Truck door light weight designs using topology optimization

Pierre DUYSINX[1], William WEBER[1], Jules REMES[1],
Jan STROOBANTS[2], Freek DE BRUIJN[3], Jean-Pierre HEIJSTER[3],
Elke DECKERS[2,5], Carlos LOPEZ[2], Philip EYKENS[2]

[1] University of Liège, Aerospace and Mechanical Engineering, Liège, Belgium

[2] Flanders Make, Codesign Corelab, Leuven, Belgium

[3] Automotive NL, The Netherlands

[4] Flanders Make, DMMS Corelab, Leuven, Belgium

[5] KU Leuven, Department of Mechanical Engineering, Belgium

LightVehicle 2025 project

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

Project Objective

- Showcase the potential of lightweight design and CO_2 reduction in automotive components
- Create demonstrators with a weight & CO_2 emissions reduction of at least -25%.
- Enhance cross-border cooperation of companies all along the value chain in automotive industry.

Project Partners

FLANDERS MAKE — DRIVING INNOVATION IN MANUFACTURING
AutomotiveNL
LIÈGE université
TECHNIFUTUR® CENTRE DE COMPETENCES CAMPUS FRANCORCHAMPS
AMAC Advanced Materials Advisory & Consultancy

Co-Financers

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

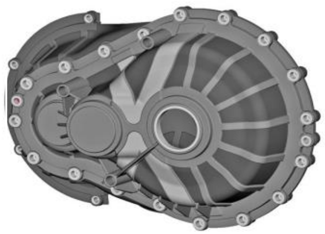
Light Vehicle 2025 Demonstrators

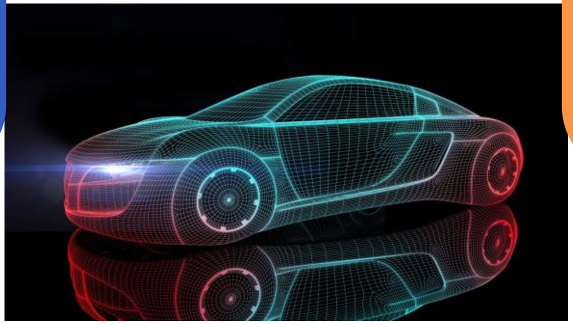
See papers by I. Koutla et al.
and by C. Lopez
This conference

This paper

Body
Lightweight door

E-Powertrain
Gearbox housing





Suspension
e.g. anti roll bar

Energy storage
H_2 tank

Light Vehicle 2025 Truck Door Demonstrator

SEKISUI S-Lec B.V.
→ Prototype and assembly

Automotive NL
→ Demo Leader

Flanders Make
→ Design & Engineering

GBO Innovation Makers
→ Door design and prototyping

DK Prototyping
→ Car window shields for prototypes and concept cars

A&M Uliege
→ Scientific Partner and
→ Education transfer

The industrial and the educational projects

- The educational project is a spin-out project from the demonstrator : design project assigned to master students in automotive engineering

- Illustrate the lightweight design concepts
- Sustainability of the project outcomes

- Project carried out on SIEMENS-NX (CAD) and SIEMENS NX-TOPOL (Topology Optimization)

SIEMENS NX

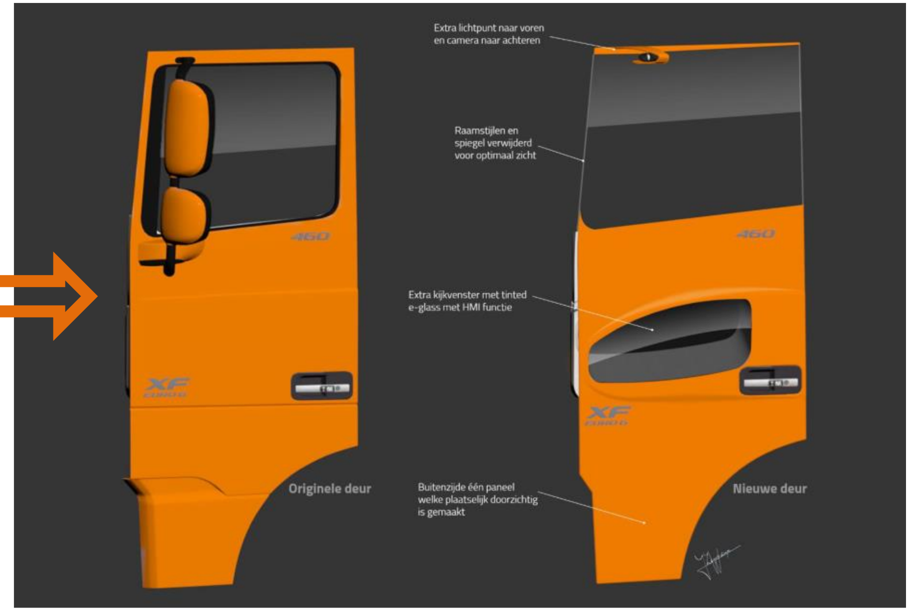
SAMTECH

Redesign approach

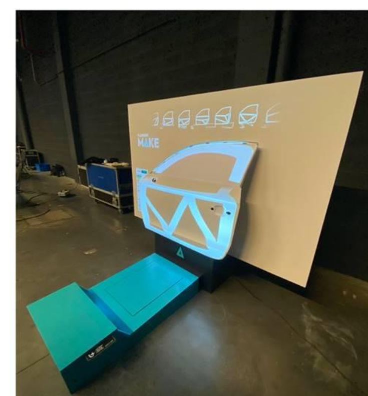
- From conceptual design to detailed design and prototype validation
  - Design specifications and load cases derived from the truck OEM
  - Layout optimization is used to define the steel frame layout
  - Topology optimization is used to explore new door concepts
  - CAD design derived from the new concept suggested by the preliminary design
  - Verification using advanced simulations
  - Prototype fabrication
  - Physical testing and final assessments
  - Life Cycle Analysis of the final product

THE DESIGN PROBLEM

Redesign of a medium size truck door



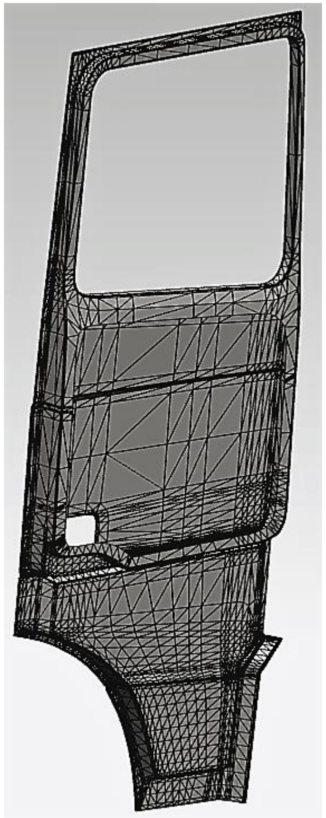
- New door concept:
  - All-Steel → Glass cover reinforced with steel beams and robomoulded inner panel
  - Frameless windows
  - Mirror → cameras and new glass openings to maximum visibility
  - Function integration into inner cover of the door



Design problem: specifications

- Boundary conditions:
  - The door fits on the cabin geometry
  - Hinge and handle positions are given

- Design scenarios
  - Static Load Cases: 4 LC
  - Eigenfrequencies
    - Free-free modes
    - Mounted on the hinges and the lock
    - Constrained on the edge

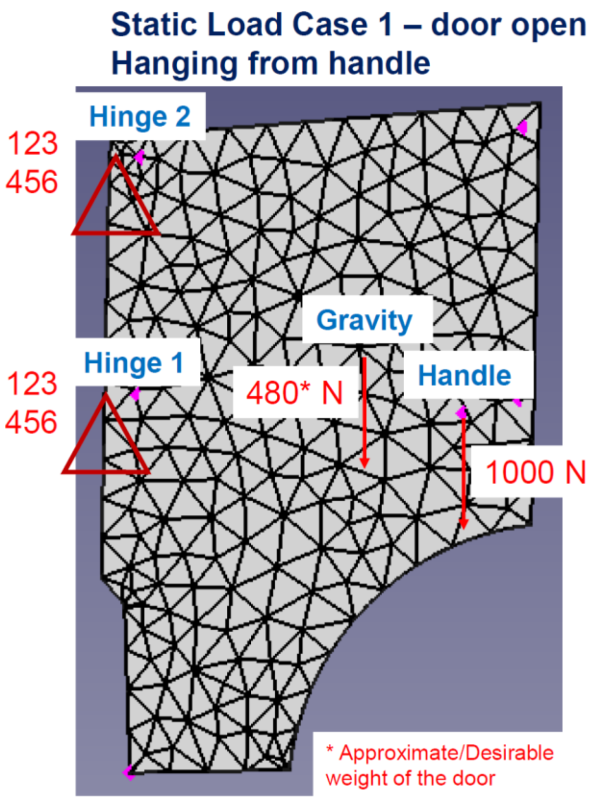


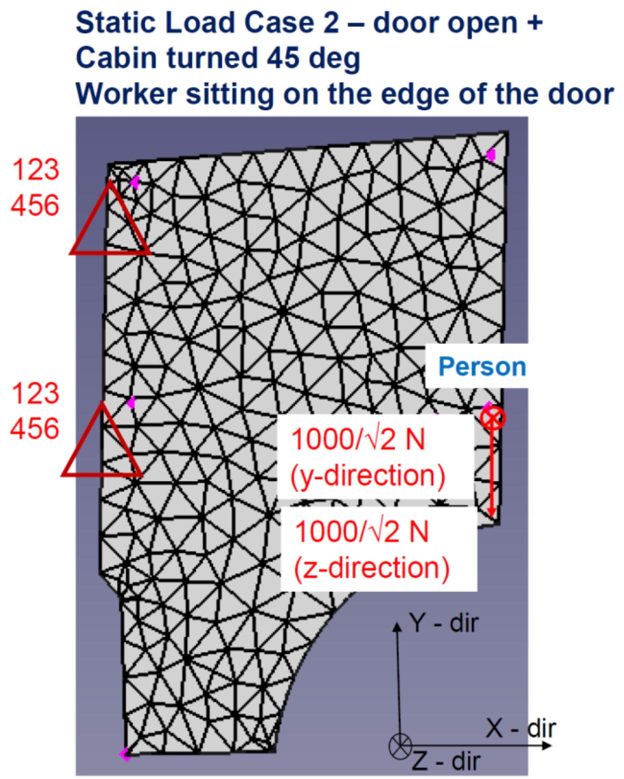
- Design objectives and constraints:
  - Mass → -25%
  - CO_2 → -25% (LCA)
  - Maximize Stiffness
  - Max displacements < 3 mm for each LC
  - Natural frequencies > 50 Hz

Design Problem: load cases

- Load case 1: door open, hanging on its hinges. Downward load of 1000 N applied at the hinge
- ➔ in plane loading

- Load case 2: Door open and cabin turned 45°. A worker is standing on the far corner of the door
- ➔ bending + in plane



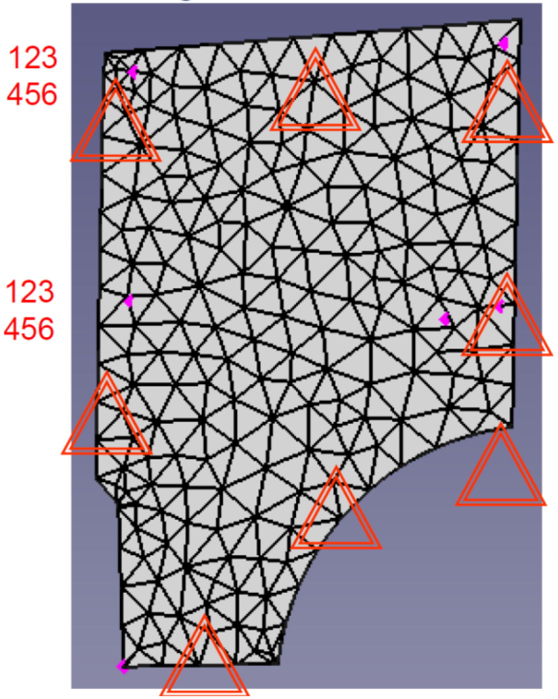


Design Problem: load cases

- Load case 3: Door is closed and with an impact distributed load from outside. Door is supported along its boundary
- ➔ Homogeneous pressure loading

- Design case 4: eigen frequencies. Natural frequencies of the door simply supported along the cabin joint

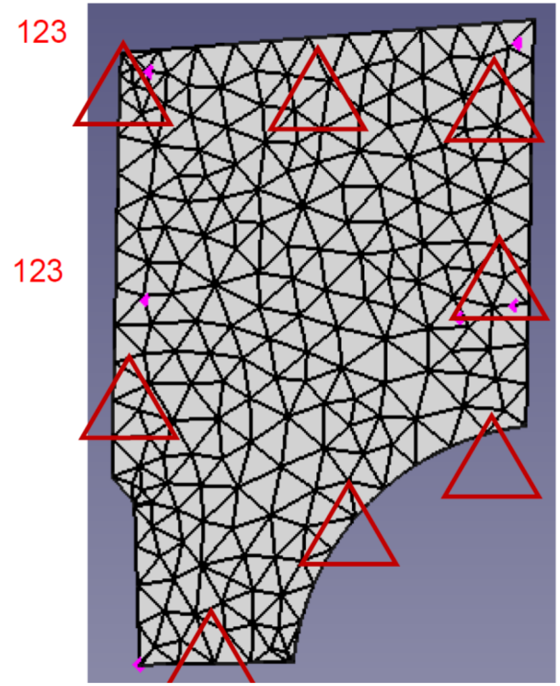
Static Load Case 3 – door closed
Homogeneous Pressure



$$V = 50\, m/s$$
$$C_x = 1.0$$
$$\rho = 1.22 kg/m^3$$

$$F/S = 1/2 \rho\, C_x\, V^2$$
$$= 1525\, N/m^2$$
$$= 1.5\, kPa$$

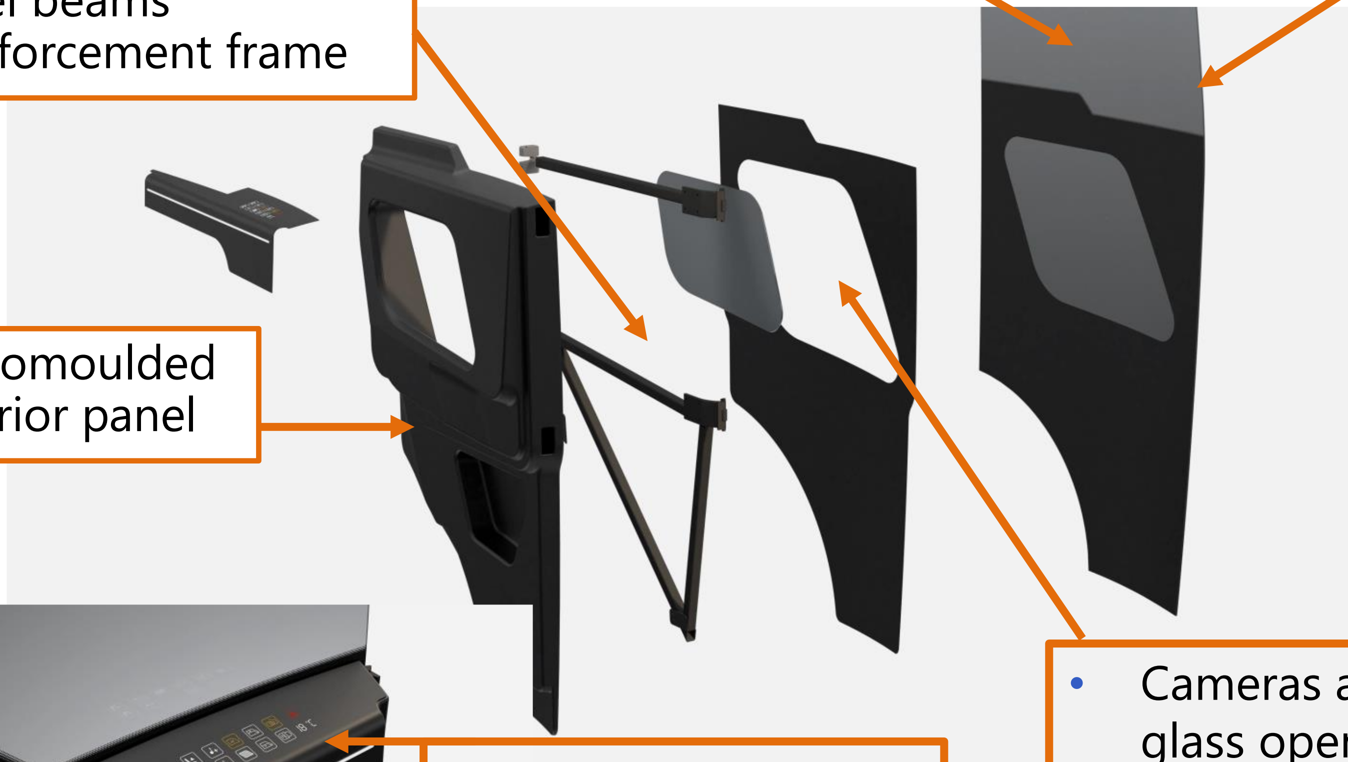
Modal Analysis Load Case – door closed
Simply Supported



The industrial project

The new design based on frameless window

- Frameless windows
- Glass cover
- Steel beams reinforcement frame
- Robomoulded interior panel
- Cameras and new glass openings to maximum visibility
- Function integration

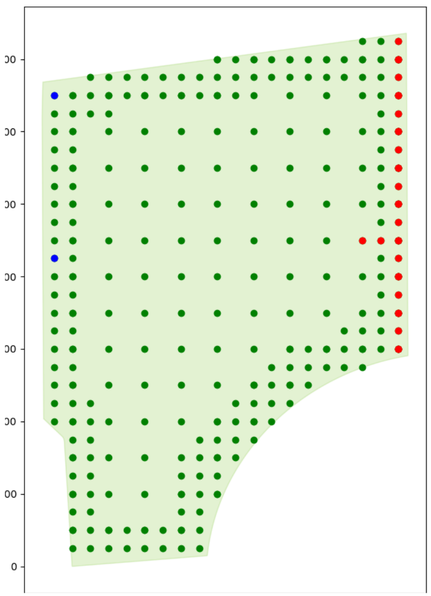


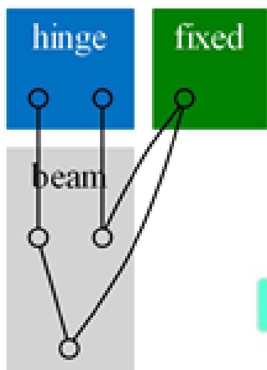
Design concept generation

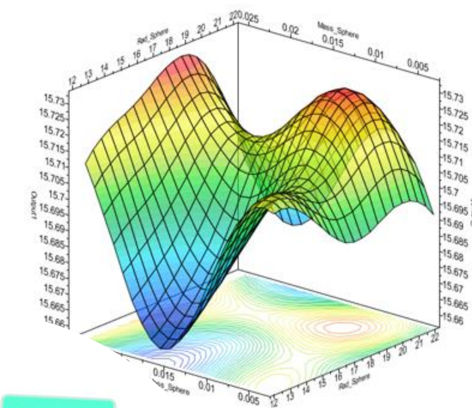
STEP 1

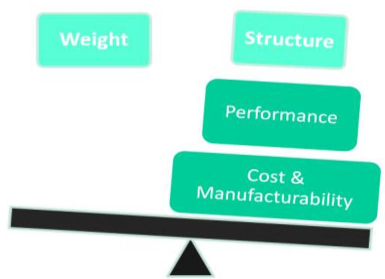
STEP 2

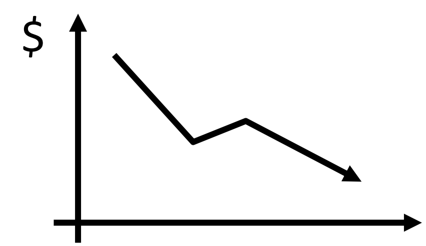
Design concepting → **Design optimization**







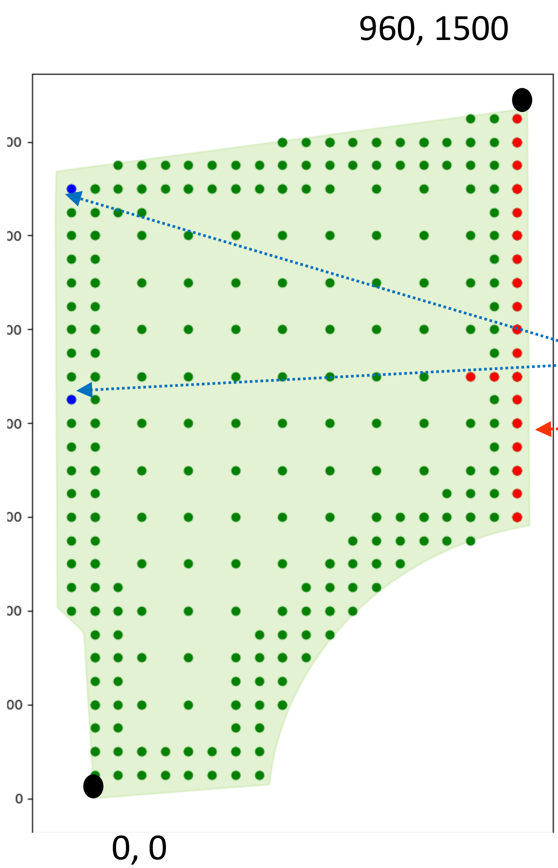




Info needed : The new CAD (in 2D projection) so that the design space is updated

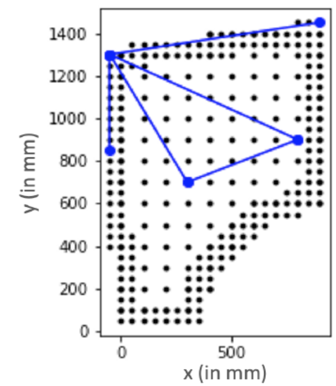
Algorithm for beam reinforcement structure generation

Design Decisions

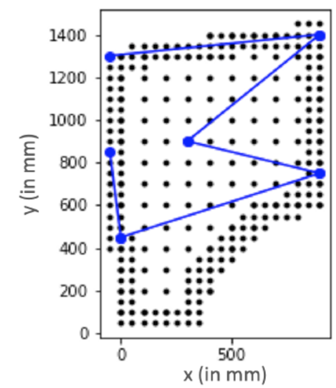


1. Reinforcement connected to the position of the hinges of the reference door
2. Reinforcement at the opposite side of the door
   - 2 fixed hinges
   - Reinforced zone : 2 connections
3. Max number of beams per joint =4
4. No smaller than 100 mm length of the beams
5. Make grid of possible beams, increase solutions to the borders

Examples

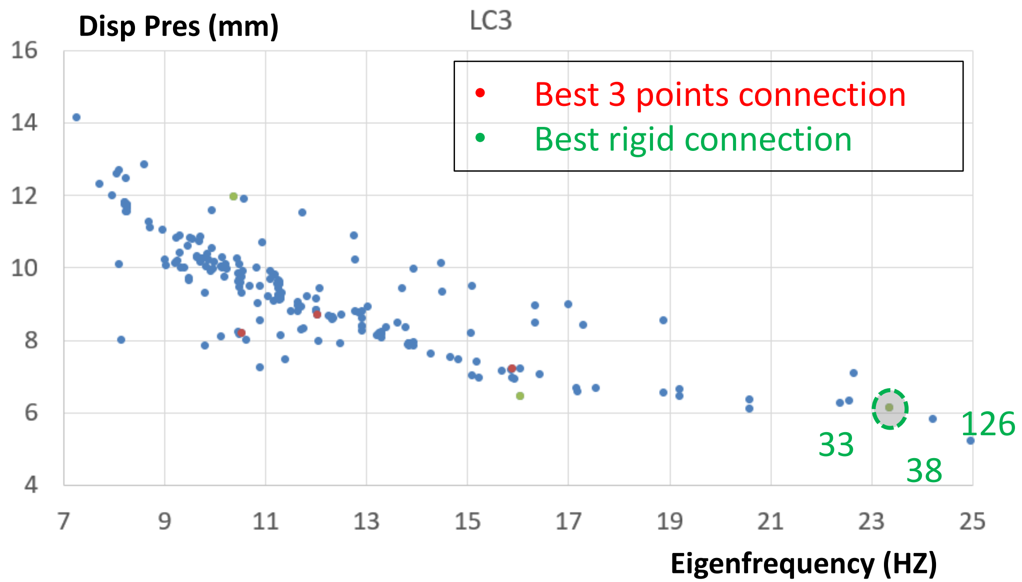


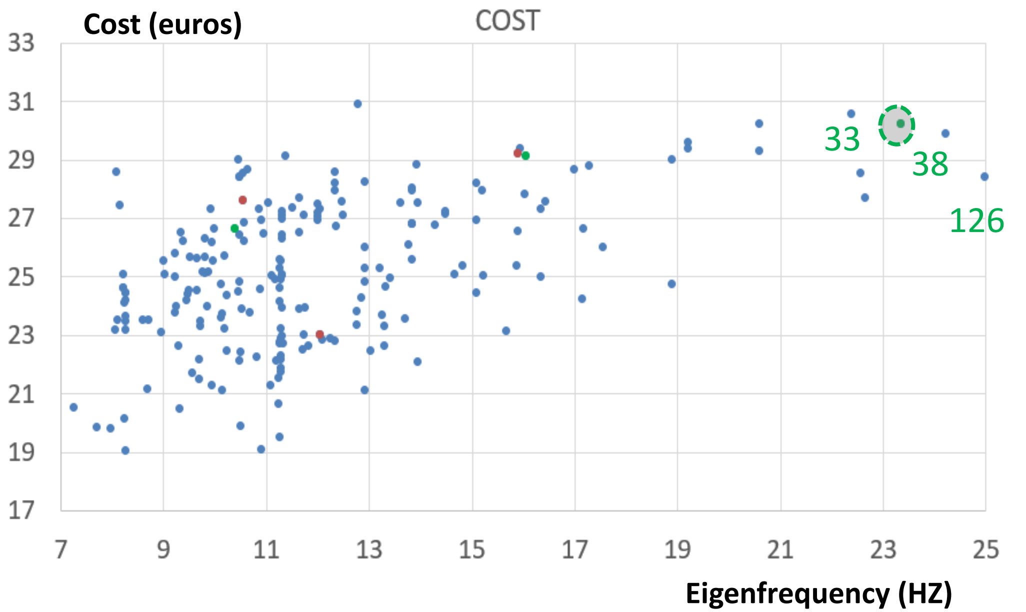
Location of joints	1 -> (-50, 850) 2 -> (-50, 1300) 3 -> (800, 900) 4 -> (900, 1450) 5 -> (300, 700)
Beam Connecti ons	(1, 2) (2, 3) (2, 4) (2, 5) (3, 5)



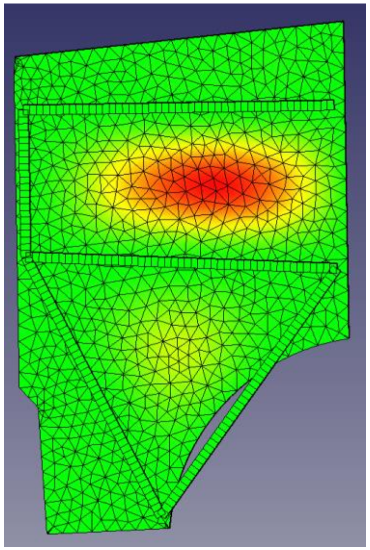
Location of joints	1 -> (-50, 1300) 2 -> (-50, 850) 3 -> (900, 750) 4 -> (900, 1400) 5 -> (0, 450) 6 -> (300, 900)
Beam Connect ions	(1, 4) (2, 5) (3, 5) (3, 6) (4, 6)

Design concept generation

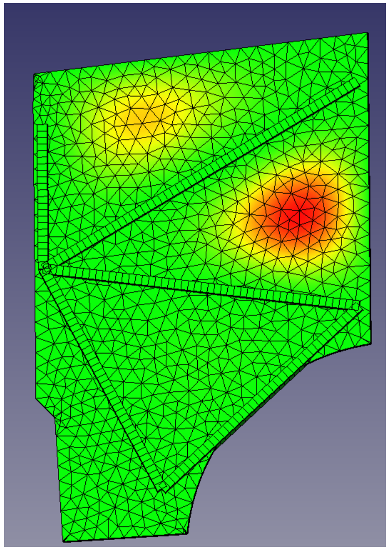




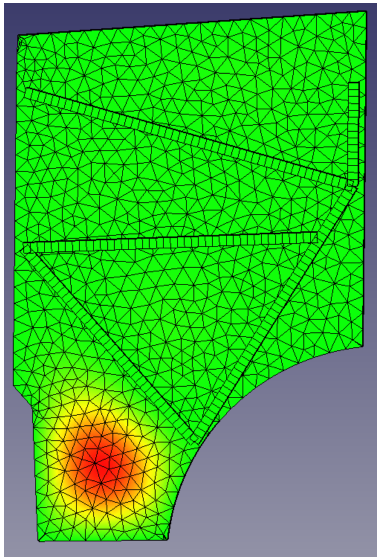
33



38



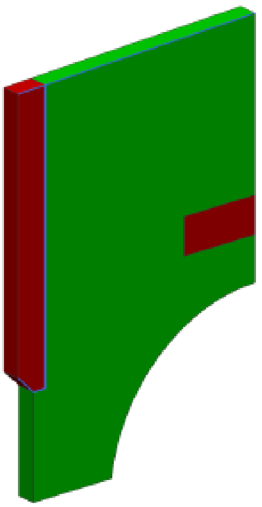
126



Innovative Layout using topology optimization

The Topology Optimization design problem

- Design domain:
  - Door maximum size
  - Non design domain: hinge and handle subdomains



- Multiple load cases (+BC)
  - Static Load Cases: 3 LC
    - Door hanging
    - Door bended during reparation
    - Constant pressure / max eigenfrequency
  - Natural frequencies

- Design objectives and constraints:
  - Maximize Min Stiffness
    - Volume < 0.5 Volume
    - Max displacements < 3 mm for each LC
    - (Natural frequencies > 50 Hz)

$$\begin{array}{ll} \min & \max_{\text{L.C.}} \mathbf{f}^{(k)\,T}\mathbf{u}^{(k)} \\ \text{d.v.} & \\ \text{s.t.:} & V(\mathbf{x}) \leq \bar{V} \\ & \mathbf{K}\,\mathbf{u}^{(k)} = \mathbf{f}^{(k)} \end{array}$$

- Topology Optimization Software: SIEMENS-NX (CAD) and SIEMENS NX-TOPOL (Topology Optimization)

SIEMENS NX

NX-TOPOL Design environment

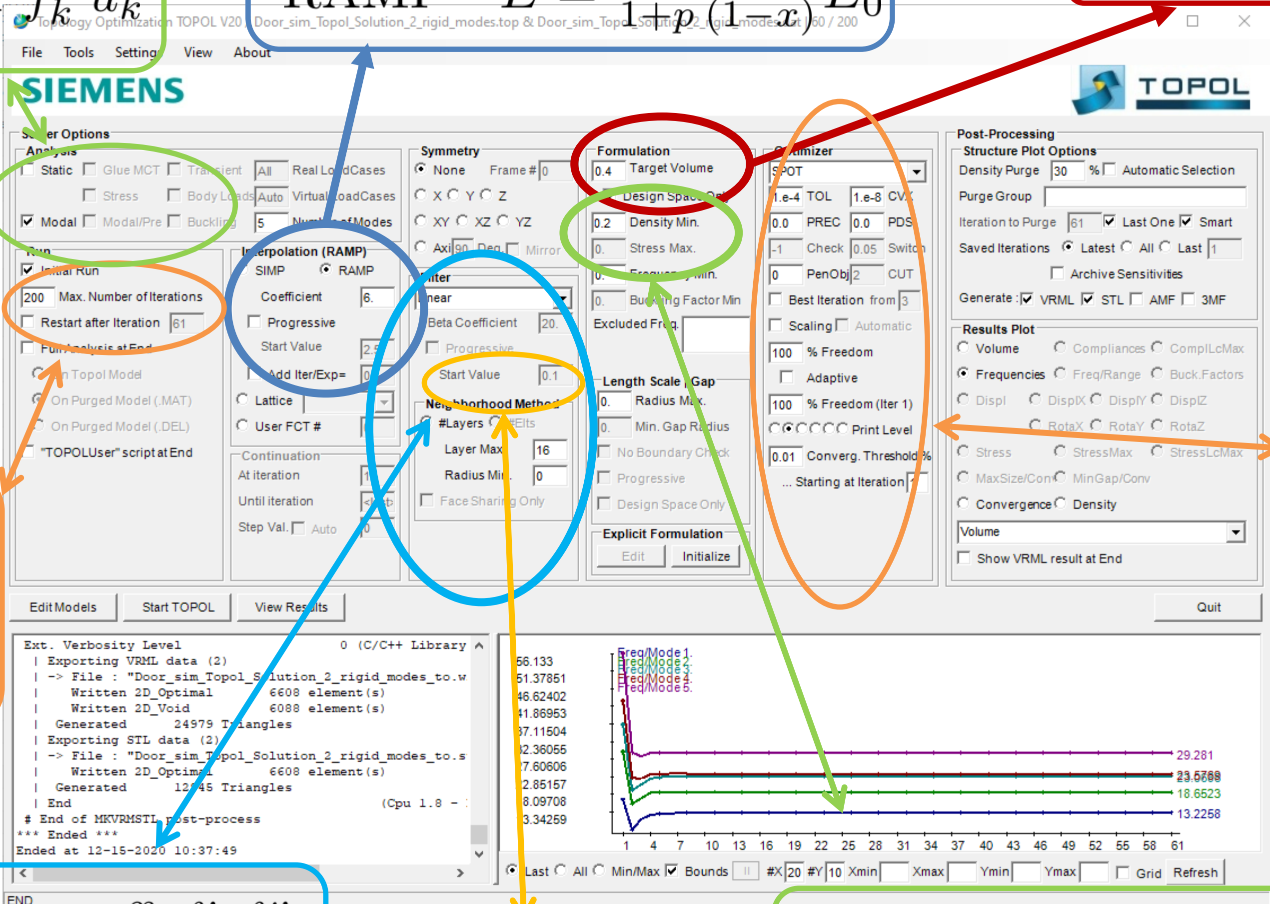
All static load cases

$$\min_{L.C.} \max f_k^T u_k$$

SIMP $\quad E = x^p E_0$

RAMP $\quad E = \frac{x}{1+p(1-x)} E_0$

$$V \le \bar{V} = 0.4\, V_{max}$$



Max number of iterations 1000

CONLIN: approximation and 2nd order dual solver

$$\tilde{x}_i = \frac{\sum_{e\in B(r_i)} x_e v_e w_e}{\sum_{e\in B(r_i)} v_e w_e}$$

$$x_i^{(0)} = 0.1 \ \forall i$$

$$\underline{x}_i \le x_i \le \overline{x}_i \qquad \underline{x}_i = 0.2 \qquad \overline{x}_i = 1.0$$

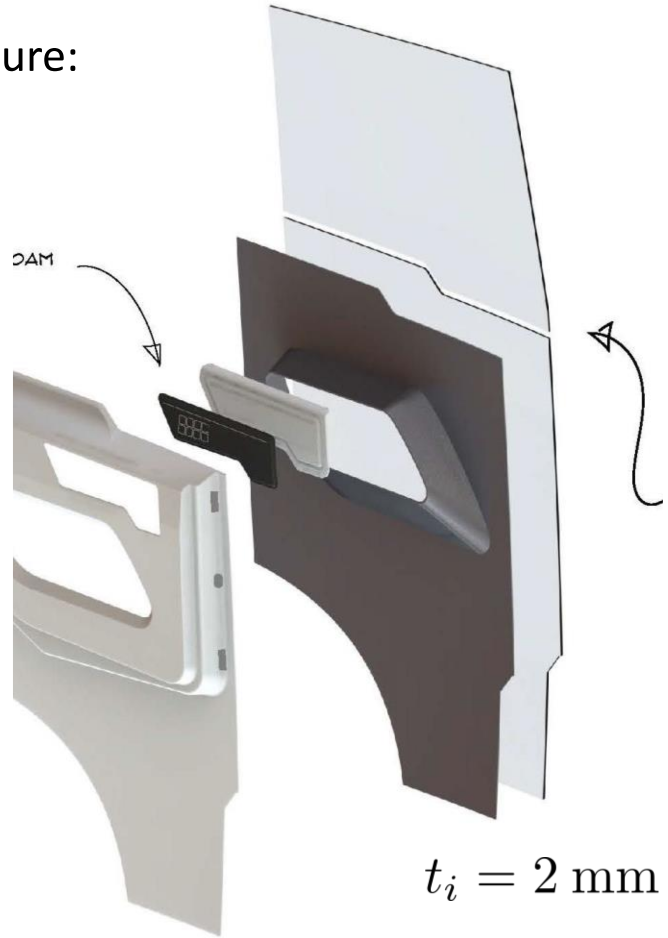
Modelling of the face sheet + steel reinforcement assembly

- Modelling of the PE face sheet / Steel Reinforcement assembly
  - The minimum gauge of density variables is to x=0.2

Reinforcement structure:
Steel S380

$$E_{S380} = 205\,000 \text{ MPa}$$

$$x_i(S380) = 1$$



$$E = x^3\, E_0$$

$$E = 0.2^3\, 205000$$
$$= 1656 \text{ MPa}$$

Face sheet made of PE

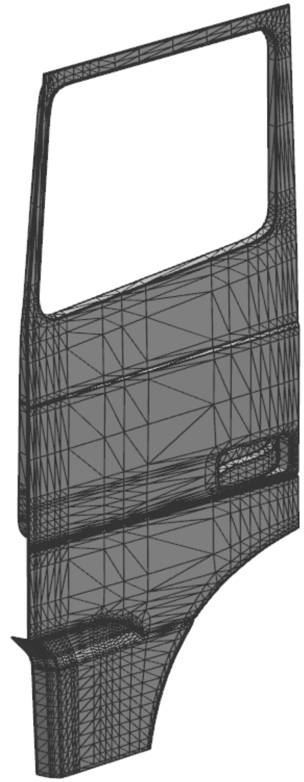
$$E_{PE} = 1000 \text{ MPa}$$

$$x_i(PE) \simeq 0.2$$

$$t_i = 2 \text{ mm}$$

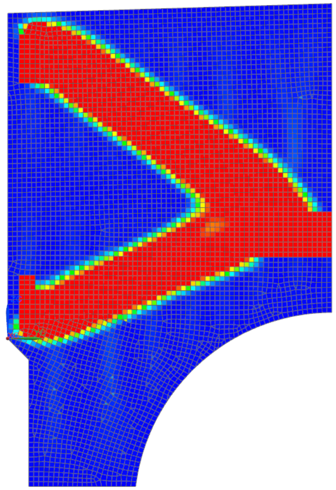
Model "ready for topology optimization"

Complete door model



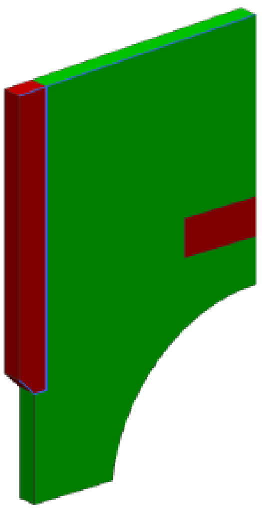
FE door model

2D



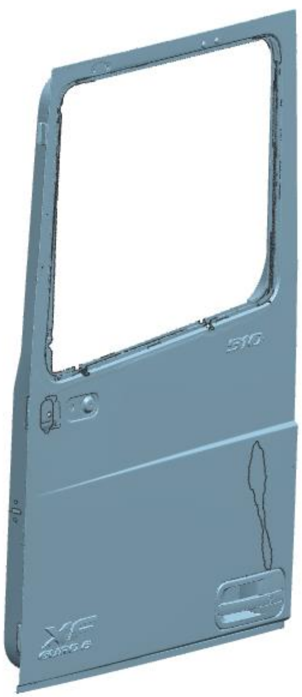
models for topology optimization

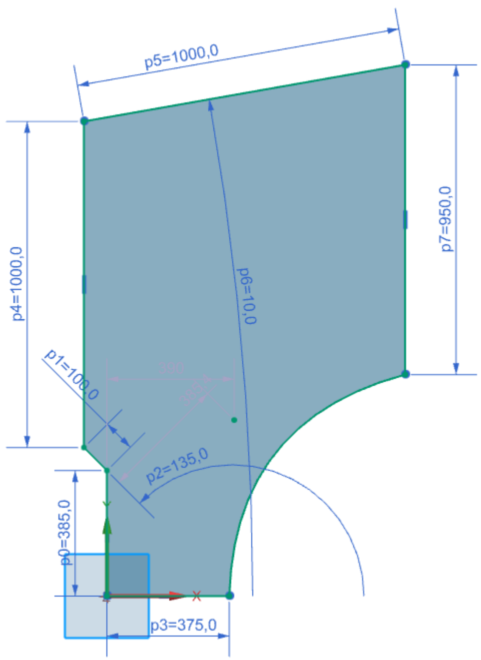
3D

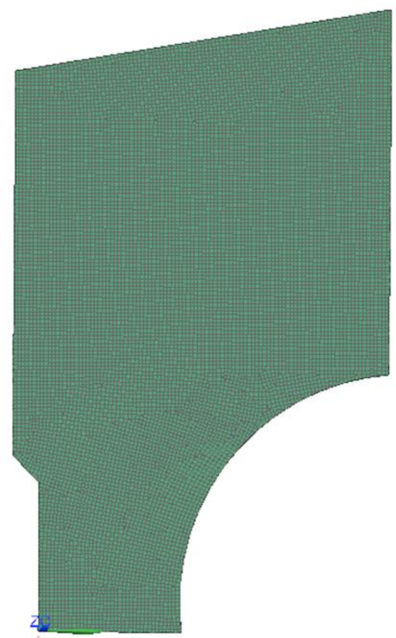


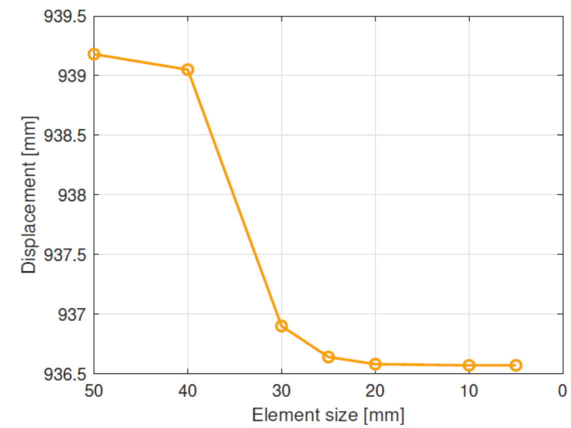
Simplified geometrical model and mesh

- Preparation of FE models for optimization
  - Simplified geometrical model → design domain
  - Finite Element discretization assumptions
    - Mindlin Shell [T29 in NX-Samcef] ➔ 2D
    - Brick elements [T8 in NX-Samcef] ➔ 3D
  - Optimized mesh size for optimization business





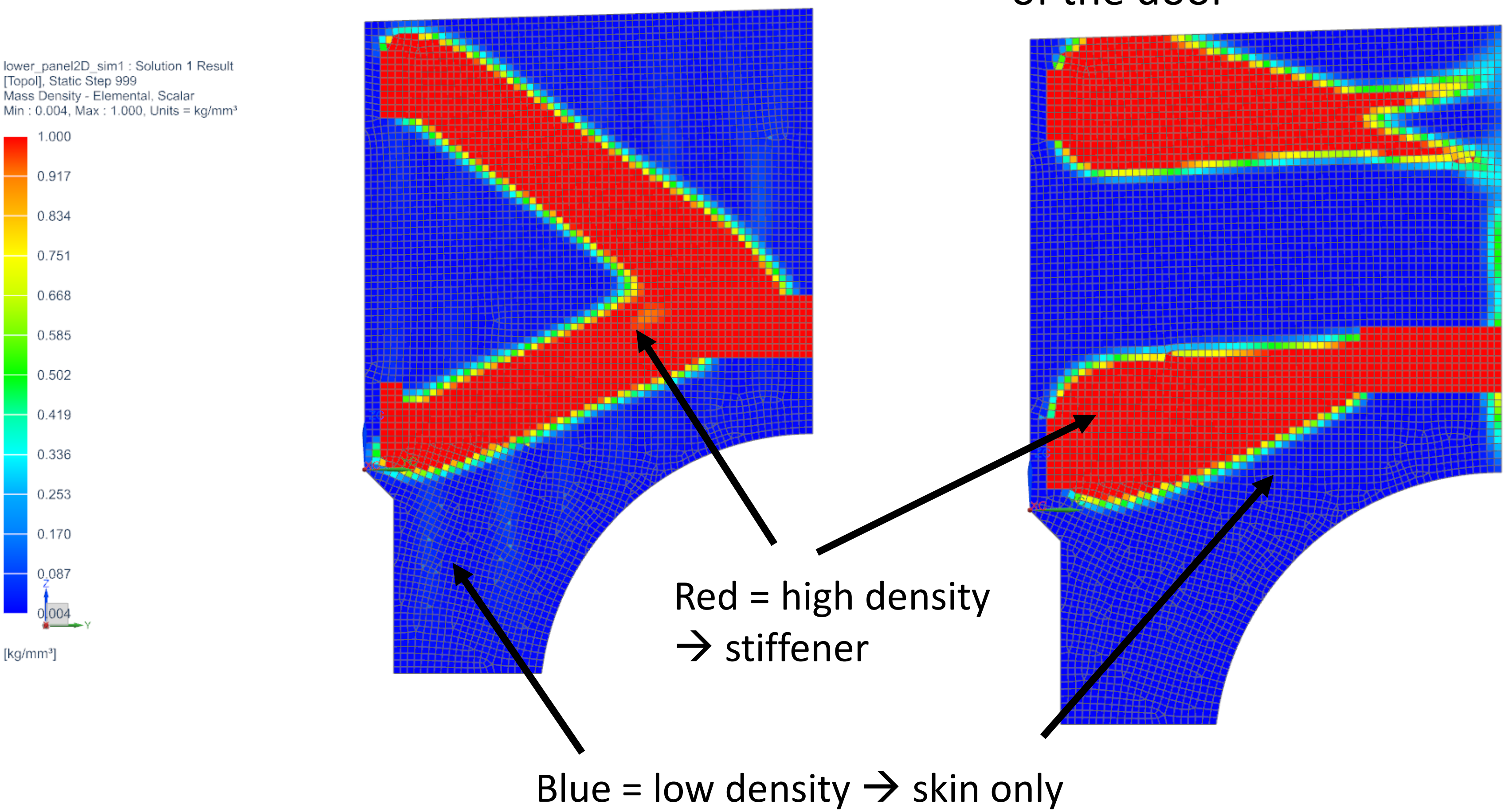




Redesign based on 2D shell model

<u>Load case 1:</u> door open, hanging on its hinges. Downward load of 1000 N applied at the hinge

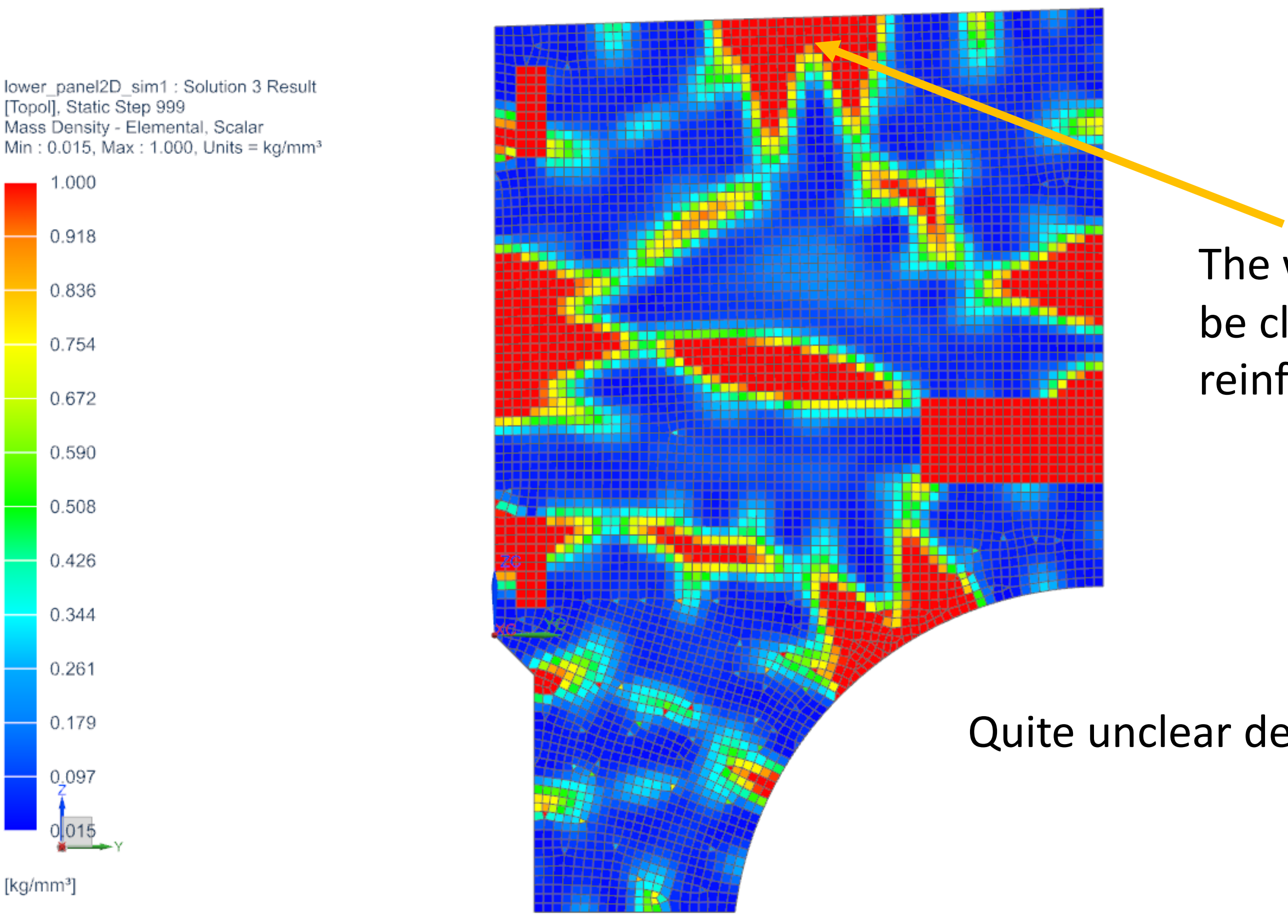
<u>Load case 2:</u> Door open and cabin turned 45°. A worker is standing on the far corner of the door



Redesign based on 2D shell model

<u>Load case 3:</u> Door is closed and with pressure from outside

$$F/S = 1525\ N/m^2$$



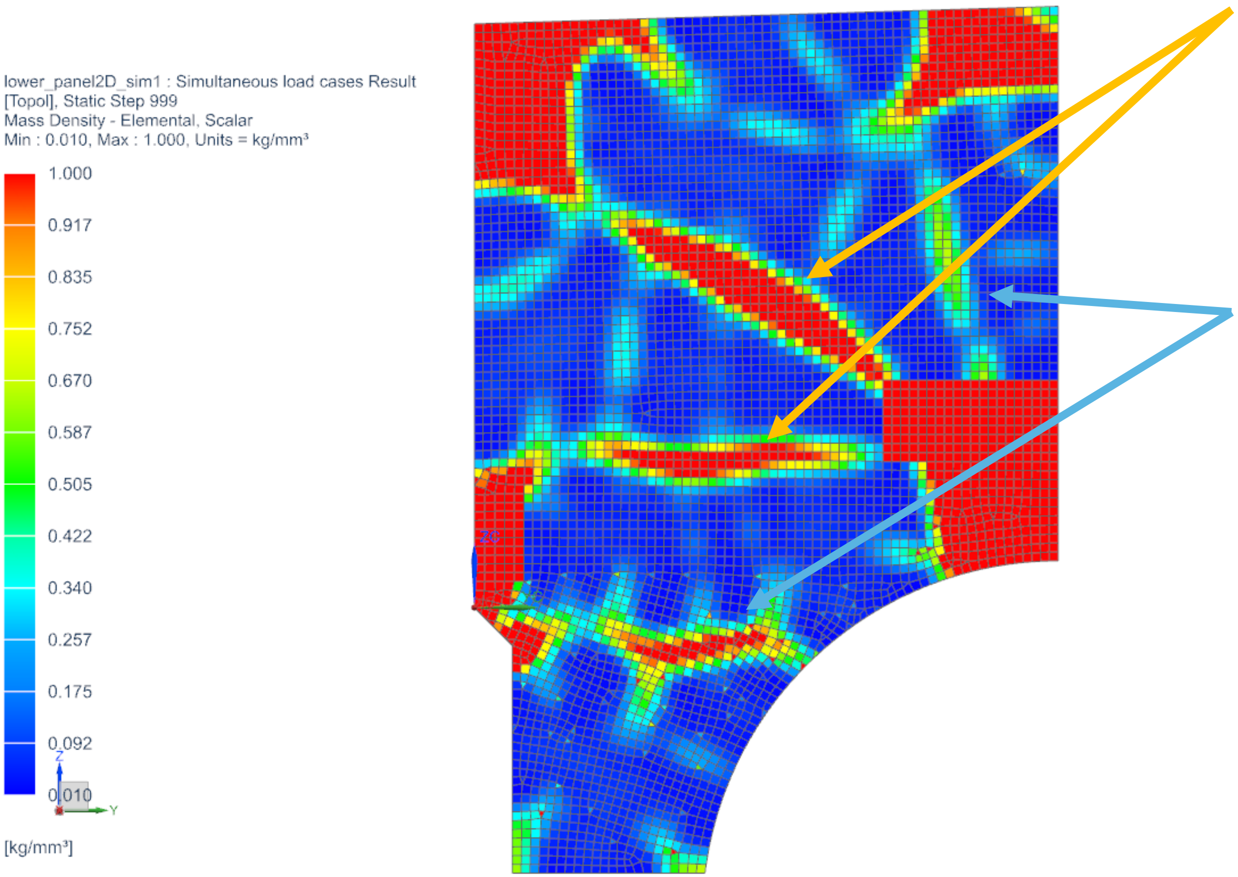
The window is supposed to be clamped ? ➔ artificially reinforced!

Quite unclear design!

Redesign based on 2D shell model

Load case 1 & 2 & 3: using min max formulation

$$
\begin{array}{cc}
\min\limits_{0.2 \leq x_i \leq 1.0} & \max_{1,2,3} \mathbf{f}^{(k)\,T} \mathbf{u}^{(k)} \\
\text{s.t.:} & V(\mathbf{x}) \leq \bar{V} \\
& \mathbf{K}\,\mathbf{u}^{(k)} = \mathbf{f}^{(k)}
\end{array}
$$



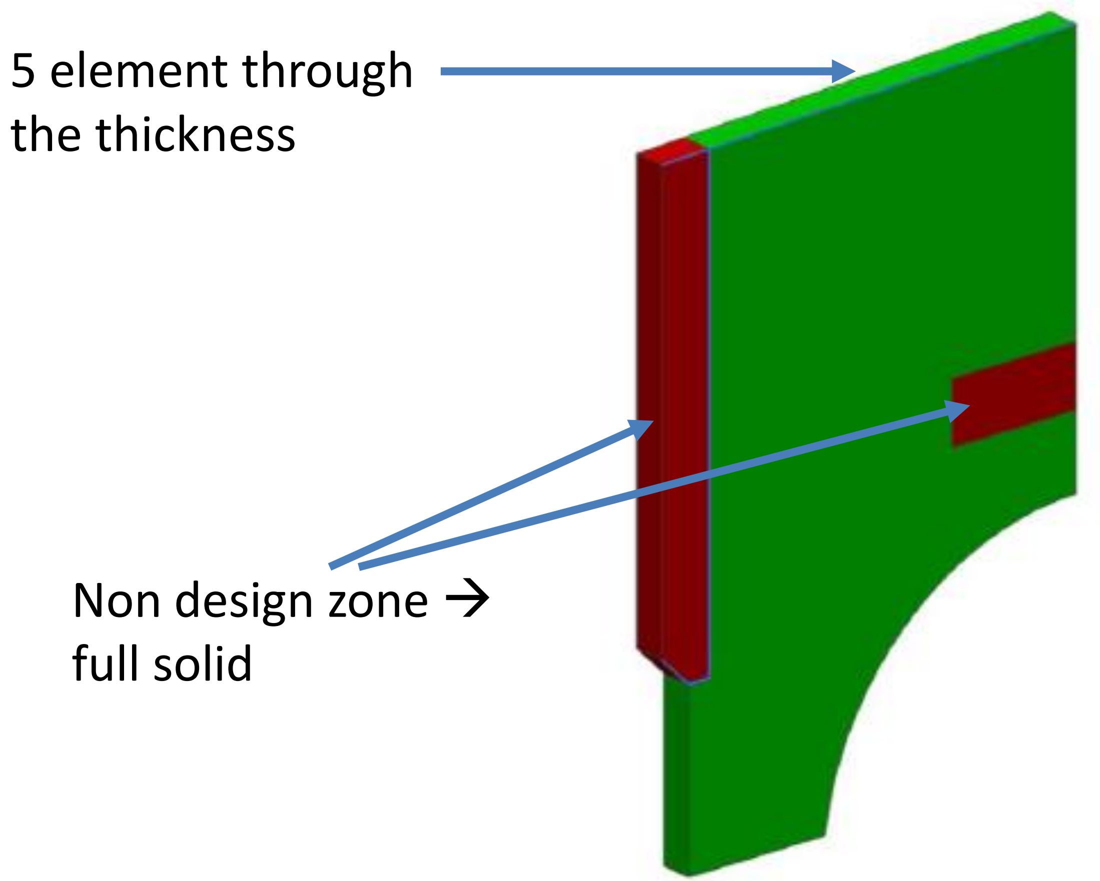
Bending load case (LC2) is dominant

Pressure load case (LC3) rules the design of secondary stiffeners

Very nice connection between the two hinges and the door handle

Redesign based on 3D solid element model

- Design domain and non design zones



Redesign based on 3D solid element model

Load case 1 & 2 & 3: using min max formulation

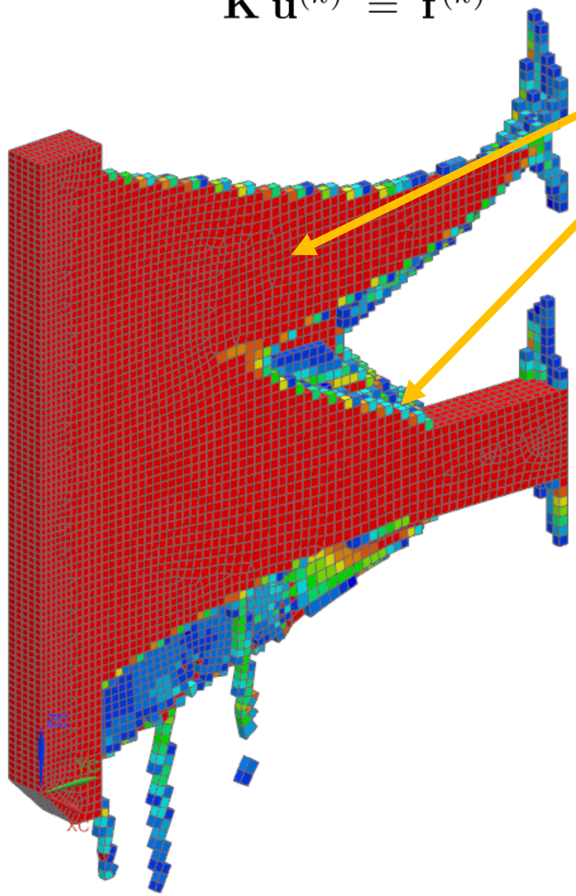
$$\min_{0.2 \leq x_i \leq 1.0} \max_{1,2,3} \mathbf{f}^{(k)\,T}\mathbf{u}^{(k)}$$

s.t.:

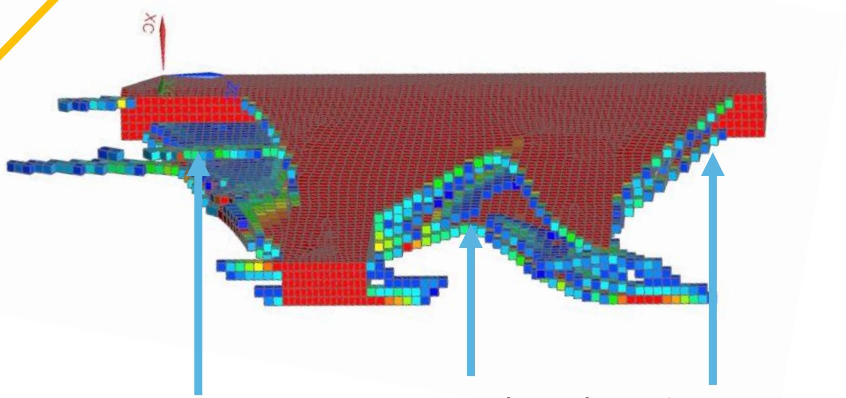
$$V(\mathbf{x}) \leq \bar{V}$$

$$\mathbf{K}\,\mathbf{u}^{(k)} = \mathbf{f}^{(k)}$$

$$F/S = 1.5\,\mathrm{kPa}$$



Bending load case (LC2) is dominant



Pressure load case (LC3) enforces a sandwich structure

When subject to a lower pressure load case ➔ Mix between two bar truss and sandwich panel concept!

Redesign based on 3D solid element model

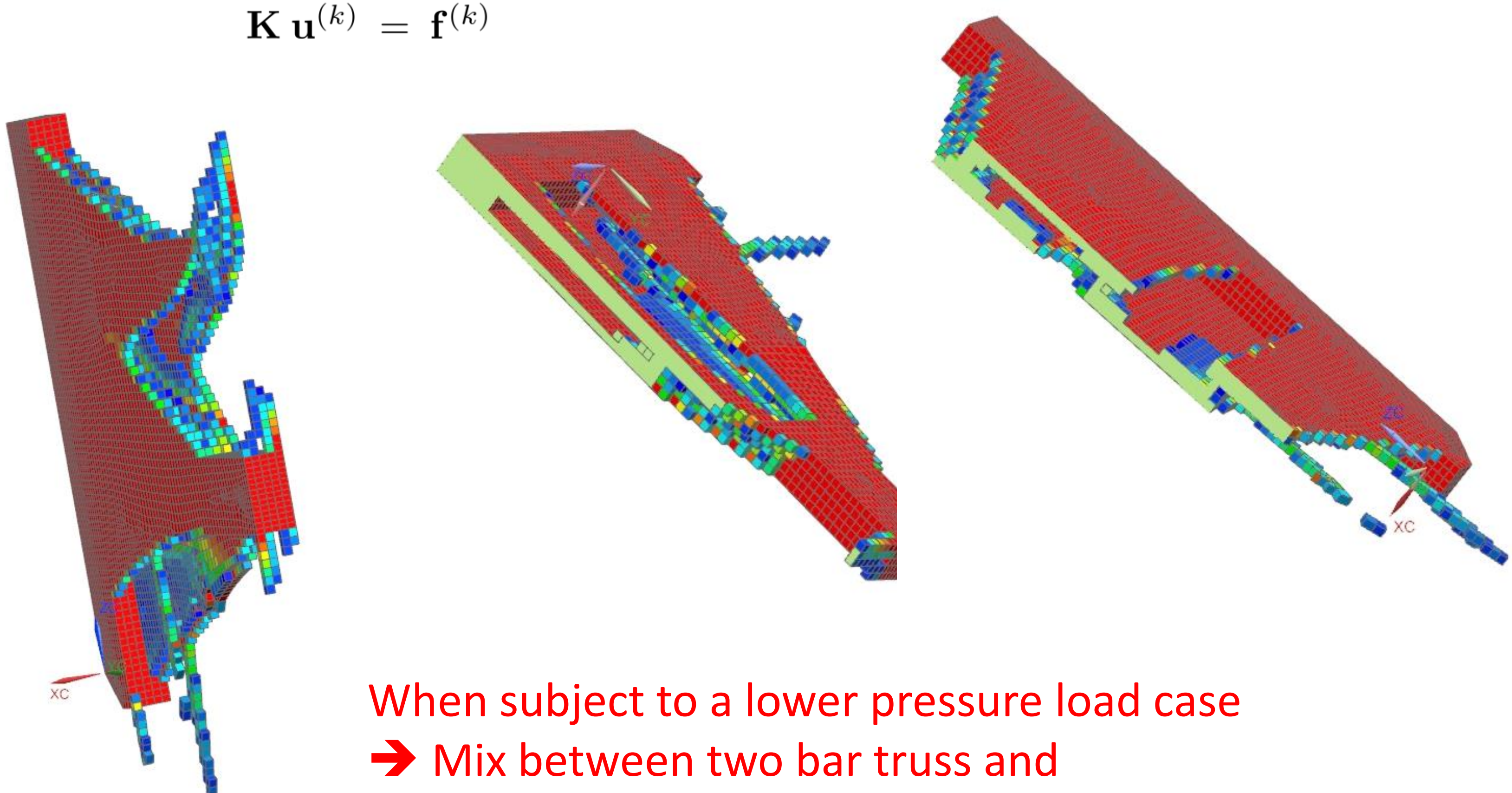
Load case 1 & 2 & 3: using min max formulation

$$\min_{0.2 \le x_i \le 1.0} \max_{1,2,3} \mathbf{f}^{(k)\,T}\mathbf{u}^{(k)}$$

s.t.:

$$V(\mathbf{x}) \le \bar{V}$$
$$\mathbf{K}\,\mathbf{u}^{(k)} = \mathbf{f}^{(k)}$$

$$F/S = 1.5\,\mathrm{kPa}$$



When subject to a lower pressure load case
➔ Mix between two bar truss and sandwich panel concept!

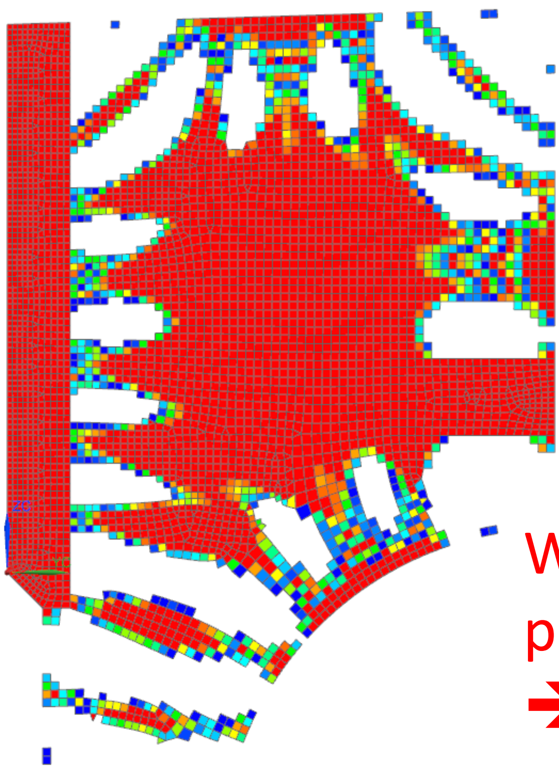
Redesign based on 3D solid element model

<u>Load case 1 & 2 & 3</u>: using min max formulation

$$\min_{0.001 \leq x_i \leq 1.0} \max_{1,2,3} \mathbf{f}^{(k)\,T} \mathbf{u}^{(k)}$$

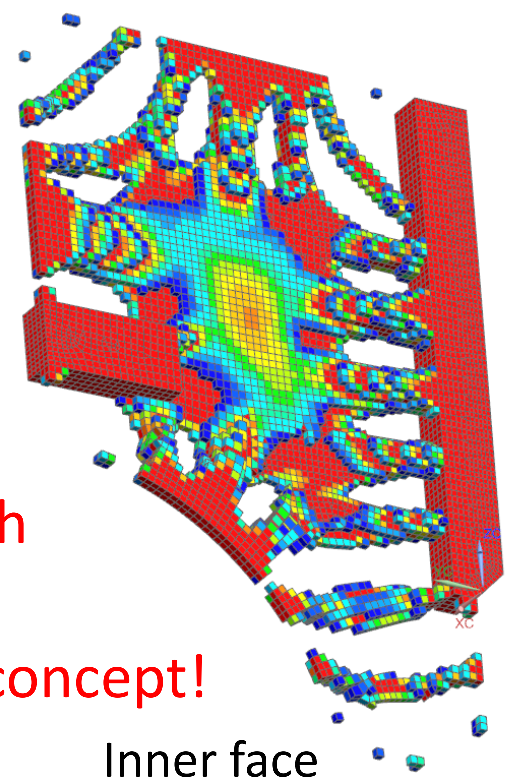
$$\text{s.t.:} \quad V(\mathbf{x}) \leq \bar{V}, \quad \mathbf{K}\,\mathbf{u}^{(k)} = \mathbf{f}^{(k)}$$

$$F/S = 100 \text{ kPa}$$



Upper face

When subject to high pressure load case
➔ Sandwich panel concept!

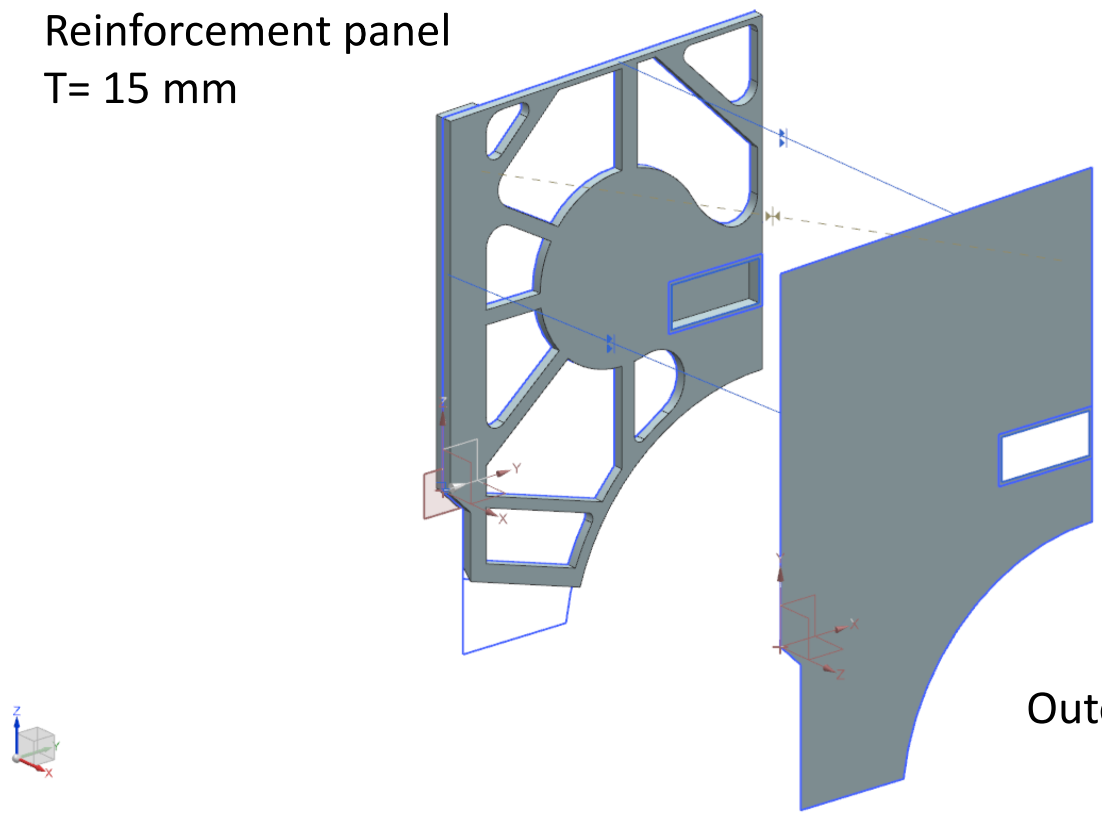


Inner face

Concept derived from 3D TO optimization

- Redesign concept make use of the sandwich concept

Reinforcement panel
T= 15 mm

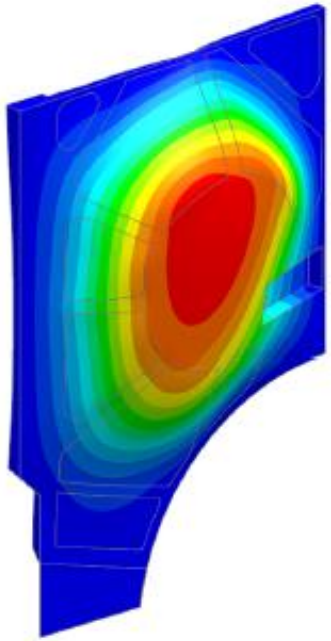


Outer sheet (PE) T=2 mm

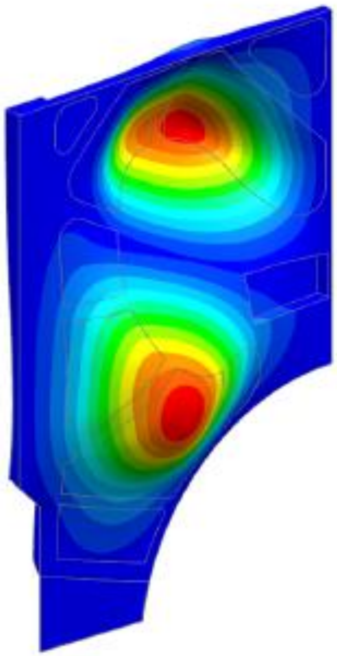
Validation of new concept derived from 3D TO optimization

- A posteriori verification of eigenfrequencies

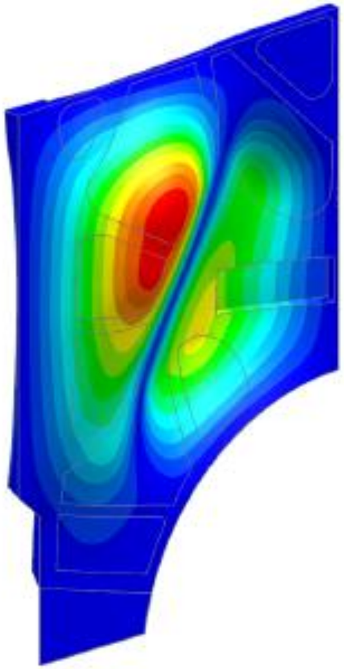
- Mode 1: 178,62 Hz



- Mode 2 : 368,02 Hz



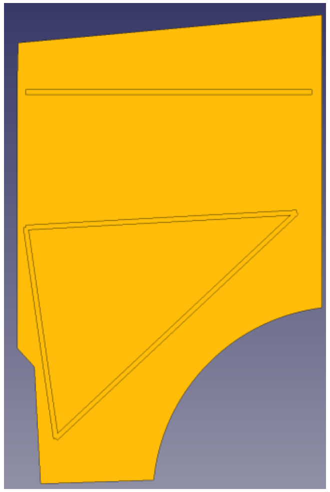
- Mode 3 : 444, 62 Hz



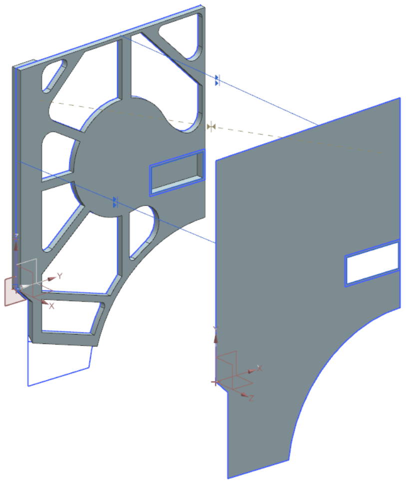
CONCLUSION AND PERSPECTIVES

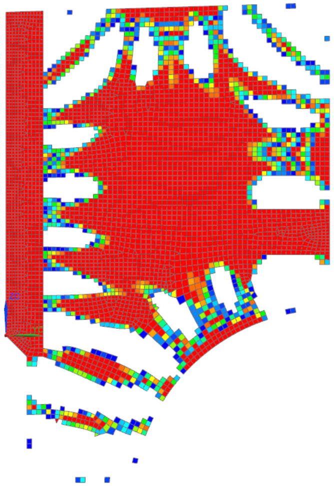
Conclusions

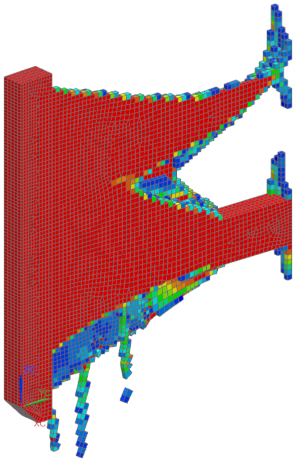
- Redesign of a lightweight truck door design

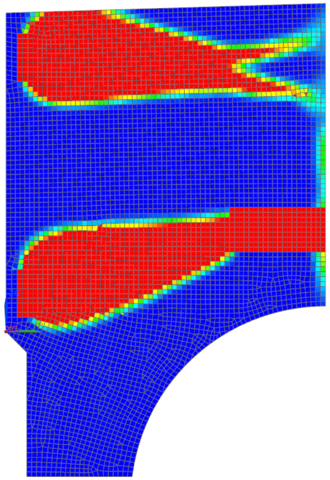


- Beam layout optimization has been successfully applied to derive a new concept of glass sheet structure reinforced by steel beams
- Topology optimization has been used to reinvestigate the nature of the solution
  - 2D models come to similar designs
  - 3D models are able to suggest more breakthrough solutions



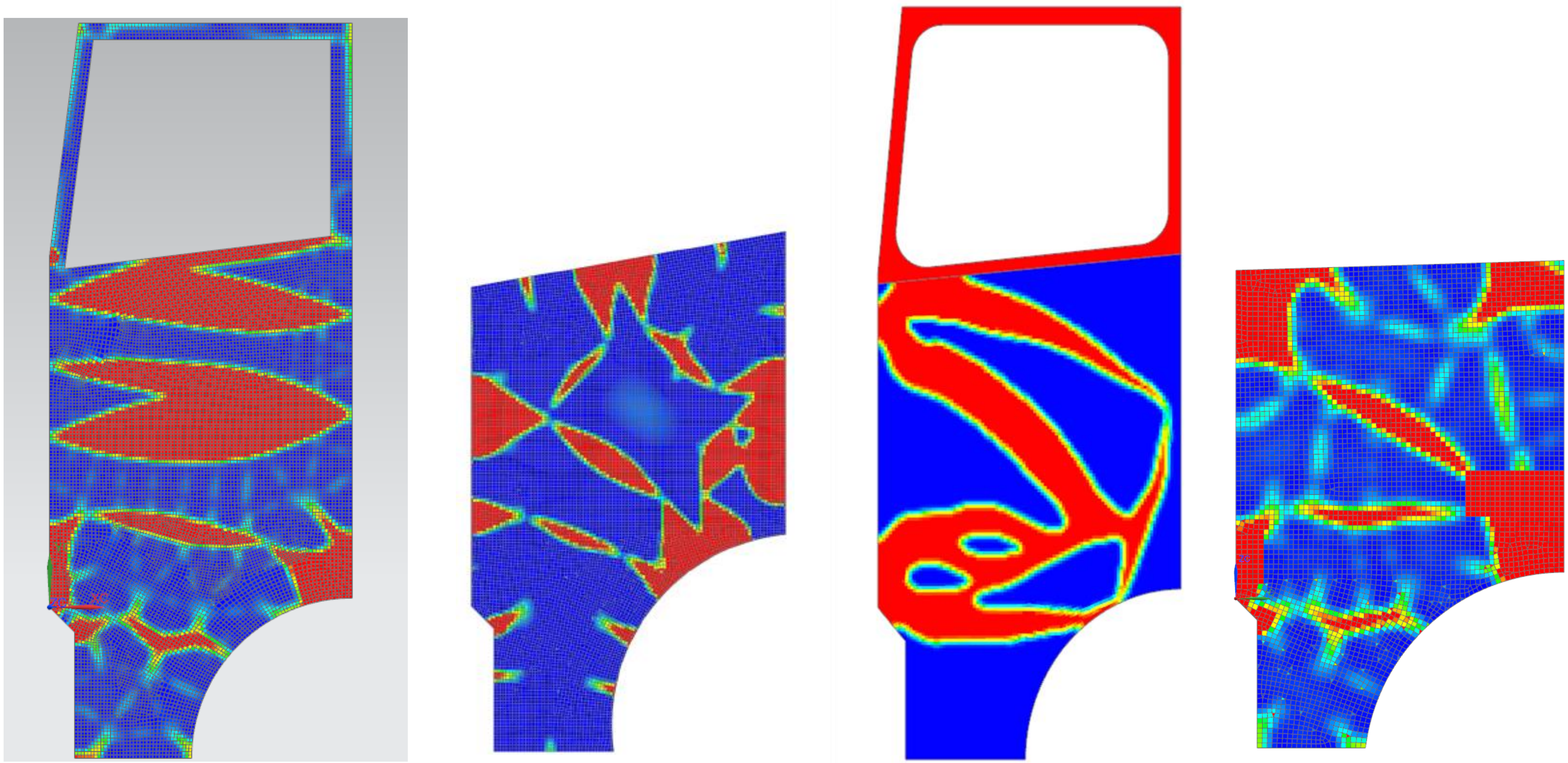






Conclusions

- Lightweight design concepts offers challenging opportunities for engineering student education



François & Giacomo Alexandre & Benjamin Louis & Calogero Jules & William

Acknowledgement

- 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.

Acknowledgement

- This project has been carried in the project of the course MECA0063 Vehicle Architecture and Components of the Master in Mechanical Engineering and of the Certificate in Sustainable Automotive Engineering of University of Liege and Campus Automobile Spa Francorchamps.

- Many thanks for the students who were the creative manpower of this project: Benjamin Degryse, Louis Delanaye, Olivia Dulon, Calogero Gallo, Audric Gaspar, Alexandre Radoux, Giacomo Realdini, Jules Remes, François Van de Putte, William Weber.