Design study of a lightweight electric gearbox rear cover using multi-material topology optimization and CAD design

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LightVehicle 2025 project

‘Light Vehicle 2025’ is an EU-funded Automotive cross-border project (by Interreg) in the Euregio Meuse-Rhine

Project Objective

- Create demonstrators with a weight & CO_2 emissions reduction of at least -25%.
- Enhance cross-border cooperation of companies all along the value chain.

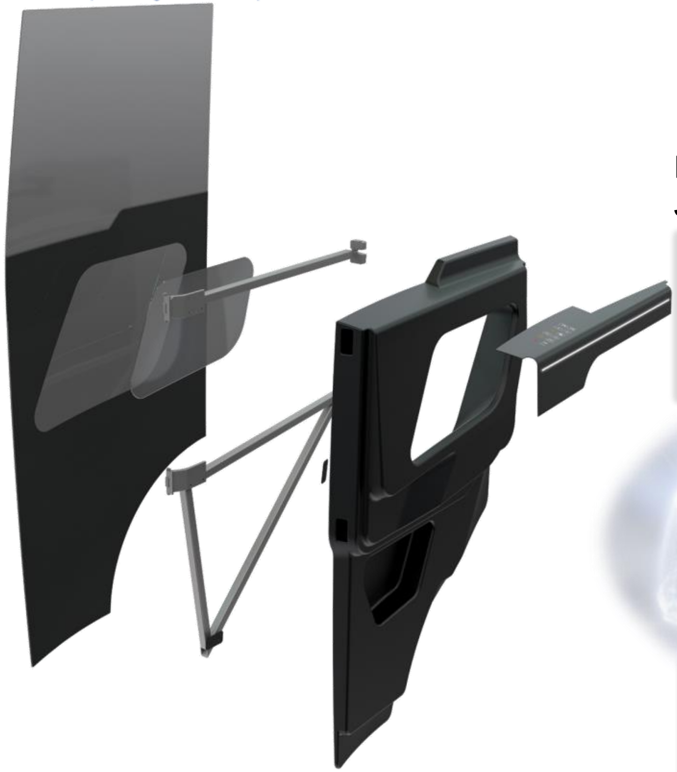
Project Partners

Flanders Make — AutomotiveNL — Liège université — Technifutur — AMAC

Co-Financers

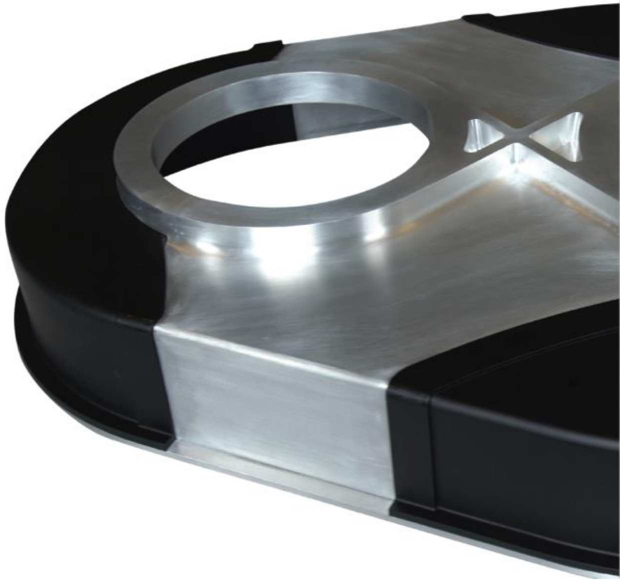
provincie limburg — Provincie Noord-Brabant — provincie Limburg (met steun van limburg.be) — Ministerie van Economische Zaken — Wallonie

Light Vehicle 2025 Demonstrators



Demo Leader:
Jean-Pierre Heijster

 # Body module
Truck door



Demo Leader:
Pierre Duysinx

 # e-Powertrain module
Gearbox Housing

 # Suspension module
Anti-Roll Bar

Demo Leader:
Jan Stroobants

 # Energy Storage module
Hydrogen Tank

Demo Leader:
Michael Effing

1. Presentation of the case study: Motivation

2. New concept generation using multi-material topology optimization
    1. Single material
    2. Two materials
    3. New approach: Selection of the optimization domaine using a T-spline as support
    4. New multimaterial topology optimization

3. CAD design and Life Cycle Analysis

4. Final product assessment

5. Conclusions

The Consortium

GDTECH
→ Topology optimization
→ Innovative design using
→ multimaterial

Code PS
→ Plastic injection simulation

A&M Uliege
→ Scientific Partner
→ Demo Leader

Flanders Make
→ Design & Engineering
→ Project leader

POLYSCOPE
→ Xiloy Material provider

ARRK
→ manufacturing of prototypes

V2i
→ Vibration testing & Validation

MOTIVATION

Interreg Euregio Meuse-Rhine
European Regional Development Fund
EUROPEAN UNION

LIGHTVEHICLE 2025

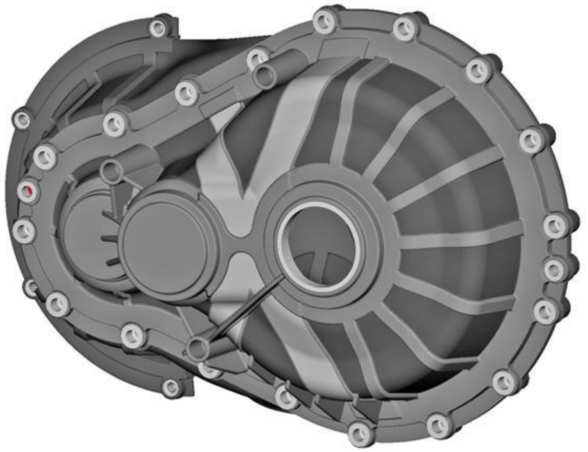
Motivation: Electric Vehicle Gearbox

- Revisit the gear box concept for new electric vehicle powertrains reducing simultaneously the weight (-25%) and CO_2 emissions (-25%)

BorgWarmer e-DM

New generation of e-axles for EV and P4 hybrid vehicles

The integrated design of the electric motor and transmission enables weight, cost and space savings. Since both functions are combined into one housing, installation is also easier.



First Thermoplastic Composite Gearbox Housing: 30% Lighter Than Aluminum by ARRK Engineering Division (www.materialsforengineering.co.uk)

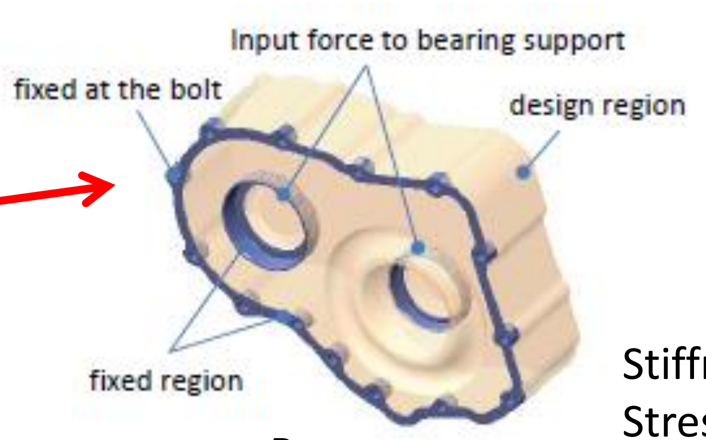
T. Schneider. Reinforced Plastics. Volume 63, Issue 1, January–February 2019, Pages 40-45

Motivation: Electric Vehicle Gearbox

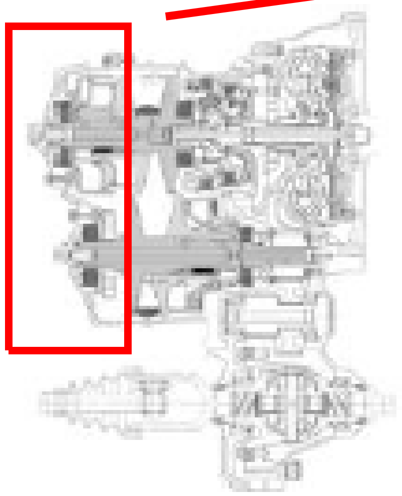
- A generic model of EV gear box rear cover

Load cases &
Boundary Conditions

Simplified design problem



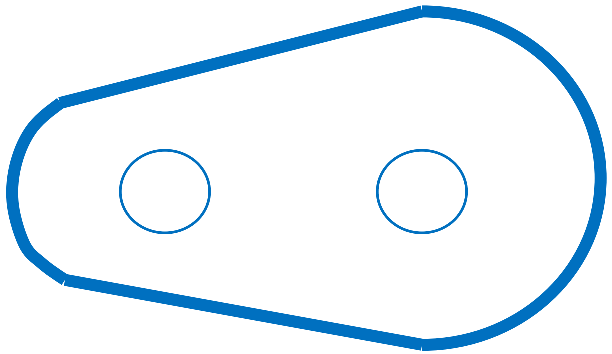
Rear cover

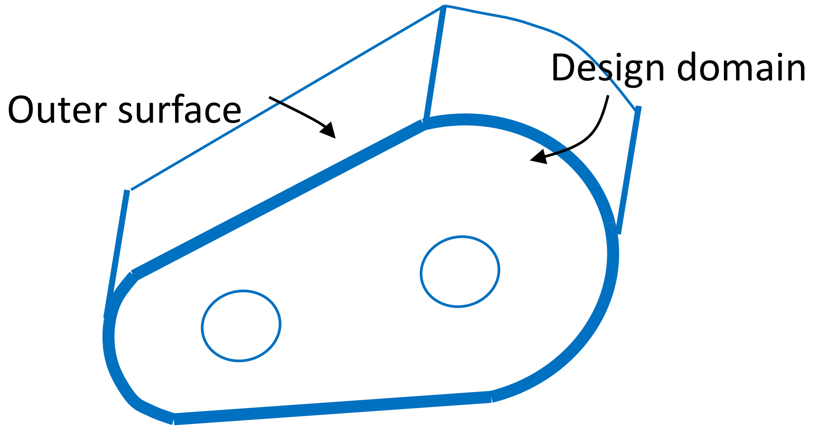


Proprietary EV gear box

Stiffness
Stress and durability
Sealing
Oil containment
Lubrication
Sound propagation
Easiness of manufacturing

Design domain for the use case

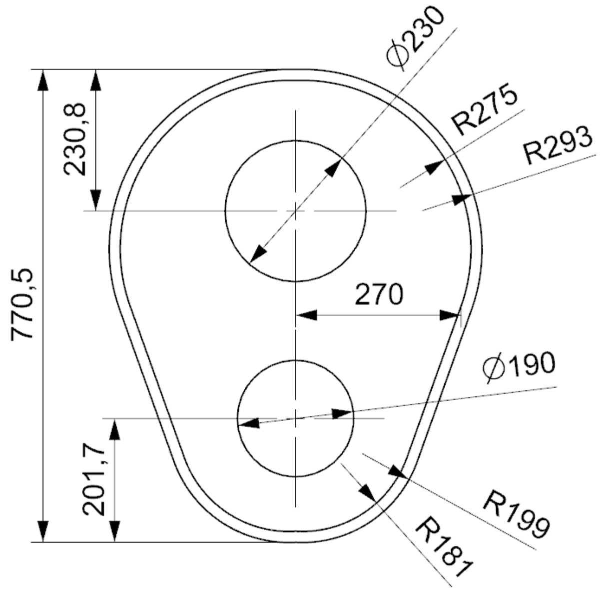


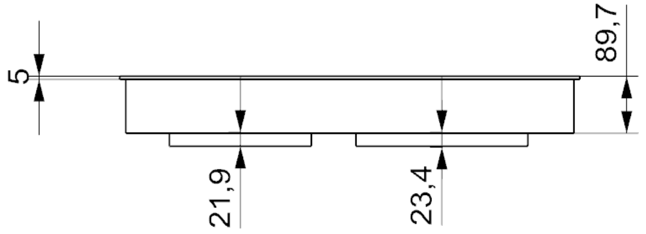


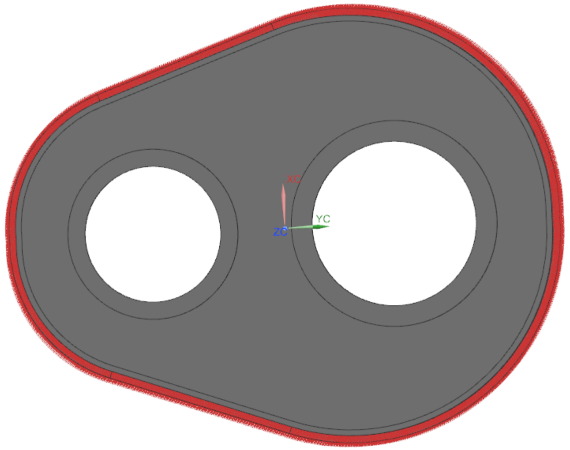
Generic EV gear box (open source)

Motivation: Electric Vehicle Gearbox

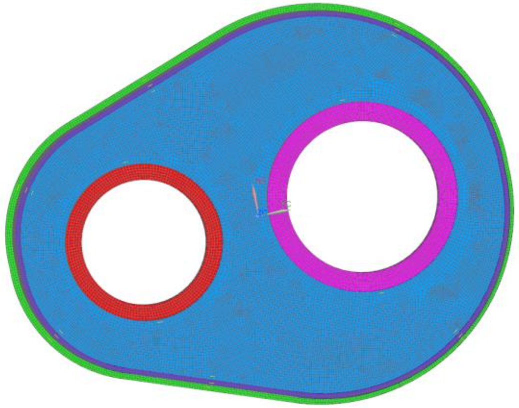
- A generic model of e-gear box rear cover



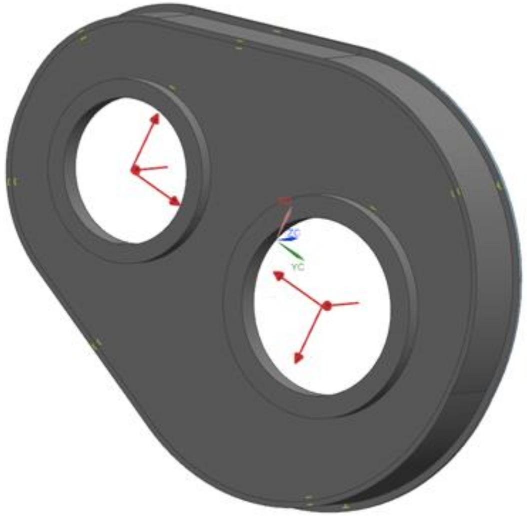




Boundary Conditions



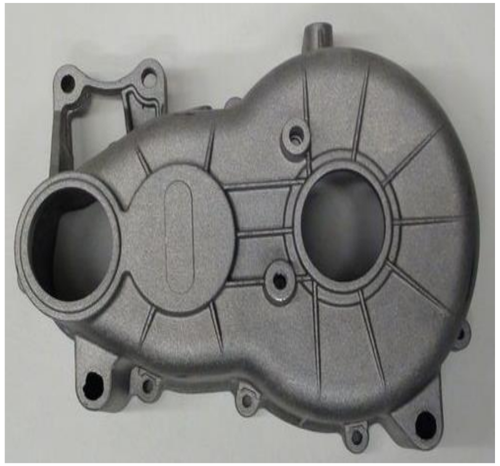
Mesh

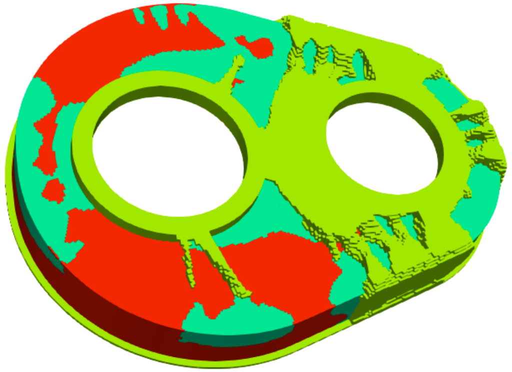


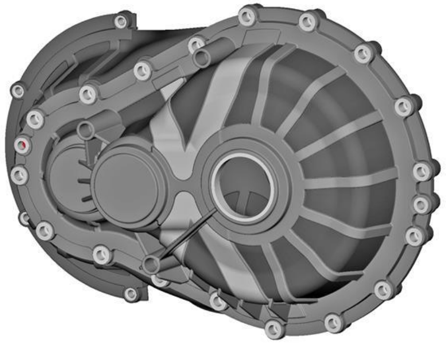
Load Cases

Generic EV gear box rear cover

Motivation: Electric Vehicle Gearbox







Reference part made of aluminium
Initial mass (alu) = 11.7kg

New design part made of aluminium and PA

- Multimaterial design: Aluminum and composite
- Selected composite: Xiloy SX1859 (styrene maleic anhydride N-phnylmaleimide (SMANPMI / PA6)

POLYSCOPE fresh thinking, great products

- 30% glass fiber (short fibre)
- Excellent dimensional stability

- High temperature resistance
- Good adhesion with metals

NEW CONCEPT GENERATION USING TOPOLOGY OPTIMIZATION

1. Presentation of the case study: Motivation

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   1. Single material
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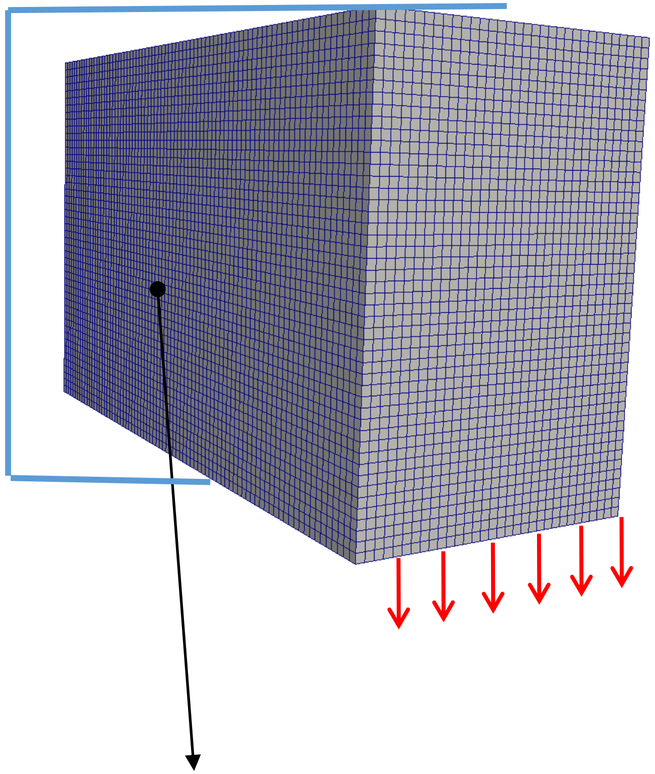
4. Final product assessment

5. Conclusions

Topology optimization: generating new structural concepts



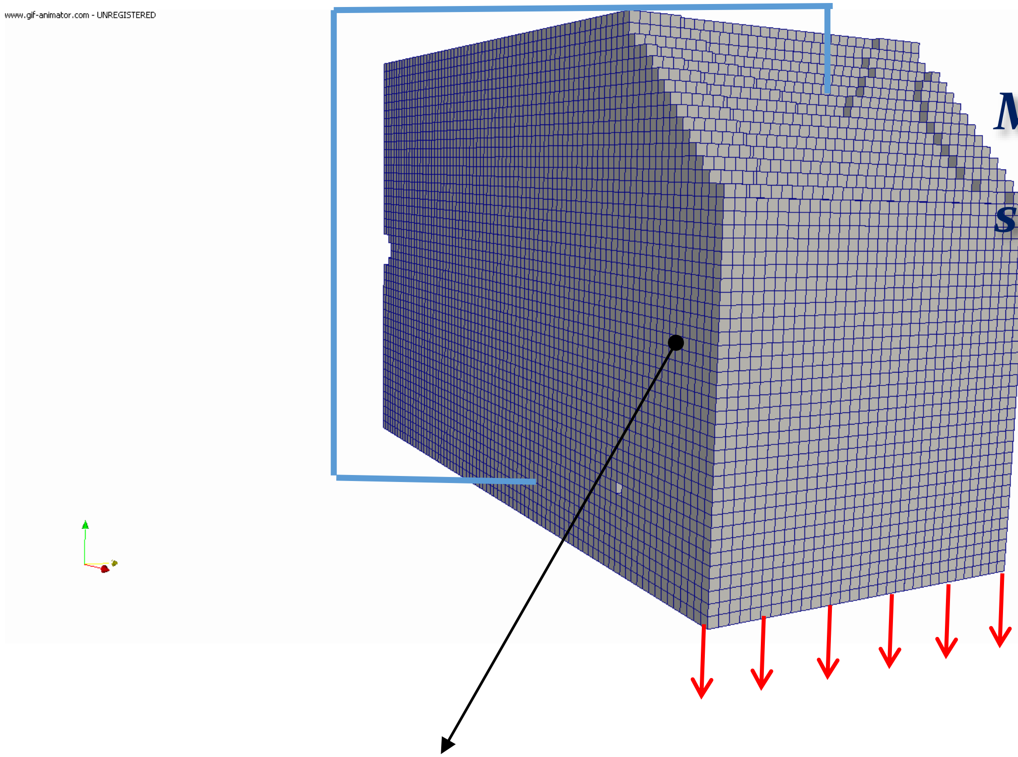
Max. *Performance*

s.t. *Design Constraints*

Density Variables: $\rho_e \mid 0 \leq \rho_e \leq 1$

$$\begin{cases} \rho_e = 0 & \text{Void} \\ \rho_e = 1 & \text{Solid} \end{cases} \qquad E_e = \rho_e^3 \, E^0$$

Topology optimization: generating new structural concepts



Max. *Performance*

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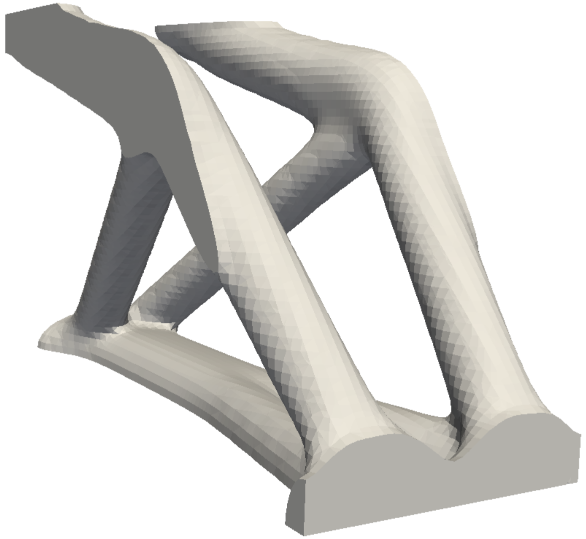


Topology optimization: a new design tool that offers innovative design ideas.

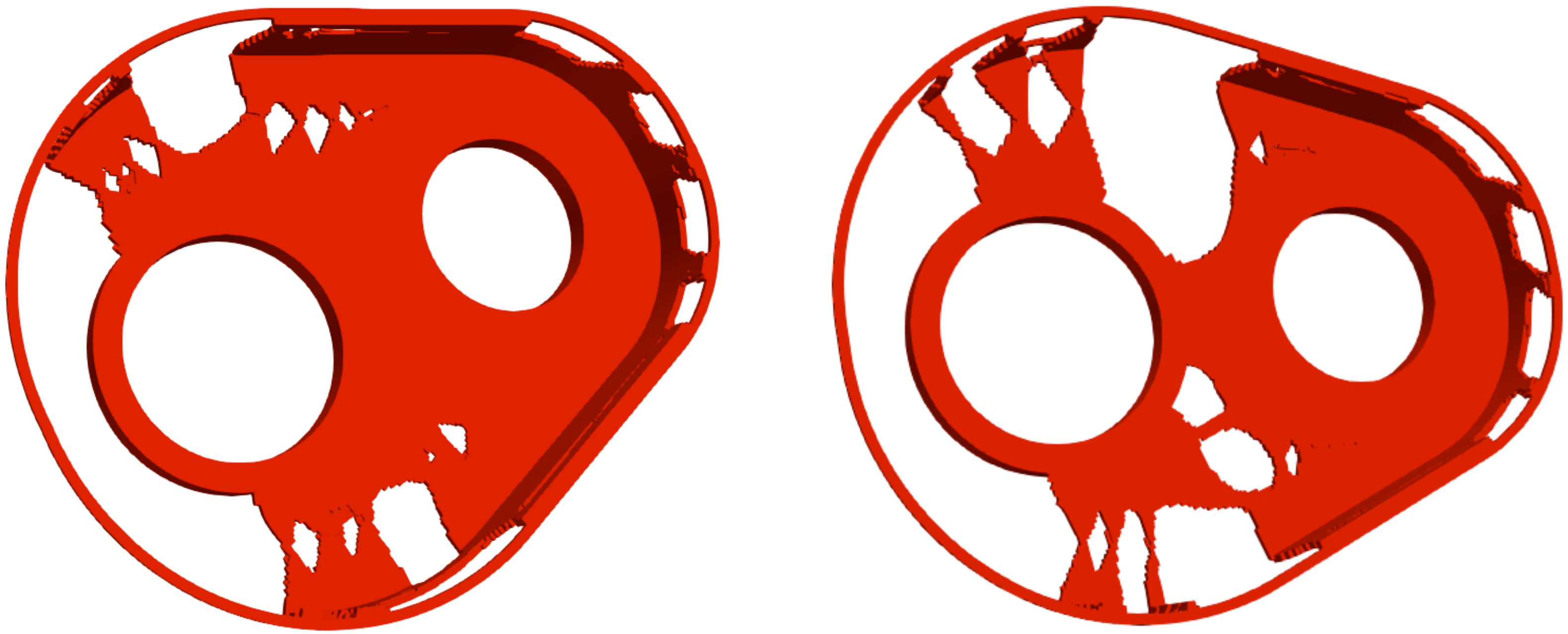
Topology optimization: generating new structural concepts

min Compliance
density

st Volume
Equilibrium

$$\min_{\mu_e} \quad \mathbf{f} \cdot \mathbf{u}$$

$$\text{st} \quad \sum_e \mu_e V_e$$
$$\mathbf{Ku} = \mathbf{f}$$



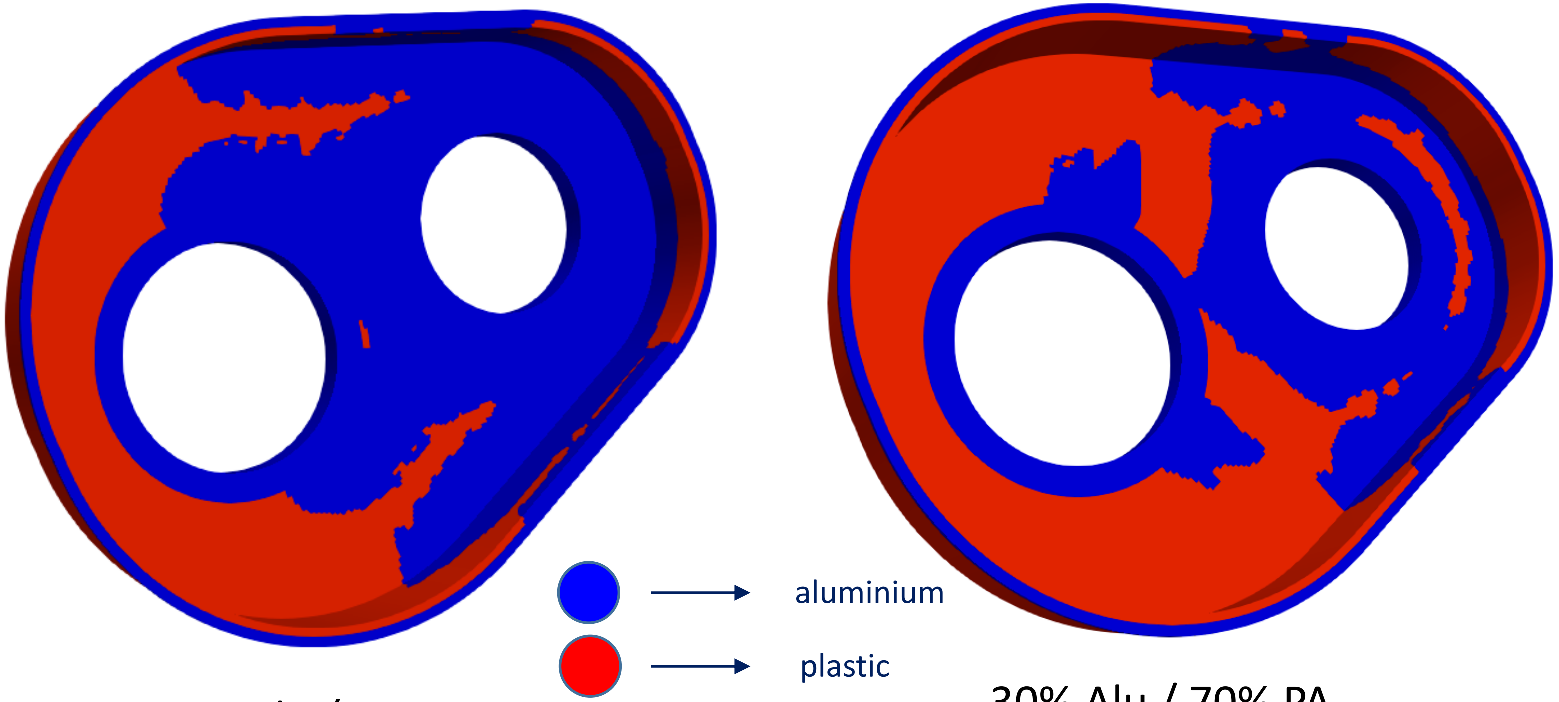
$$E_e = E_{min} + \rho_e^3 \left(E^0 - E_{min}\right)$$

- One material (aluminum)
  - Topology optimization aluminum / void
  - Volume: 60%

Topology optimization: generating new structural concepts

$$\begin{array}{ll} \text{min} & \text{Compliance} \\ \text{density} & \\ \text{st} & \text{Volume} \\ & \text{Equilibrium} \end{array}$$

$$\begin{array}{ll} \min\limits_{\mu_e} & \mathbf{f} \cdot \mathbf{u} \\ \text{st} & \sum_e \mu_e V_e \\ & \mathbf{Ku} = \mathbf{f} \end{array}$$



50% Alu / 50% PA

30% Alu / 70% PA

- Two materials (aluminum / PA) & void
  - Topology optimization aluminum / PA / void
  - Volume: 50%/50% - 30%/70%

$$E_e = \rho_e^3 \left(x_e^3 \, E_1 + (1 - x_e)^3 \, E_2 \right)$$

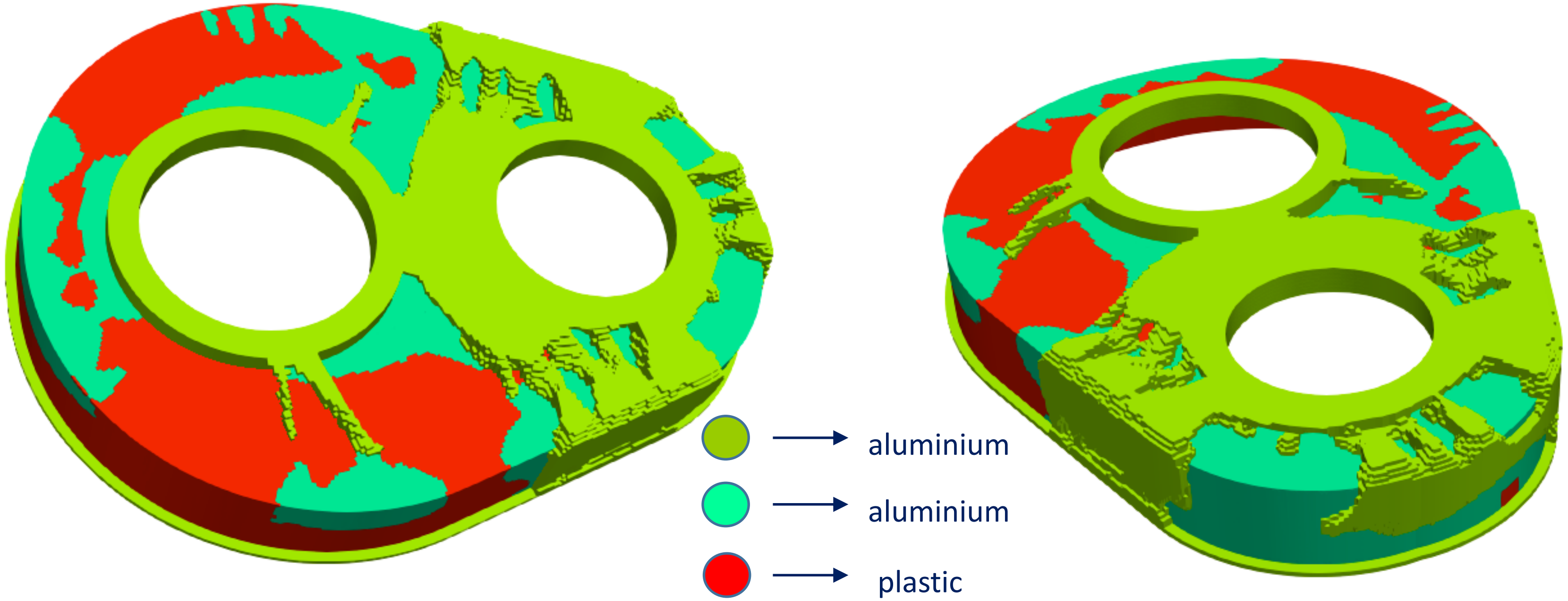
Topology optimization: generating new structural concepts

min Compliance
density

st Volume
Equilibrium

$$\min_{\mu_e} \quad \mathbf{f} \cdot \mathbf{u}$$

$$\text{st} \quad \sum_e \mu_e V_e$$
$$\mathbf{K}\mathbf{u} = \mathbf{f}$$



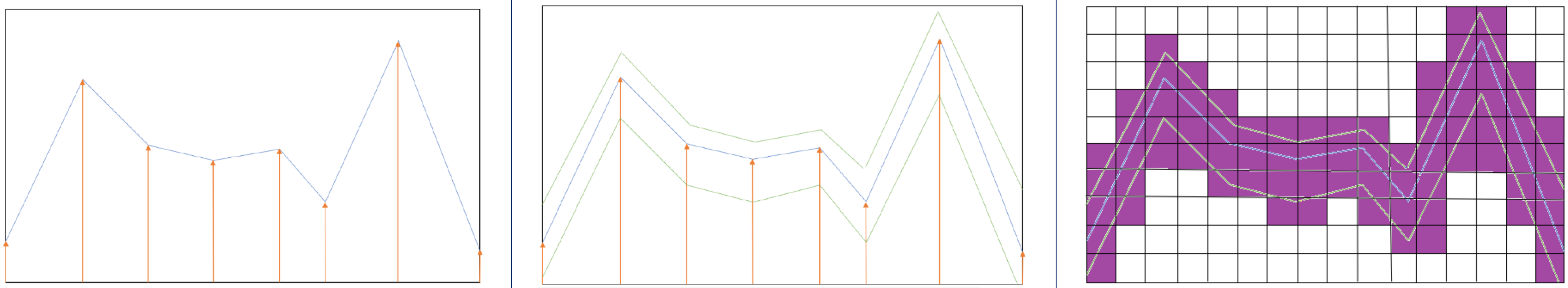
Base shell: 50% Alu / 50% PA

Stiffening layer : 20% Alu / 80% void

$$E_e = \rho_e^3 \ \left(x_e^3 \, E_1 + (1 - x_e)^3 \, E_2\right)$$

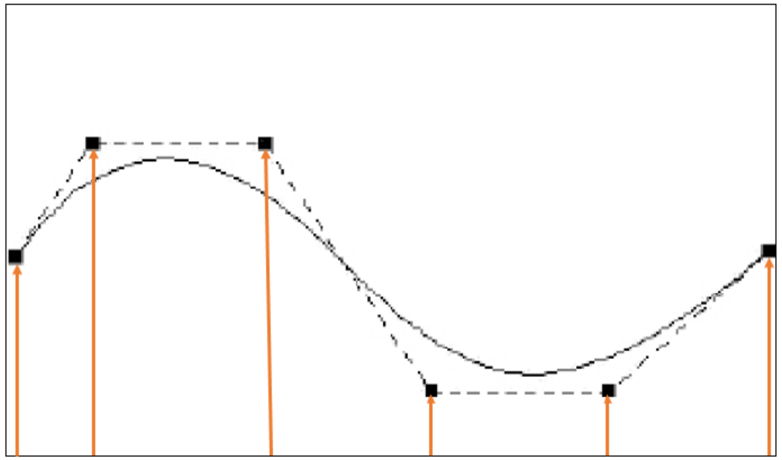
- Base shell : two materials (aluminum / PA) & void
  - Oil containment
- One layer of stiffener in aluminum / void
  - Bending stiffness

‘Level-sets’ method

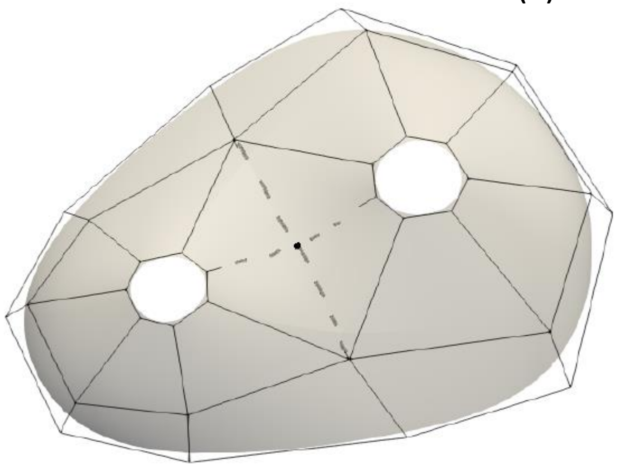


(a) (b) (c)

The support used for the creation of level-sets is a T-spline



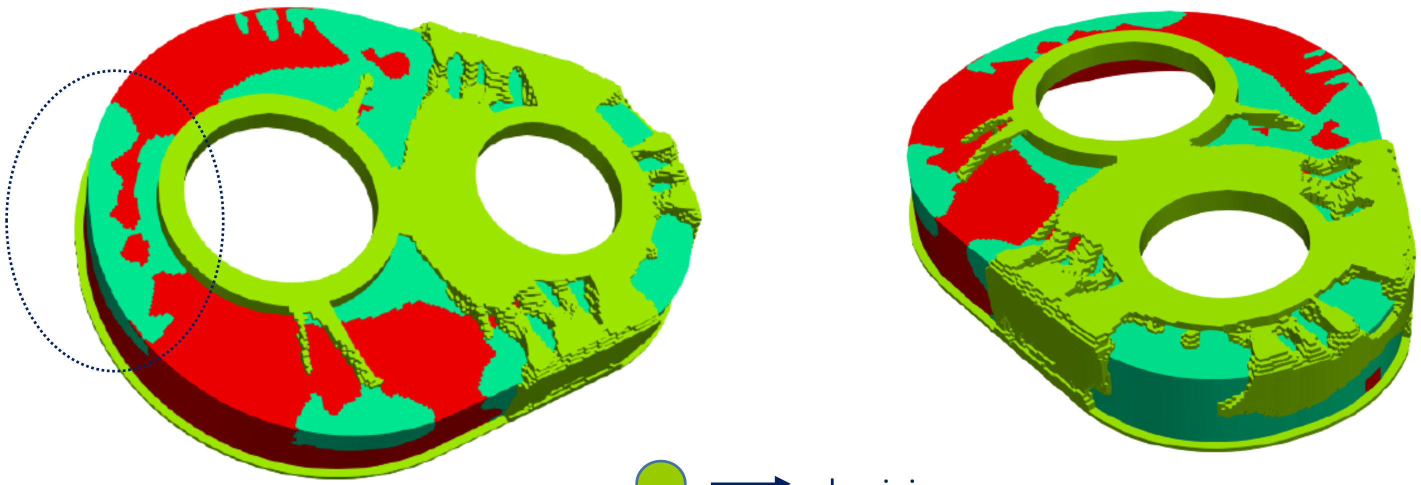
Optimization of the coordinates of the nodes of the T-mesh



T-spline surface generated by T-Mesh.

Multi-block topology optimization

Block nº1/Inner layer	Block nº2/External layer
Aluminium	Aluminium
Plastic	Void



→ aluminium

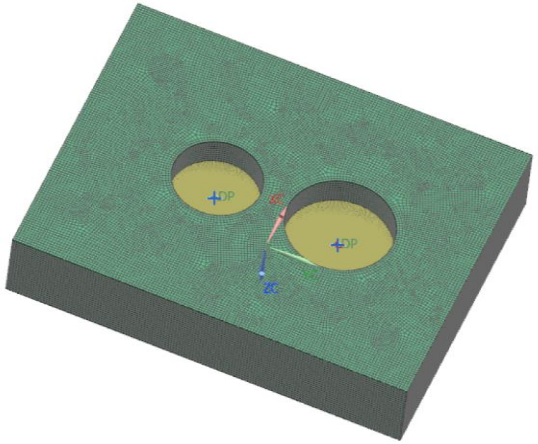
→ aluminium

→ plastic

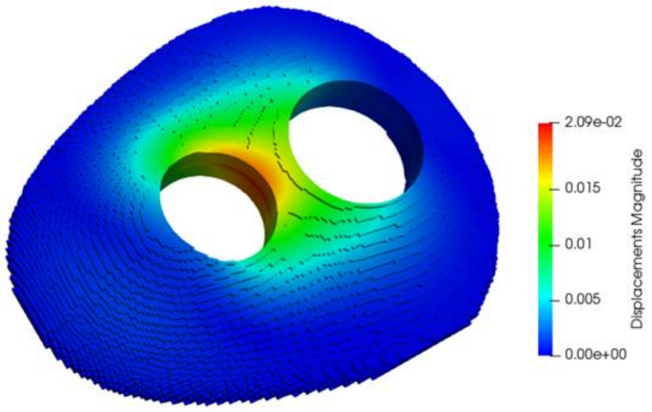
Inner layer: aluminium/plastic (50/50%) → Offers the necessary sealing against oil leakage

External layer: aluminium/void (20/80%)

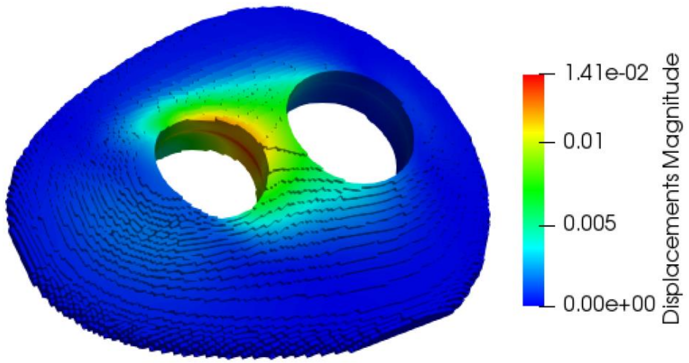
Shape optimization on the domain of the T-splines



Block from which the optimization area is selected.



Static analysis of the initial surface



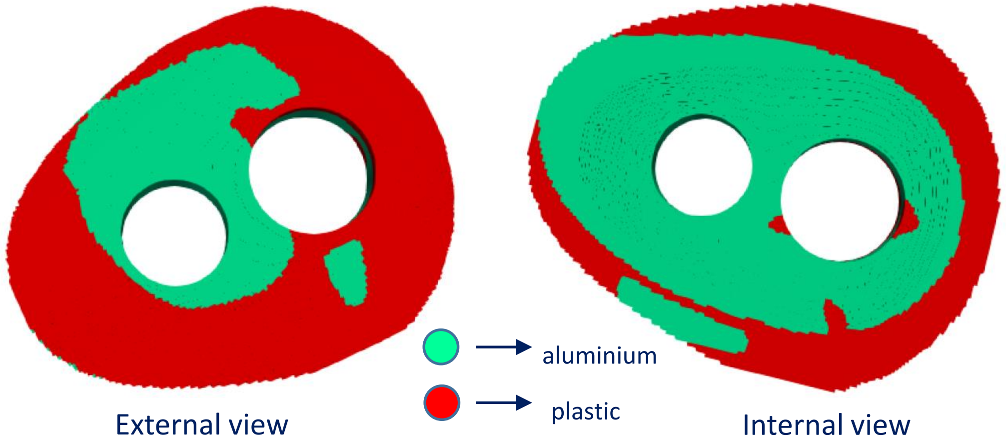
Shape optimization on the ‘z’ axis

Before optimization

After optimization on the ‘z’ axis

	Compliance (J)	Max displacement (mm)
Before optimization	0.142	0.021
After optimization on z	0.106 (-25.4%)	0.014 (-32.5%)
After optimization on x, y	0.137 (-5.0%)	0.020 (-2.9%)
After optimization on x, y, z	0.102 (-28.3%)	0.013 (-36.4%)

Multi-material & multi-block topology optimization



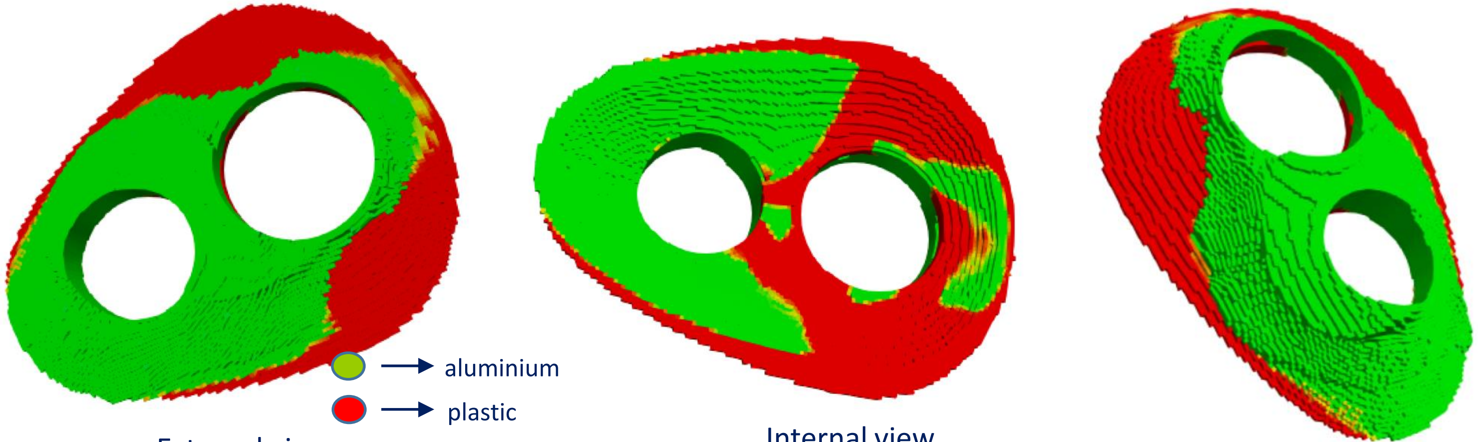
External view

Internal view

Aluminium/Plastic (50/50%)

Compliance is -1.5% comparing to the result of TO with Aluminium/void (50/50%)

Multi-material & multi-block topology optimization



External view

Internal view

Stiffeners

Inner layer: aluminium/plastic (50/50%)

External layer: aluminium/void (20/80%)

CAD DESIGN
AND
LIFE CYCLE ANALYSIS

1. Presentation of the case study: Motivation

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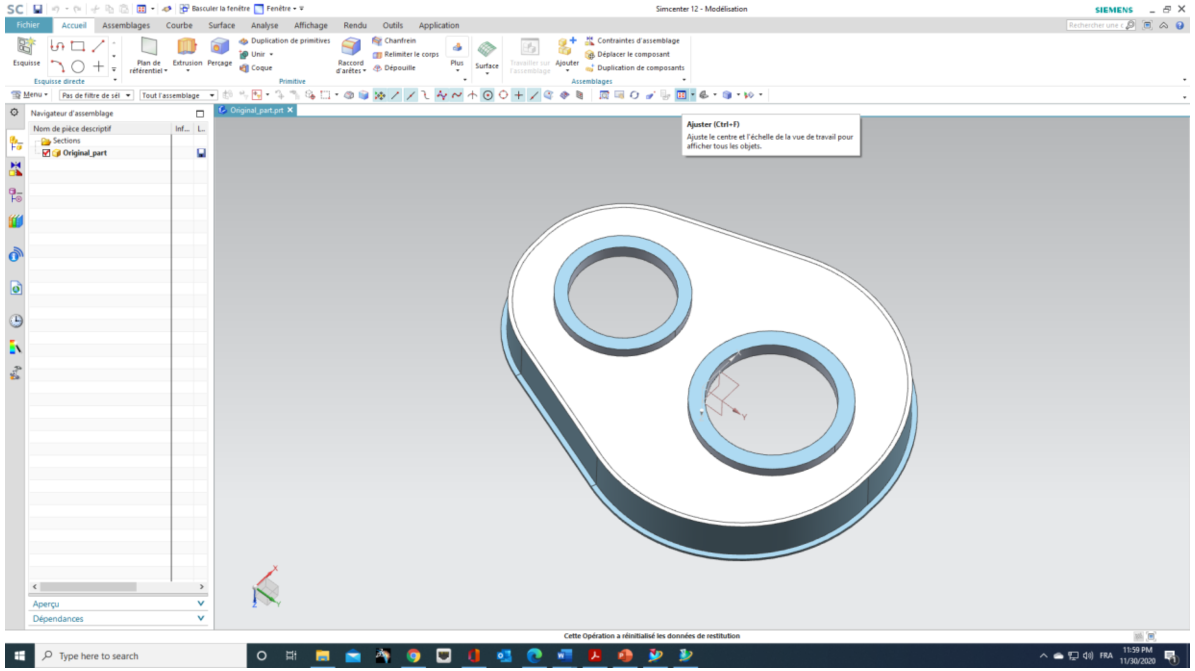
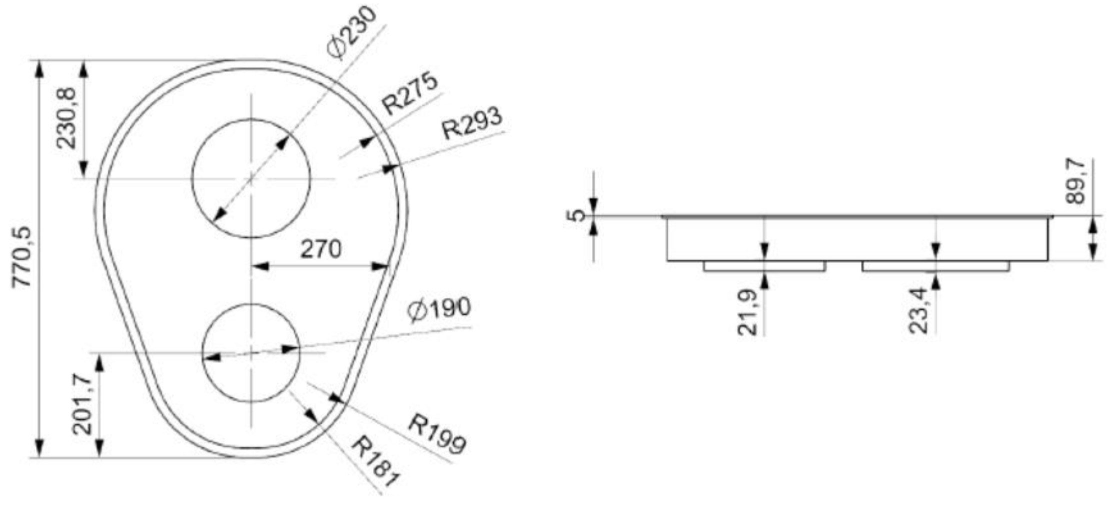
New design

- Initial Aluminum design



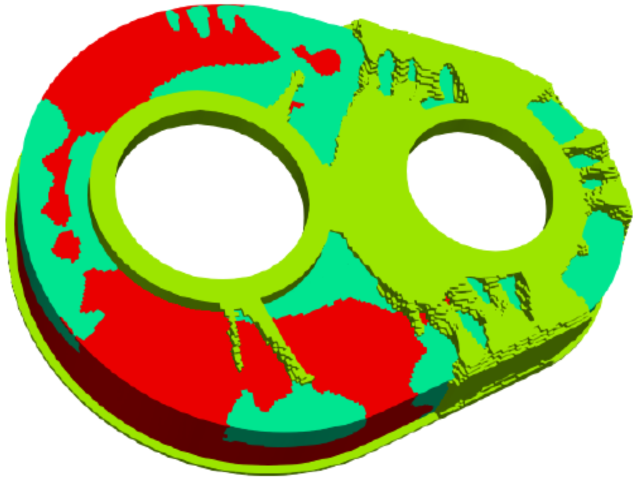


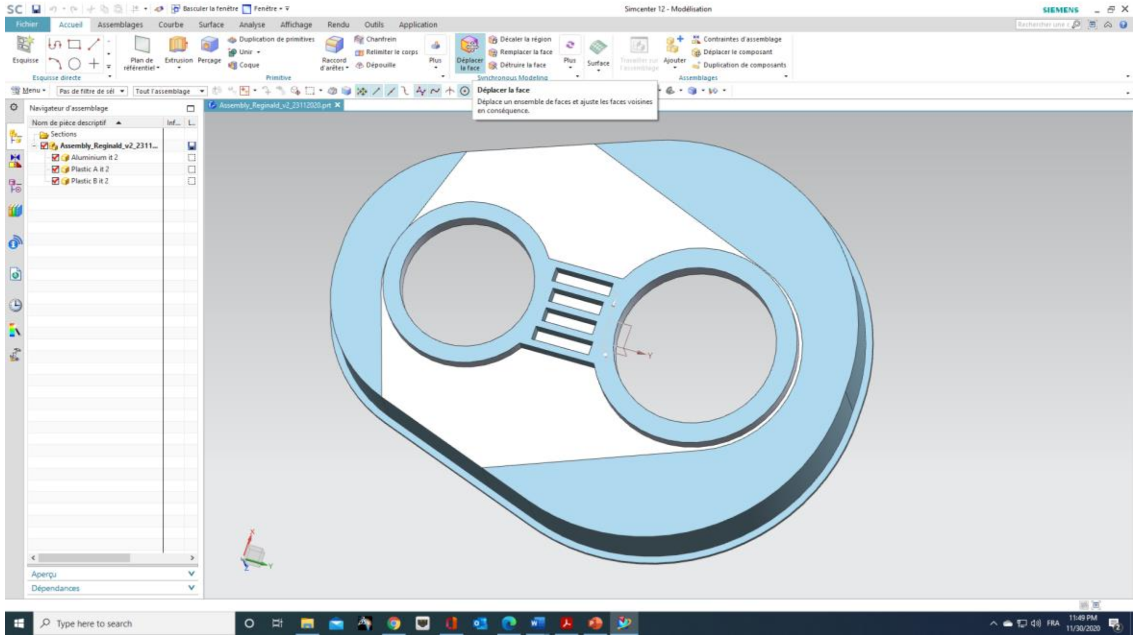
(A) Vue du dessus   (B) Vue latérale

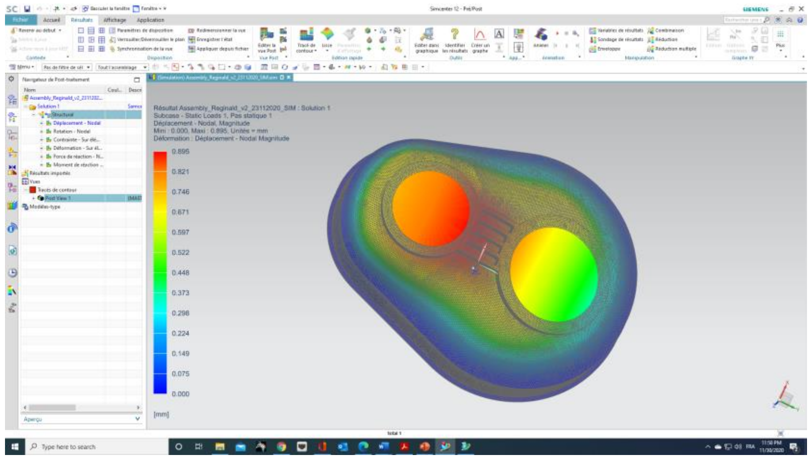
Weight 11.7kg
Wall thickness 7.7mm

New design

Topology optimized design







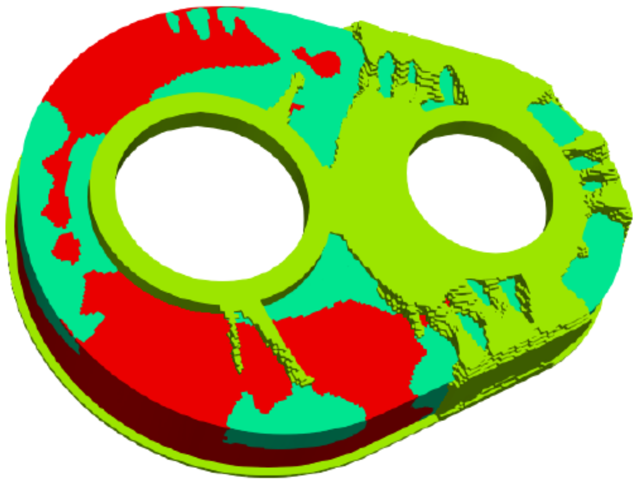
A first design

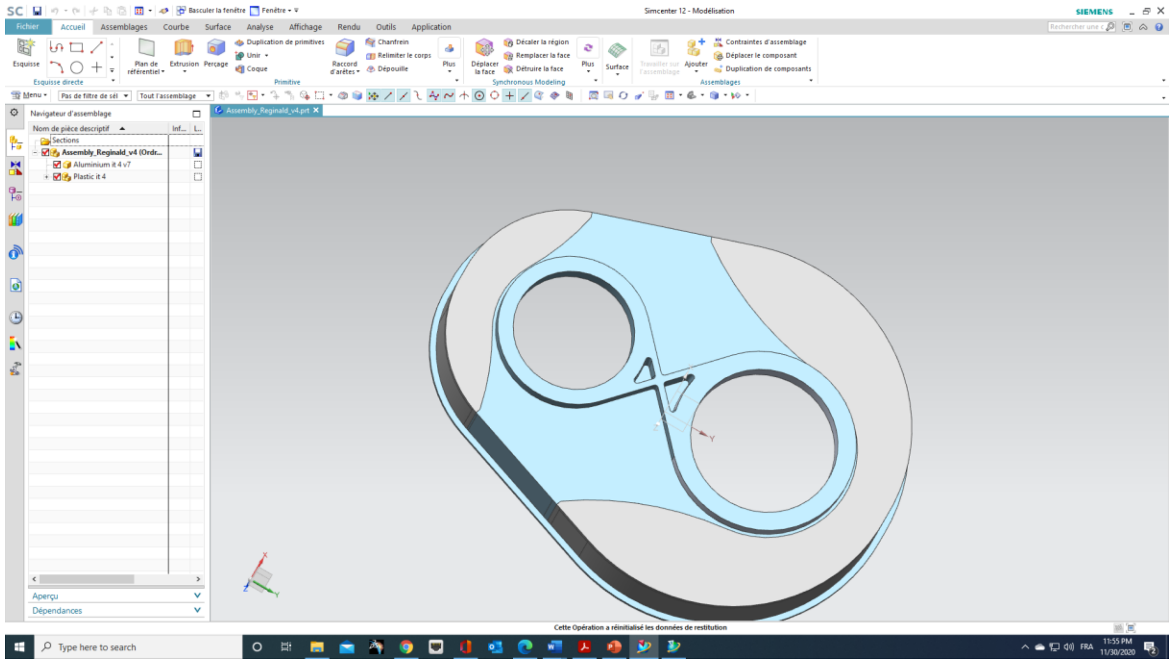
Weight 9.5 kg

Wall thickness 7.7 mm

New design

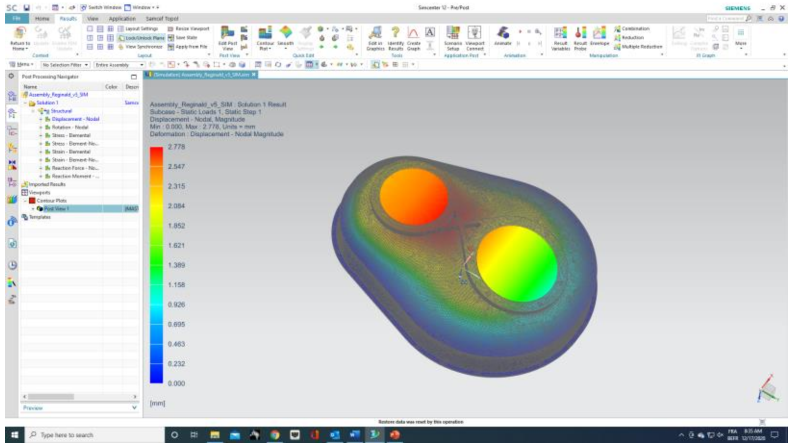
Topology optimized design





CAD design inspired by material distribution

Final design

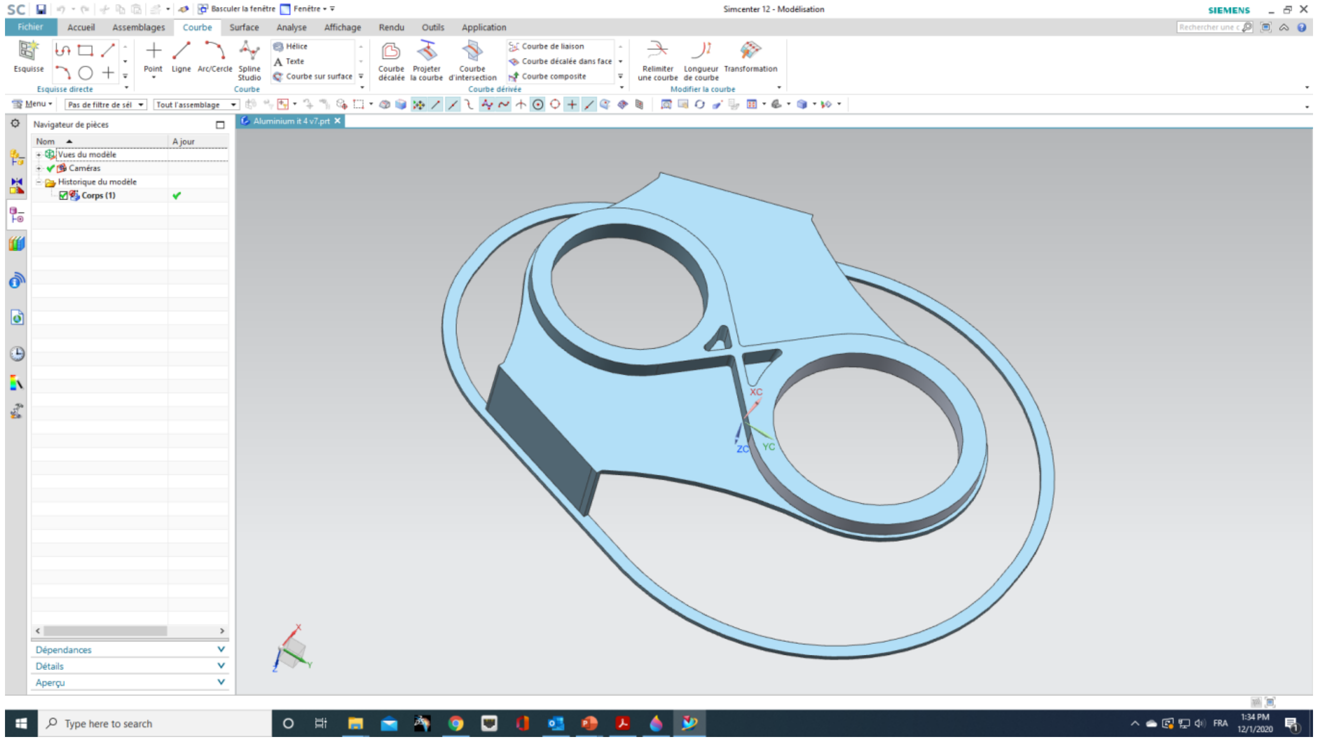


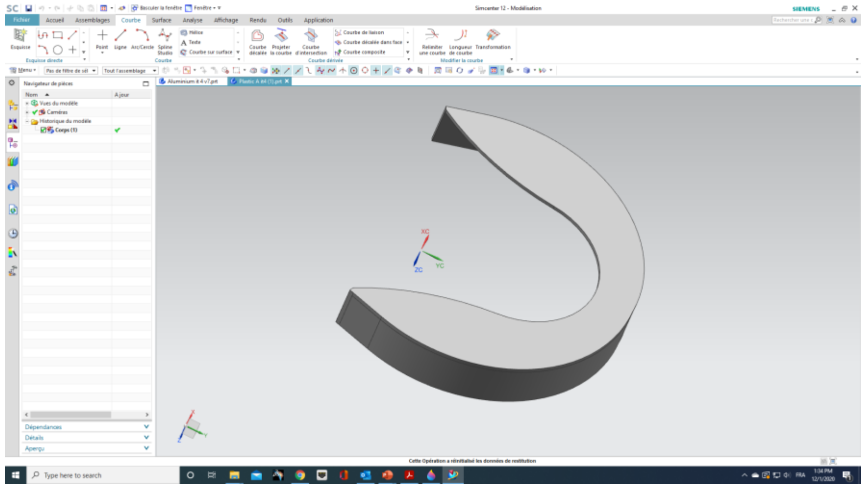
Weight 8.21 kg

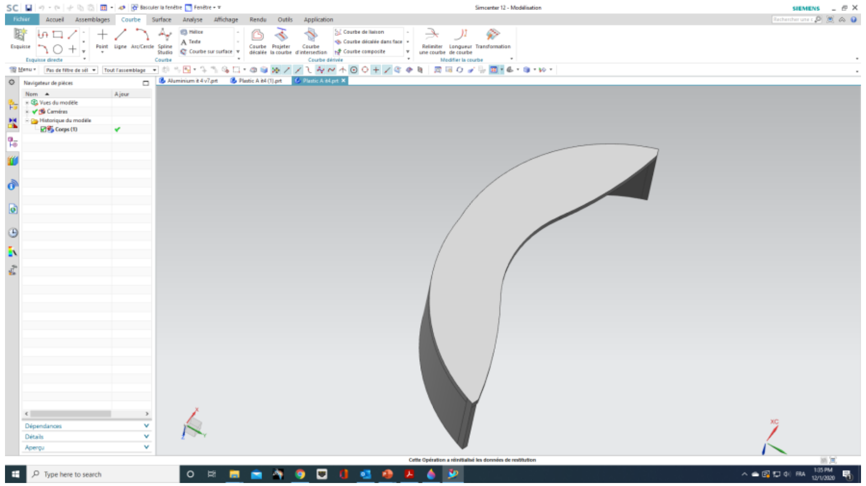
Wall thickness 5.0 mm

New design

- Multimaterial (Aluminum PA) design







Weight 8.0 kg

Wall thickness 5.0 mm

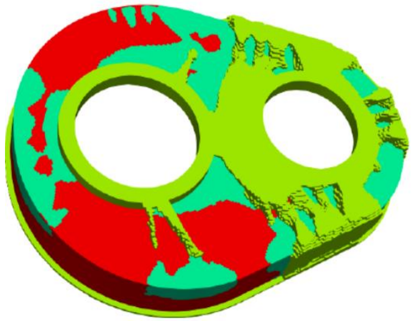
New Concept based on Topology Optimization results

Simplified geometry

TO results without stiffeners

30%Al / 70%plastic

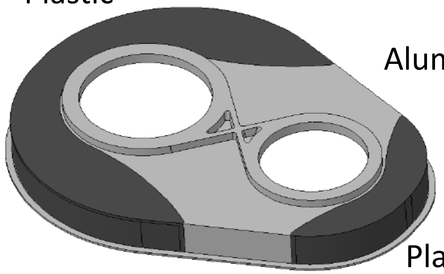
TO results with stiffeners



50%Al / 50%plastic

- Manufacturability constraints of plastic injection molding
- Thickness reduction to 5mm, max allowed for plastic injection molding
- Addition of stiffener in the area of stress concentration

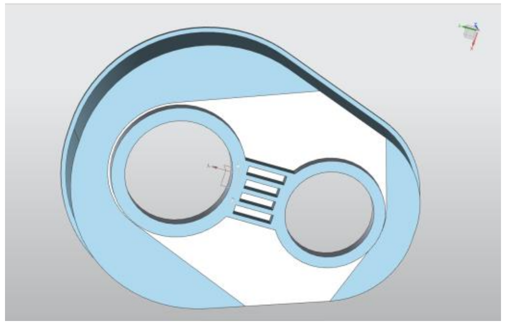
Plastic



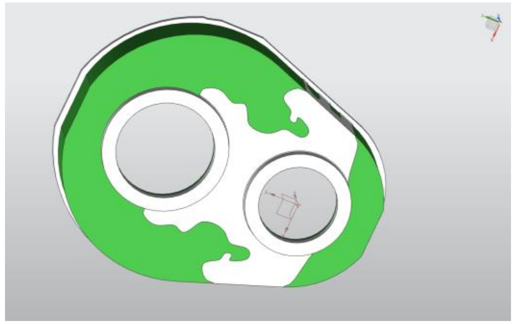
Aluminium

Plastic

Optimised concept



Attempt with reduced thickness & stiffener

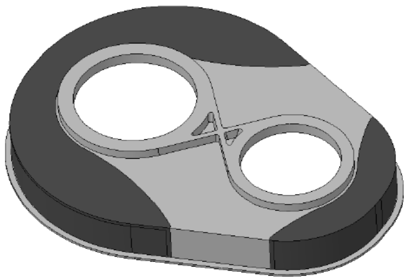


Raw result exported from TO

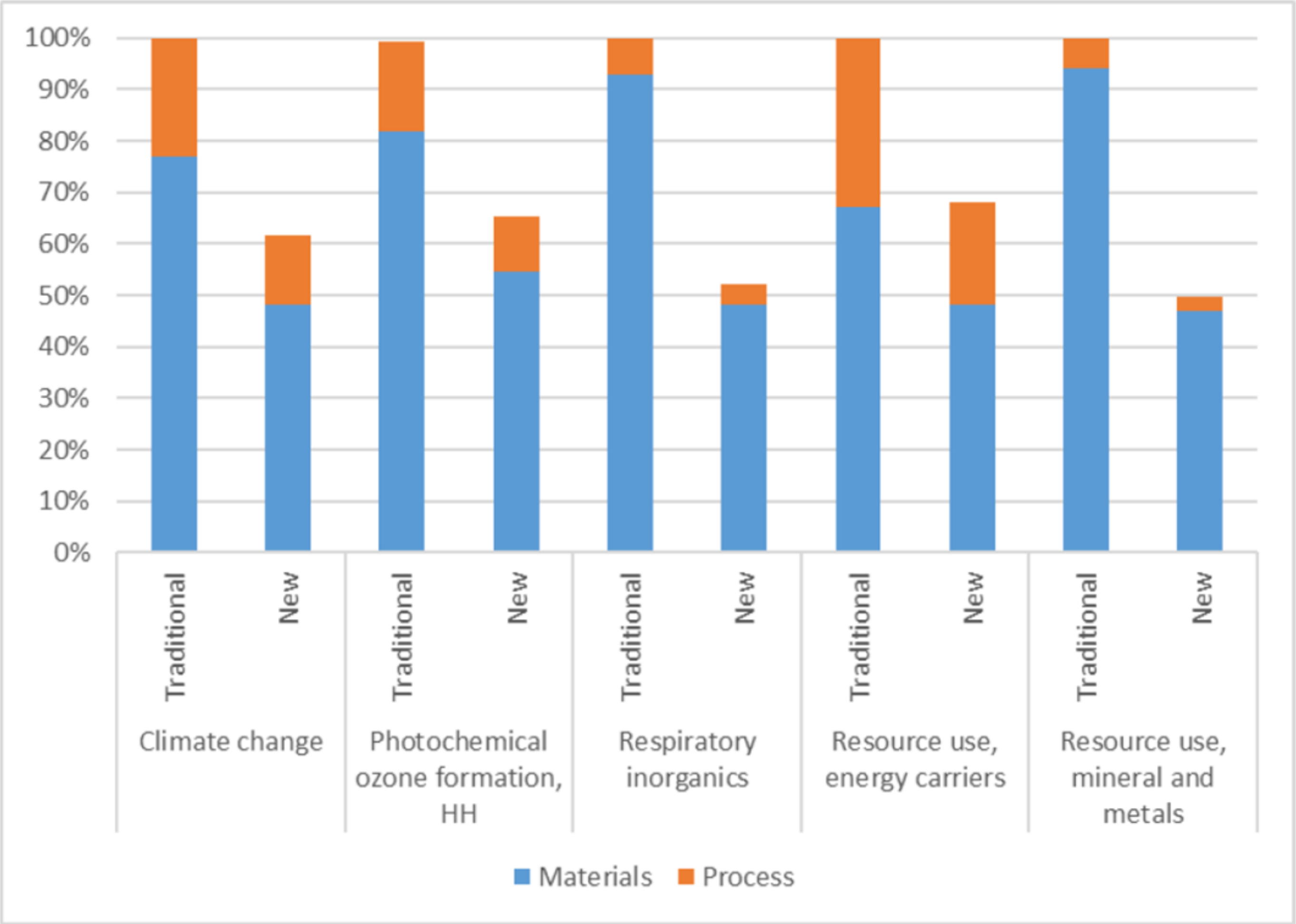
Life Cycle Assessment (LCA)

Total weight reduction of approx. 30%

Simplified geometry



Optimized concept



LCA results - Comparison of the reference and the new concept gearbox cover demo

FINAL PRODUCT PERFORMANCE ASSESSMENT

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    4. New multimaterial otpology optimization

3. CAD design and Life Cycle Analysis

4. **Final product assessment**

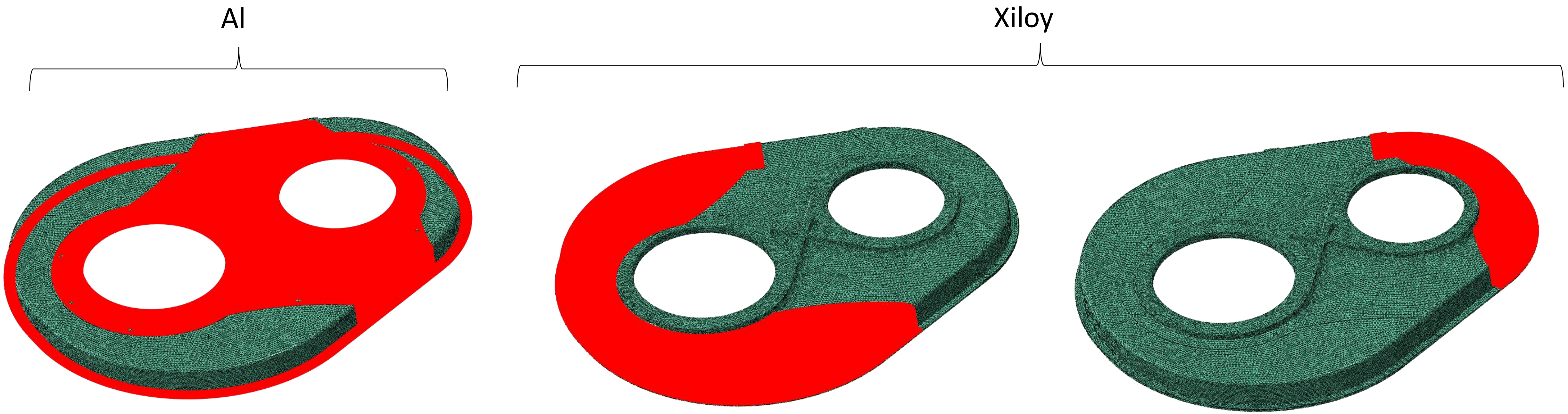
5. Conclusions

Abaqus model

- The model includes 668974 second order tetrahedral elements (C3D10, Ten-node tetrahedral element) and 1046140 nodes

Materials

- The part is made of two different materials:
  - Aluminum: E = 70 GPa and Poisson coefficient = 0,3
  - Xiloy: short fiber reinforced plastic, here considered as isotropic, with E = 6914 MPa and Poisson coefficient = 0,35

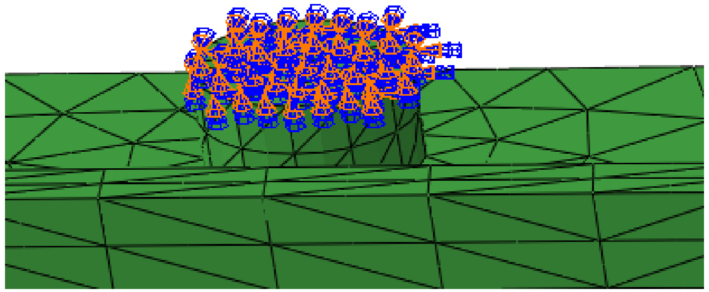


Boundary Conditions

- Two kinds of boundary conditions are considered
  - Part fully clamped on its outline
  - Part clamped at given fasteners locations
    - Locations were already defined in the model received from the partners

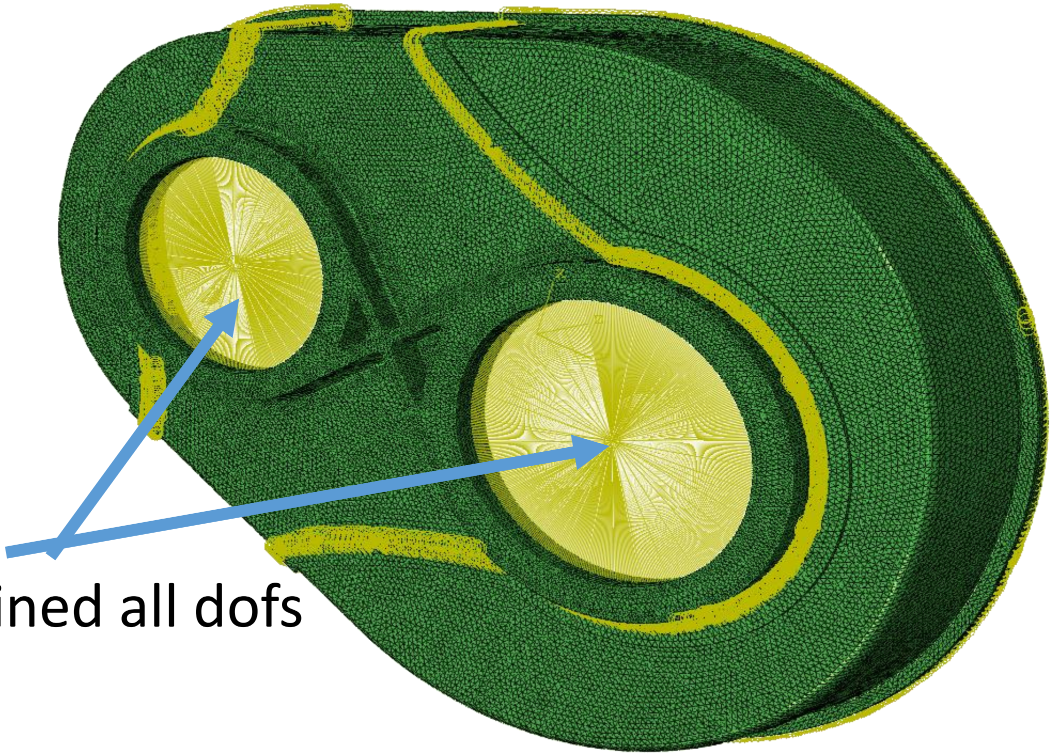
Fully clamped

Constrained at fasteners locations

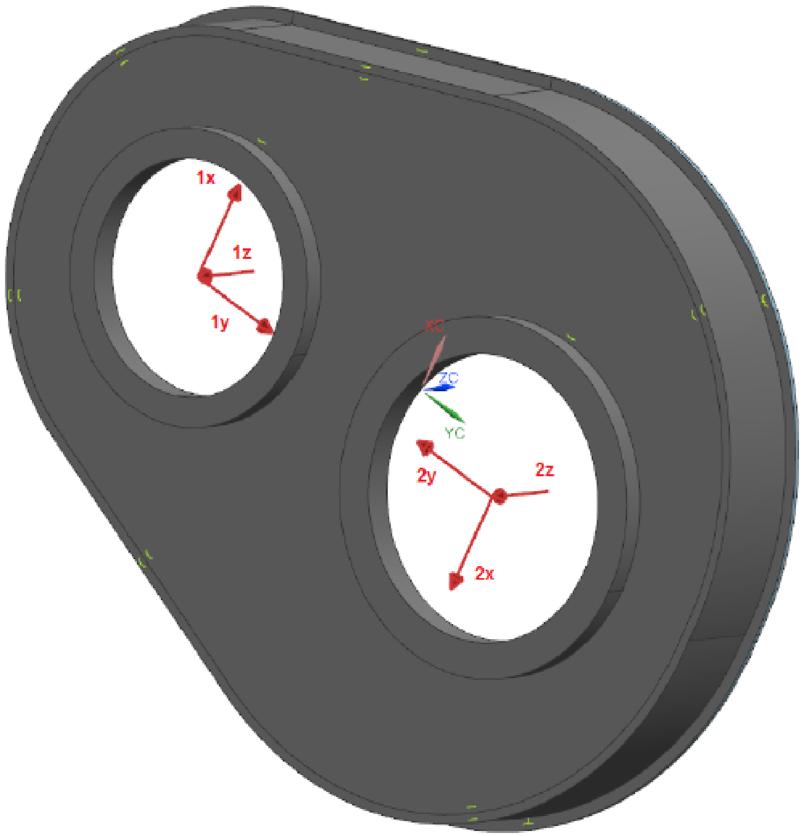


Forces

- Concentrated loads are defined for each gear
- Loads are applied to the bearing surface via rigid body elements
  - At point 1: Fx = 0,46F; Fy = F, Fz=0,86F
  - At point 2: Fx = 0,17F; Fy = 0,29F, Fz=0,06F



Constrained all dofs



Modal Analysis

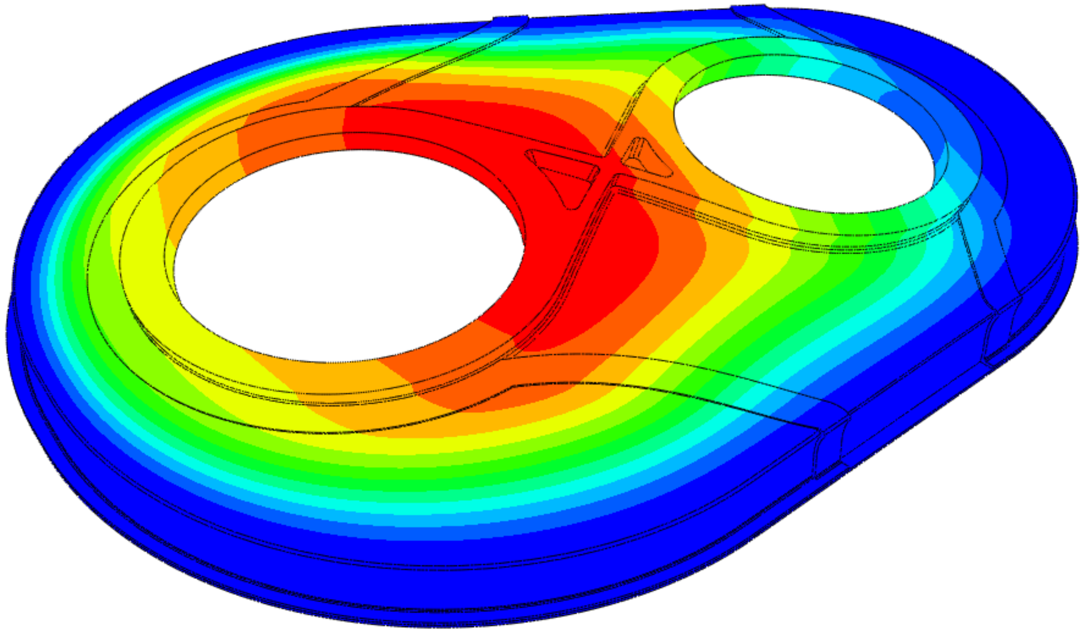
Frequencies, in Hz for full clamp: 144.71, 237.45, 279.59, 430.96, 552.80

Frequencies in Hz for clamp at fasteners: 134.91, 227.59, 267.76, 419.64, 445.64

Mode 1

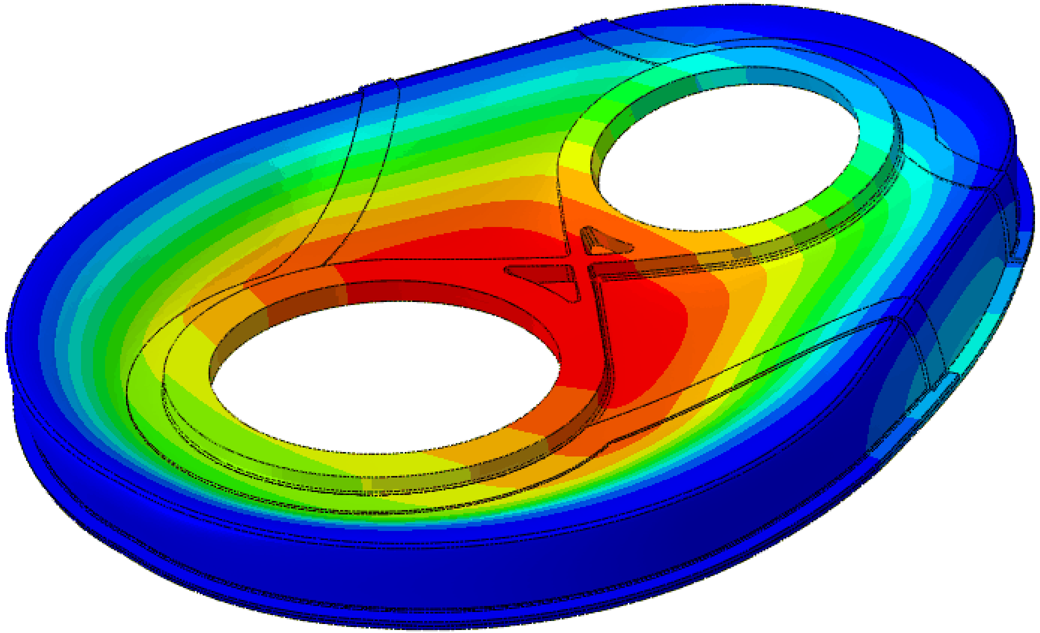
Fully clamped

144.71 Hz



Clamp at fasteners

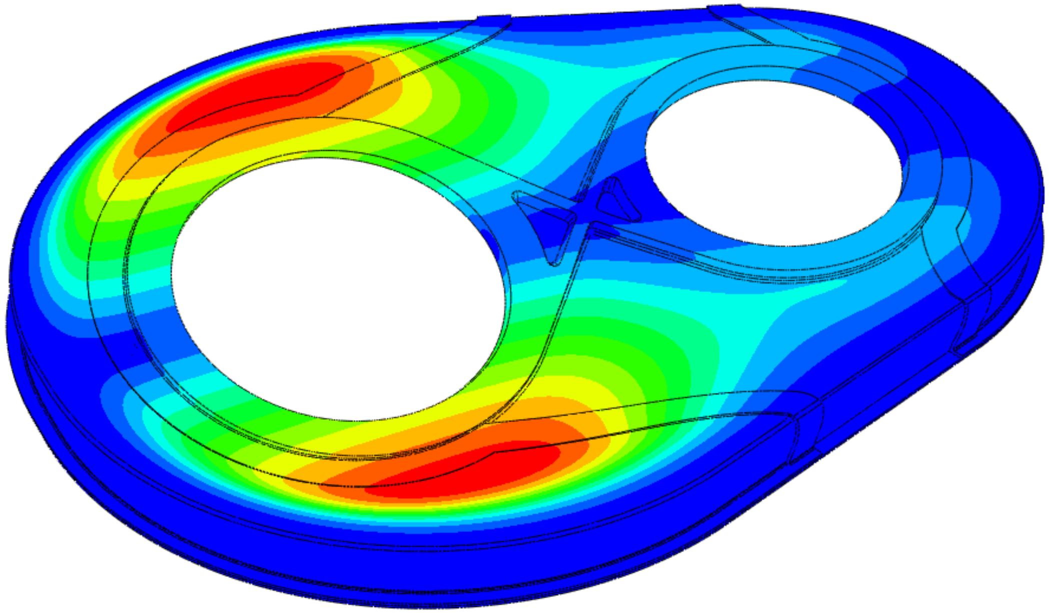
134.91 Hz



Mode 2

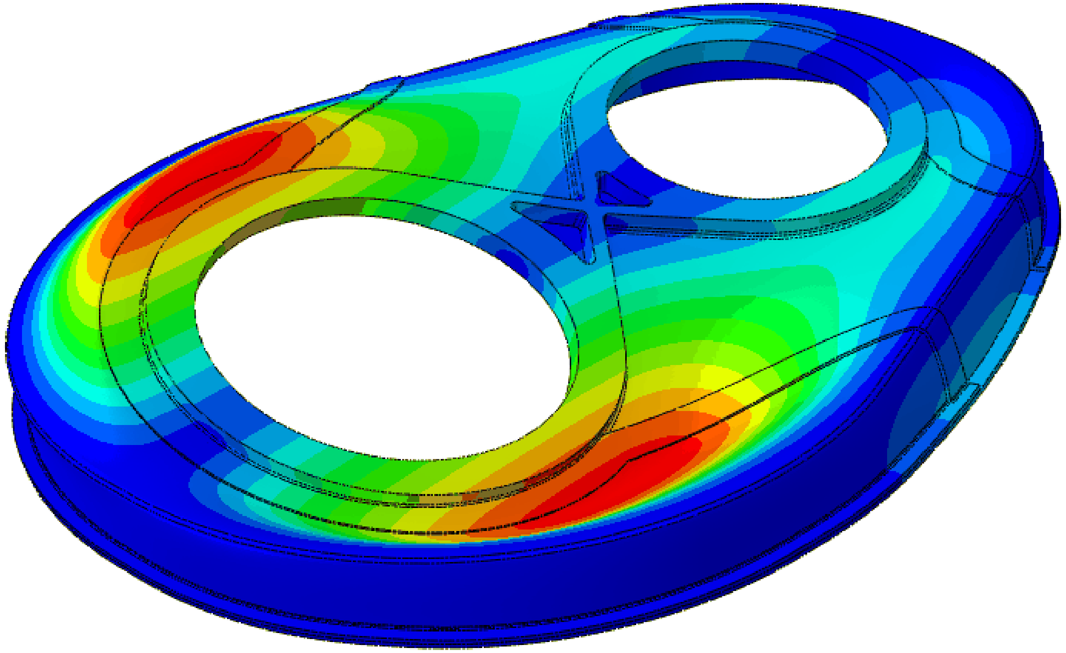
Fully clamped

237.45 Hz



Clamp at fasteners

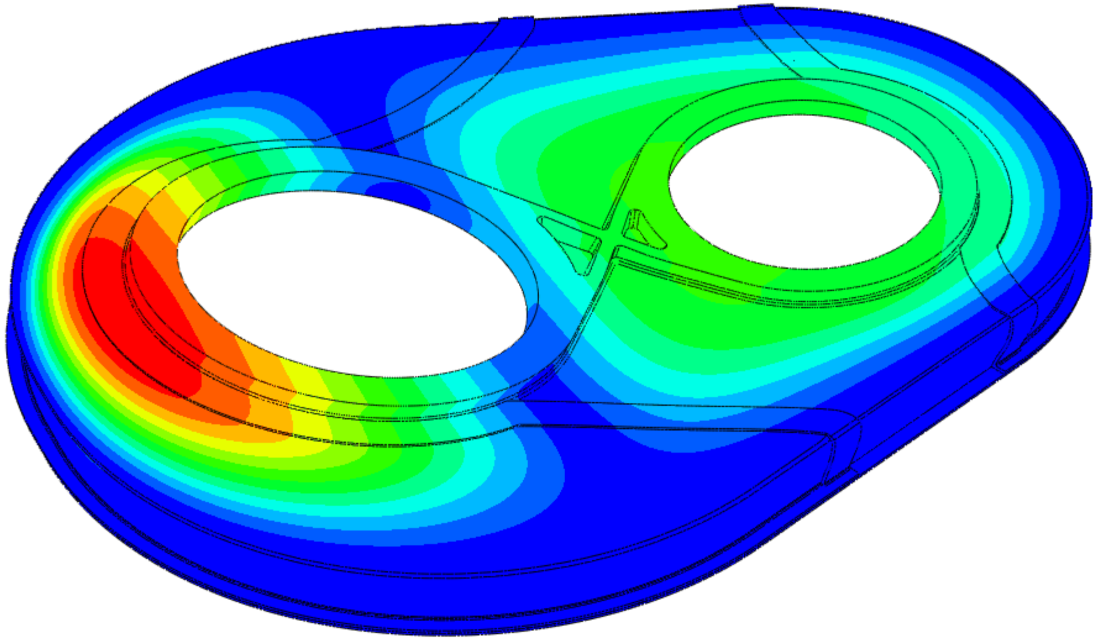
227.59 Hz



Mode 3

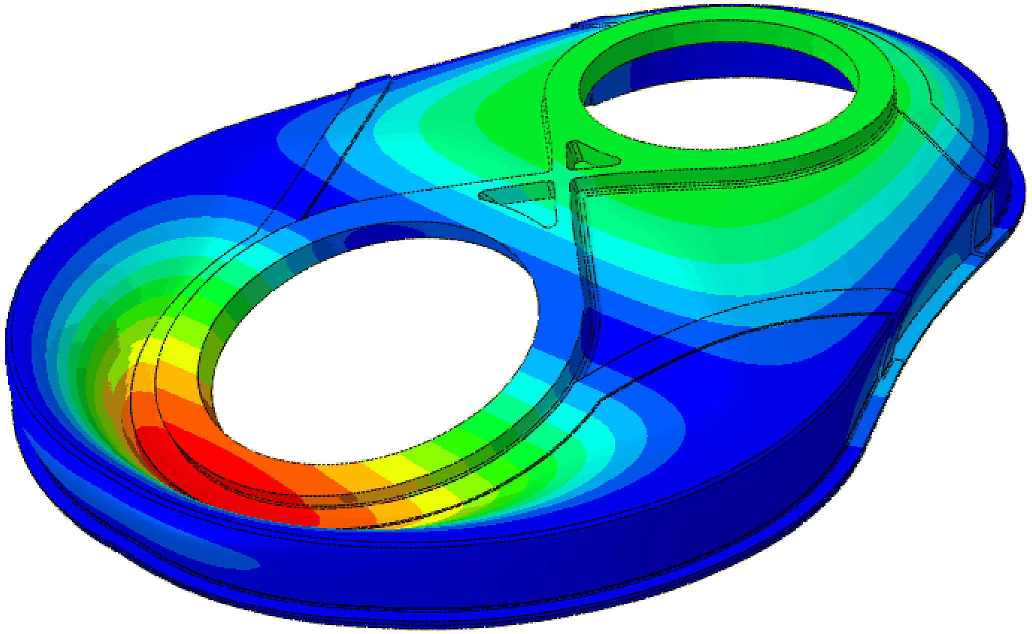
Fully clamped

279.59 Hz



Clamp at fasteners

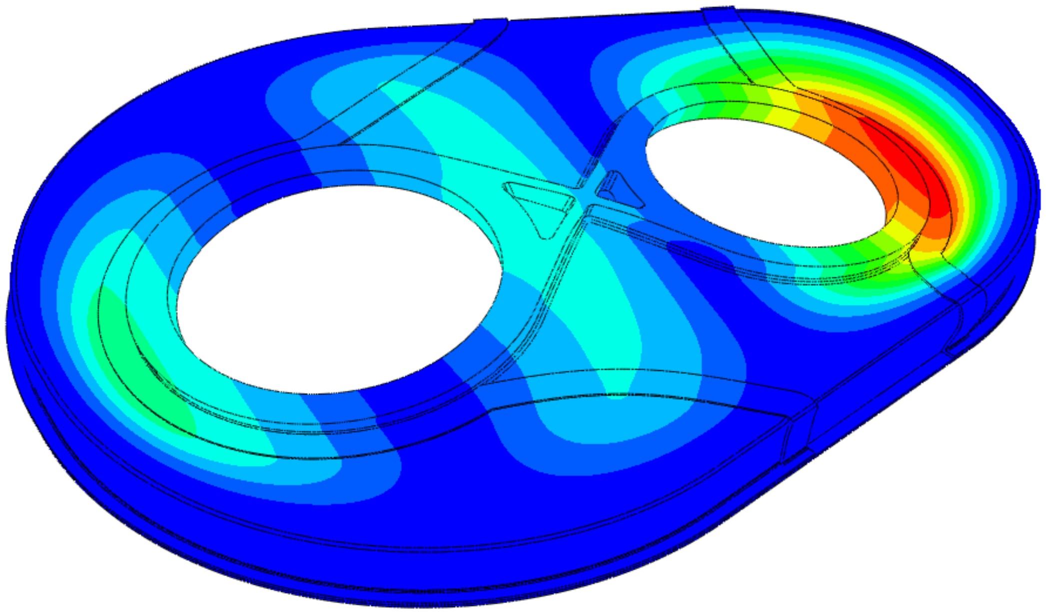
267.76 Hz



Mode 4

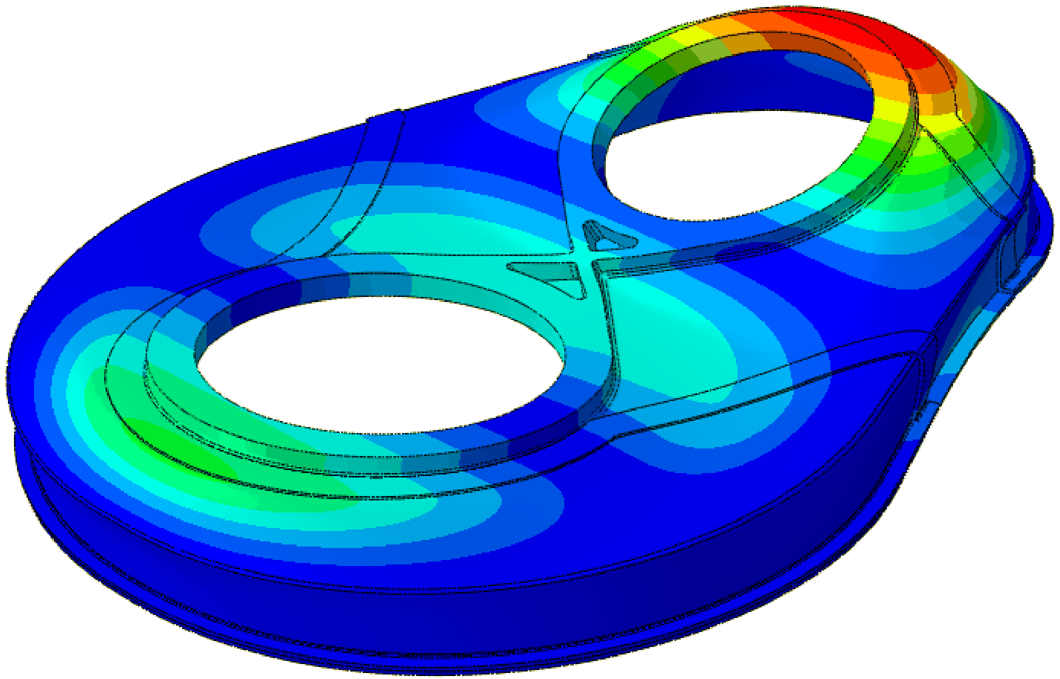
Fully clamped

430.96 Hz



Clamp at fasteners

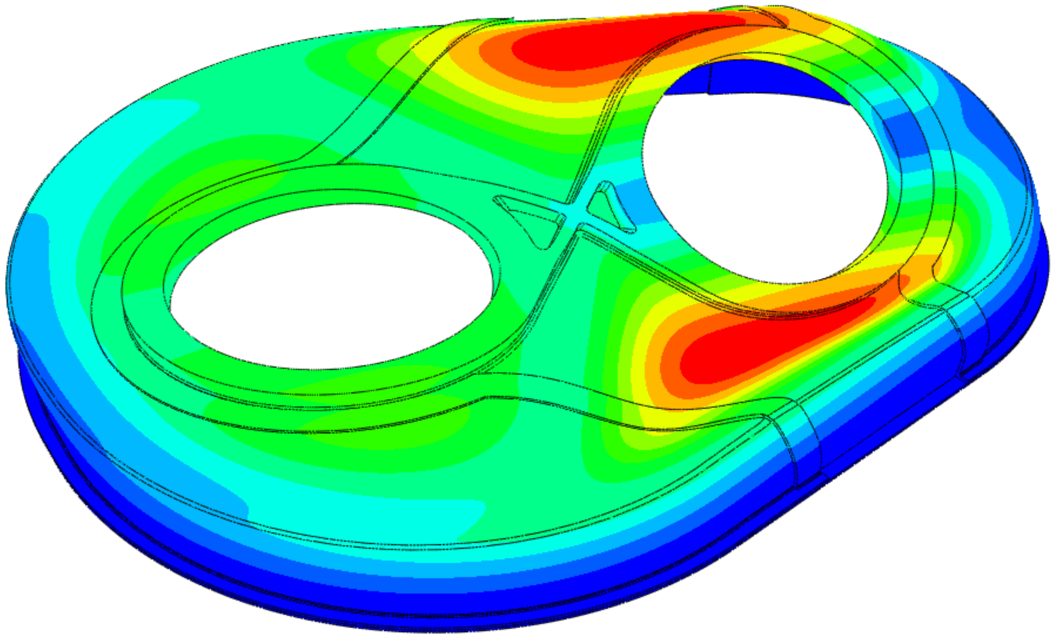
419.64 Hz



Mode 5

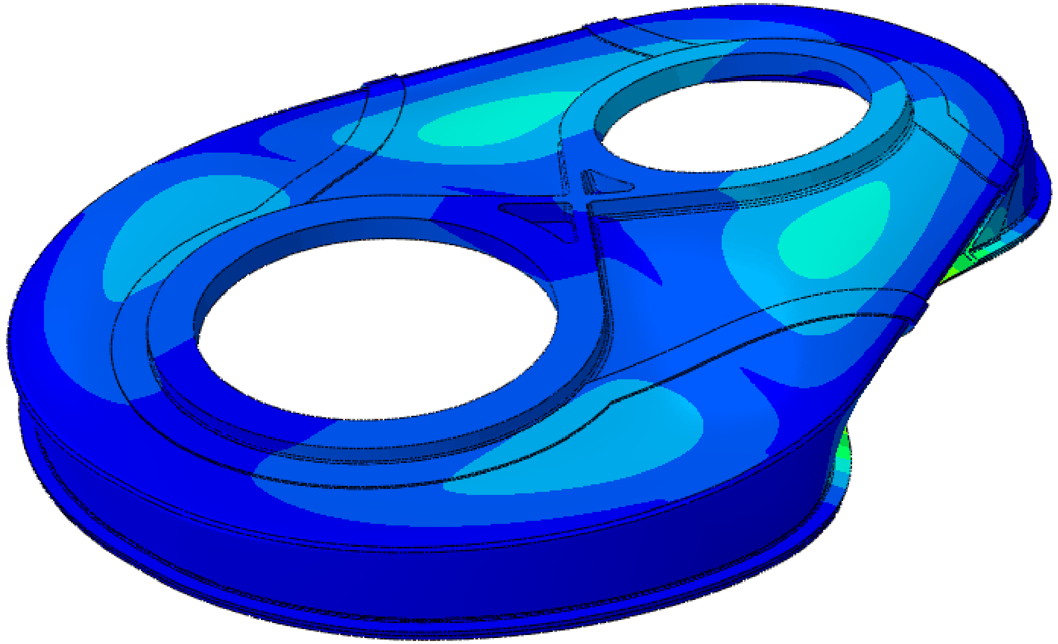
Fully clamped

552.80 Hz



Clamp at fasteners

445.64 Hz



STATIC Analysis

For full clamp design:

- Max stress in aluminum part: 375MPa
- Max stress in plastic part: 124MPa

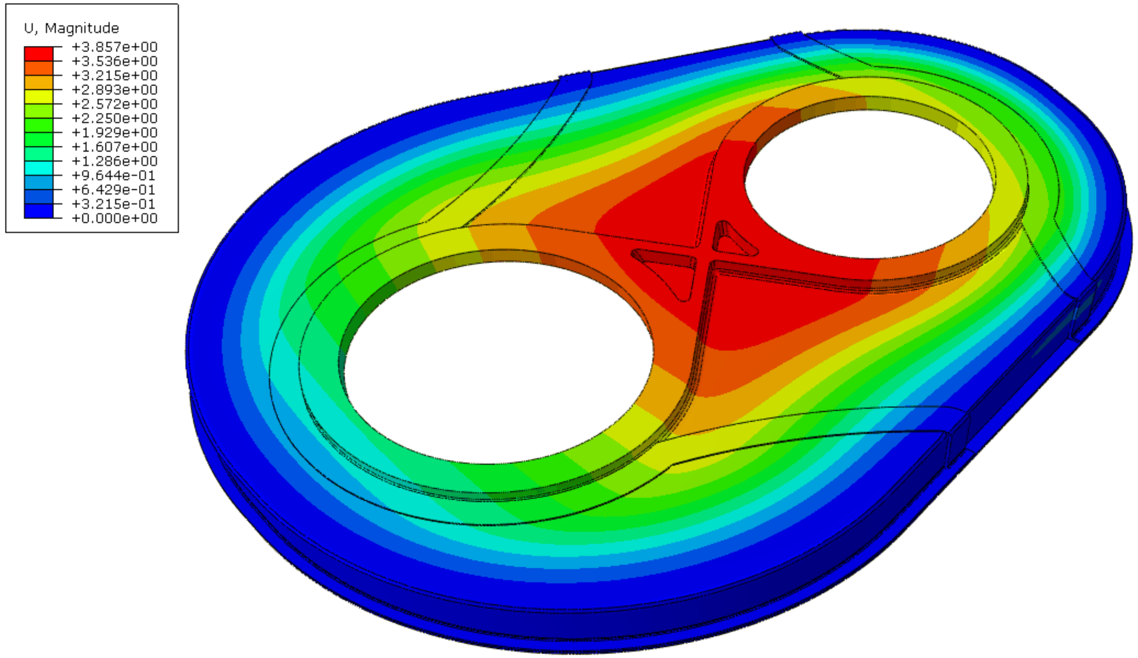
For clamp at fasteners design:

- Max stress in aluminum part: 394MPa
- Max stress in plastic part: 100MPa

Resultant displacement

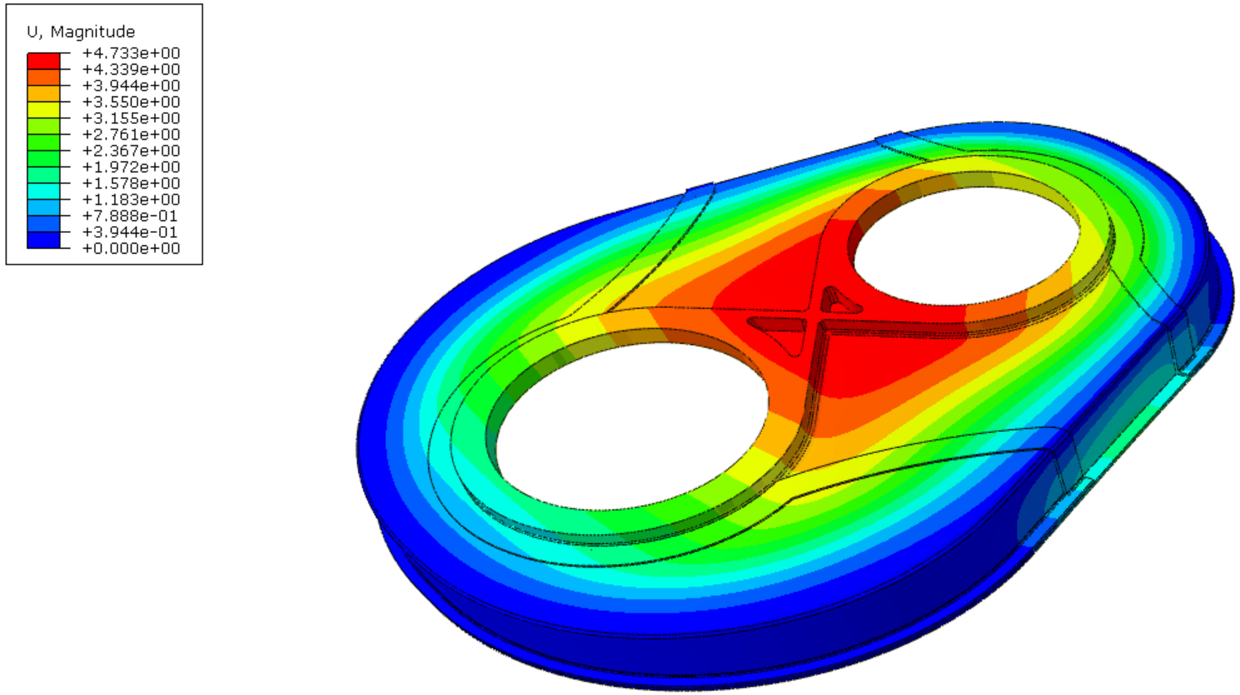
Fully clamped

Umax = 3,86mm
Umin = 0



Clamp at fasteners

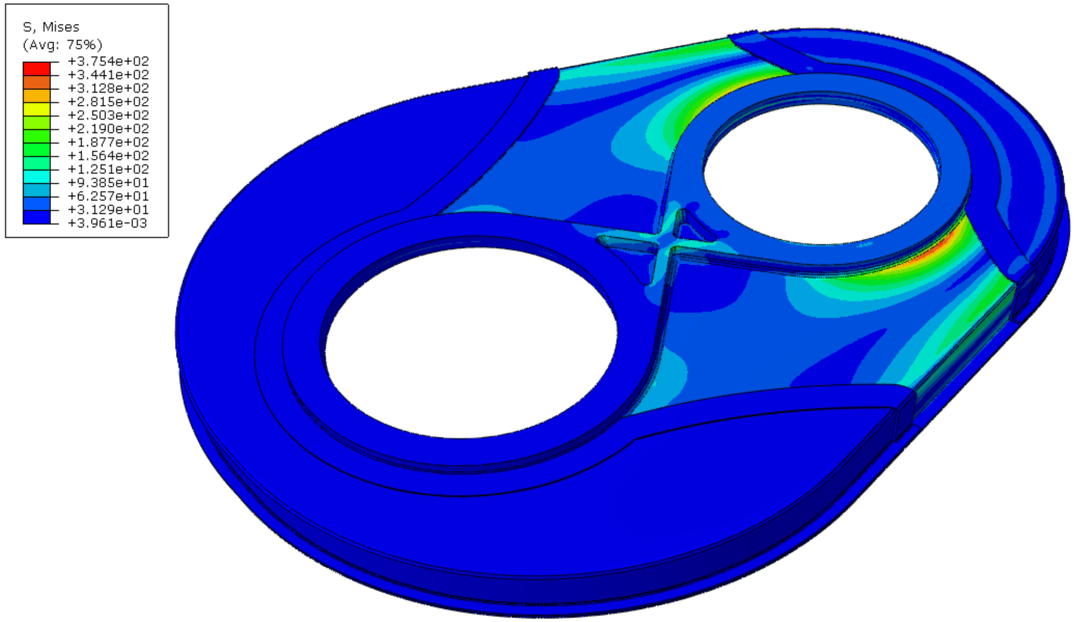
Umax = 4,73mm
Umin = 0



VM stress-Assembly

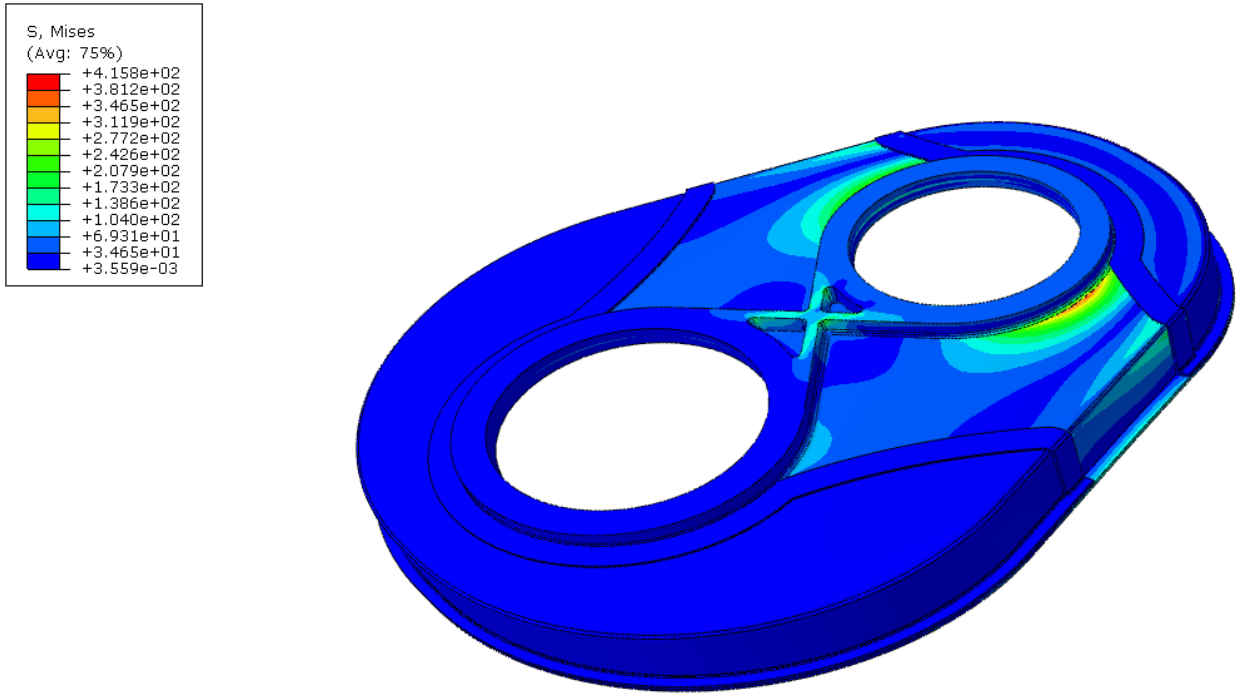
Fully clamped

Sigma_max = 375MPa
Sigma_min = 0



Clamp at fasteners

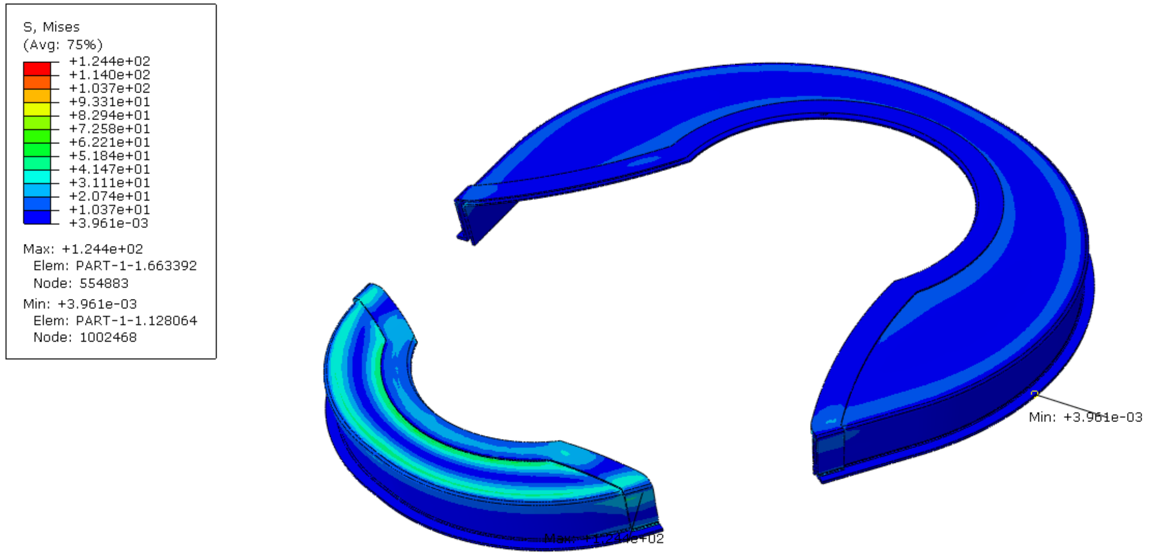
Sigma_max = 416MPa
Sigma_min = 0



VM stress-Plastic cavities

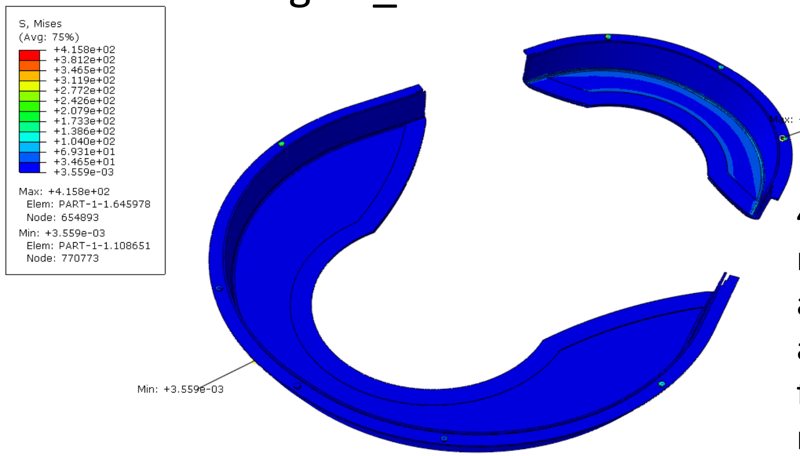
Fully clamped

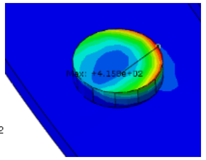
Sigma_max = 124MPa
Sigma_min = 0



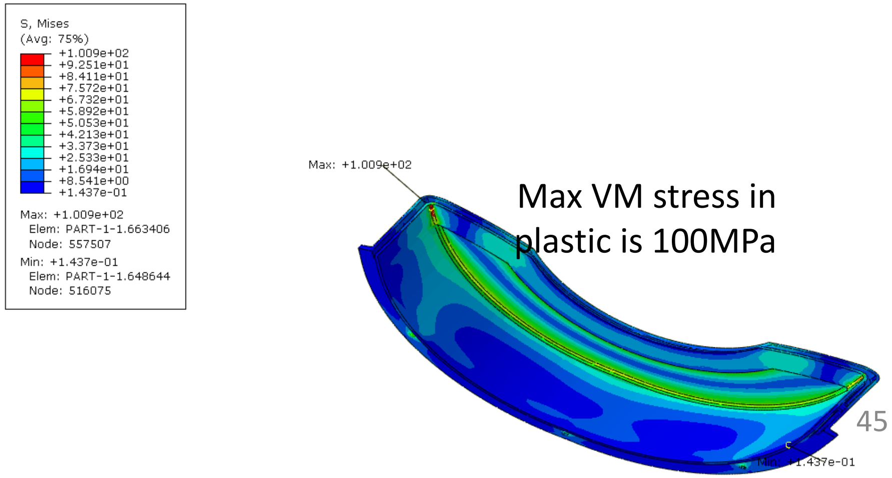
Clamp at fasteners

Sigma_max = 416MPa and 100MPa
Sigma_min = 0





416 MPa not relevant (local analysis and adapted design at fasteners are required)



Max VM stress in plastic is 100MPa

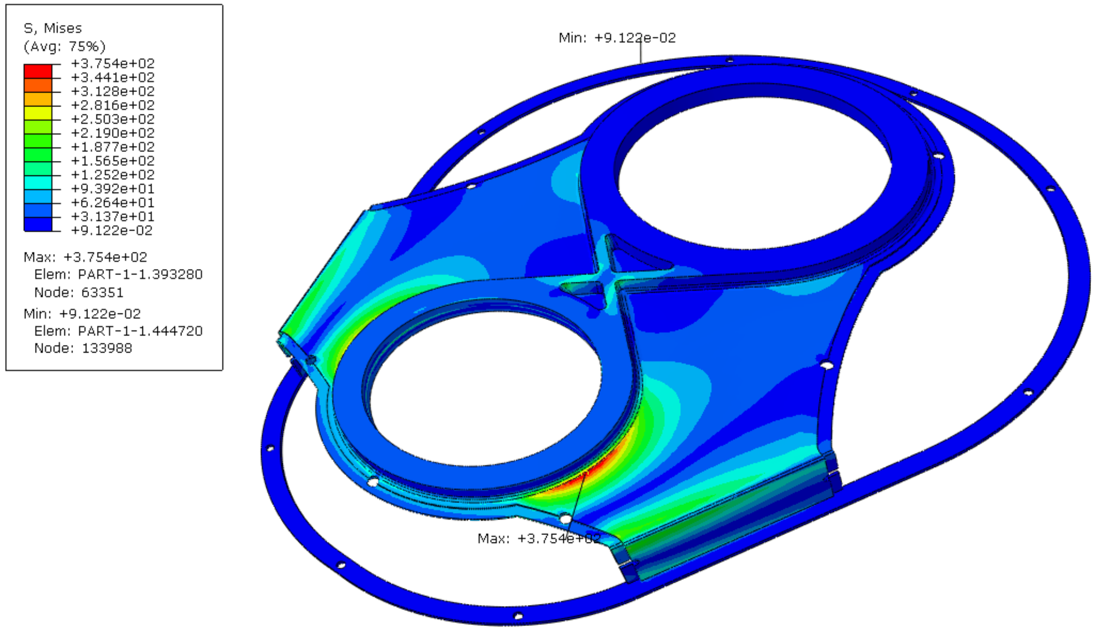
VM stress- Al insert

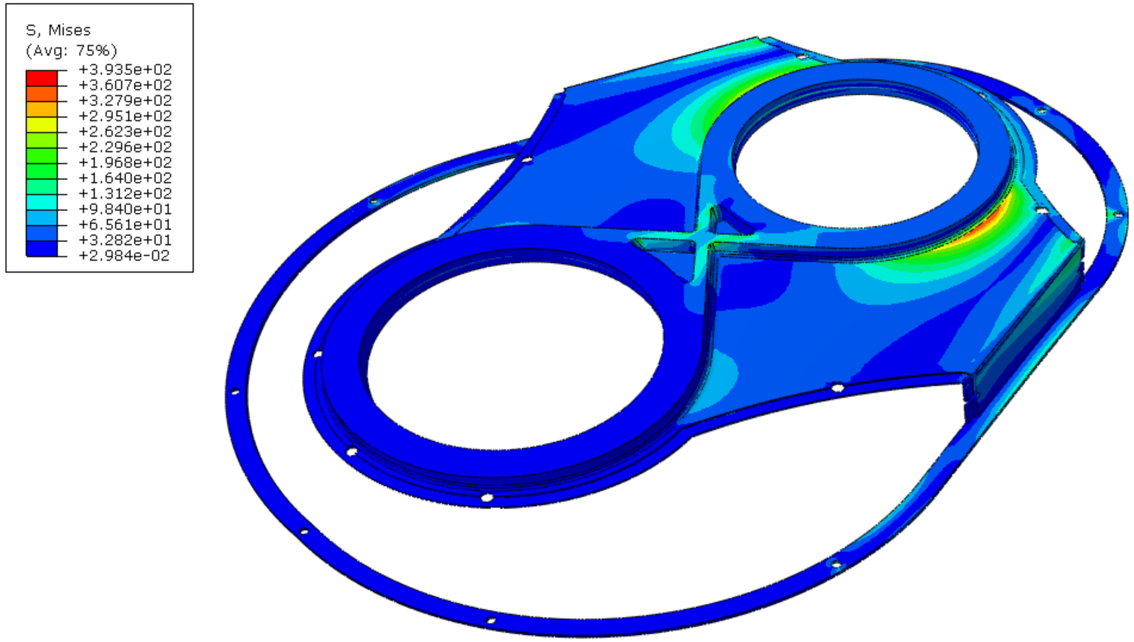
Fully clamped

Sigma_max = 375MPa
Sigma_min = 0

Clamp at fasteners

Sigma_max = 394MPa
Sigma_min = 0

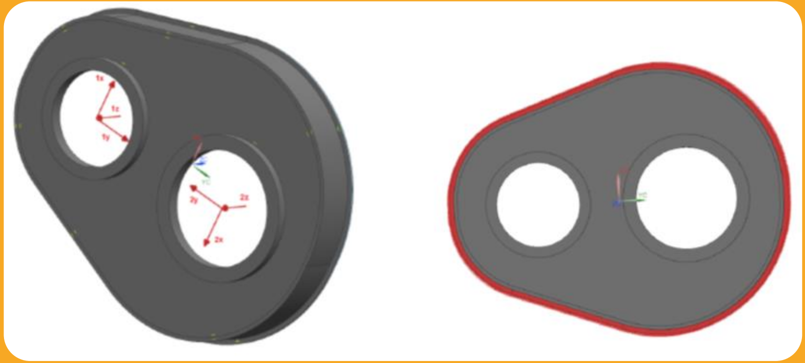


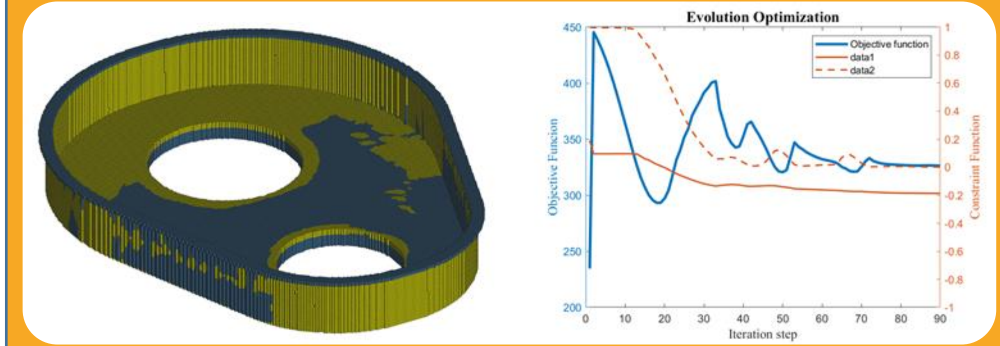


CONCLUSION
&
PERSPECTIVES

Conclusions

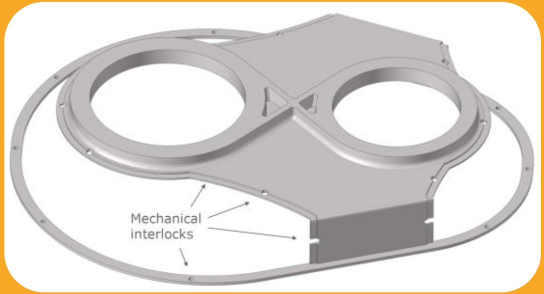
- **Functionalities & requirements:**
  - Load-carrying (gears)
  - leak-tightness (oil)
  - Heat dissipation
- **Traditional design:** aluminum casting

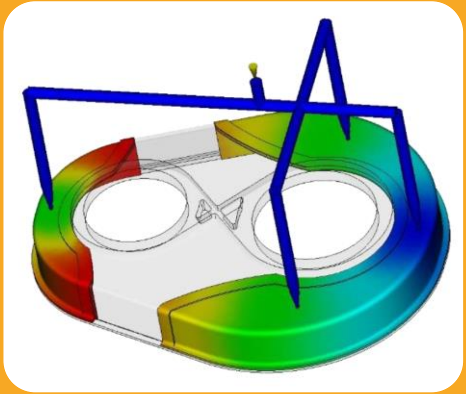




- **New Lightweighting strategy**
  - 2-material: Alum & (SFR) plastic
  - Multi-material Topology Optimization

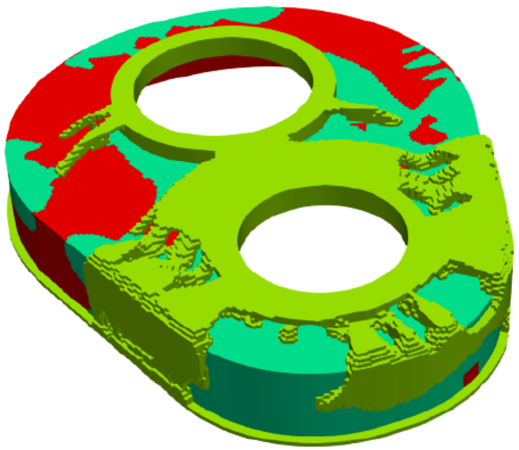
- **Mass production route**
  - Aluminum casting
  - Insert injection moulding

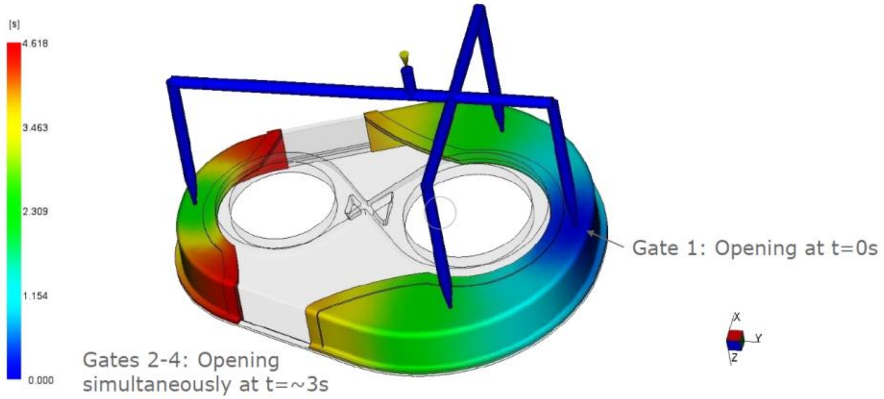




Conclusions

- New design concept of e-gear box rear cover available on the shelve
- Development process from end-to-end: from design concept to prototyping
- Consortium from companies of EMR region offer a solid supply chain partnership to take over lightweight design challenge

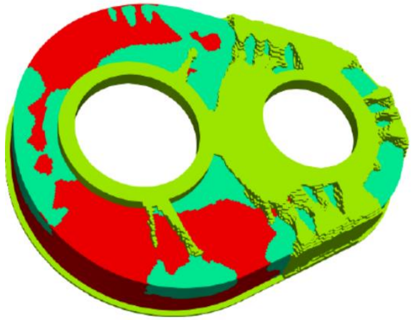


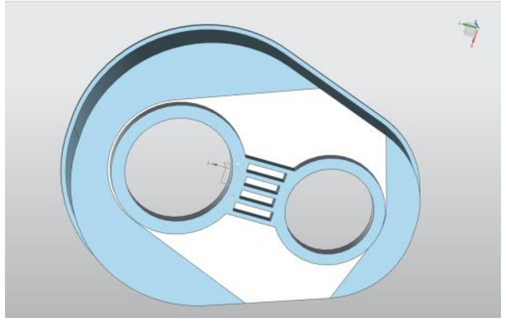


(a)

Conclusions

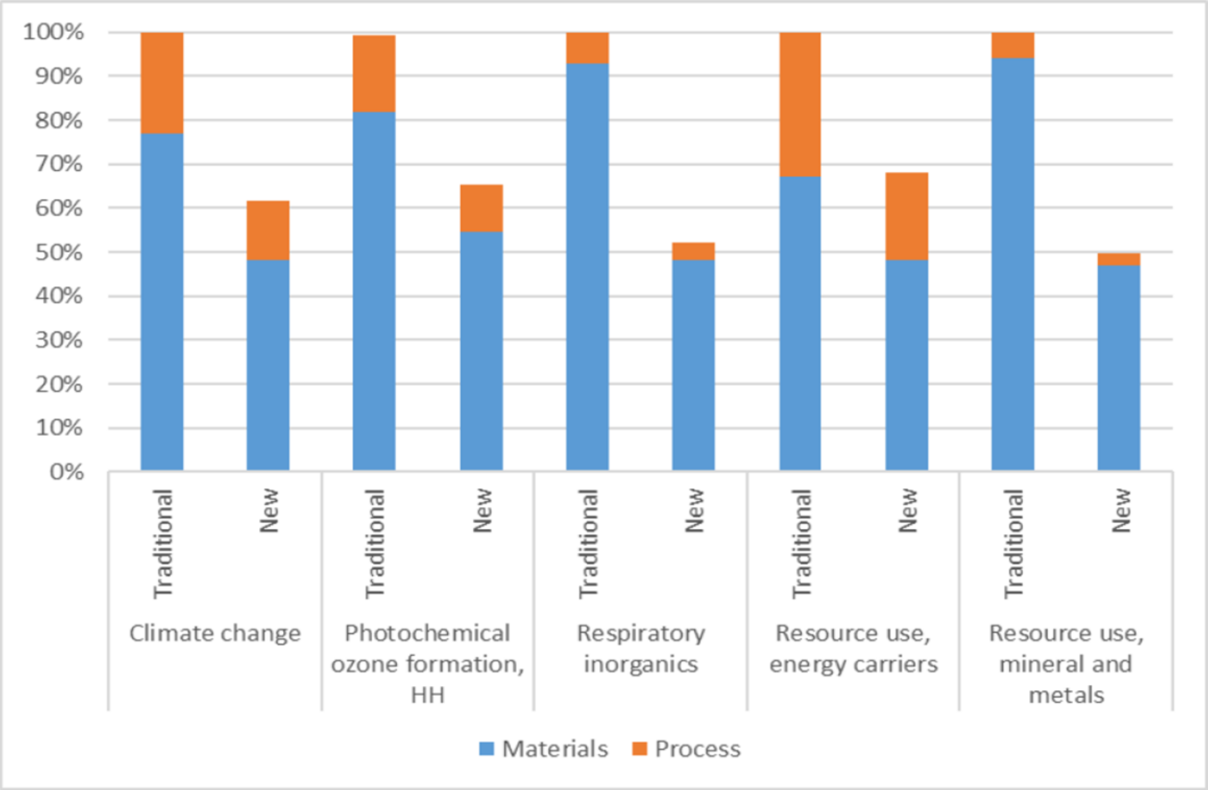
- **Topology optimization** has been used as creative tool for new concept of lightweight components.
- **Multi-material topology optimization** permitted the conception of a tight gearbox housing, using aluminum and plastic, while reducing weight by almost 30%.
- Topology Optimization results give a very good indication of **where to use plastic to take advantage of lightweight materials**.
- Raw results of topology optimization have been **post-processed** to propose a CAD accounting for manufacturability restrictions based on injection molding production method (mass production).





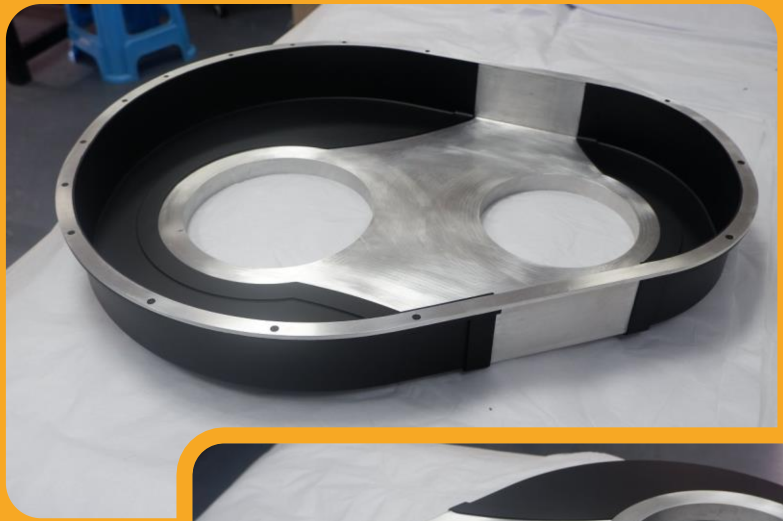
Conclusions

- Life Cycle Analysis demonstrates a major reduction of CO_2 emissions (-25%) when considering full life emissions



LCA results - Comparison of the reference and the new concept gearbox cover demo

Multi-material gearbox housing demonstrator



Cost in high-volume production
✓ **20% reduction**

Weight
✓ **30% reduction**

LCA: CO2 emissions in production
✓ **40 % reduction**

Acknowledgements

- Light Vehicle 2025“ is an EU-funded cross-border project under INTERREG 5A program in the Euregio Meuse-Rhine (Wallonia and Flanders in Belgium, Limburg and North-Brabant in the Netherlands and North-Rhine Westphalia in Germany).
- Implemented in 2018 by 6 partners (Flanders Make (Leader), Automotive NL, AMAC GmbH, Technifutur, University of Liège and Campus Automobile Spa – Francorchamps), it will run for three years until 2021.