HELYX®
ADJOINT

Next-Generation Design Optimisation for Enterprise applied to Internal Combustion Engines

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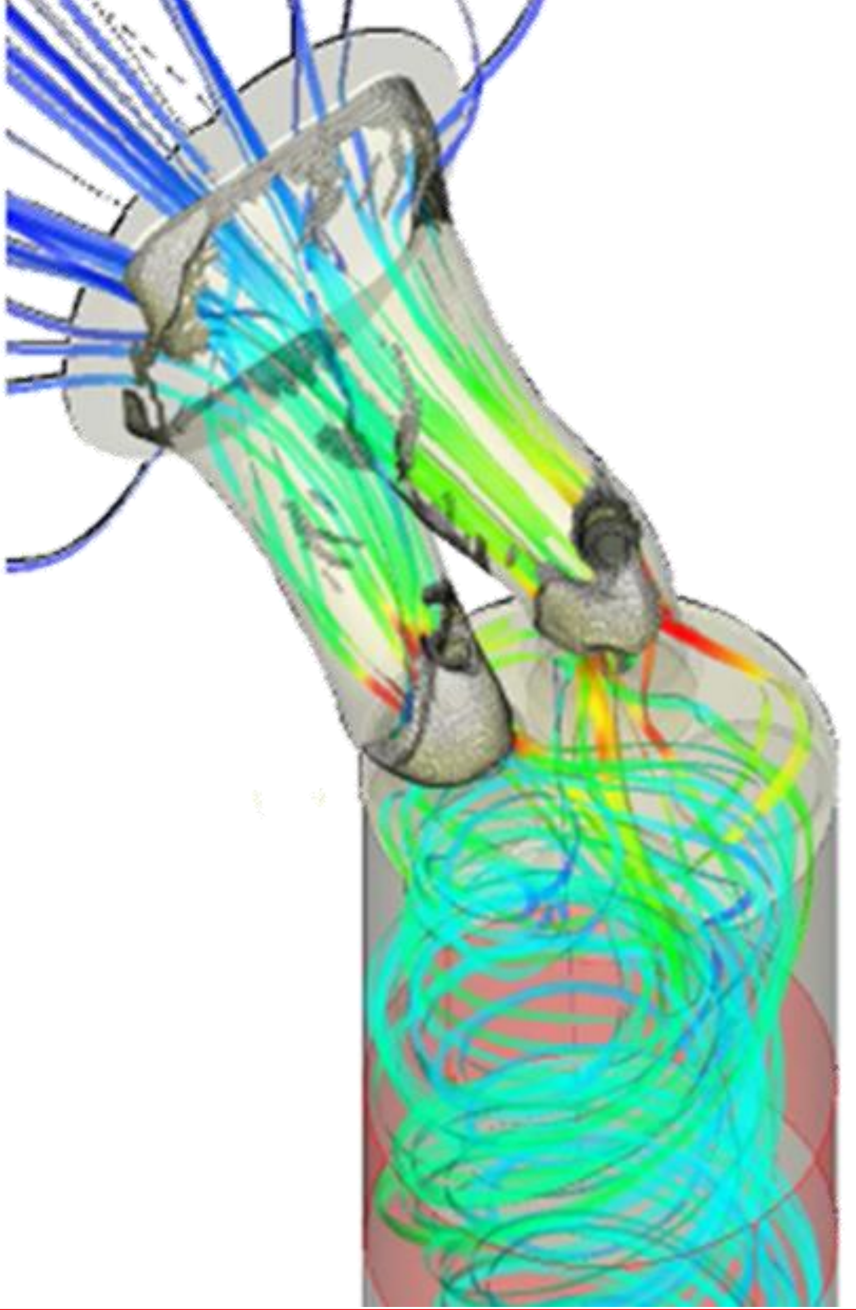
23 February 2018



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About ENGYS

- Global providers of professional quality CFD Products
  - Based on Open Source Software (OPENFOAM)
  - Driven by innovation
- Founded in the UK (2009)
  - FOAM/OPENFOAM developers since 1999
- 6 offices worldwide
  - UK, Germany, Italy, USA, Australia, RSA
- Well established resellers network
  - Japan, Benelux, Korea, China, USA

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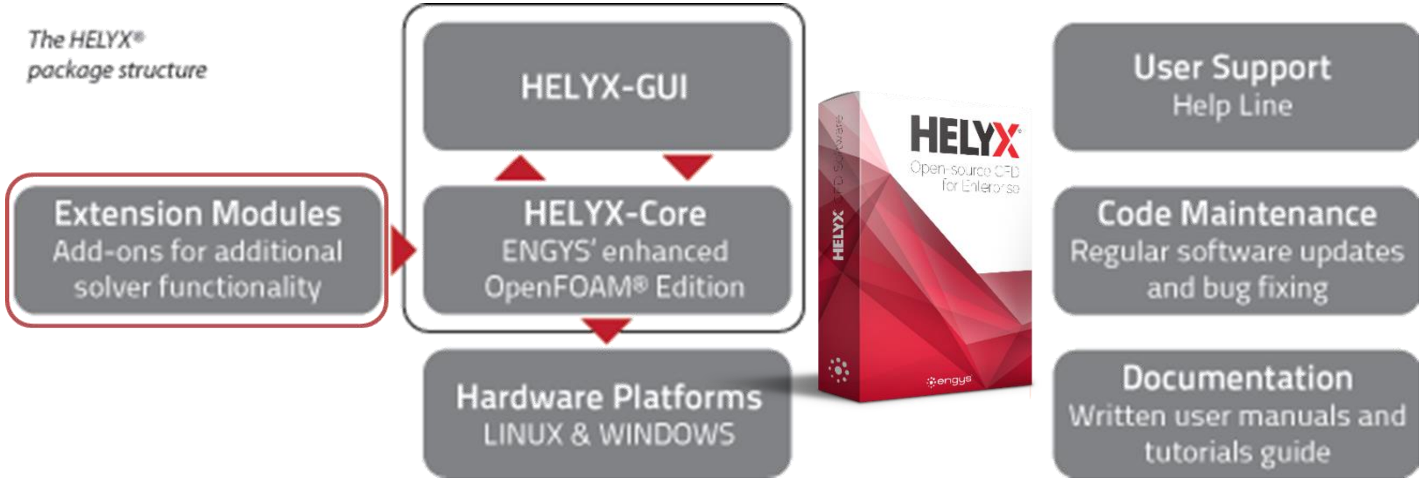
HELYX

- General purpose CFD software suite
- Enterprise product → professional quality + open-source
- In production since 2010
- HELYX-Adjoint → add-on solver module



HELYX®

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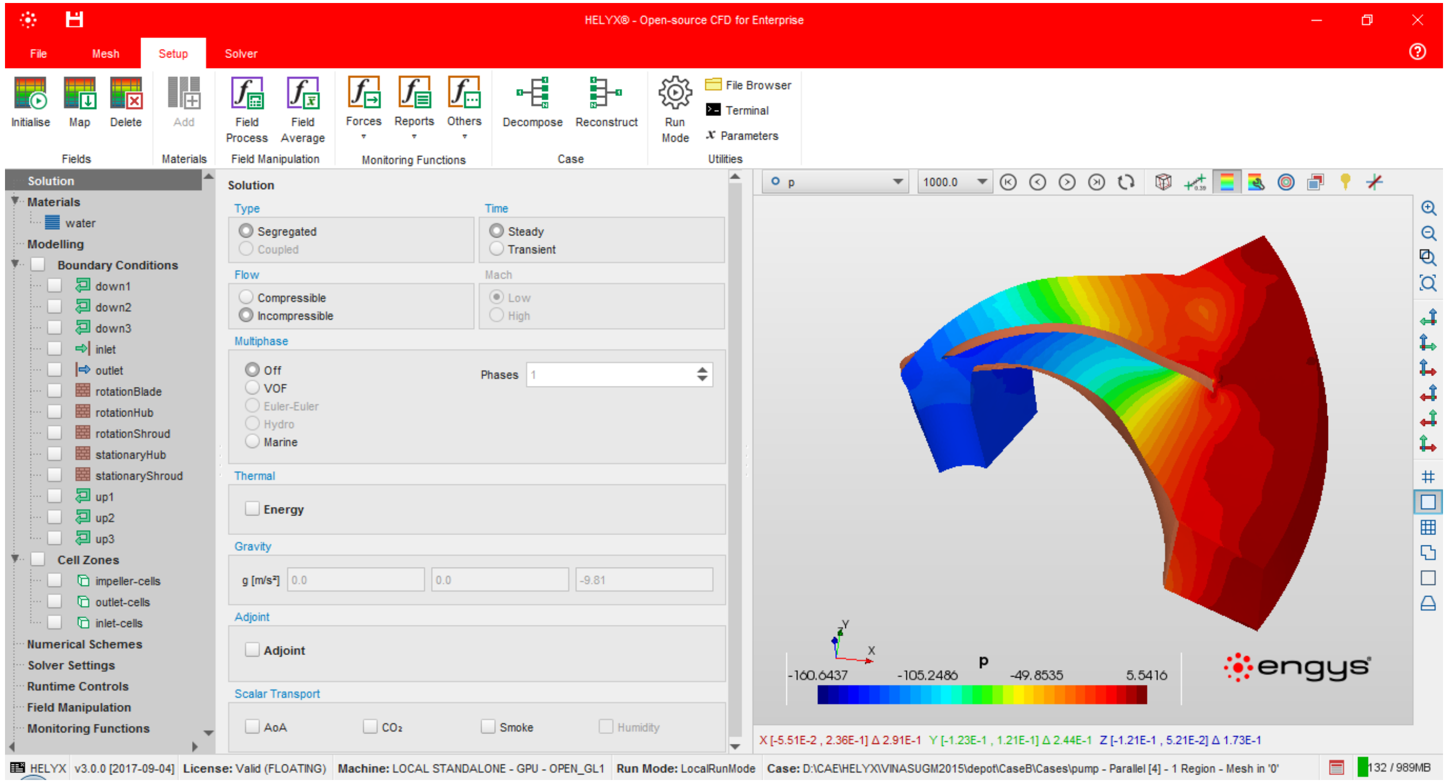


OUTLINE

1. What is HELYX-Adjoint?
2. Topology Optimisation
3. Shape Optimisation
4. Conclusions

HELYX-Adjoint | Background

- Originally commissioned by C. Othmer, VW Research
- Mission → Build a practical adjoint optimisation tool that anyone can use
- Focus remains on utility
- Accuracy is important, but not the only concern
- Performance, ease-of-use, robustness – all equally significant
- Built on HELYX-Core
- Continuous adjoint
  - Support for industrial problems (> 200M cells)

HELYX-Adjoint | Continuous vs. Discrete

Continuous Adjoint

Differentiate ➡ Discretise ➡ Solve

- Difficult / time consuming derivation from governing equations
- Intuitive numerics, can reuse primal methods
- Gradient accuracy depends on details of implementation
- Highly efficient in terms of run time and RAM usage

Discrete Adjoint

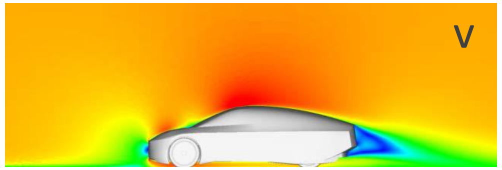
Discretise ➡ Differentiate ➡ Solve

- Manual and/or automatic differentiation of code
- Black-box numerics, optimisation can be challenging
- Produces exact sensitivities (consistent)
- High RAM requirements (taping and/or check-pointing)

HELYX-Adjoint | Continuous Formulation

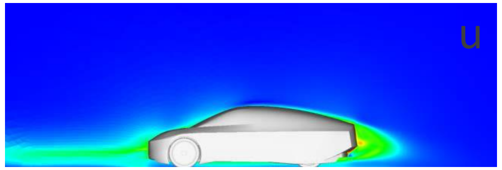
- CFD computation: v, p → primal fields

$$
\begin{aligned}
(\mathbf{v}\cdot\nabla)\,\mathbf{v} &= -\nabla p + \nabla\cdot(\nu\,\nabla\mathbf{v}) - \alpha\mathbf{v} \\
\nabla\cdot\mathbf{v} &= 0
\end{aligned}
$$



- Adjoint CFD computation: u, q → “dual” fields

$$
\begin{aligned}
-(\nabla\mathbf{u})\,\mathbf{v} - (\mathbf{v}\cdot\nabla)\,\mathbf{u} &= -\nabla q + \nabla\cdot(\nu\,\nabla\mathbf{u}) - \alpha\mathbf{u} \\
\nabla\cdot\mathbf{u} &= 0
\end{aligned}
$$



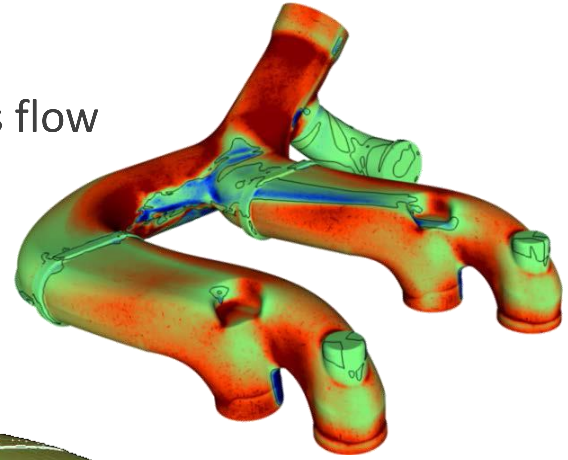
- Computation of sensitivities:
  - Surface sensitivities → $\dfrac{\partial J}{\partial \beta} \sim \dfrac{\partial \mathbf{v}}{\partial n}\cdot\dfrac{\partial \mathbf{u}}{\partial n}$
  - Volume sensitivities → $\dfrac{\partial J}{\partial \alpha} \sim \mathbf{v}\cdot\mathbf{u}$

HELYX-Adjoint | Sensitivities

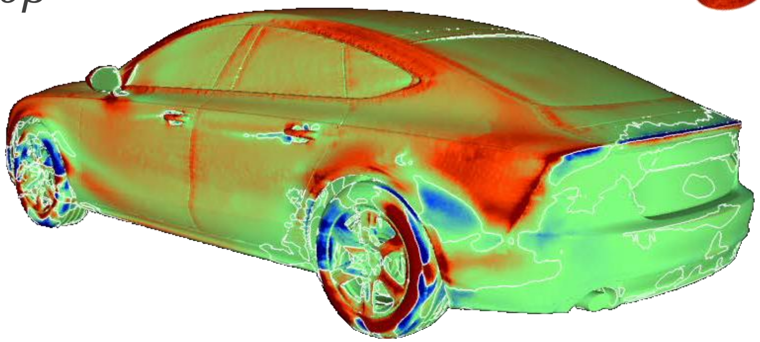
Surface Sensitivities $\partial J / \partial \beta$

red → push surface in
blue → push surface out

$\frac{\partial J}{\partial \beta}$ → mass flow

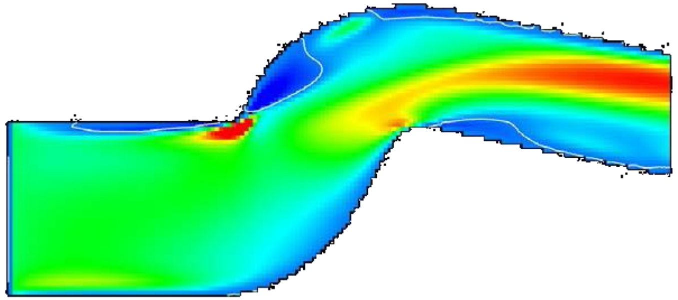


$\frac{\partial J}{\partial \beta}$ → drag

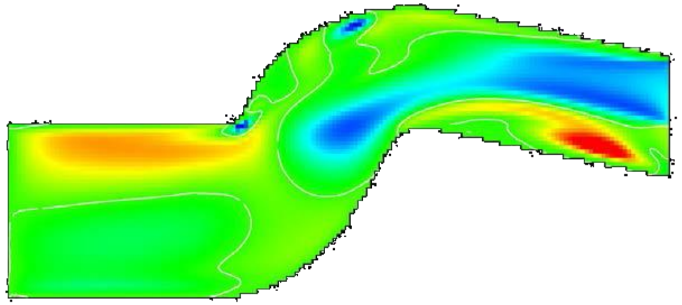


Volume Sensitivities $\partial J / \partial \alpha$

red → free volume cells
blue → penalise volume cells



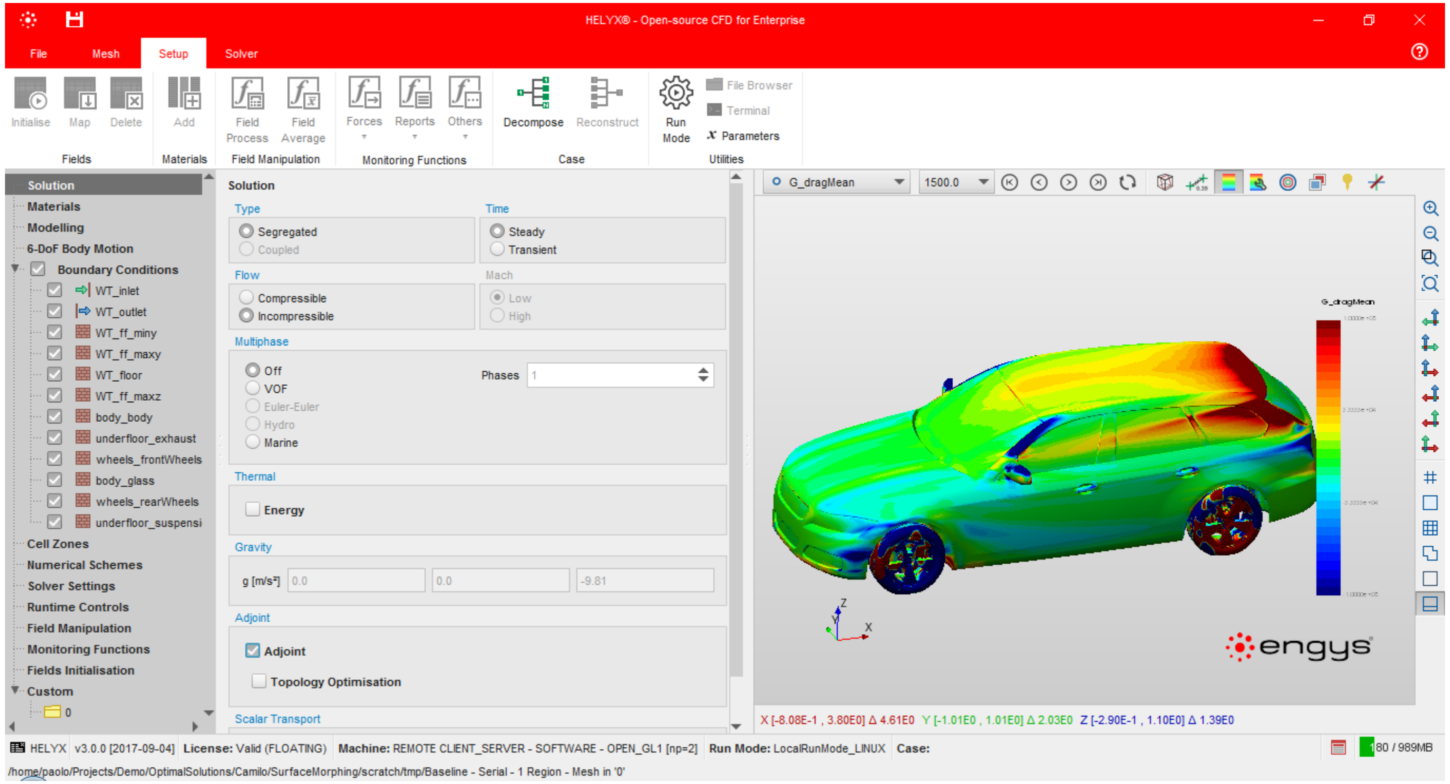
$\frac{\partial J}{\partial \alpha}$ → pressure drop



$\frac{\partial J}{\partial \alpha}$ → flow uniformity

HELYX-Adjoint | Key Features

- Multi-objective (> 20 different cost functions)
- Objective and constraints
  - Manufacturability constraints
- Adjoint turbulence & wall-function
- 2nd order accurate
- Easy to use GUI



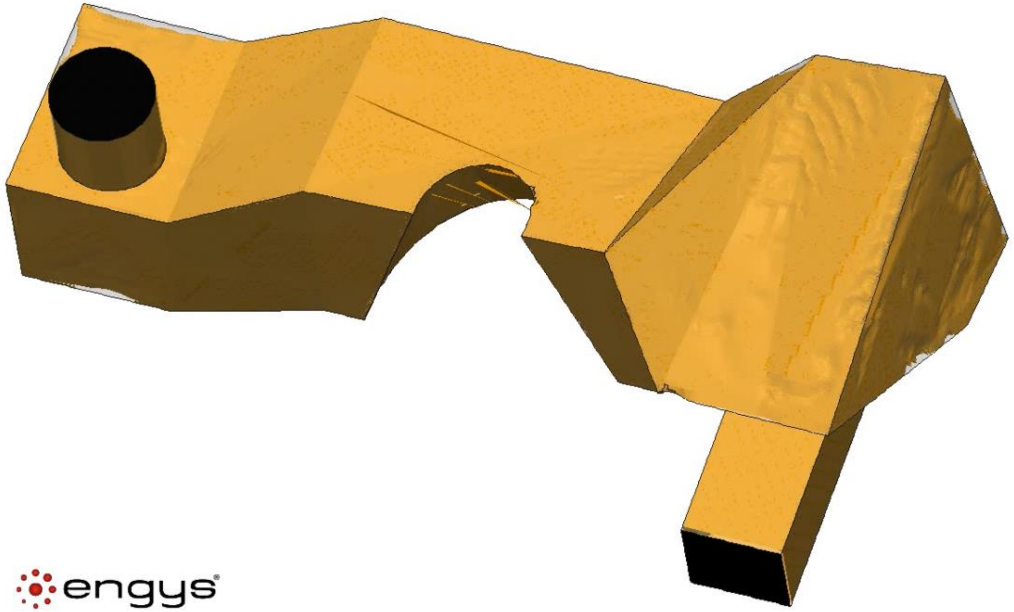
OUTLINE

2. Topology Optimisation

- What is Topology Optimisation?
- Success Stories
  - Oil Channel
  - Engine Intake Port
  - Internal Flows

Topology Optimisation

- Specify design space and inlet/outlet interfaces
- Define optimisation objectives
- Calculate volume sensitivities → $\partial J / \partial \alpha$
  - Volume cells penalised according to objective function
  - Track "optimum" interface using level-set with immersed boundary
- Output "smooth" surface optimised shape
- "One-shot" approach

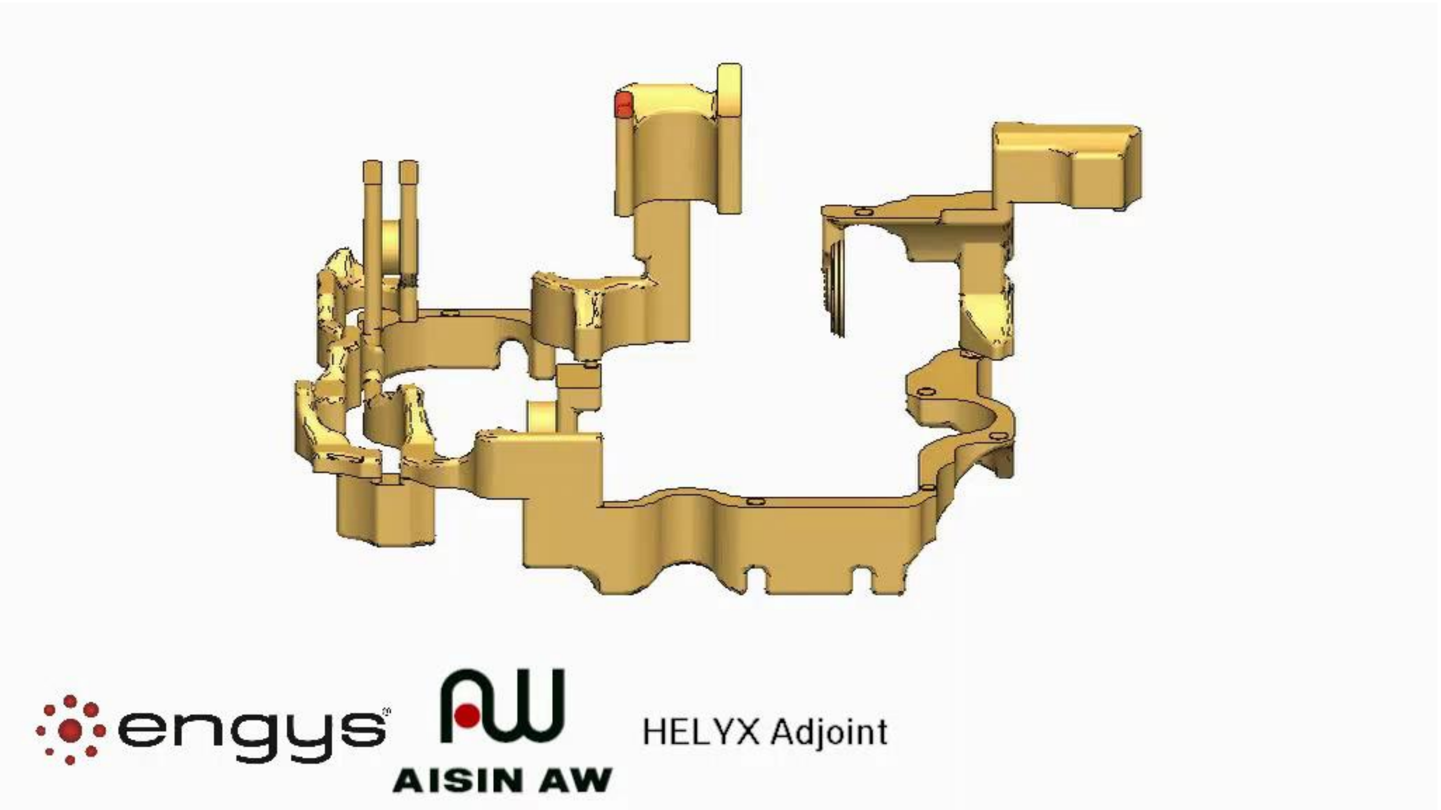


Topology Optimisation | Success Story

AISIN AW

Oil Channel

- Decrease system power losses
- Improved level-set immersed boundary representation
- Mitigate recirculation induced local optima

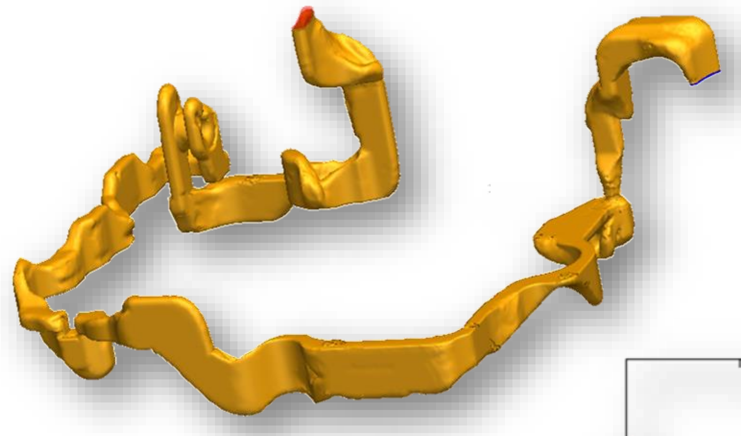


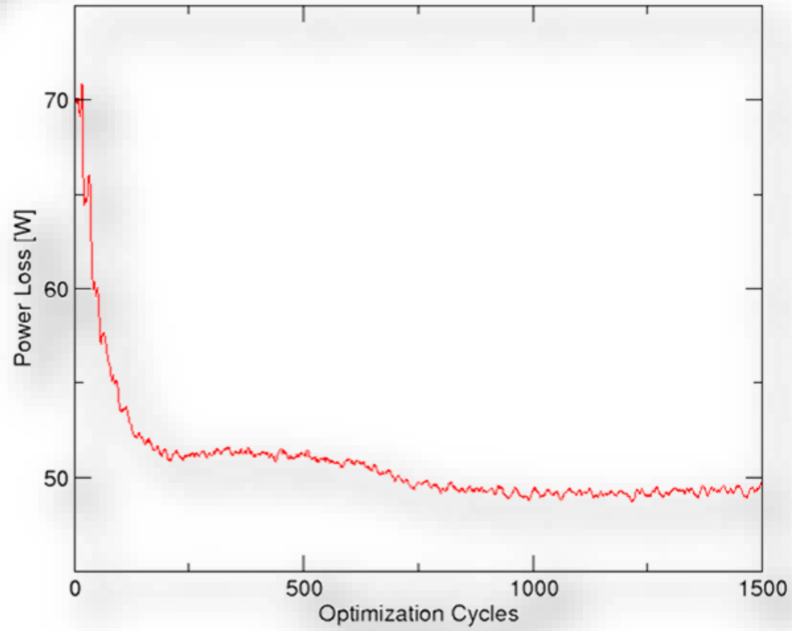
Courtesy of Dr. Takeshi Yamaguchi (AISIN AW)

Topology Optimisation | Success Story

Oil Channel

- Optimisation complete in <1hr
- Zero level-set extracted and new design re-meshed
- ~30% reduction in power losses verified
- HELYX-Adjoint makes optimal design routine

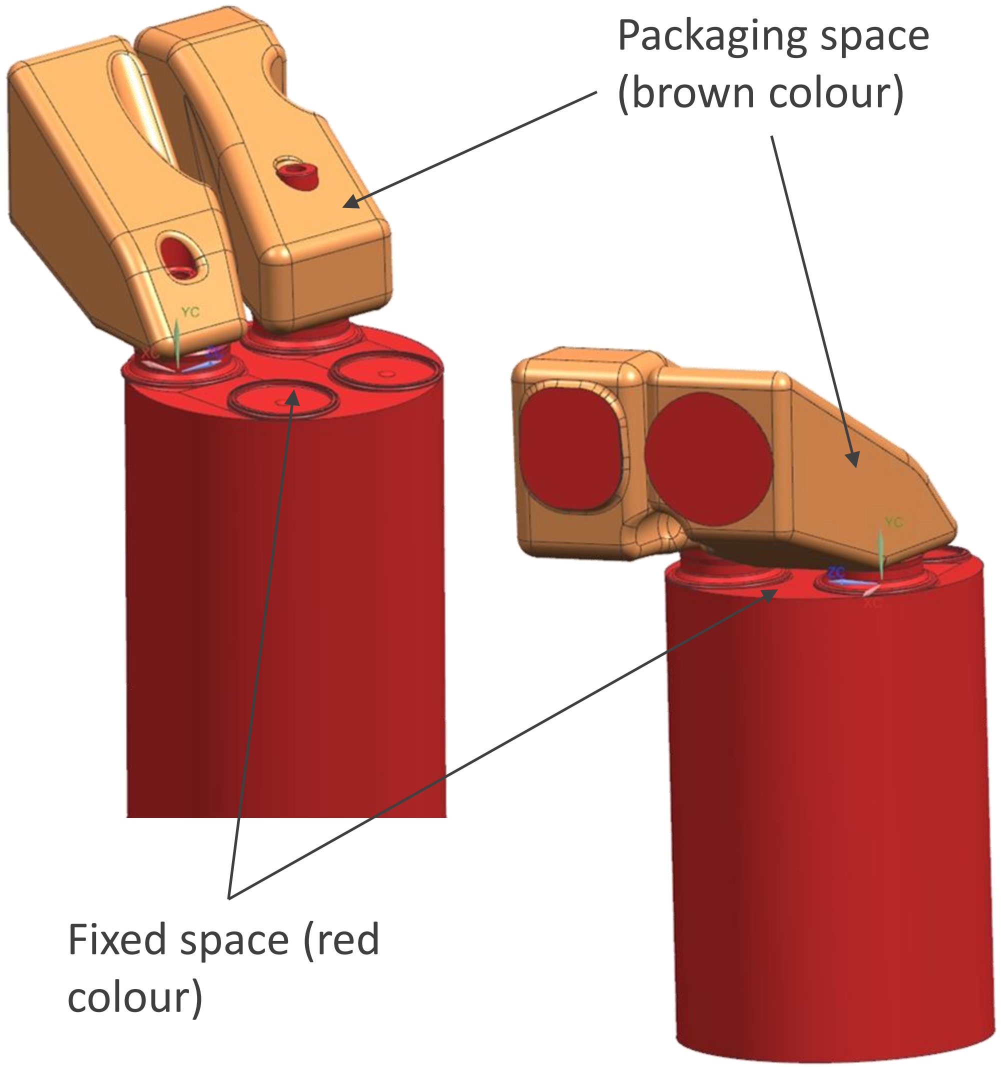




Topology Optimisation | Success Story

Engine Intake Port

- Design port flow
- Targets to achieve:
  - Maximise Mass Flow Rate
  - Maximise Swirl Index ω
- Compressible flow
- k-ω SST turbulence model



Topology Optimisation | Success Story

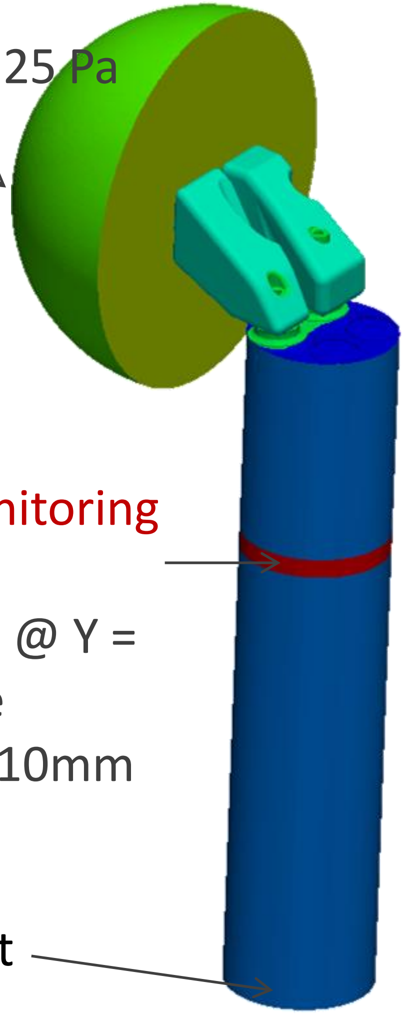
CENTRO RICERCHE FIAT

Engine Intake Port

- Input data for the project:
  - Number of valves = 2
  - Valve lift = 9mm
- Targets to achieve:
  - Maximise Mass Flow Rate
  - Maximise Swirl Index ω

$$\omega = \frac{\sum_{V} V_y \rho dV \cdot (zV_x - xV_z)}{\sum_{V} \rho dV}$$

Inlet
$P_1 = 101325$ Pa



Swirl monitoring cylinder
Centered @ Y = 1.5x bore
Height = 10mm

Outlet
P_2 = const

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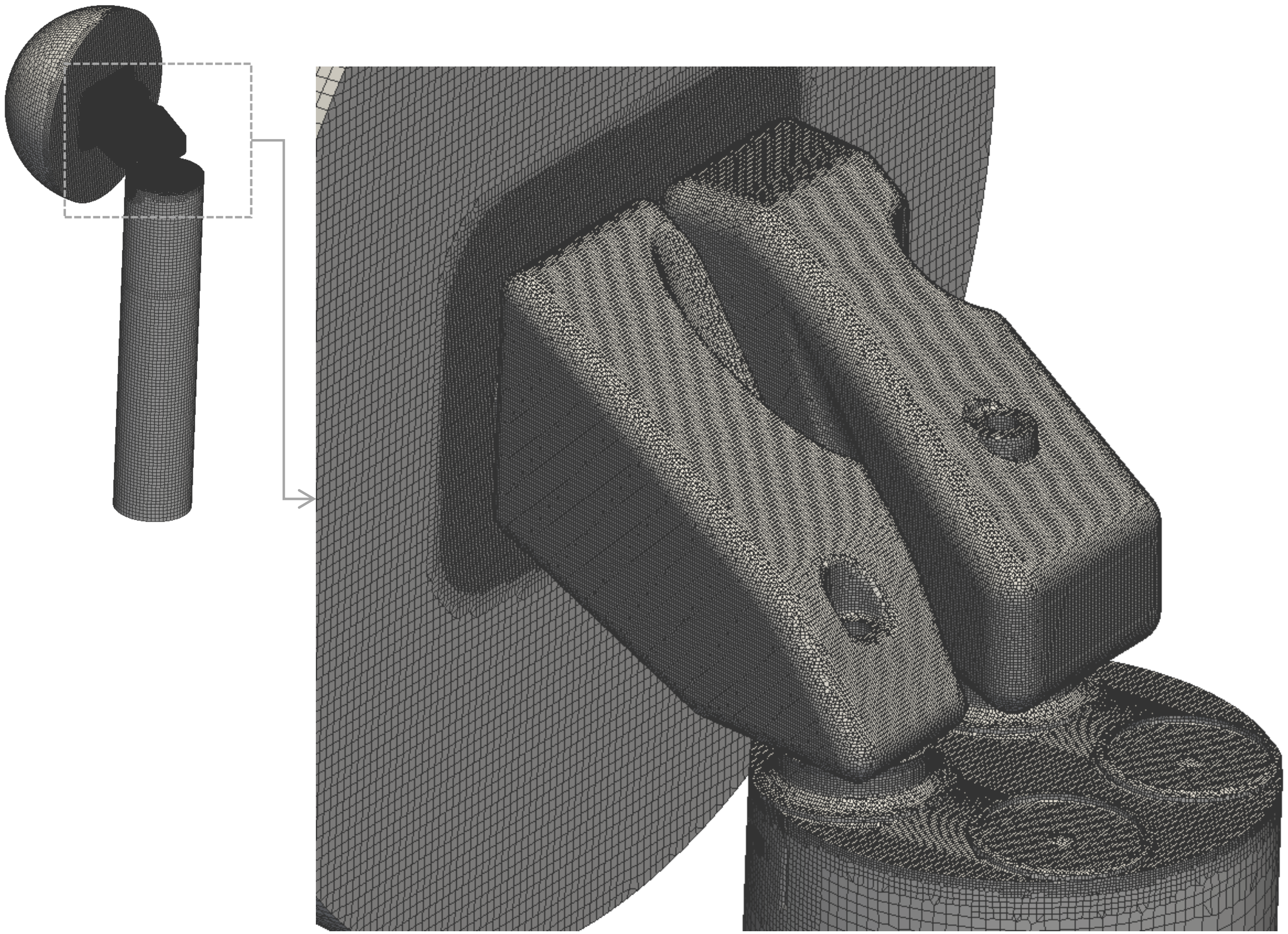
Topology Optimisation | Success Story

CENTRO RICERCHE FIAT

Engine Intake Port

- `helyxHexMesh` utility
- Mesh size: 3.6M cells
- Near-wall layers: 3
- Target cell size (port arms and valves): 0.4mm



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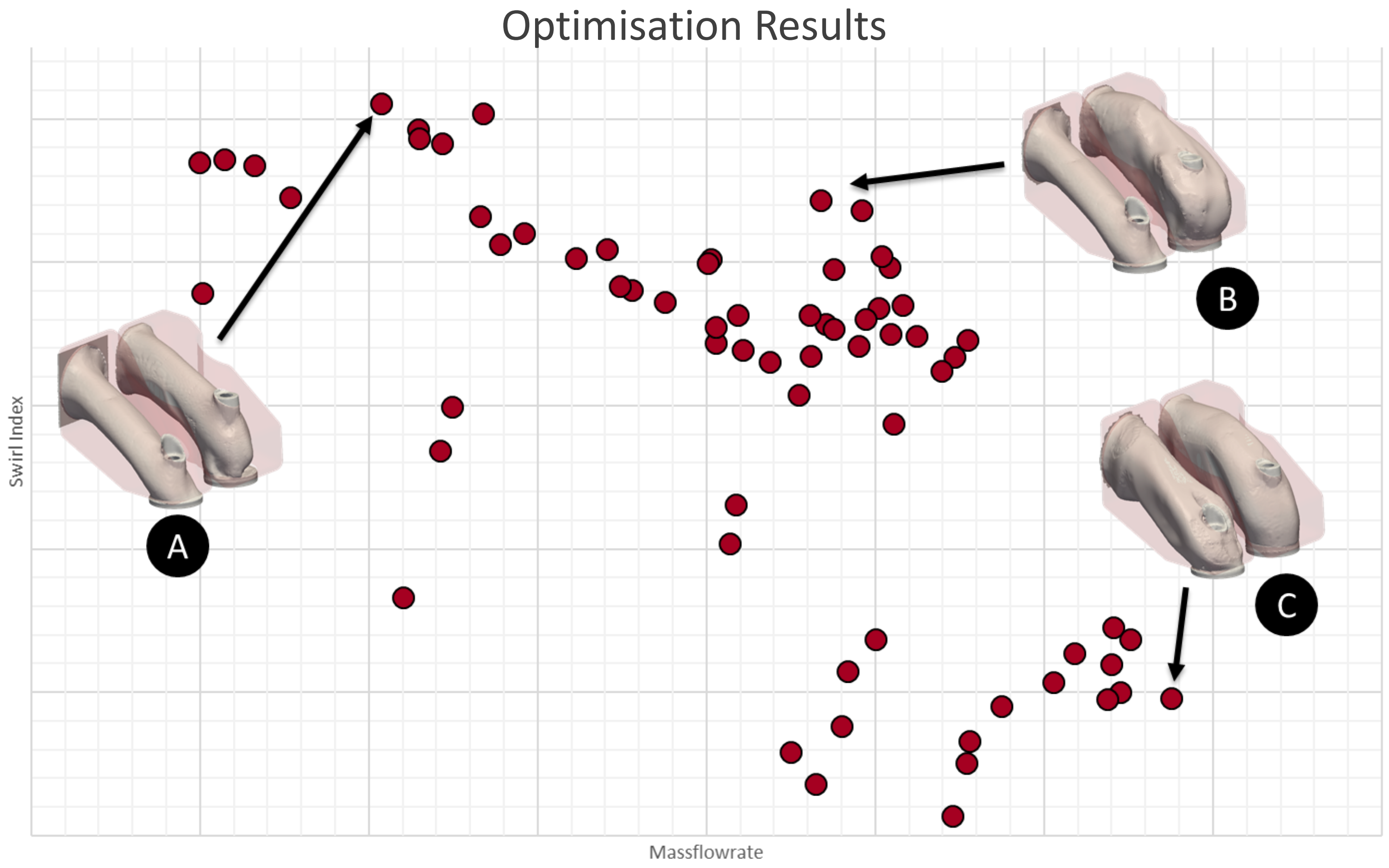
Topology Optimisation | Success Story

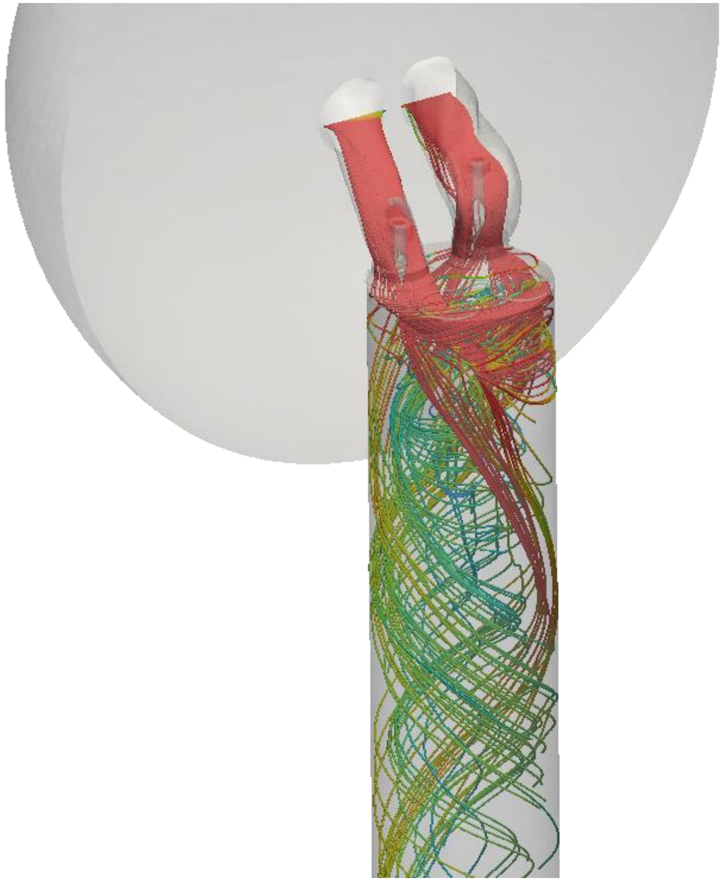
Engine Intake Port

- Design A is the optimal solution for swirl objective
- Design C is the optimal solution for mass flow rate objective
- Design B is a trade-off in terms of both the design objectives and was selected by the as a compromise solution

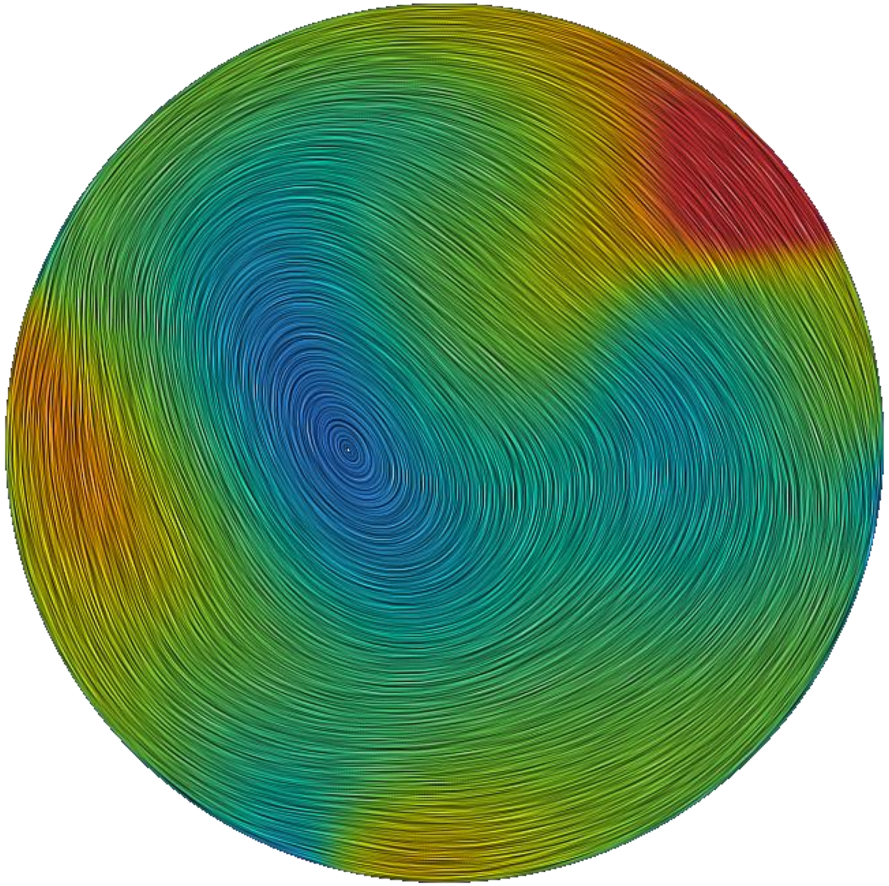


Topology Optimisation | Success Story

Engine Intake Port



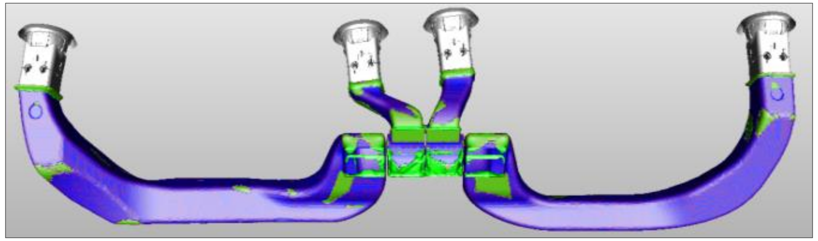
Velocity Streamlines

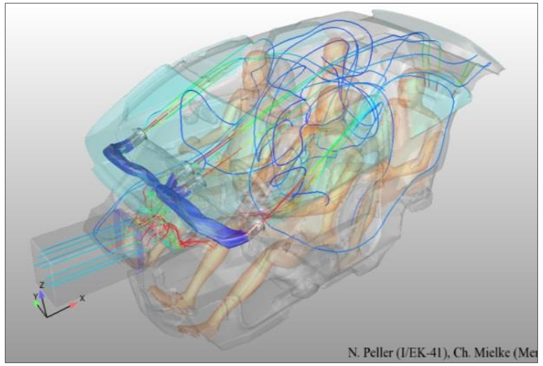


Velocity contour at swirl monitoring plane

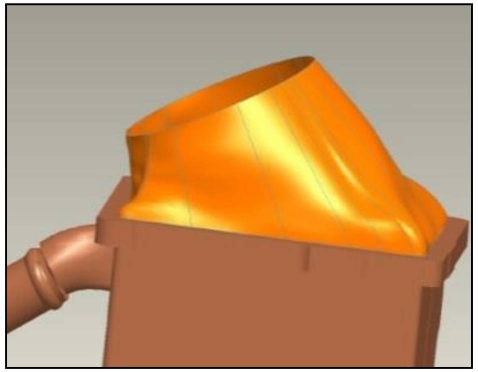
Topology Optimisation | Other Examples

Internal Flows



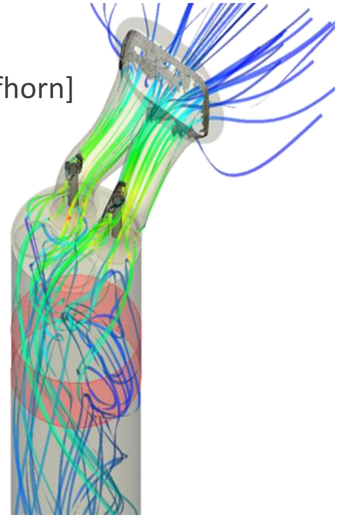


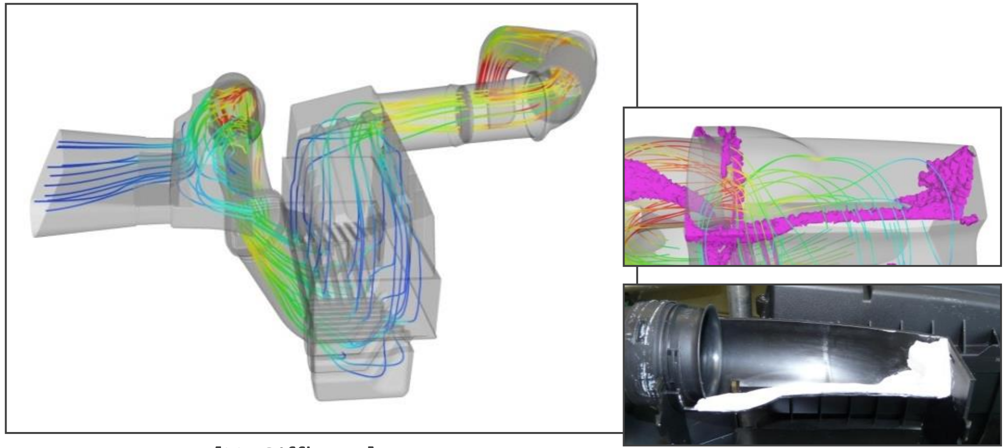
[N. Peller]



[M. Tomecki]

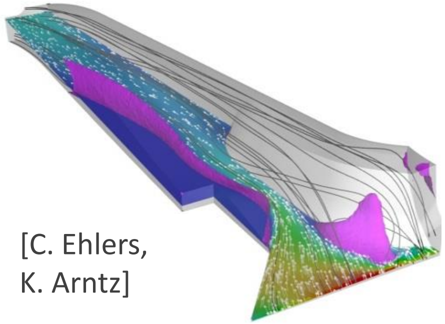
[U. Giffhorn]



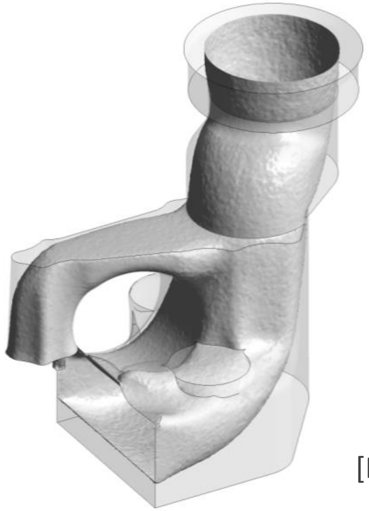


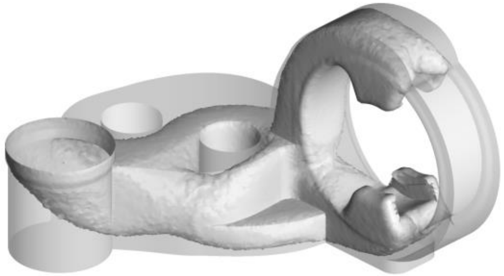
[U. Giffhorn]

[C. Ehlers, K. Arntz]



[R. Niederlein]





[M. Towara]

Taken from “The Adjoint Method Hits the Road” by C. Othmer [2014]

OUTLINE

3. Shape Optimisation

- What is Shape Optimisation?
- Morphing
- Success Stories
  - Exhaust Port
  - Manifold Optimisation

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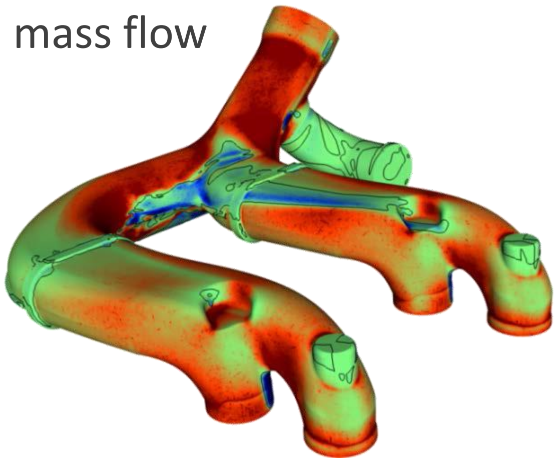
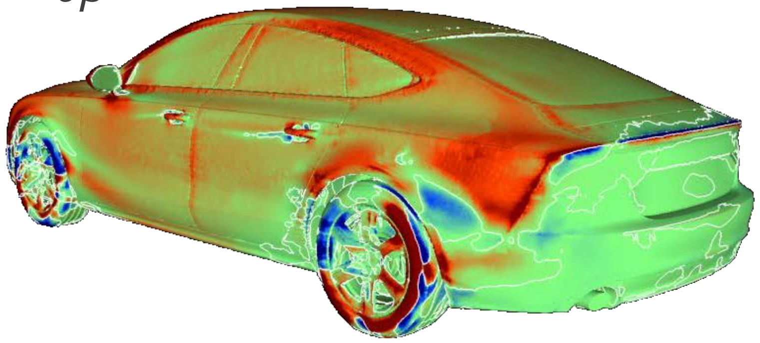
Shape Optimisation

- Based on steady RANS or time averaged primal (LES/DES)
- Morph design using HELYX morphing solutions:
  - Node-based deformation
  - Volumetric NURBS deformation
- Morphing using 3rd-party tools:
  - ANSA, Sculptor, CAMILO, etc.

$\frac{\partial J}{\partial \beta}$ → mass flow



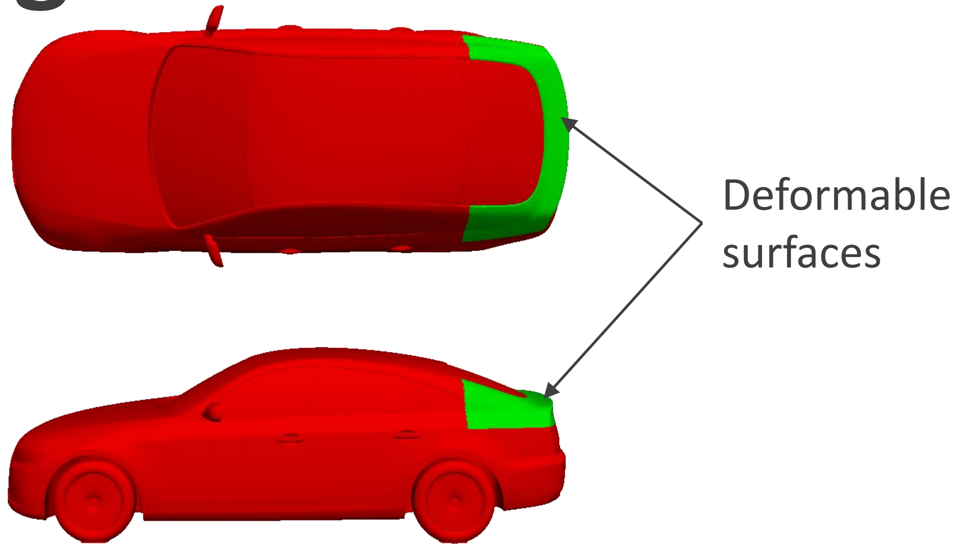
$\frac{\partial J}{\partial \beta}$ → drag

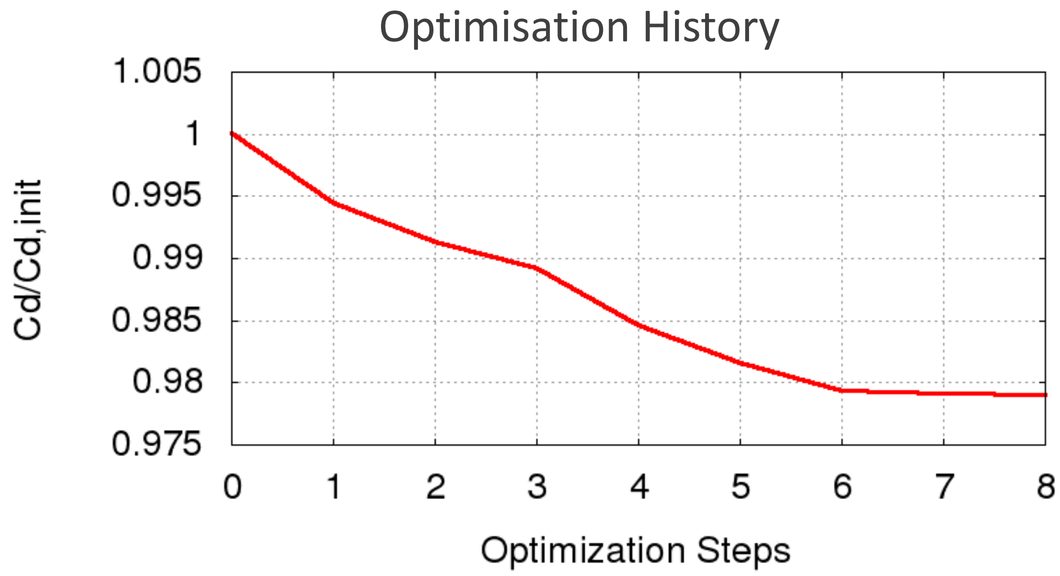


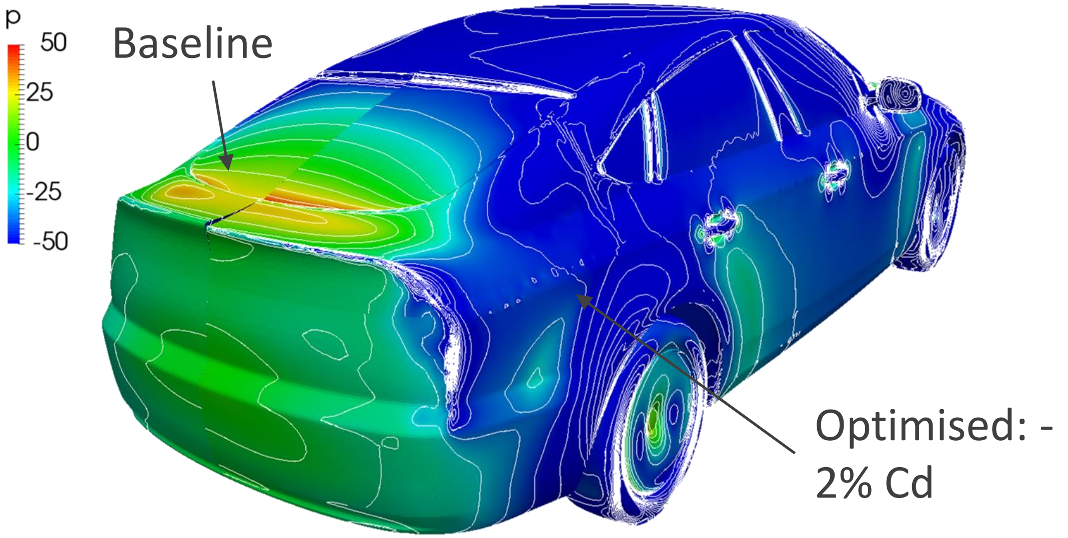
Shape Optimisation | Morphing

Node-based Deformation

- Implicit smoothing
- Mesh optimisation for improved deformation







Shape Optimisation | Morphing

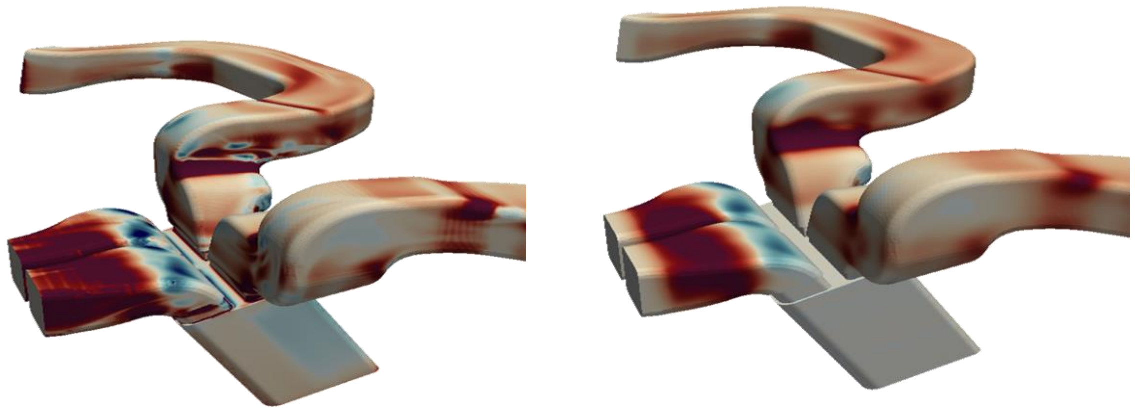
Node-based Deformation

› Smooth for vector $\vec{d} = \bar{G} \cdot \vec{n}$

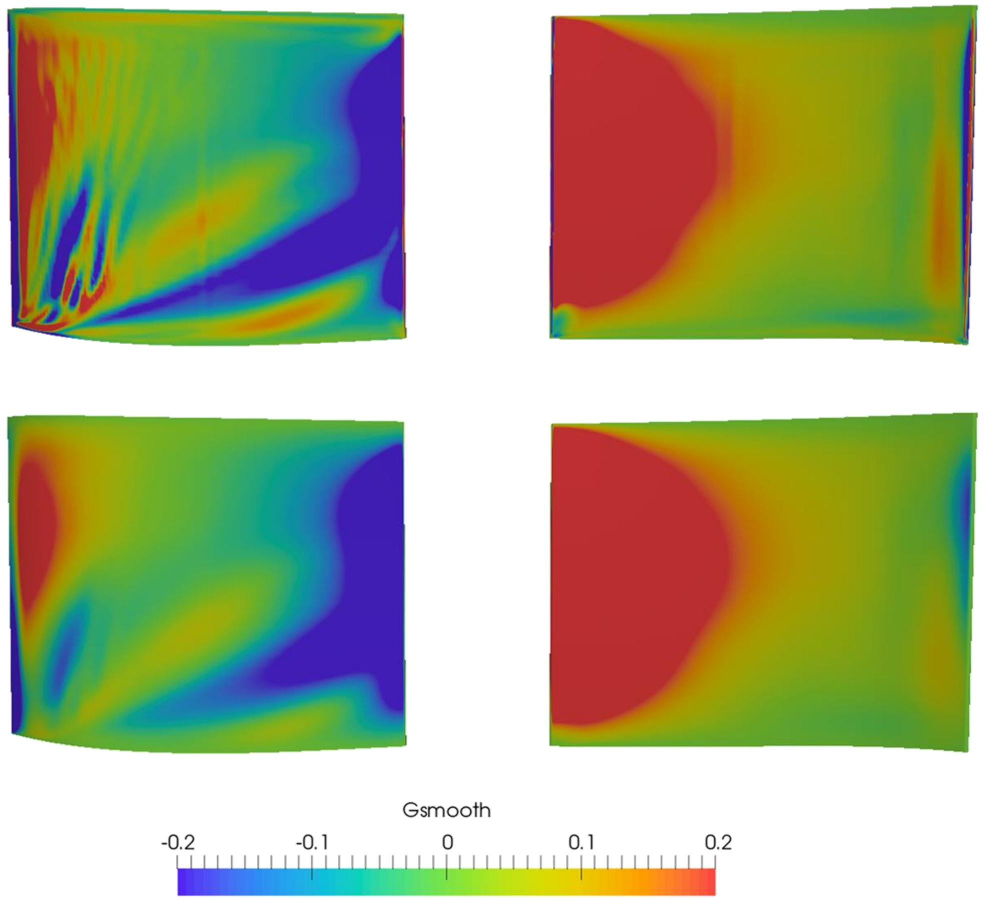
› Smooth the magnitude of the displacement

$$\vec{d} - \varepsilon \nabla^2 \vec{d} = \overrightarrow{d_{init}}$$

$\overrightarrow{d_{init}}$: *Initial Field,* $\vec{d}$: *Smooth Field,* ε *: smoothing intensity*



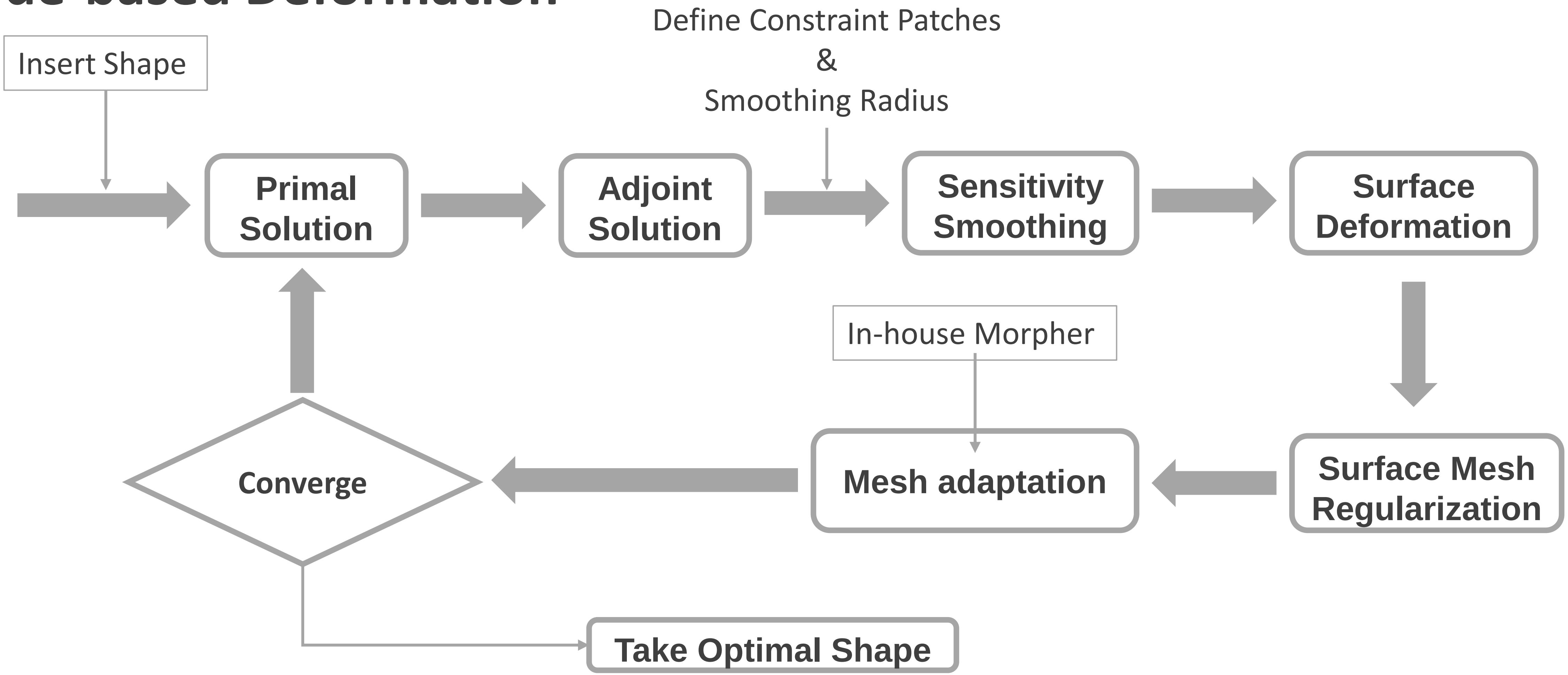
Smoothing radius of 3cm.
Courtesy of FCA



Courtesy of Rolls Royce

Shape Optimisation | Morphing

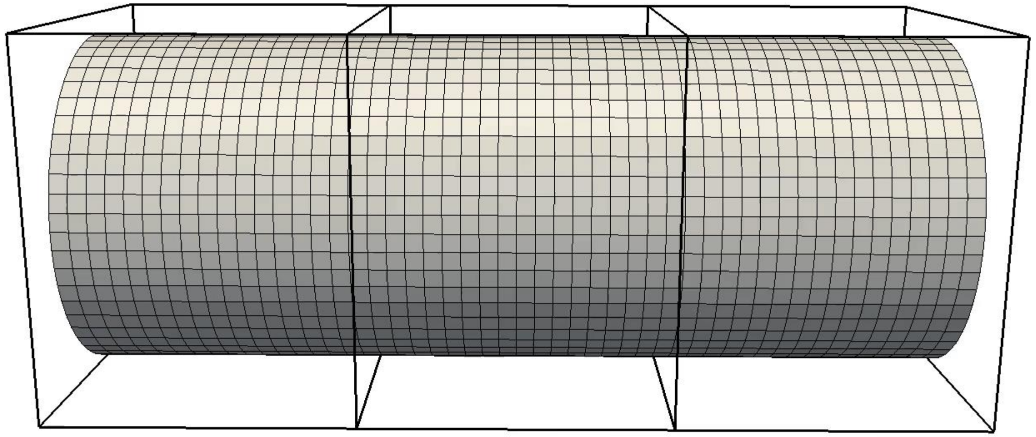
Node-based Deformation



Shape Optimisation | Morphing

vNurbs Deformation

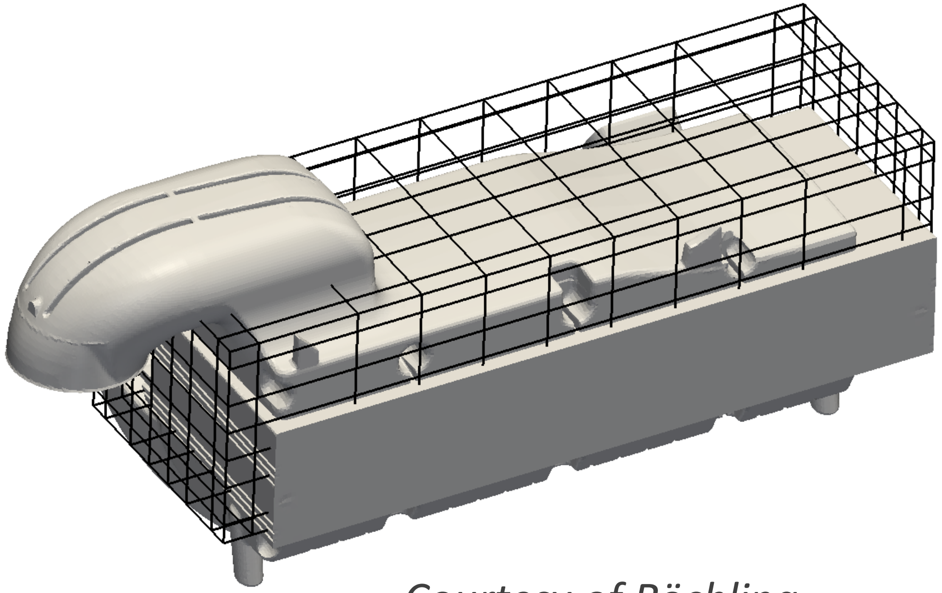
- Points construct lattices (topological cubes)
- Two step procedure:
  - Training (Mapping the mesh to the control point structure)
  - Deforming (Displacing the control points and the mesh, based on the map created)



Shape Optimisation | Morphing

vNurbs Deformation

- Input:
  - Number of control points in U, V, W directions
  - Polynomial degree in U, V, W direction
- Boundary control points can stay fixed to ensure C_0 and C_1 continuity
- Coupling with the adjoint:
  - Sensitivities can be mapped to the control point structure just like the mesh
  - Control point sensitivities can be used with an optimizer to perform optimization

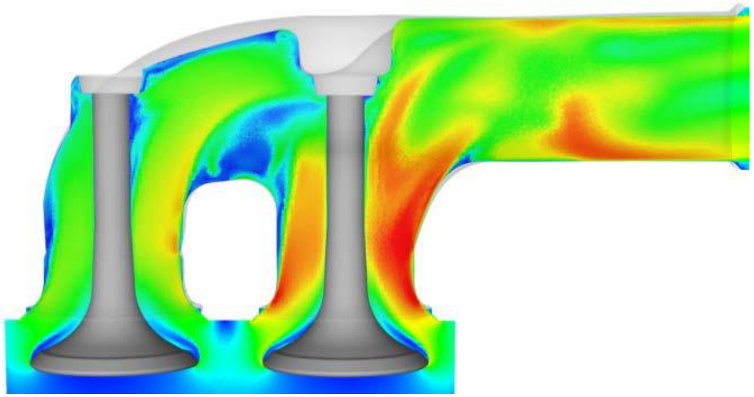


Courtesy of Röchling

Success Story | Volkswagen Group

Exhaust Port

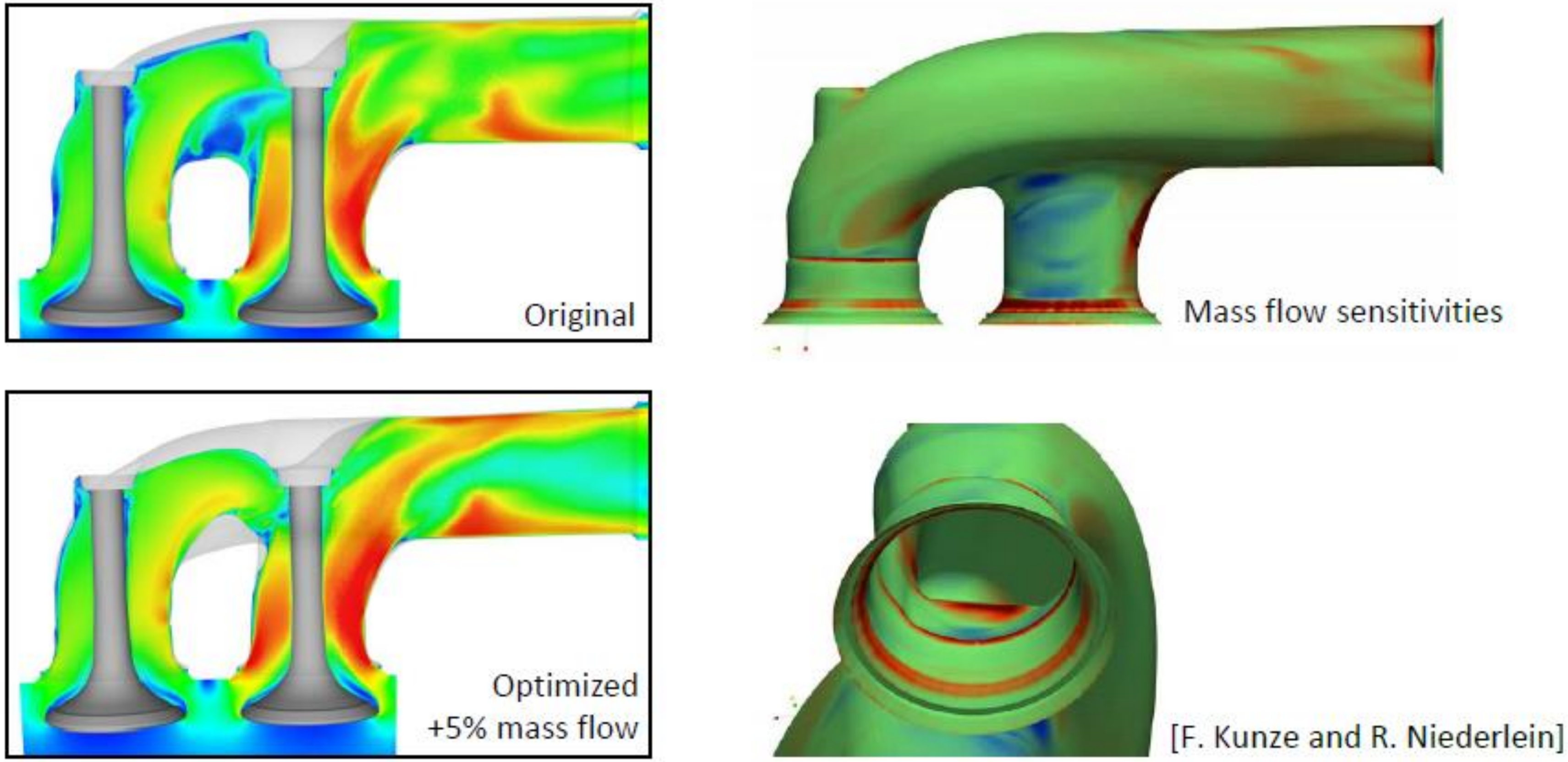
- Exhaust port modification for increased flow rate
- Shape optimisation → modify geometry based on surface sensitivities
- Design objective:
  - Maximum flow rate



Taken from "The Adjoint Method Hits the Road" by C. Othmer [2014]

Success Story | Volkswagen Group

Exhaust Port

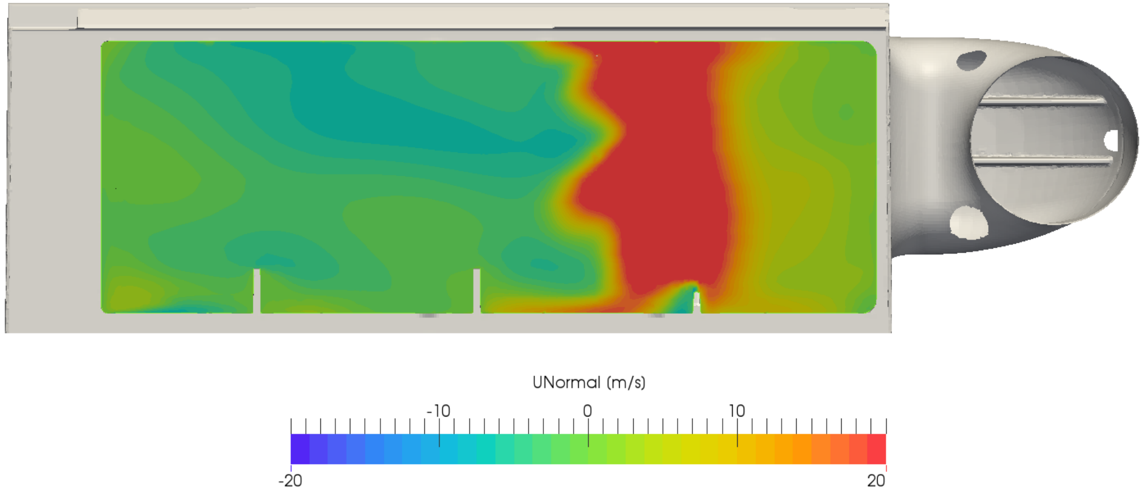


Taken from “The Adjoint Method Hits the Road” by C. Othmer [2014]

Success Story | Röchling

Manifold Optimisation

- HELYX-Adjoint employed to produce a duct configuration with maximum flow uniformity on a manifold lower end
- Three different approaches employed:
  - Surface shape optimisation
  - Volume topology optimisation
  - Topology + Shape optimisation

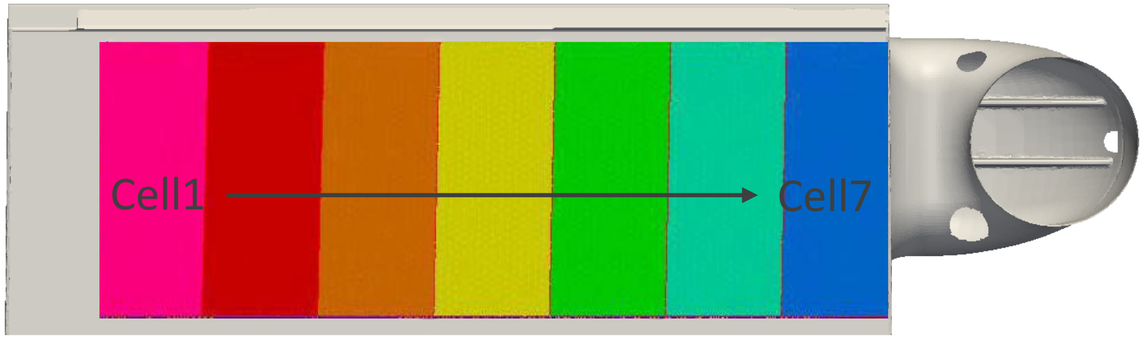


Success Story | Röchling

Manifold Optimisation

- Fluid :
  - Air @ 20°C
  - ρ = 1.204 kg/m3
  - μ= 1.812e-5 Pa·s
- Incompressible flow
- Inlet volumetric flow rate = 450 kg/h
- Outlet reference pressure = 101325 Pa

- Design Objective:
  - Maximisation of flow uniformity by measuring the average mass flow rate on 7 outlet cells on the manifold lower end

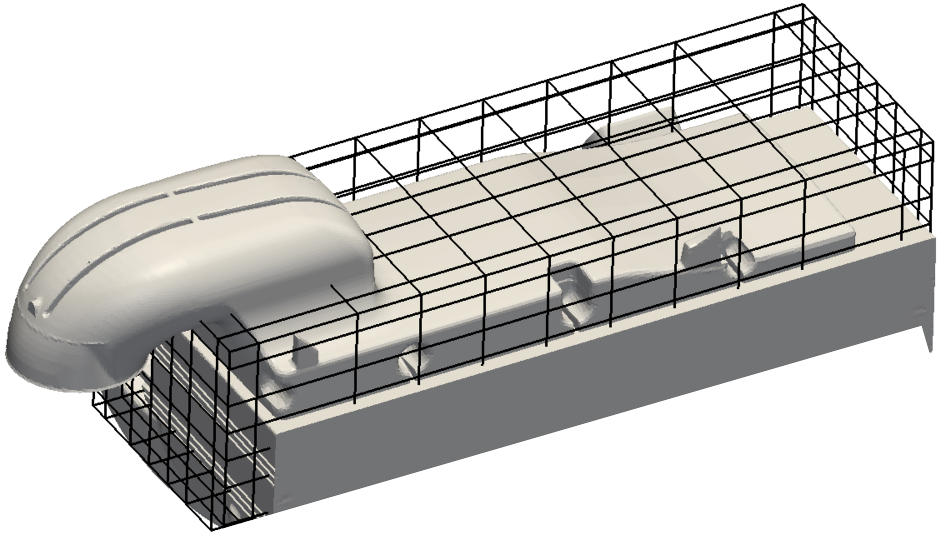


Success Story | Röchling

Manifold Optimisation

› Shape Optimisation Workflow:

1. Evaluate the adjoint surface sensitivities on the baseline shape provided by Röchling
2. Apply a free-form lattice-based mesh deformation morphing tool available in HELYX
3. Calculate the new adjoint surface sensitivities
4. Repeat 2-3 until an optimal shape is found

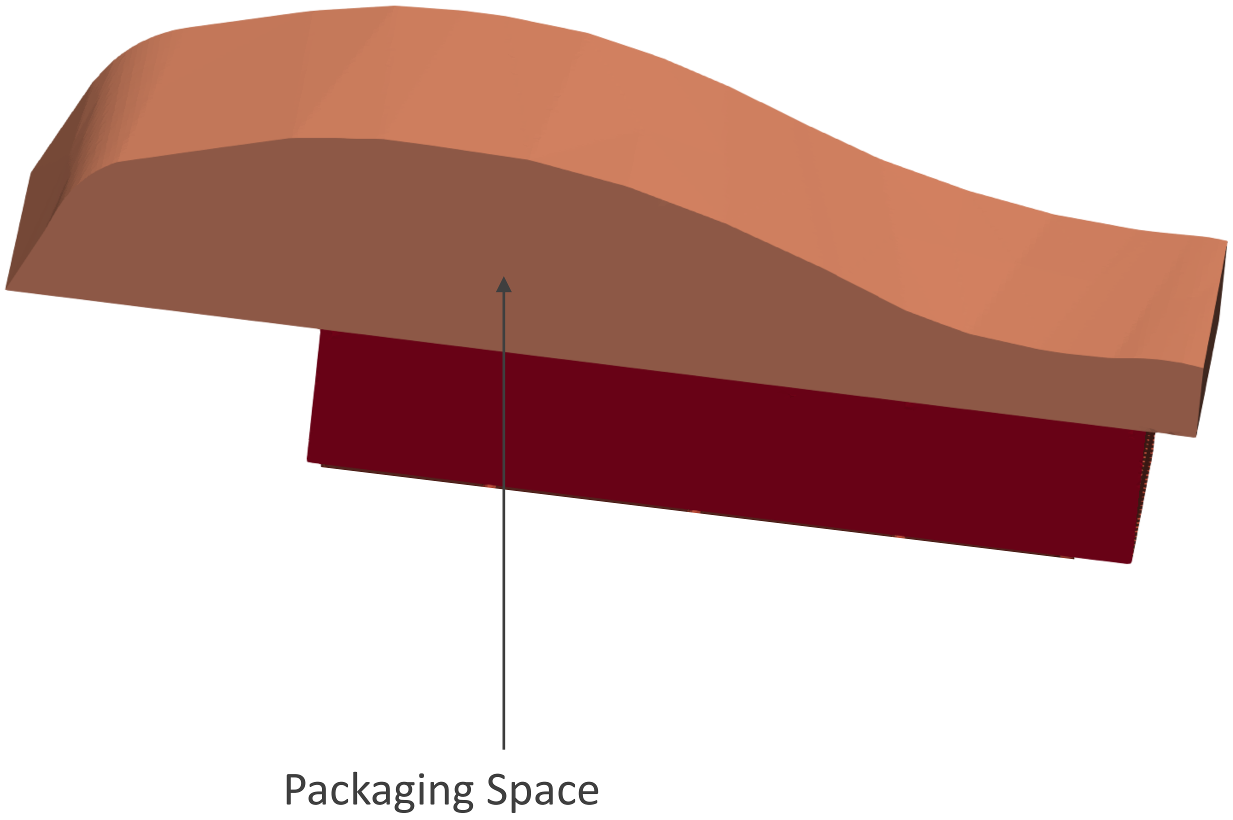


Success Story | Röchling

Manifold Optimisation

› Topology Optimisation Workflow

1. Evaluate the adjoint volume sensitivities on the packaging space provided by Röchling
2. Employ a level-set engine to track optimal solid-fluid interface
3. Apply interface curvature limitation to produce a smooth duct surface with manufacturing potential
4. Get a final smooth optimised interface

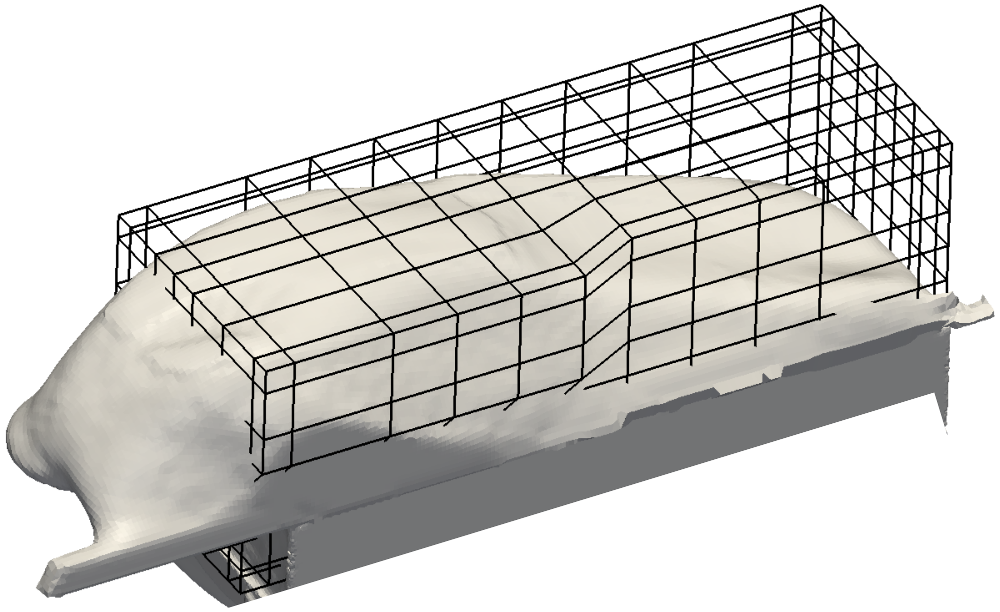


Success Story | Röchling

Manifold Optimisation

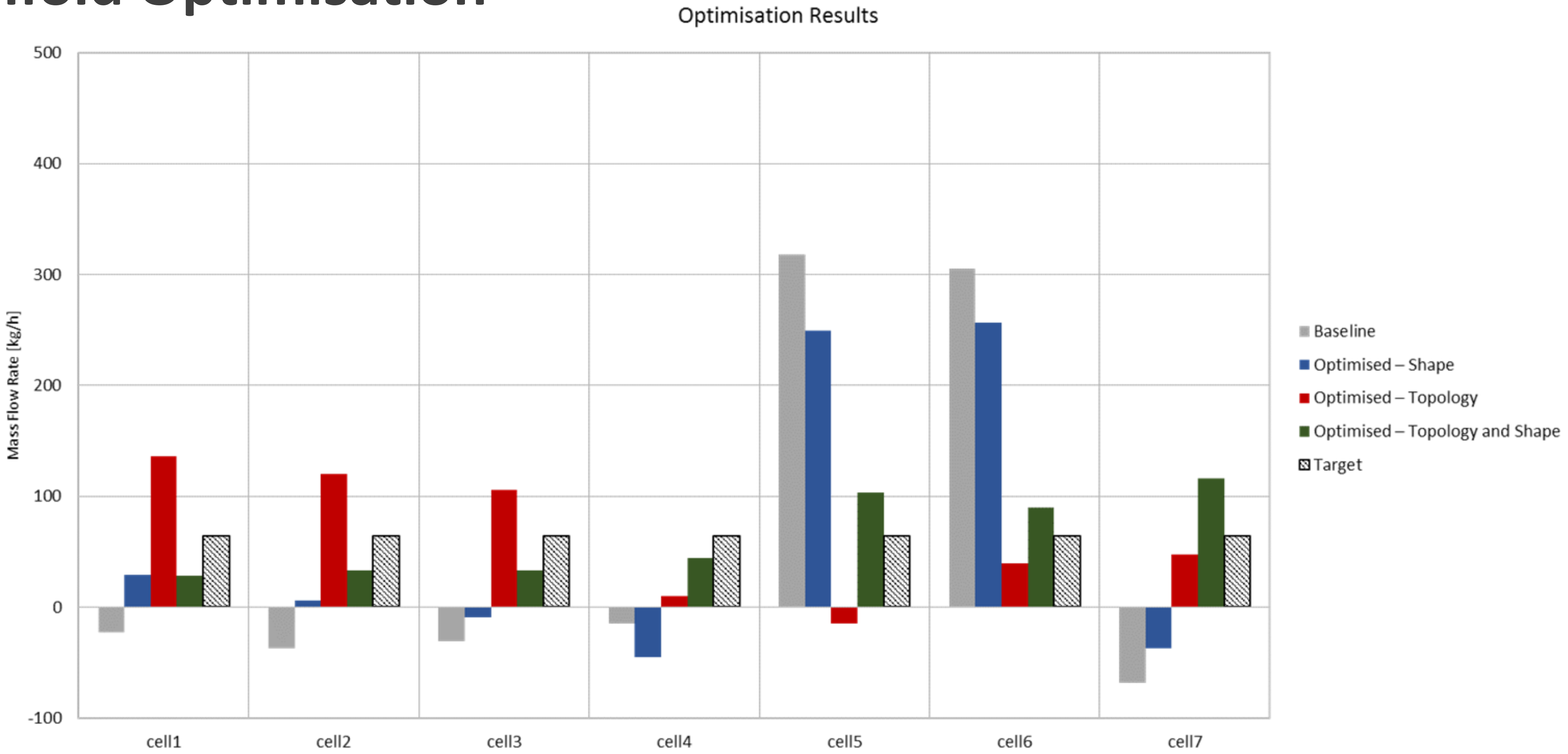
› Topology + Shape Optimisation Workflow:

1. Run the topology optimisation worflow
2. Apply a free-form lattice-based mesh deformation morphing tool available in HELYX on the optimised shape obtained in (1)
3. Calculate the new adjoint surface sensitivities
4. Repeat 2-3 until an optimal shape is found



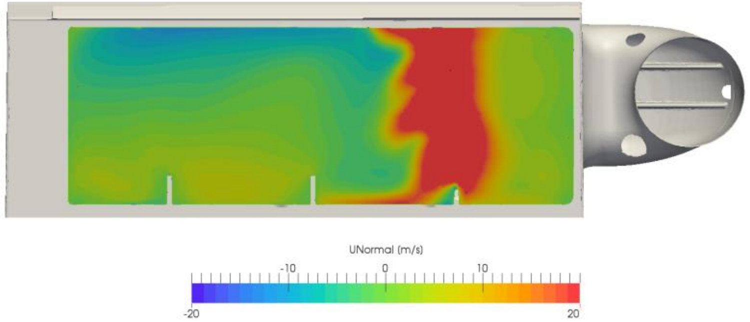
Success Story | Röchling

Manifold Optimisation

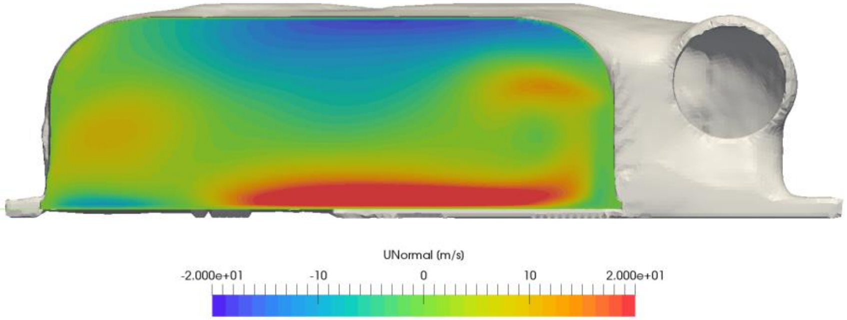


Success Story | Röchling

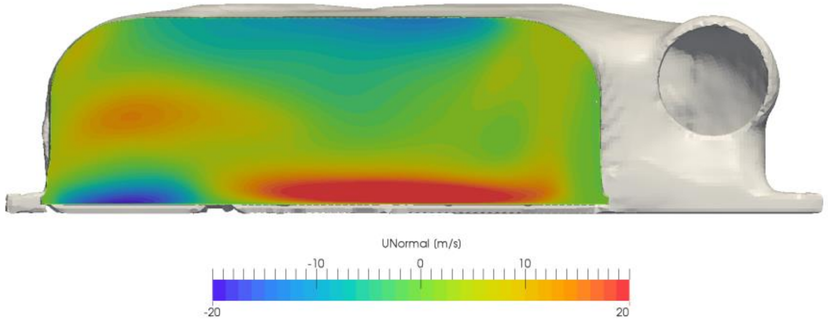
Manifold Optimisation



Shape optimisation optimal surface



Topology optimisation optimal surface



Topology+Shape optimisation optimal surface

OUTLINE

4. Conclusions

- Conclusions
- Acknowledgements
- Questions?

Conclusions

- A unique continuous adjoint formulation for topology and shape optimisation developed by ENGYS was presented
- Fully validated and deployed in industrial settings
- Professional solution available in the HELYX-Adjoint add-on module
- Unparalleled efficiency in design optimisation for fluid systems
- Large cases (200M+) cases can be handled by HELYX® Adjoint
- Automatic surface morphing for advanced shape optimisation
- Fully open-source solution

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  - Adjoint-Based optimization of industrial and unsteady flows

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- IODA MSCA-ITN-ETN – http://ioda.sems.qmul.ac.uk/
  - Industrial Optimal Design using Adjoint CFD

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Questions?

THANK YOU VERY MUCH!