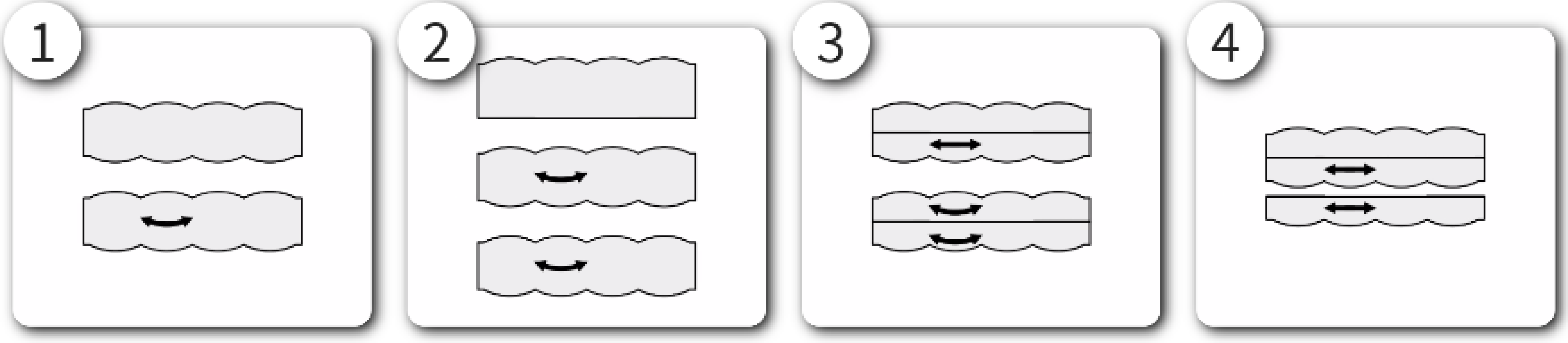
Minimize divergence of ingoing sunlight ↓Θ_{max}



Johnsen et al.- Optics Express 2020

Solar concentration with BSLAs

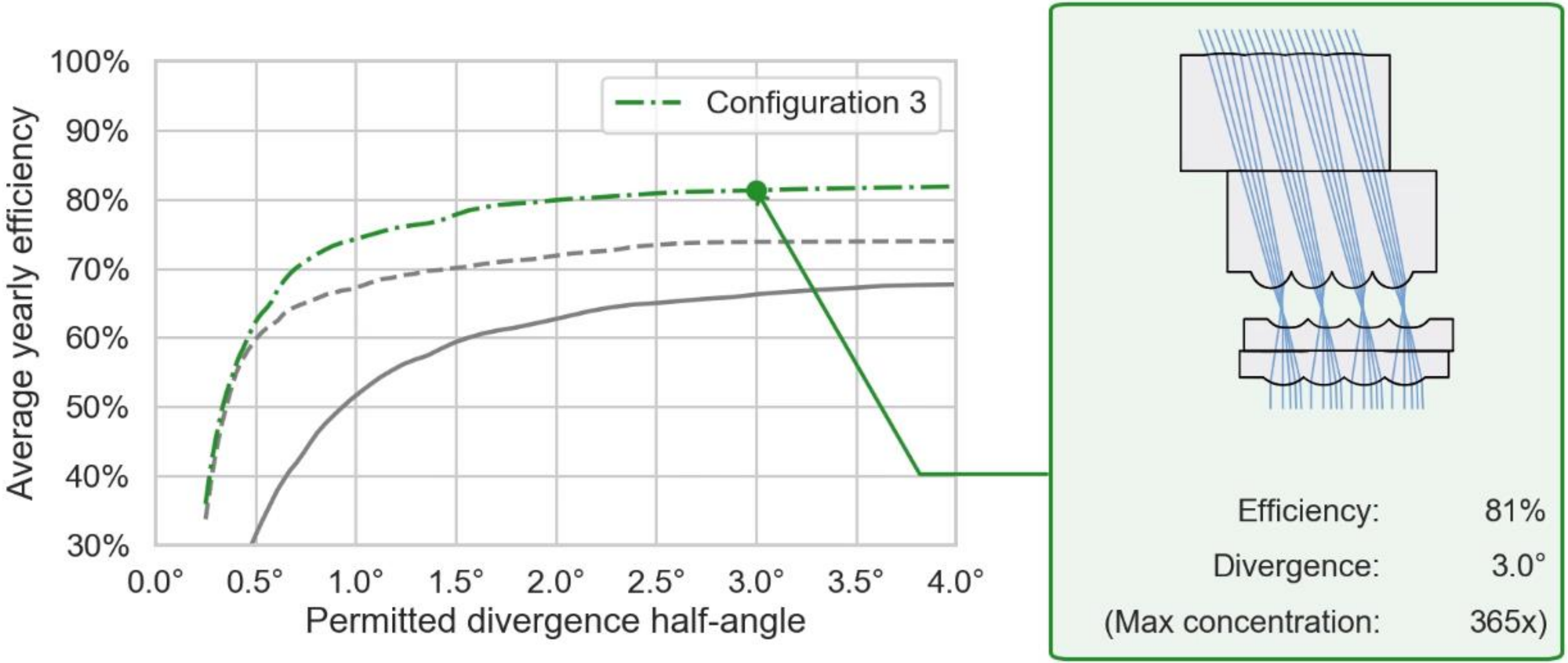
Minimize the cost/complexity of the system ↓$



- Number of lens arrays
- Number of moving parts
- Number of sliding interfaces

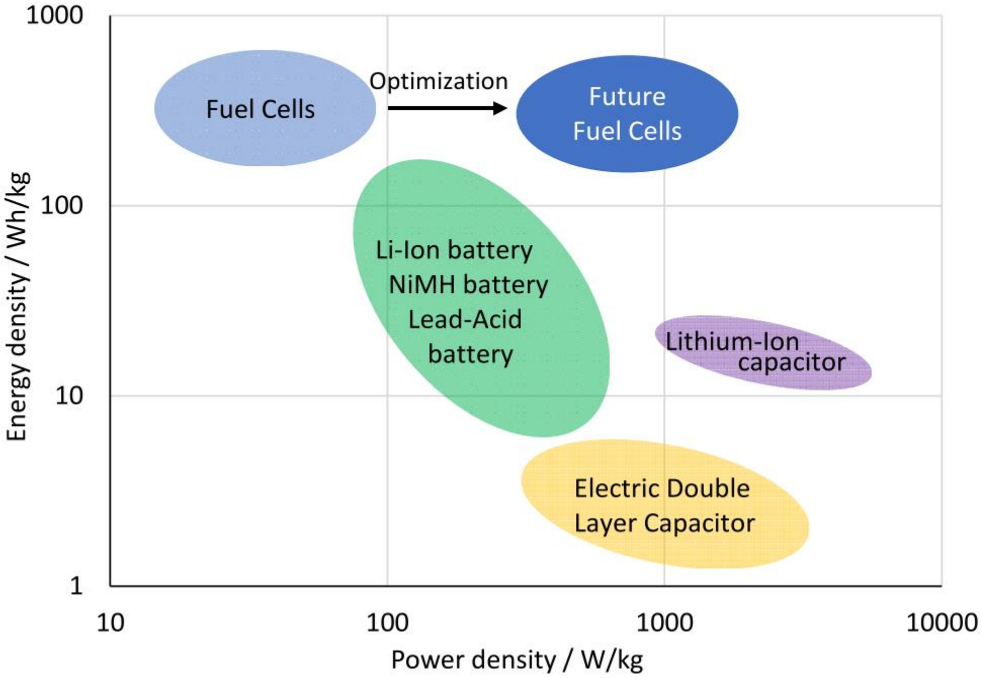
Johnsen et al.- Optics Express 2020

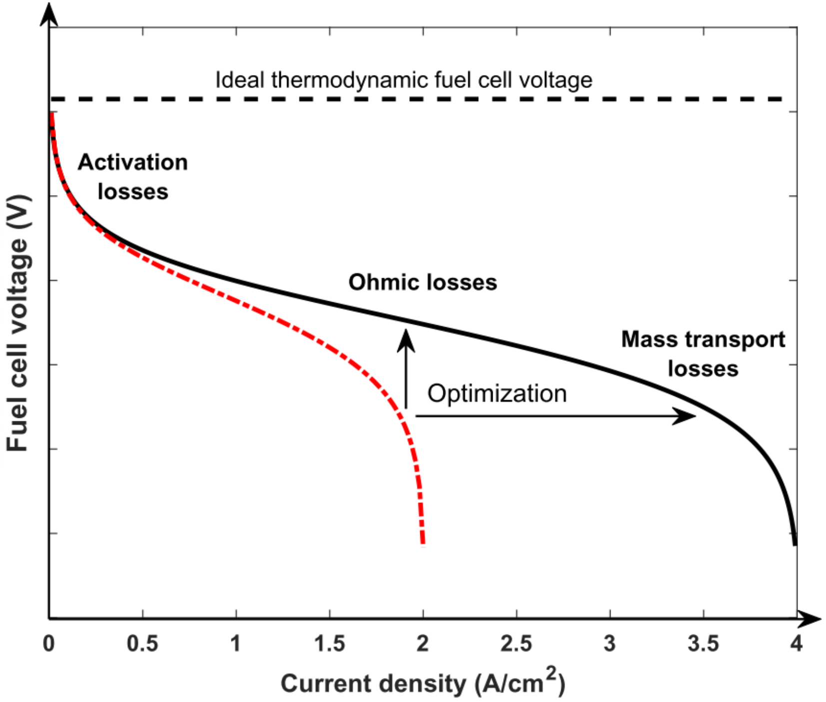
Solar concentration with BSLAs



Johnsen et al.- Optics Express 2020

Next generation PEMFCs

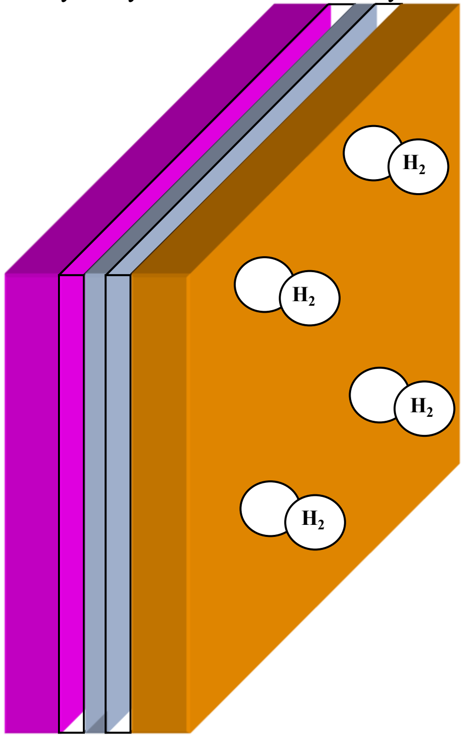




O'Hare et al.– Wiley 2016

The Gas Diffusion Layers

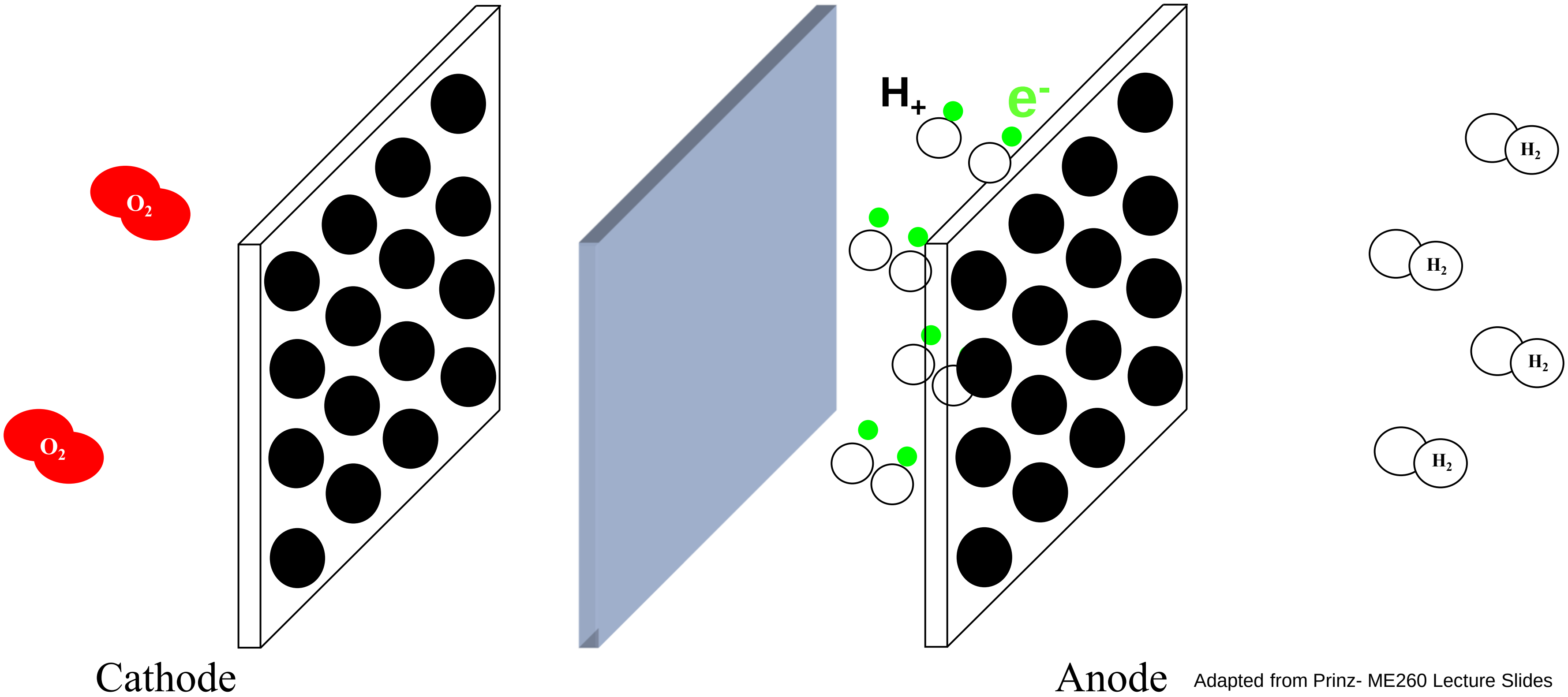
Oxidant | Gas Diffusion / Catalyst Layer | Electrolyte | Gas Diffusion / Catalyst Layer | Fuel



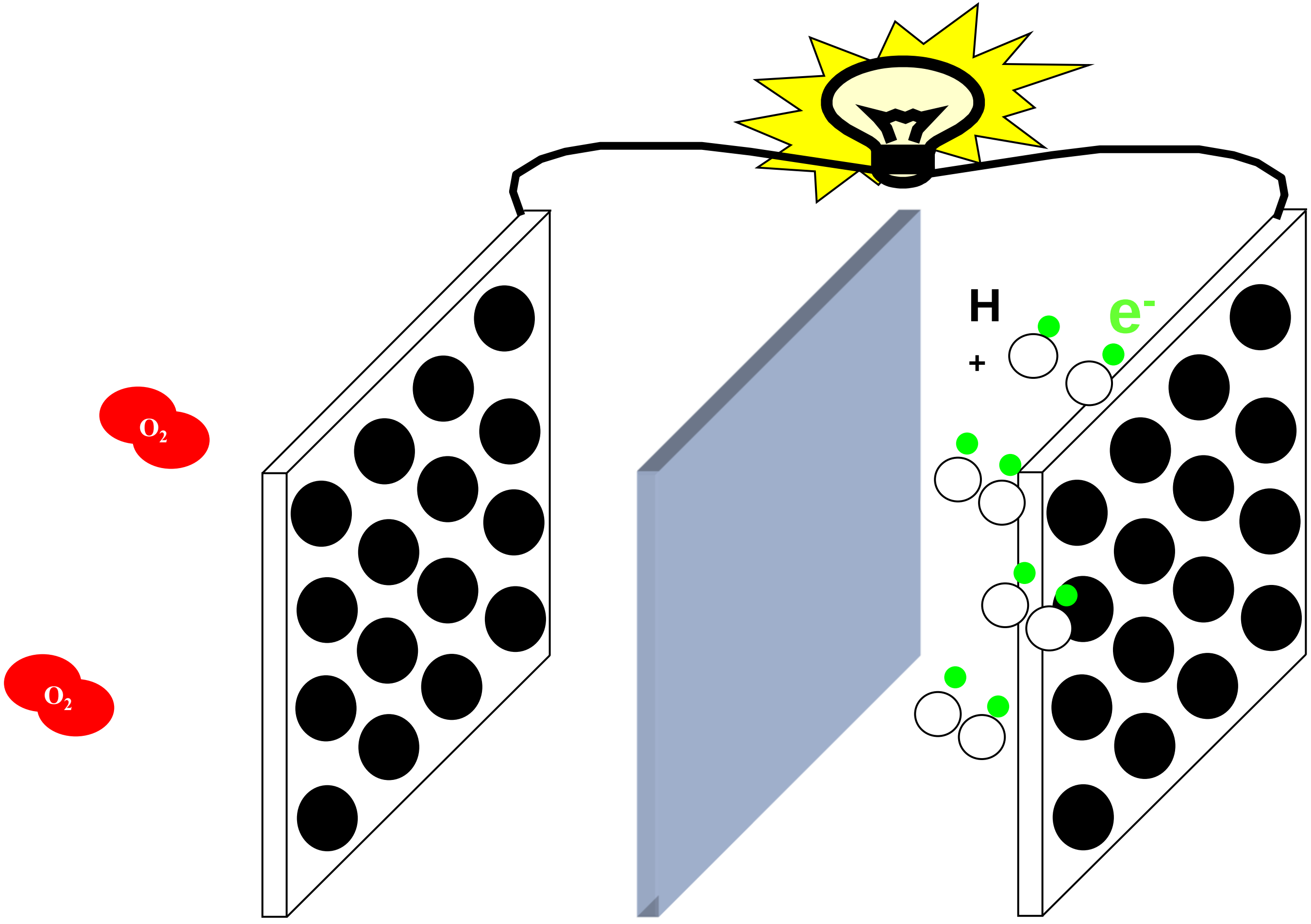
Cathode

Anode

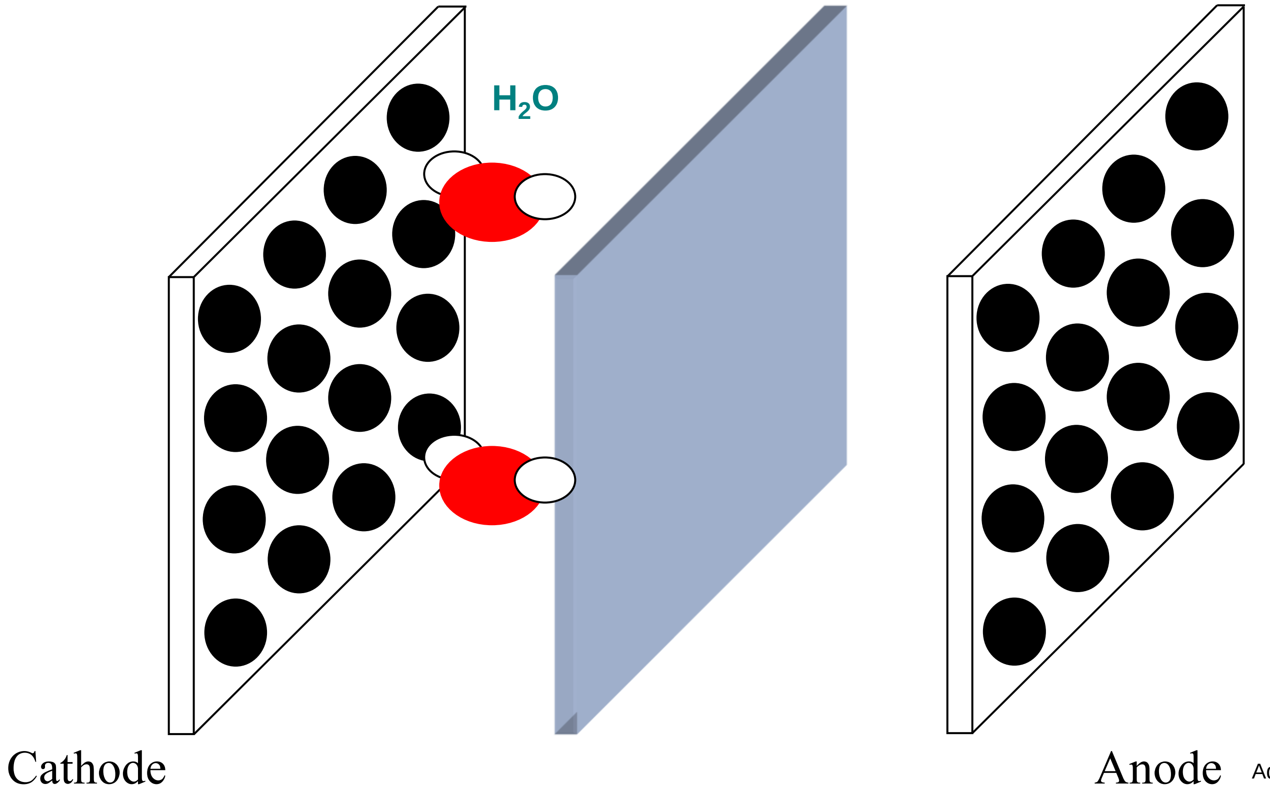
Adapted from Prinz- ME260 Lecture Slides



Adapted from Prinz- ME260 Lecture Slides



Cathode Anode



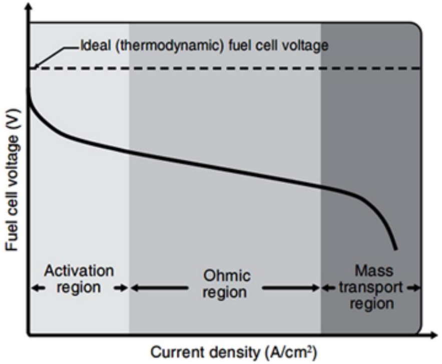
Adapted from Prinz- ME260 Lecture Slides

The optimum Gas Diffusion Layer

Objective Function

(1) Maximize fuel cell power density ↑p

Determined by activation losses, ohmic losses and transport losses

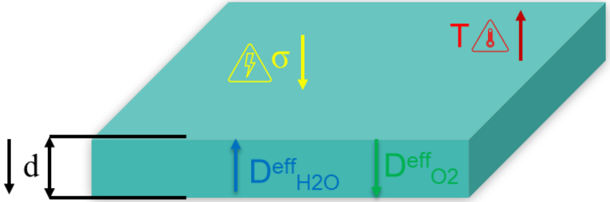


O'Hayre et. al.- Wiley 2016

Boundary Conditions

(2) At a given current density reange $i_{curr.1}$

Defines the dominating losses

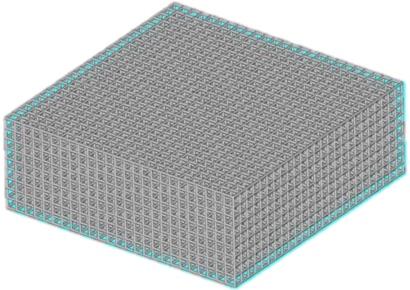


Torgersen and Bock- ECS Prime 2020

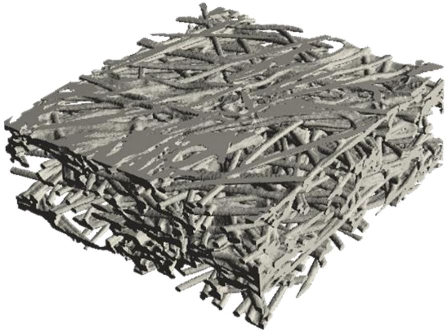
(3) At given design constraints ↓d, ↑T, ↑σ, $\uparrow D^{eff}_{H2O}$, $\uparrow D^{eff}_{air}$

The ranges of the design variables are interrelated

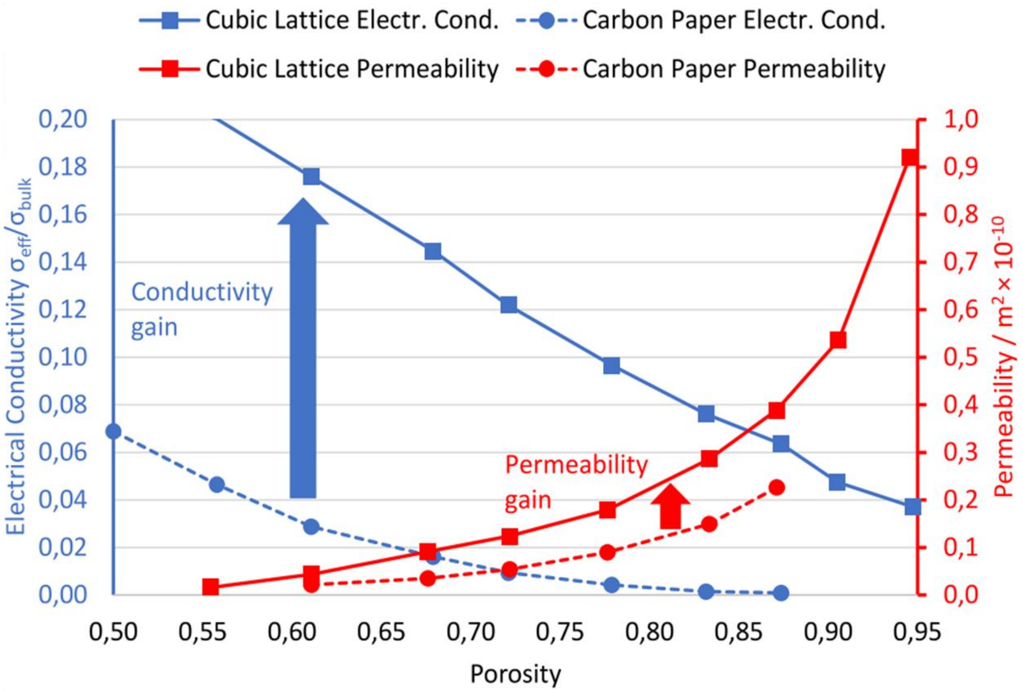
The optimum Gas Diffusion Layer



Cubic Lattice

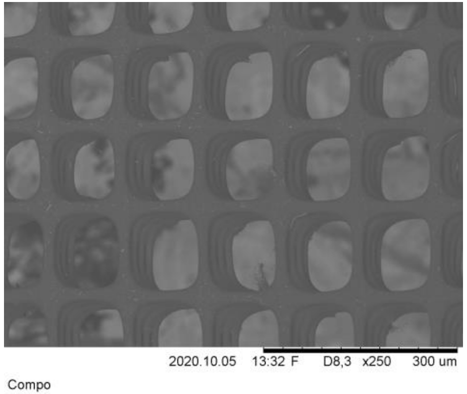


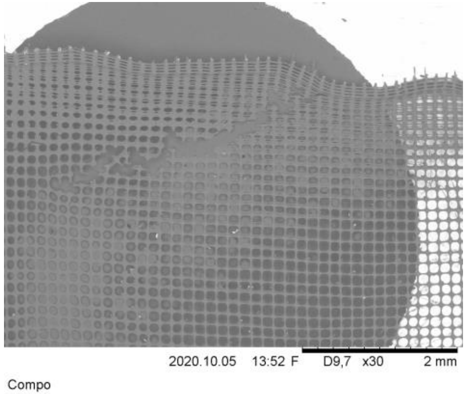
Carbon Paper

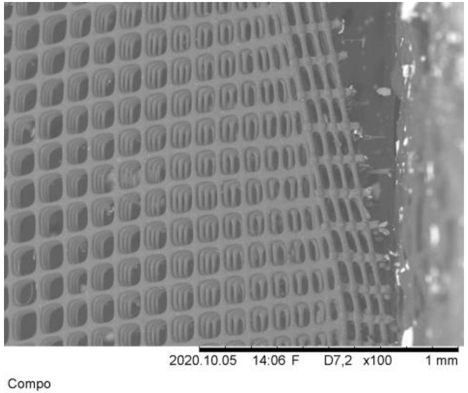


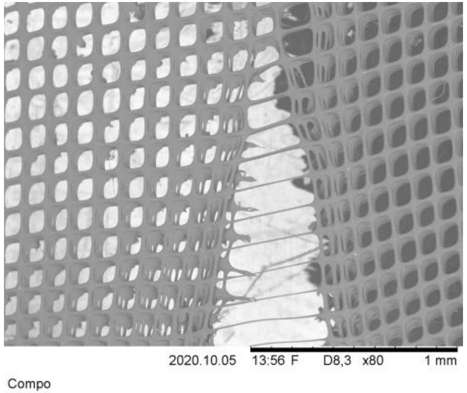
Data from Niblett et al.- Electrochem Soc 2020

The optimum Gas Diffusion Layer





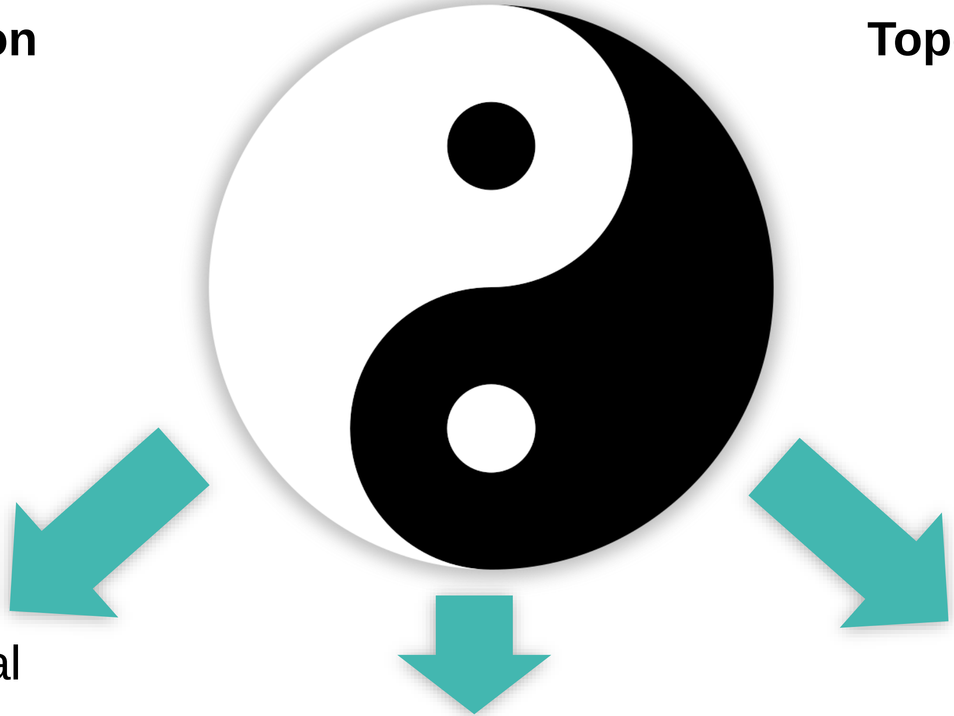




Design to…

Additive Production

Topology Optimization

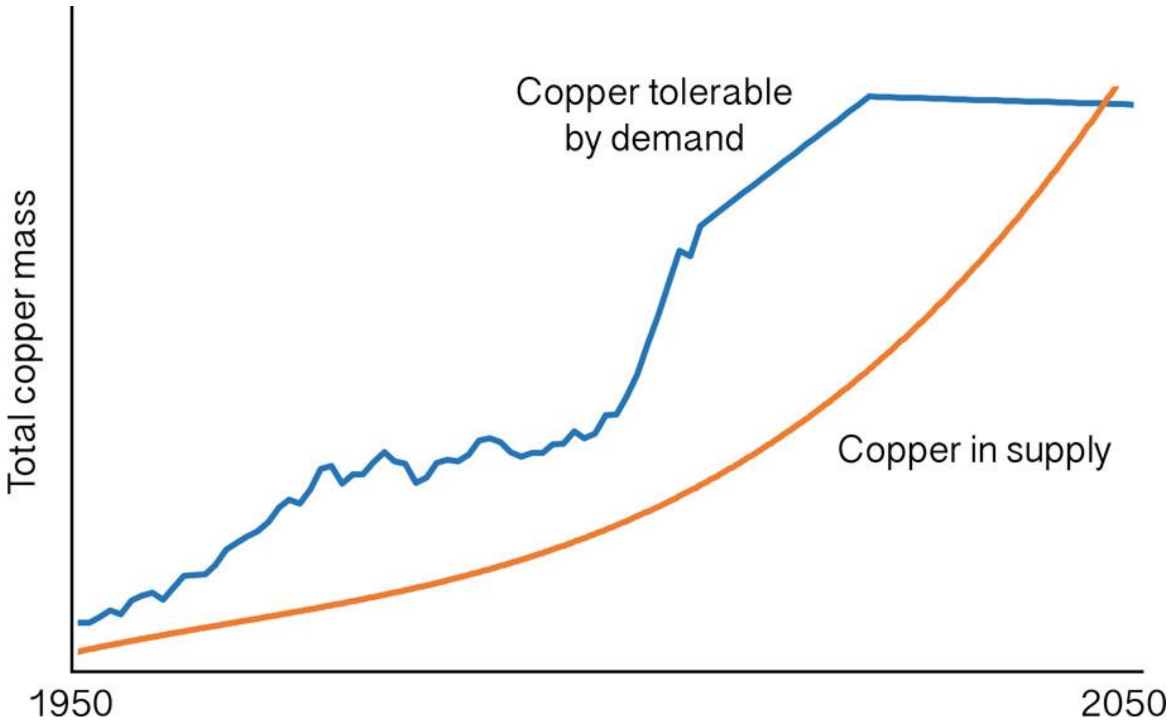


Save Material

Gain performance

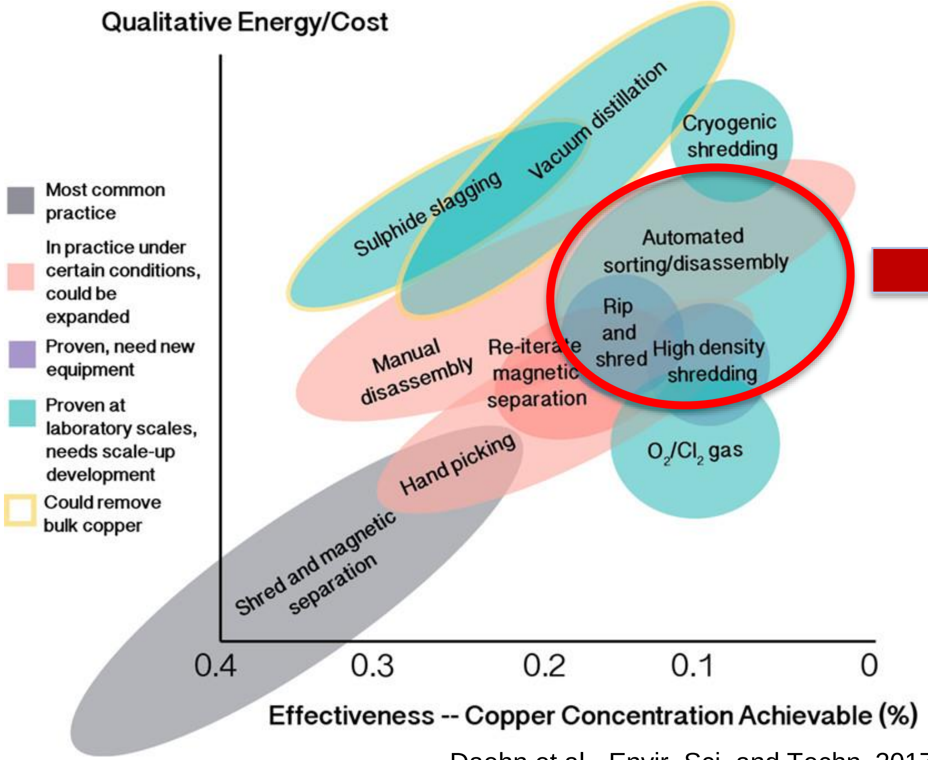
Reuse

Design for Dissassembly



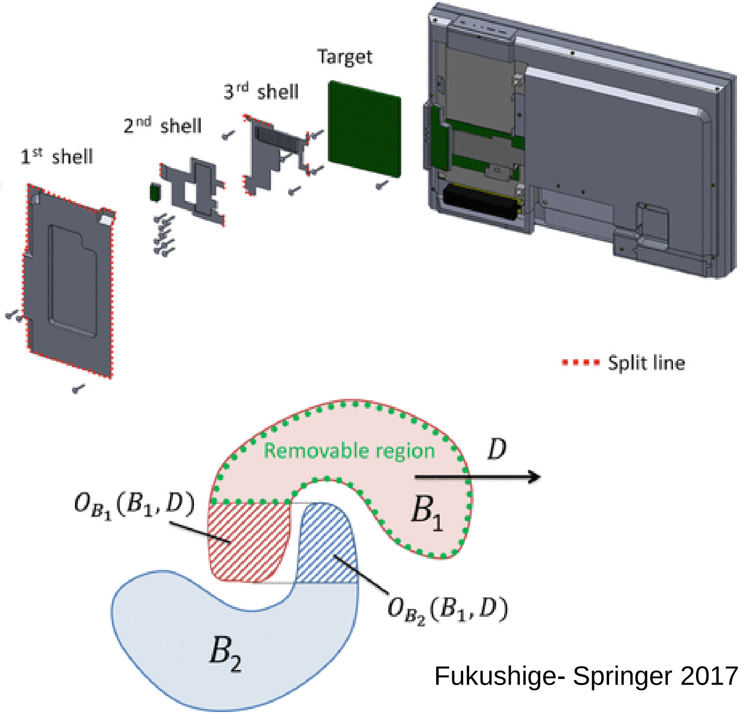
Daehn et al.- Envir. Sci. and Techn. 2017

Design for Dissassembly



Daehn et al.- Envir. Sci. and Techn. 2017

Disassembly embedded design



Fukushige- Springer 2017

Design for Dissassembly

Objective Function

(1) Minimize obstacle region ↓O_{si} by changing extraction direction D_i

Determined by size of Target component T

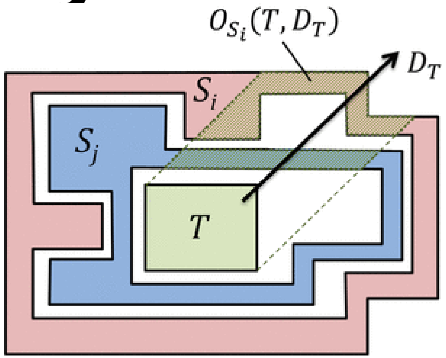
Boundary Conditions

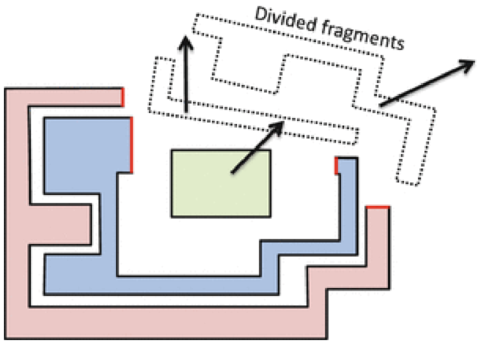
(2) At a given number of shells S_i

Given by the design

(3) At allowed number of split lines

Sets the amount of dissassembly operations





Fukushige- Springer 2017

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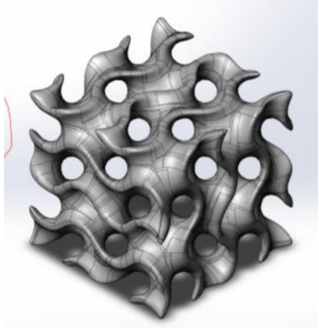
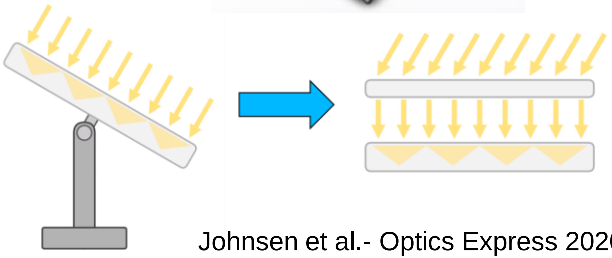
Conclusion

- Additive Manufacturing offers new solutions
- Topology Optimization can infuse Innovation in Product Design
- Million design iterations at low cost
- Readily available: Lightweight and stiff organic designs
- Future possibilities: solar trackers, next generation fuel cells, material recycling

NTNU 2017





Johnsen et al.- Optics Express 2020

Interested?
Jan.torgersen@ntnu.no