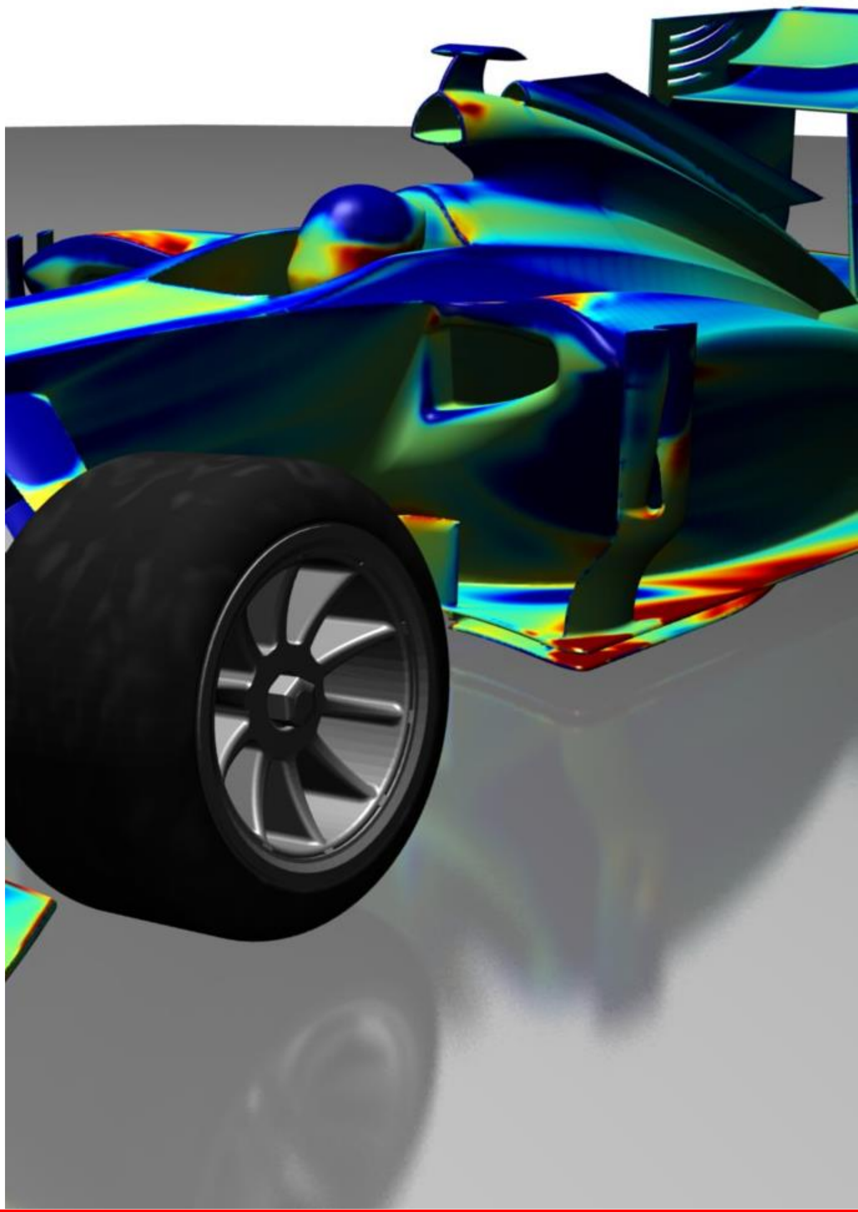
HELYX ADJOINT

Next-Generation Design Optimisation for Enterprise

Paolo Geremia
Director

22 September 2017



 | 6th OKUCC, 21-22 Sep 2017

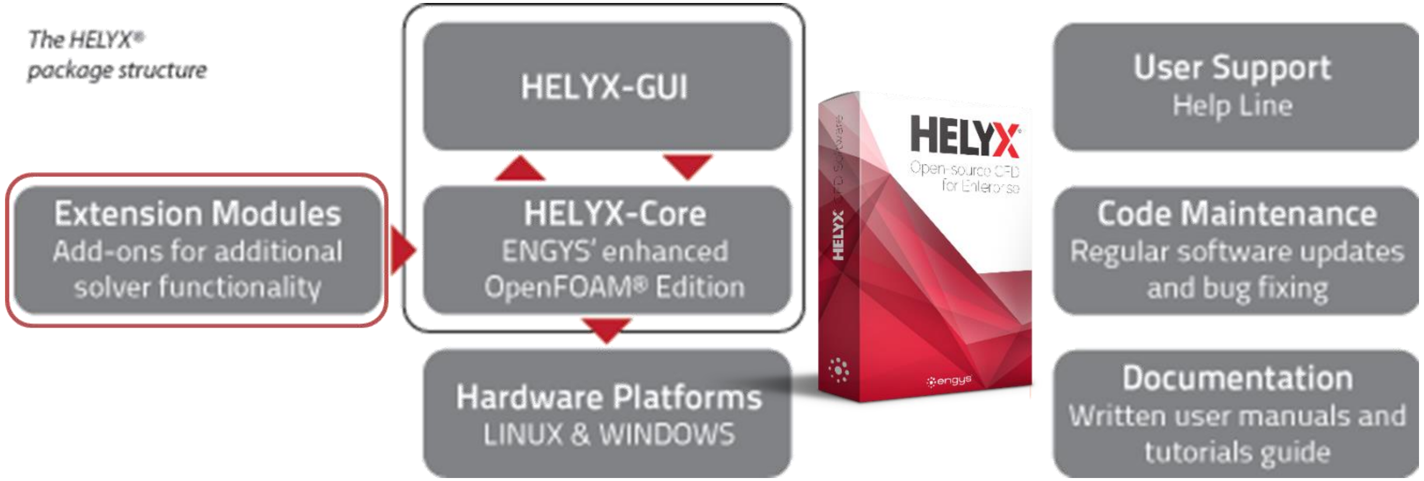
MPIAS 엠피어스 Innovative Engineering Systems
engys

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

HELYX®

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



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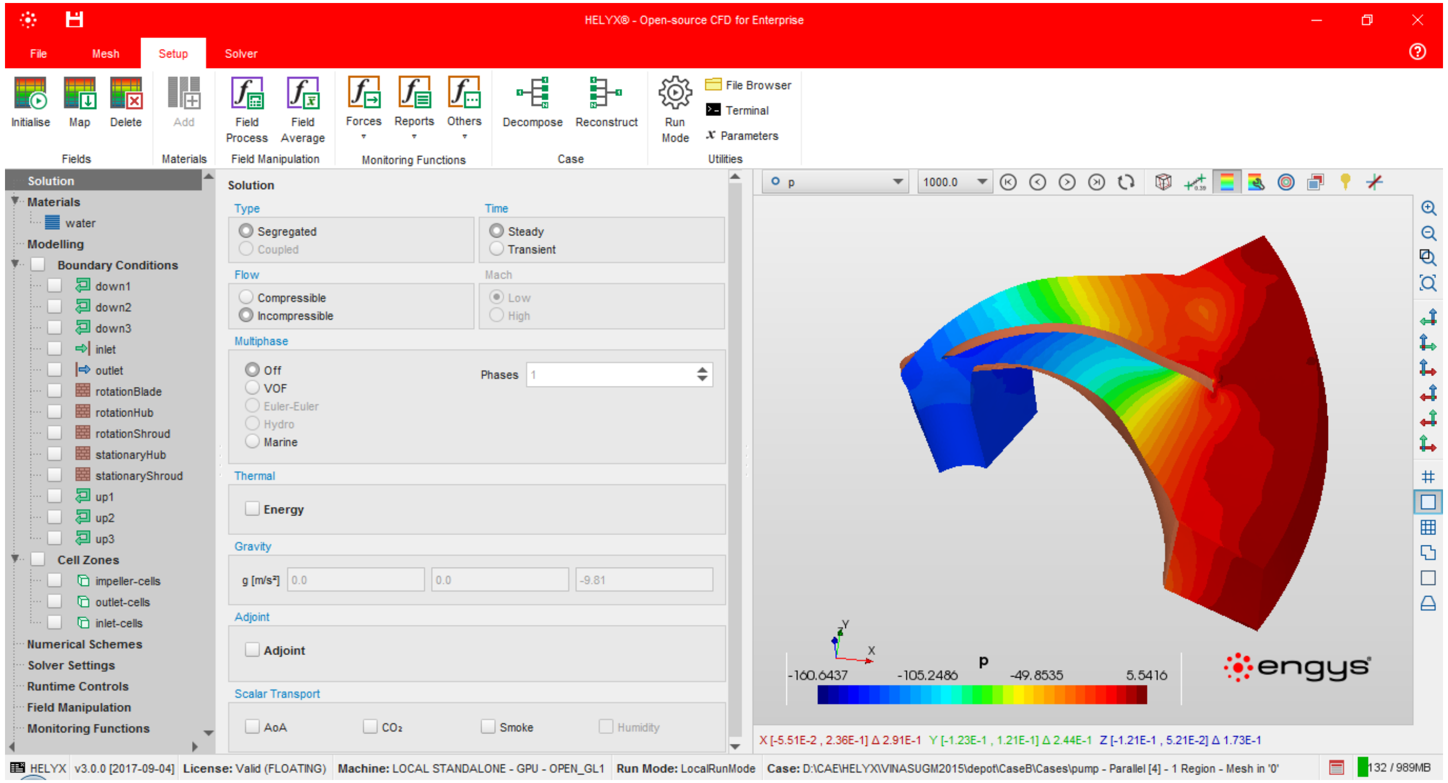


OUTLINE

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

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

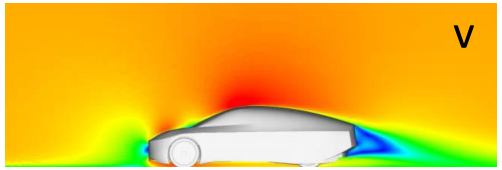
Discretise → Differentiate → Solve

- 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

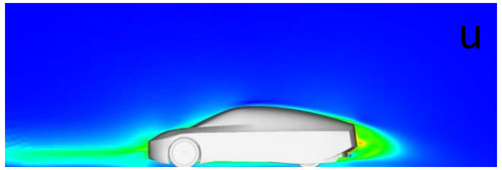
- CFD computation: v, p → primal fields

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



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

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



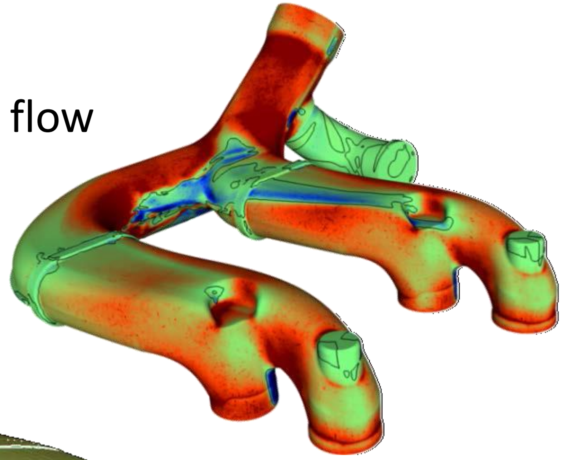
- Computation of sensitivities:
  - Surface sensitivities → $\frac{\partial J}{\partial \beta} \sim \frac{\partial \mathbf{v}}{\partial n}\cdot\frac{\partial \mathbf{u}}{\partial n}$
  - Volume sensitivities → $\frac{\partial J}{\partial \alpha} \sim \mathbf{v}\cdot\mathbf{u}$

HELYX-Adjoint | Sensitivities

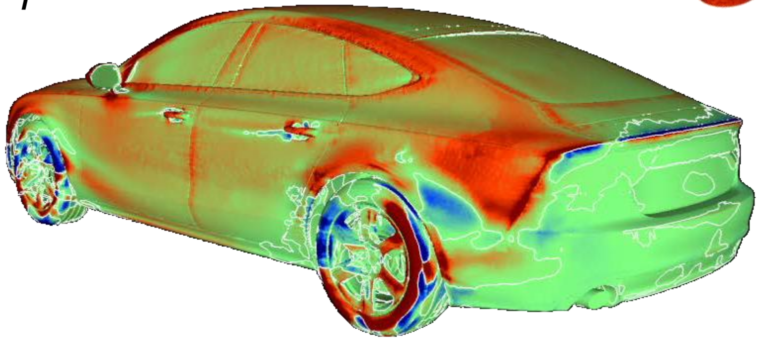
Surface Sensitivities $\partial J/\partial \beta$

red → push surface in
blue → push surface out

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

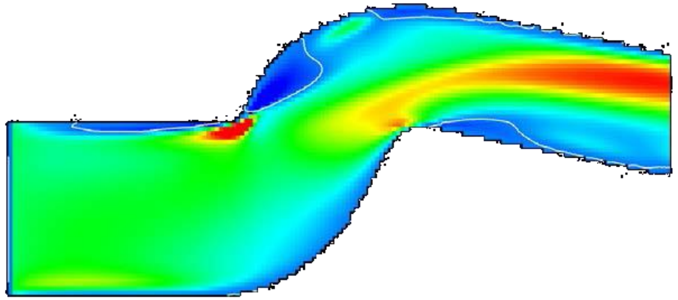


$\frac{\partial J}{\partial \beta}$ → drag

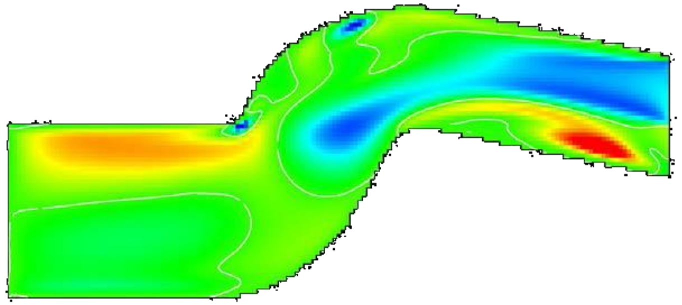


Volume Sensitivities $\partial J/\partial \alpha$

red → free volume cells
blue → penalise volume cells



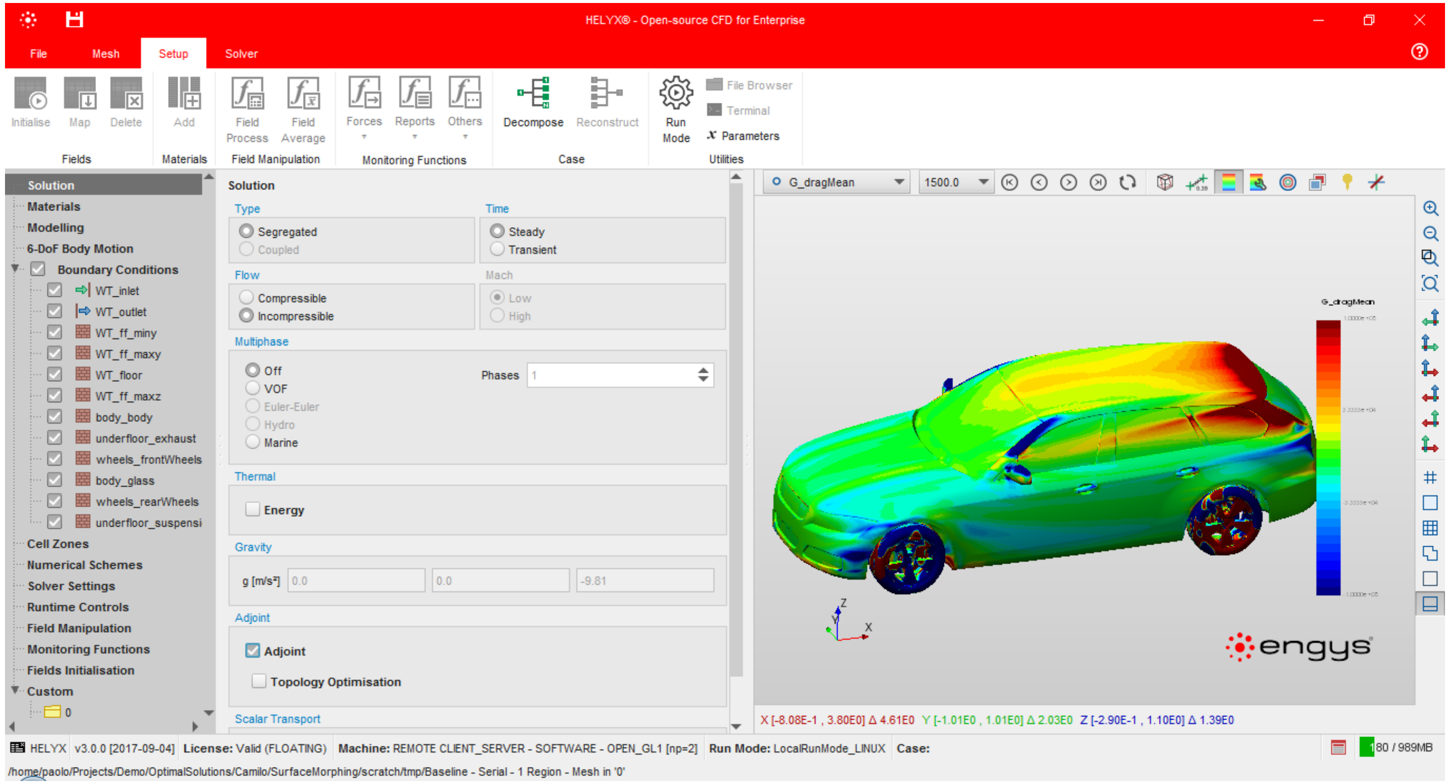
$\frac{\partial J}{\partial \alpha}$ → pressure drop



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



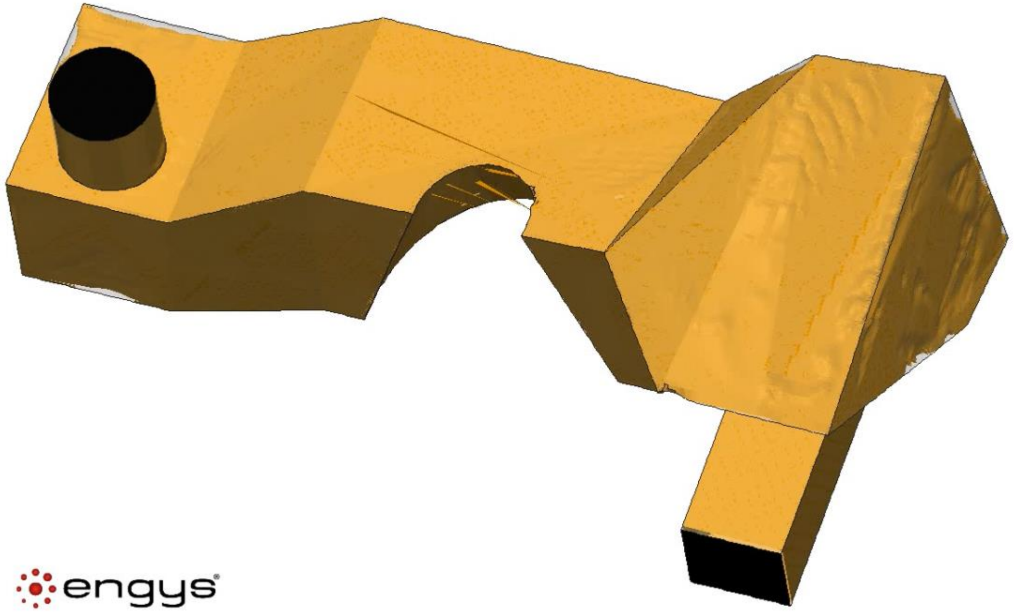
OUTLINE

2. Topology Optimisation

- What is Topology Optimisation?
- Success Stories
  - Aisin AW: Oil Channel
  - FCA: Engine Intake Port
  - Volkswagen: Internal Flows

Topology Optimisation

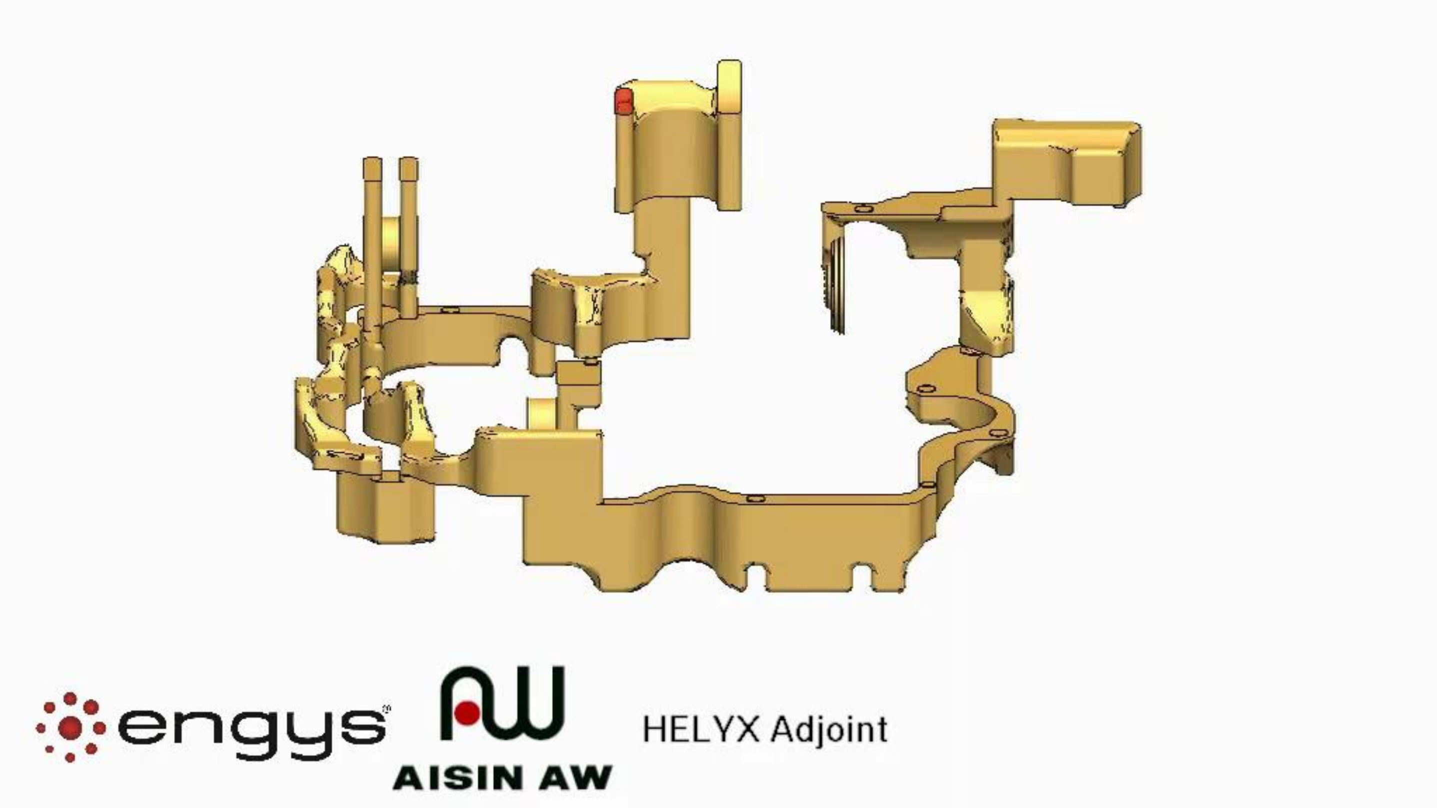
- Specify design space and inlet/outlet interfaces
- Define optimisation objectives
- Calculate volume sensitivities → $\partial J/\partial \alpha$
  - Volume cells penalised according to objective function
  - Track "optimum" interface using level-set with immersed boundary
- Output "smooth" surface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

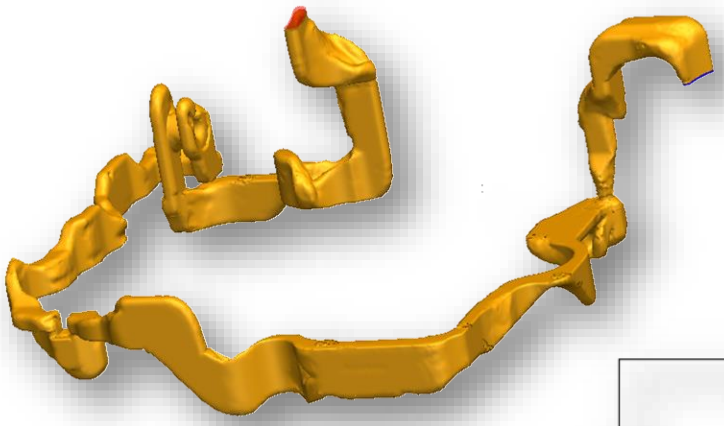


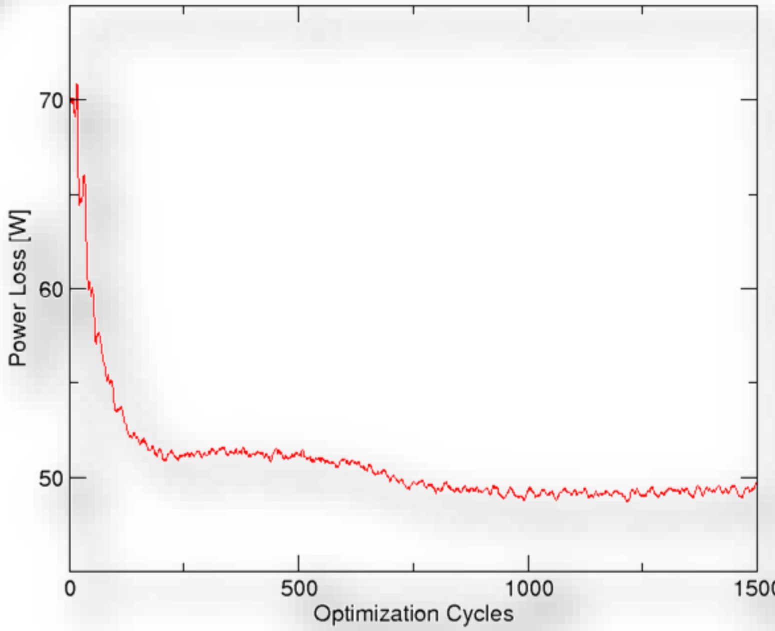
Courtesy of Dr. Takeshi Yamaguchi (AISIN AW)

Topology Optimisation | Success Story

Aisin AW 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

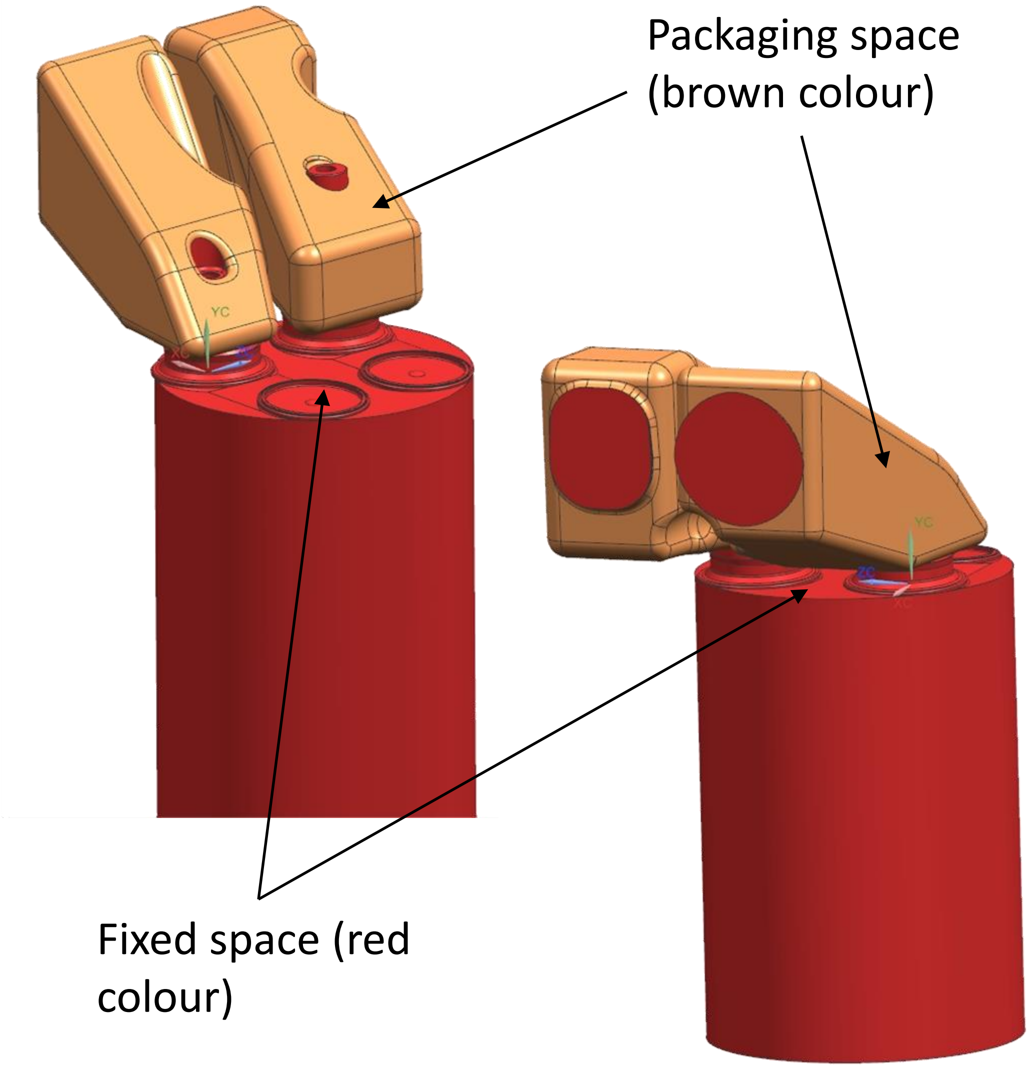




Topology Optimisation | Success Story

FCA Engine Intake Port

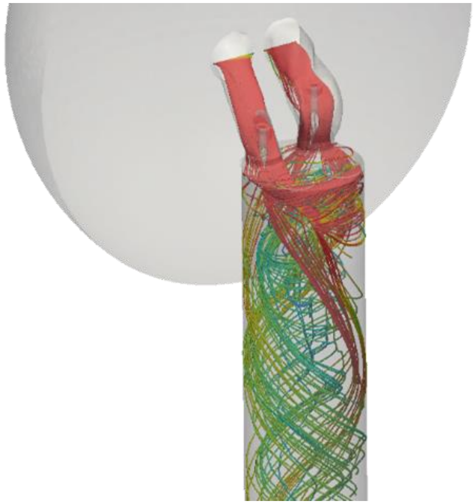
- Design port flow
- Targets to achieve:
  - Maximise Mass Flow Rate
  - Maximise Swirl Index ω
- Compressible flow
- k-ω SST turbulence model



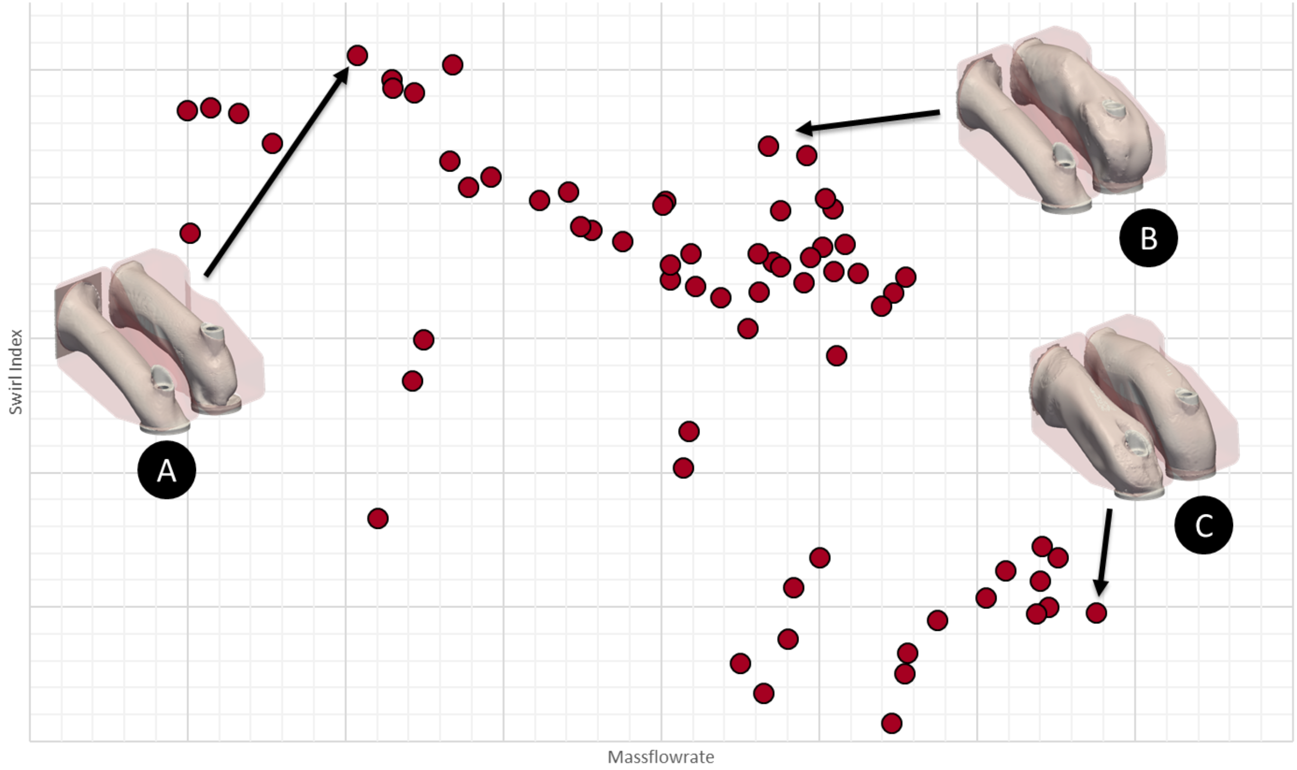
Topology Optimisation | Success Story

FCA Engine Intake Port

- Design B is a trade-off in terms of both design objectives
- Results were validated using a fine mesh with near-wall layers

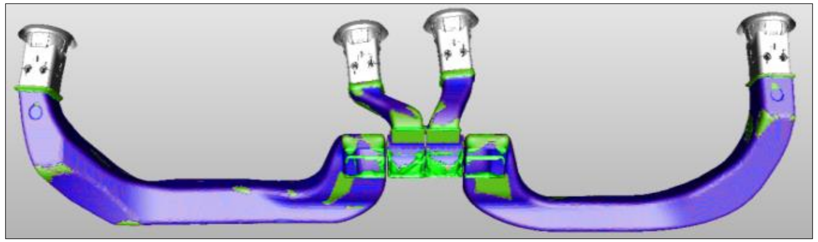


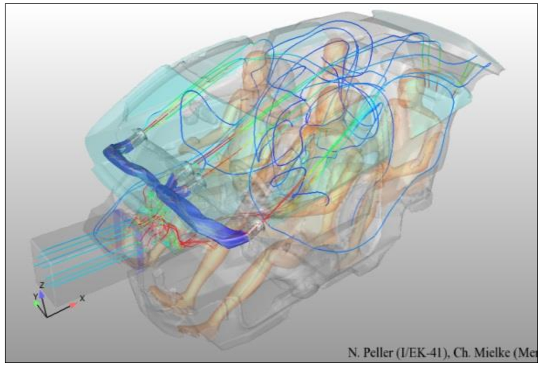
Optimisation Results



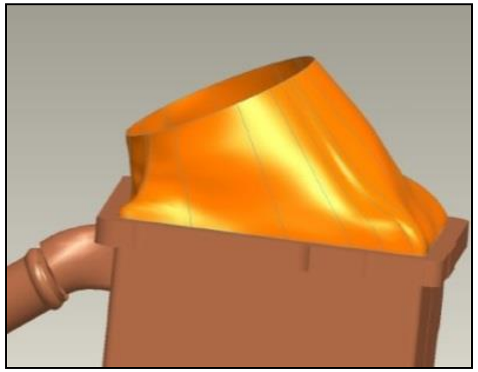
Topology Optimisation | Success Story

VW Internal Flows



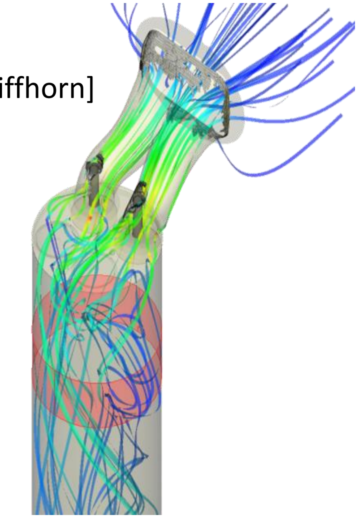


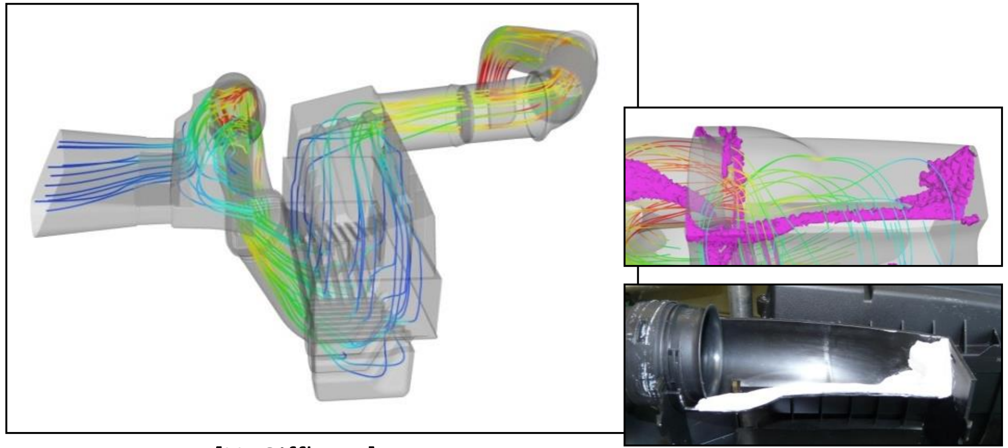
[N. Peller]



[M. Tomecki]

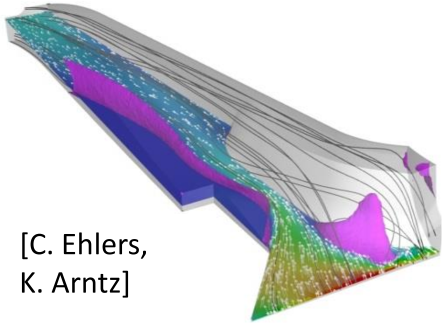
[U. Giffhorn]



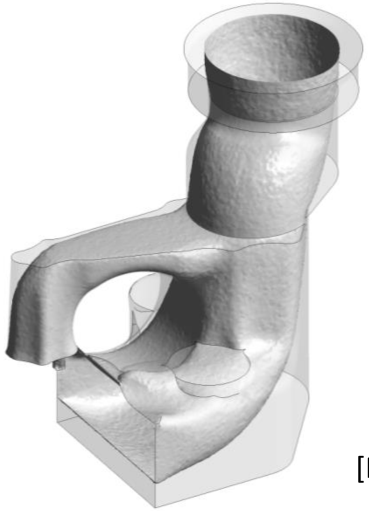


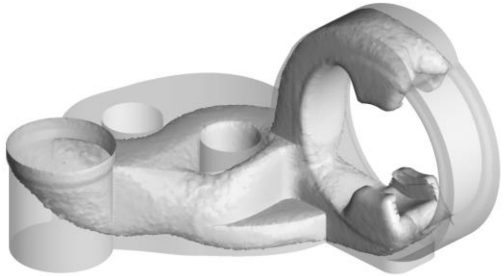
[U. Giffhorn]

[C. Ehlers,
K. Arntz]



[R. Niederlein]





[M. Towara]

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

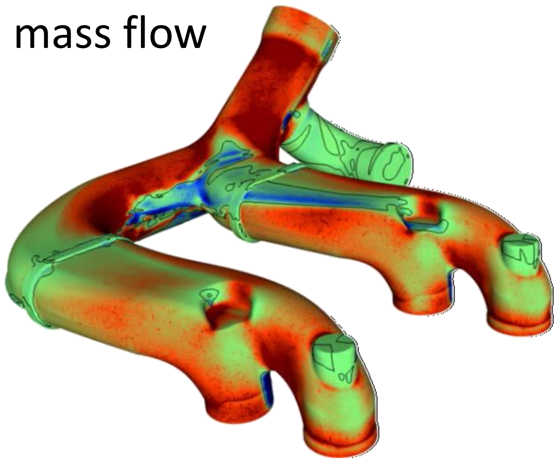
OUTLINE

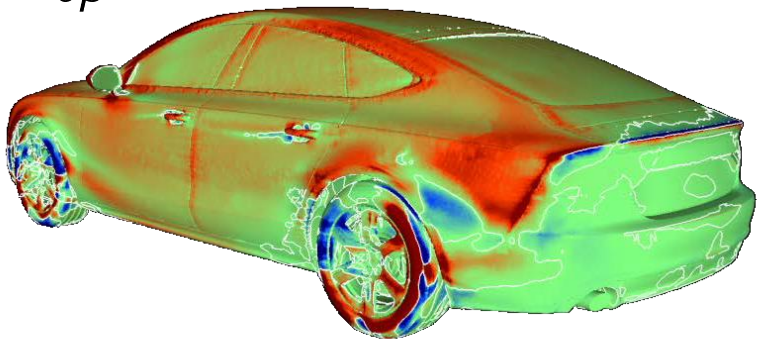
3. Shape Optimisation

- What is Shape Optimisation?
- Success Stories
  - Volkswagen: Example Cars
  - Audi: External Aero Validation

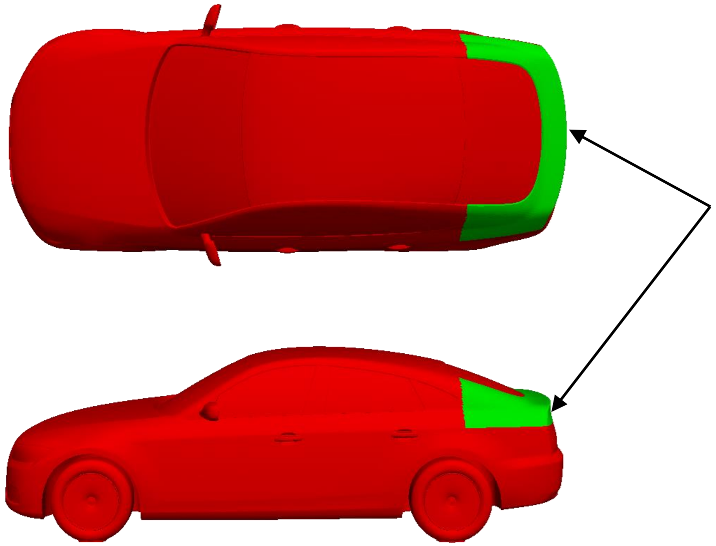
Shape Optimisation

- Based on steady RANS or time averaged primal (LES/DES)
- Time averaged primal:
  - Increased accuracy
  - Much cheaper than full transient
  - Invert mean strain/mean stress for tensorial viscosity
  - Residual can be non-zero due to stabilisation
- Morph design using HELYX® morpher or 3rd-party tools
  - ANSA, Sculptor, CAMILO, CARAT++

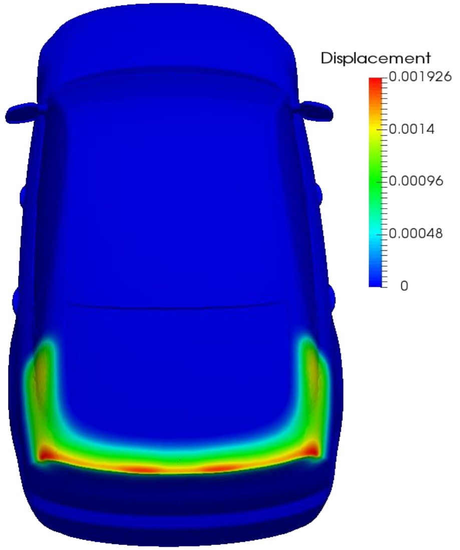




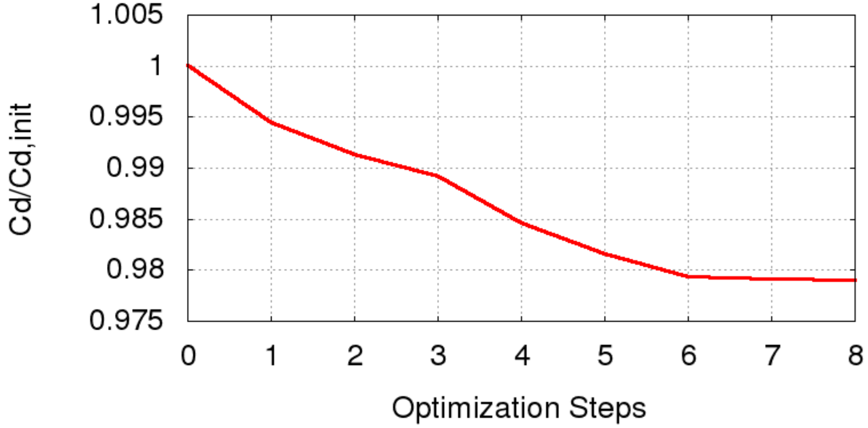
Shape Optimisation | Morphing



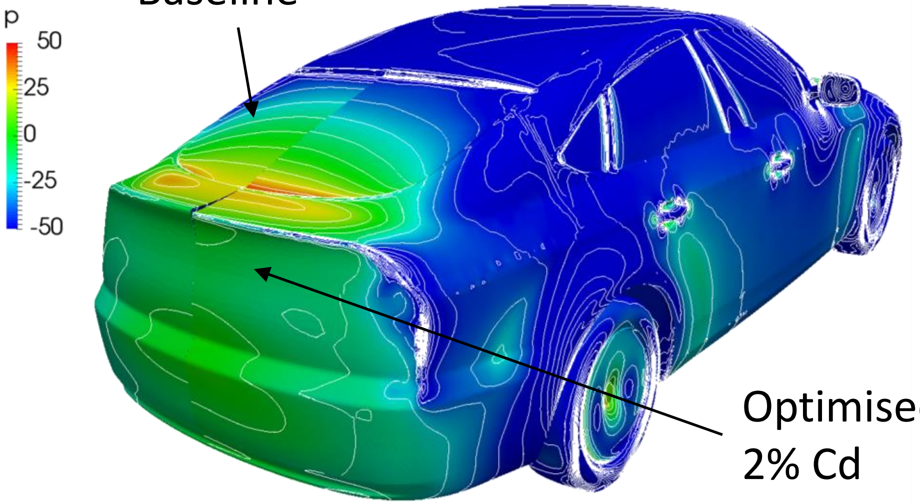
Deformable surfaces



Optimisation History



Baseline

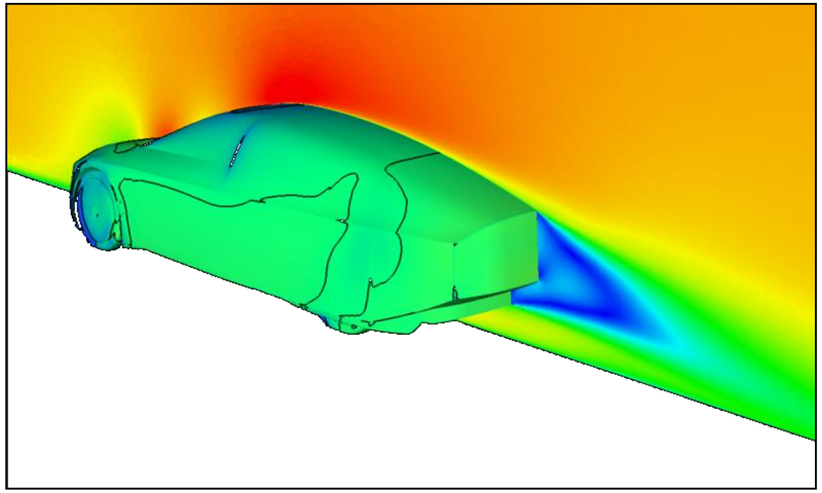


Optimised: -2% Cd

Shape Optimisation | Success Story

VW XL1 External Aerodynamics

- Objective → Minimise drag
- Primal: time-averaged DES
  - Compute drag and lift coefficients
  - Use time-averaged U and p and solve steady-state RANS-nut
  - Run adjoint RANS with averaged U, p and nut
- Qualitative agreement only (sign correct)
  - Good agreement with wind tunnel >5% drag reduction



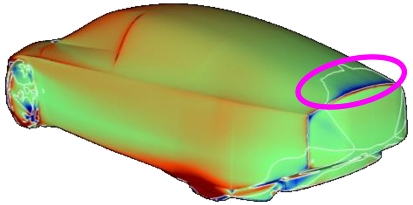
Courtesy of Dr. Carsten Othmer (VW Research)

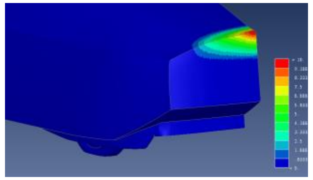
Shape Optimisation | Success Story

VW XL1 External Aerodynamics

Morphing **according to** / **opposite to** sensitivities

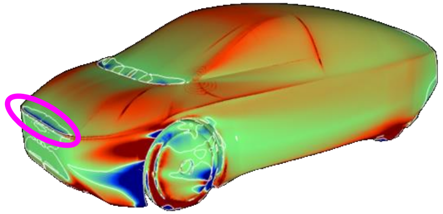
1

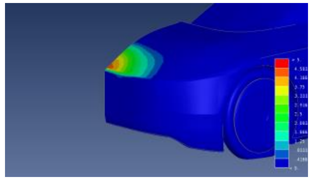




-0,9% / +1,2% for 10mm displacement
Confirmed in wind tunnel

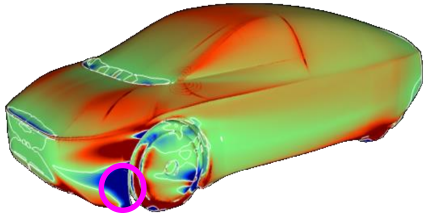
2

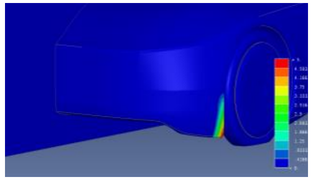




-0,13% / +0,14% for 5mm displacement

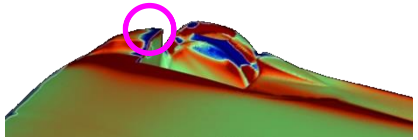
3

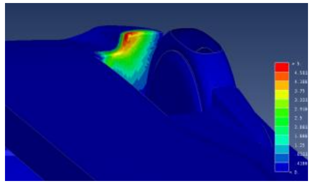




-0,6% / +0,8% for 5mm displacement

4





-0,8% / +1% for 10mm displacement
Confirmed in wind tunnel

Courtesy of Dr. Carsten Othmer (VW Research)

Shape Optimisation | Success Story

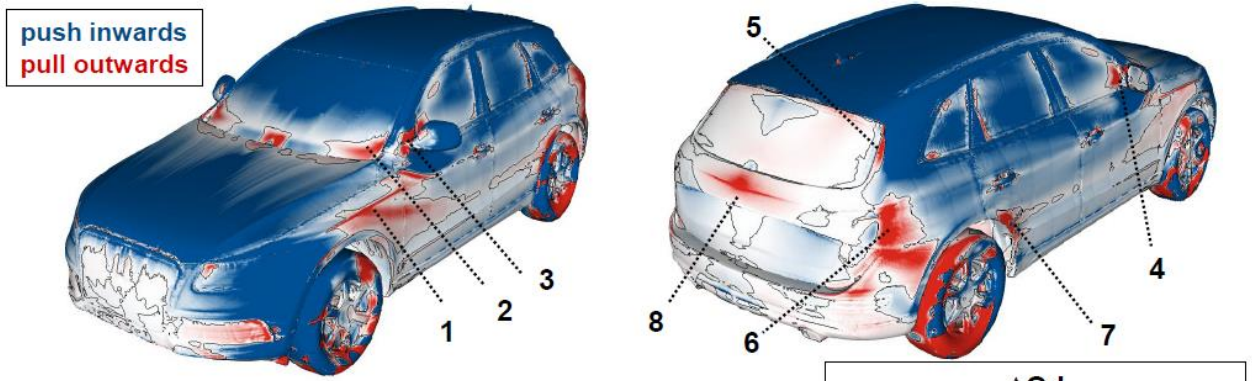
Audi Q5 External Aerodynamics

- Experimentally validate QTA
  - FKFS quarter scale wind-tunnel model
- Do not implement “known” improvement measures
  - boat tailing
  - indentation of the bonnet
  - lowering of the roof
- Only upper body
- Only outward displacement
  - Does not reduce packaging space

Reproduced with permission, Thomas Blacha, Audi AG - SAE TP 2016-01-1615

Shape Optimisation | Success Story

Audi Q5 External Aerodynamics



Measure	ΔCd CFD	ΔCd 1:4 Exp. FKFS
1: Lateral kink with bigger radius	–	-0.0005
2: More material at bottom of front window near A-pillar	–	-0.001
3: More material in front of side view mirror	–	-0.001
4: Extension of mirror base by 110mm	-0.002	-0.002
5: Sharper trailing edge on D-pillar	-0.002	-0.004 (also 1:1)
6: Outward pulling with sharp trailing edge on rear shoulder	-0.003	-0.001
7: Outward pulling before rear wheel	-	0
8: Mounting of a small horizontal plane below rear window	-0.004	+0.004

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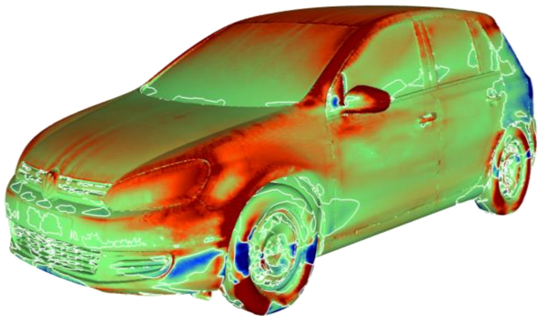
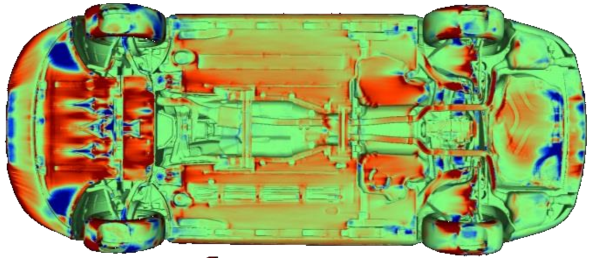
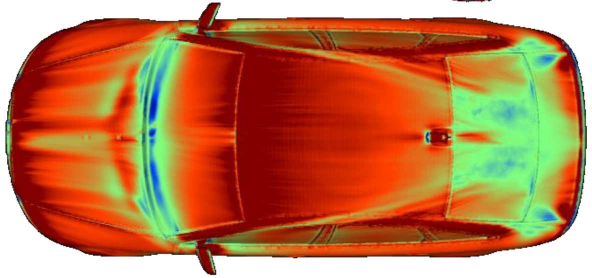
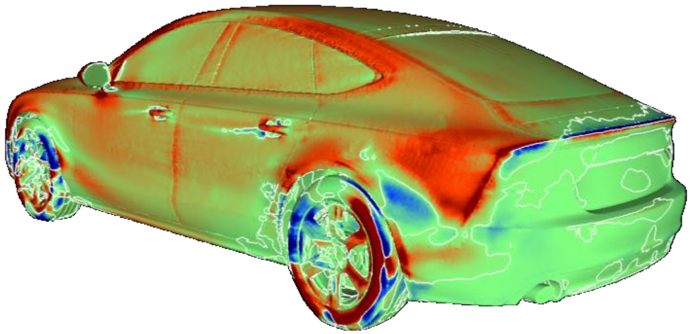
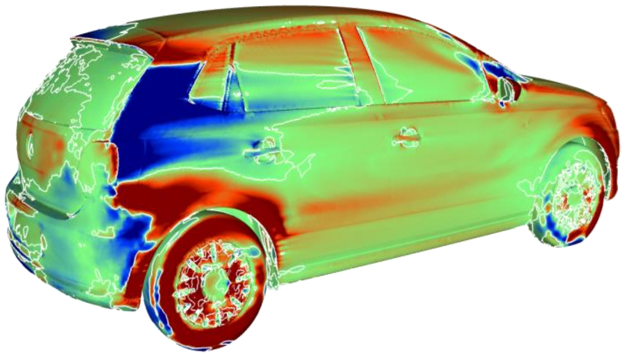
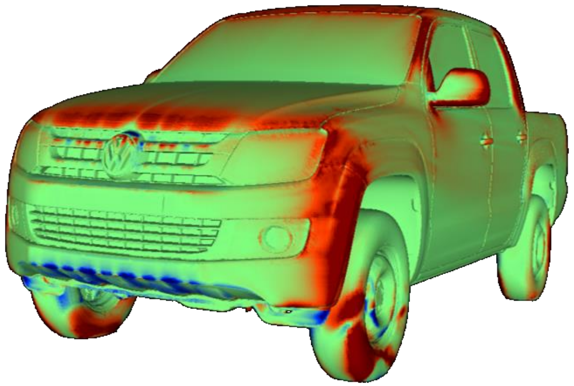
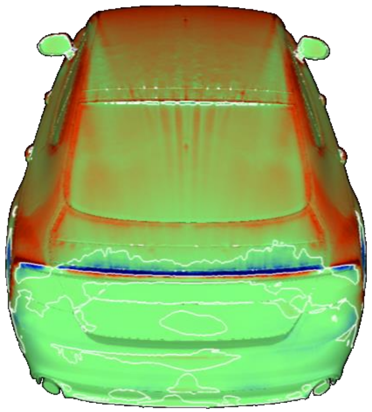
Shape Optimisation | Success Story

Examples External Flows

red: inwards for low drag
blue: outwards for low drag

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

Acknowledgements

› Volkswagen
  – VW Research: C. Othmer
  – VW Methods Development: D. Schraeder
  – VW Engine Development: W. Py

› Aboutflow MC-ITN – http://aboutflow.sems.qmul.ac.uk
  – Adjoint-Based optimization of industrial and unsteady flows

"This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement No. 317006".

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

"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 642959".

Questions?

THANK YOU VERY MUCH!