Shape optimization and active flow control for improved aerodynamic properties

Siniša Krajnovic

HPC resources used

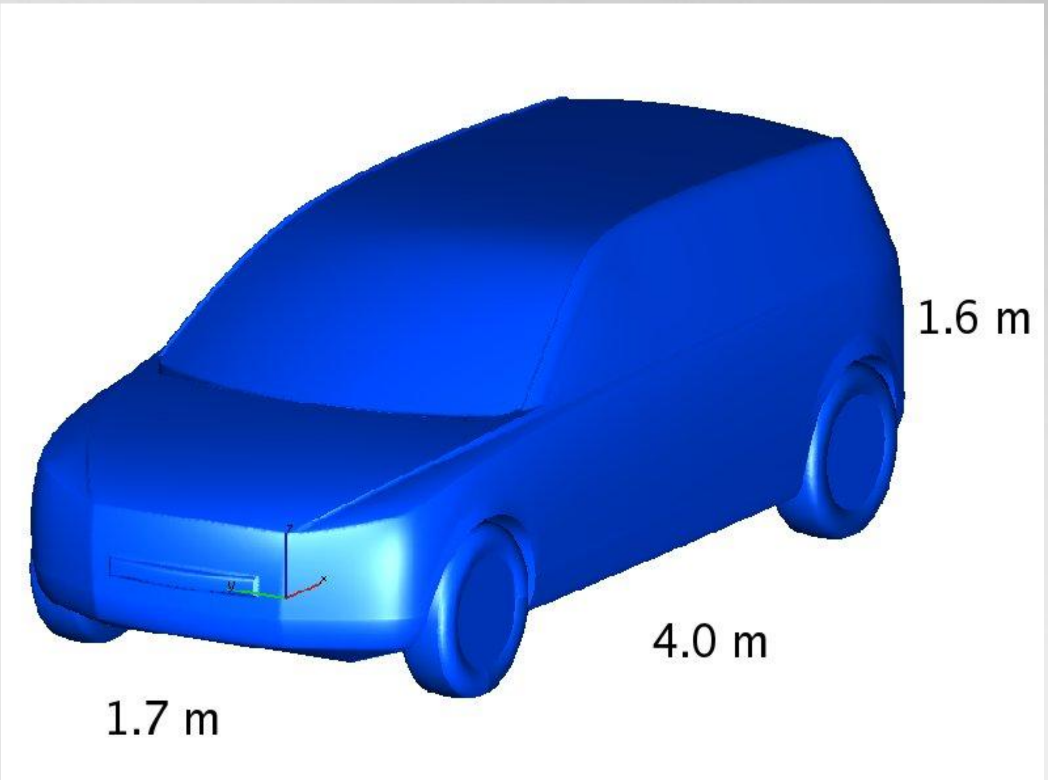
- Computer resources at C3SE at Chalmers in Göteborg
- Computer cluster: Neolith NSC Linköping 6440 cores

Automatic aerodynamical Shape Optimization (Students E. Helgason and H. Hafsteinsson)

Programs used:

- Fire
- Sculptor
- modeFrontier

Car model used:
Full scale experimental model from Volvo Cars named the VRAK



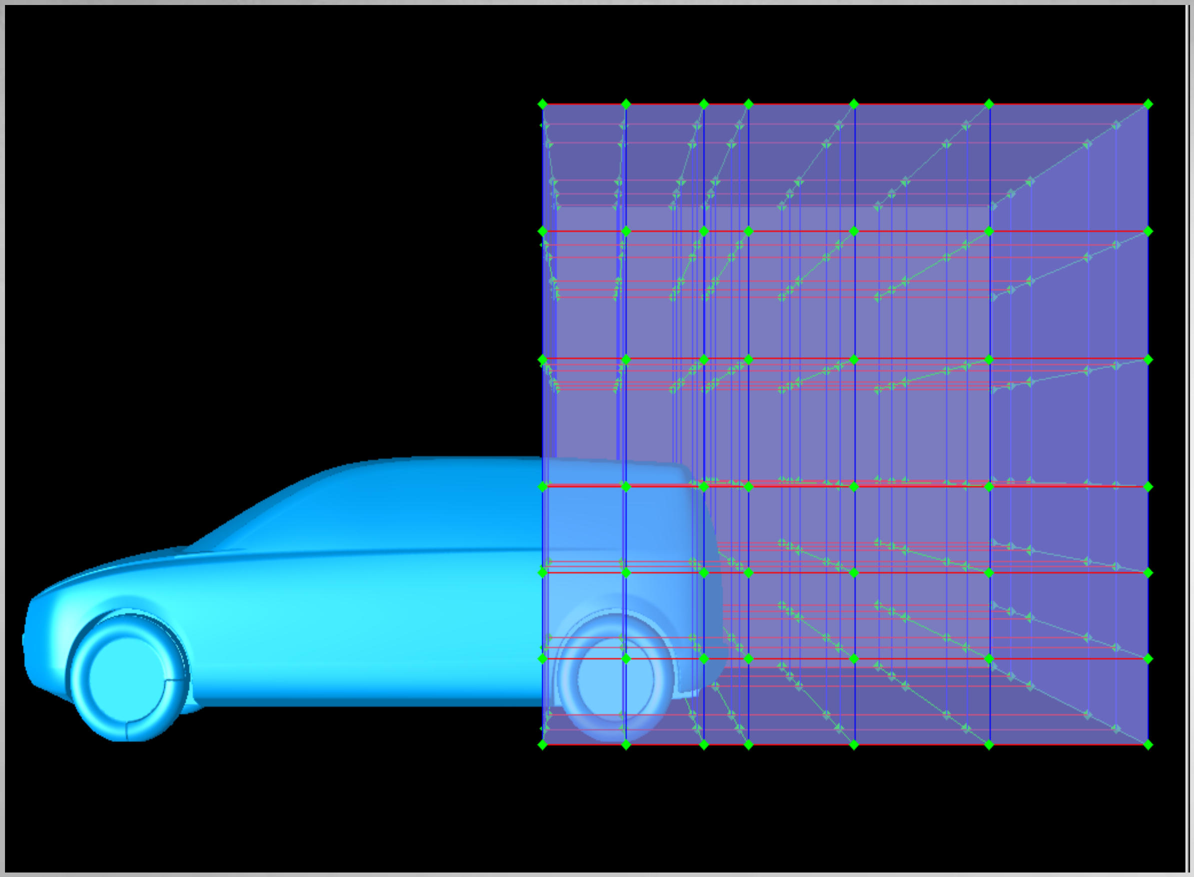
Process

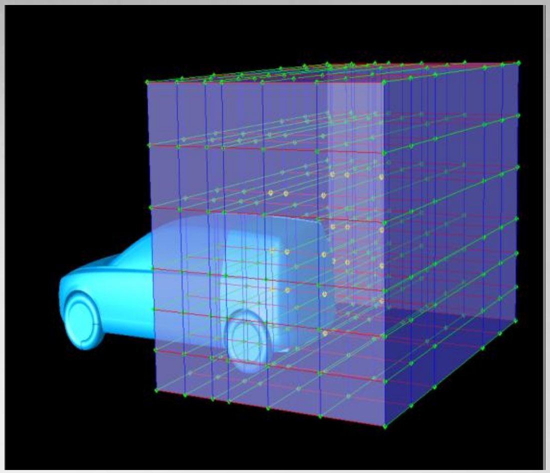
- AVL/Fire: Mesh generation
- Sculptor: Create volume for mesh morphing
- modeFrontier: Adjust control parameters for mesh morphing

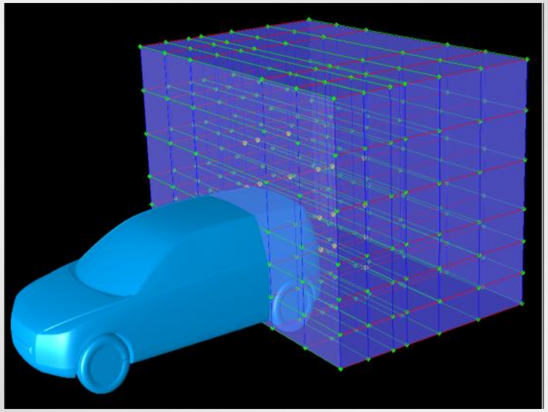
- Sculptor: Mesh morphing
- AVL/Fire: CFD calculations
- modeFrontier: Collects results and change mesh morphing parameters

- modeFrontier: Optimal solution selected

Control volume set in Sculptor



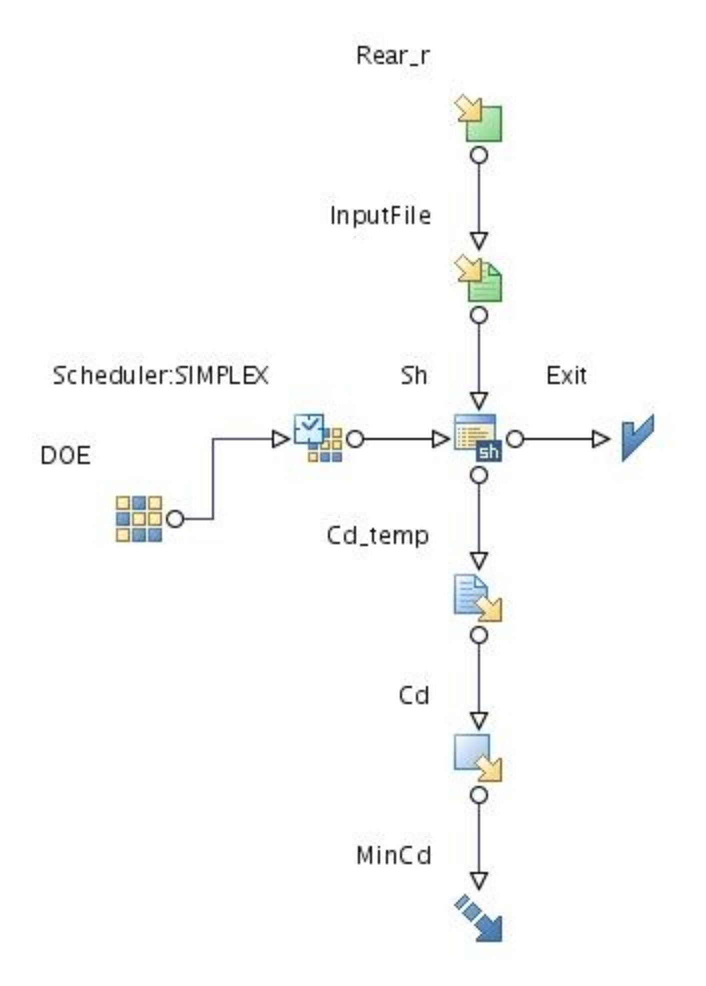




Morphing the rear end of the car

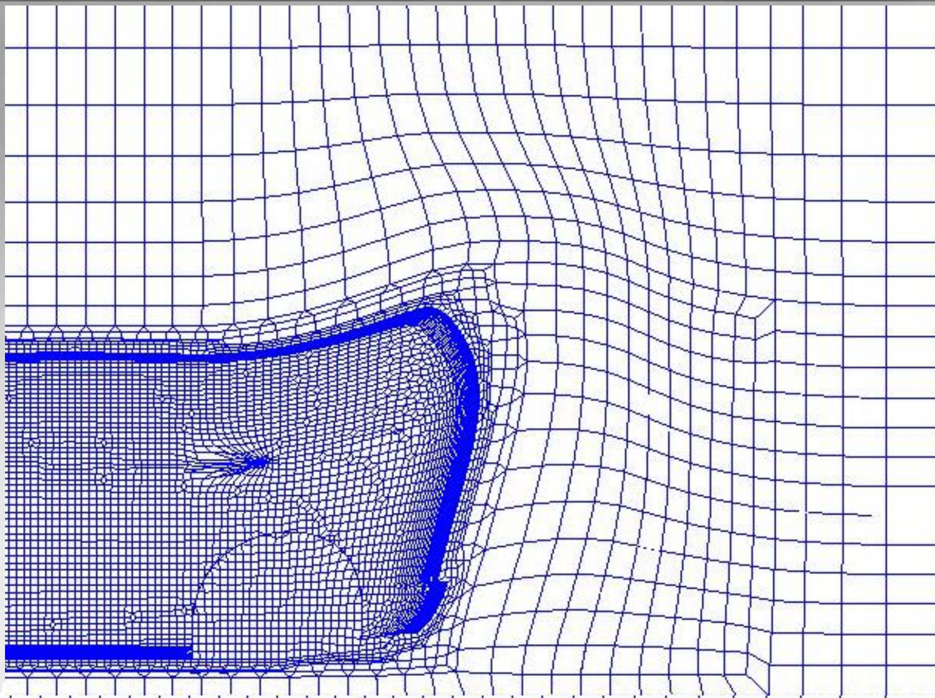
Workflow in modeFrontier

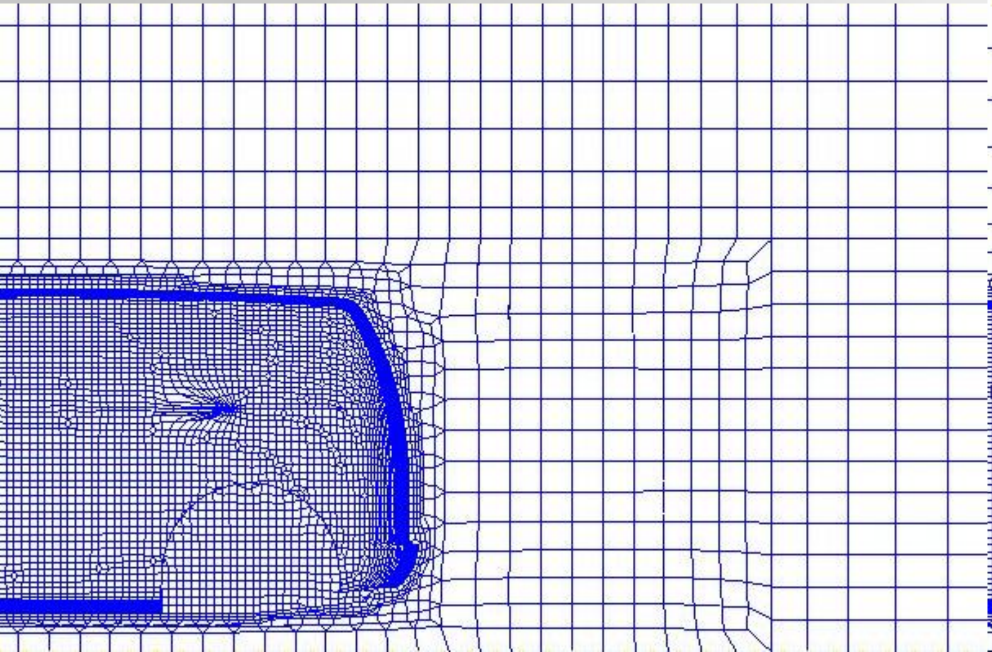
- Here one input variable (Rear_r) controls the mesh deformation in Sculptor
- ModeFrontier adjusts the control variable and collects results for Cd
- Built in optimization algorithms in modeFrontier can be used, i.e. SIMPLEX or the gradient based algorithm NLPQLP

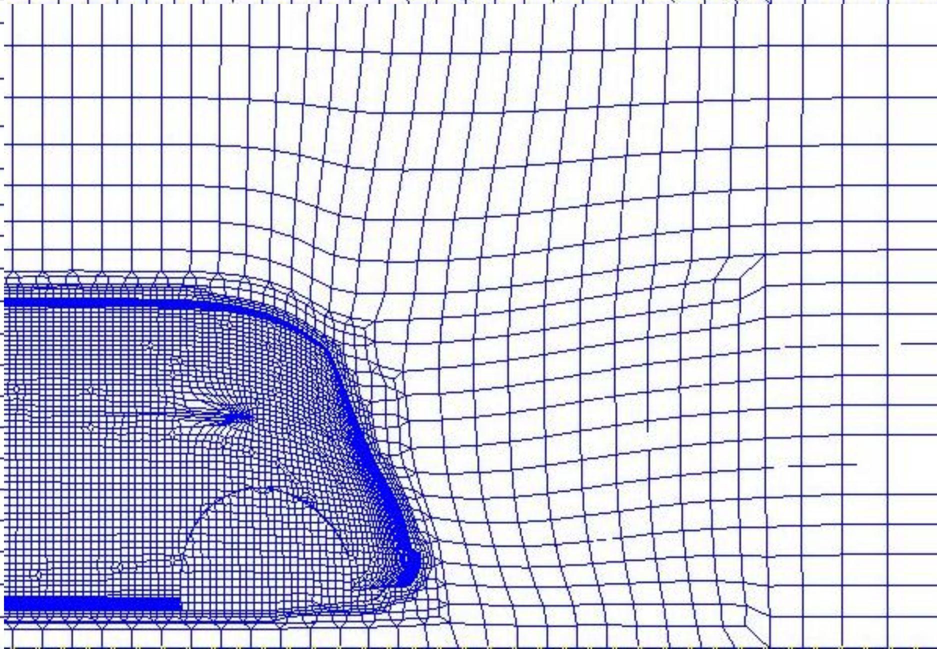


Deformed mesh

Upper right fig: Upper limit of the deformation parameter (Rear_r = 0.3)
Lower left fig: Undeformed car (Rear_r = 0)
Lower right fig: Lower limit of the deformation Paramater (Rear_r = -0.2)

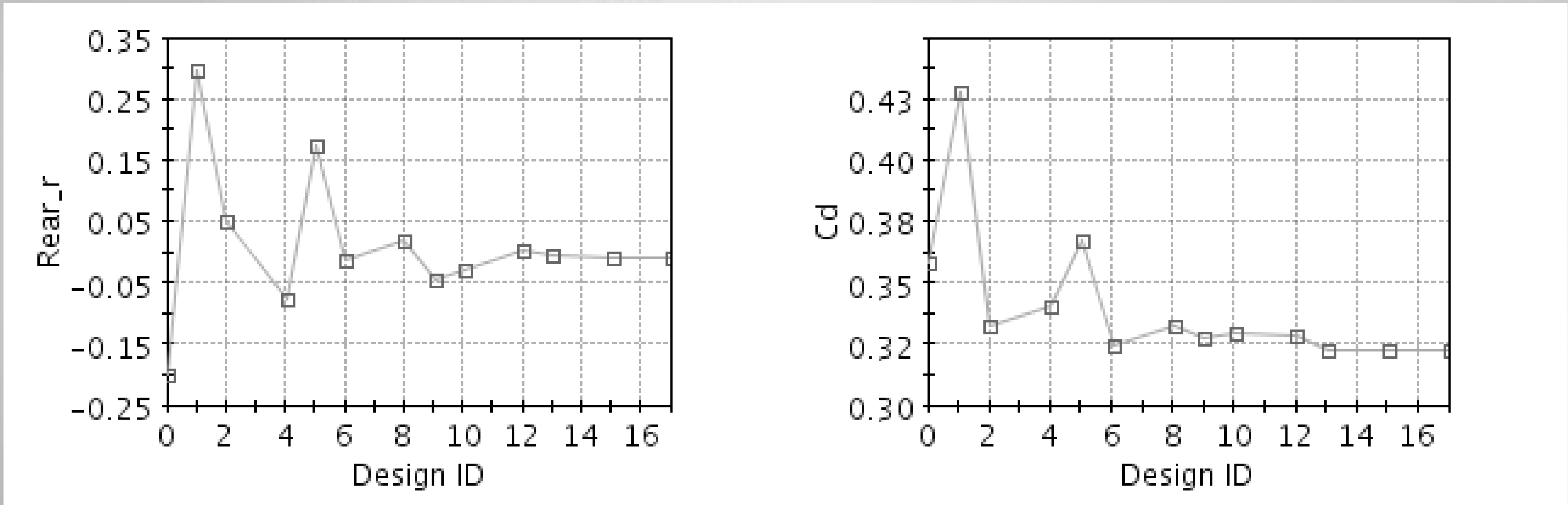






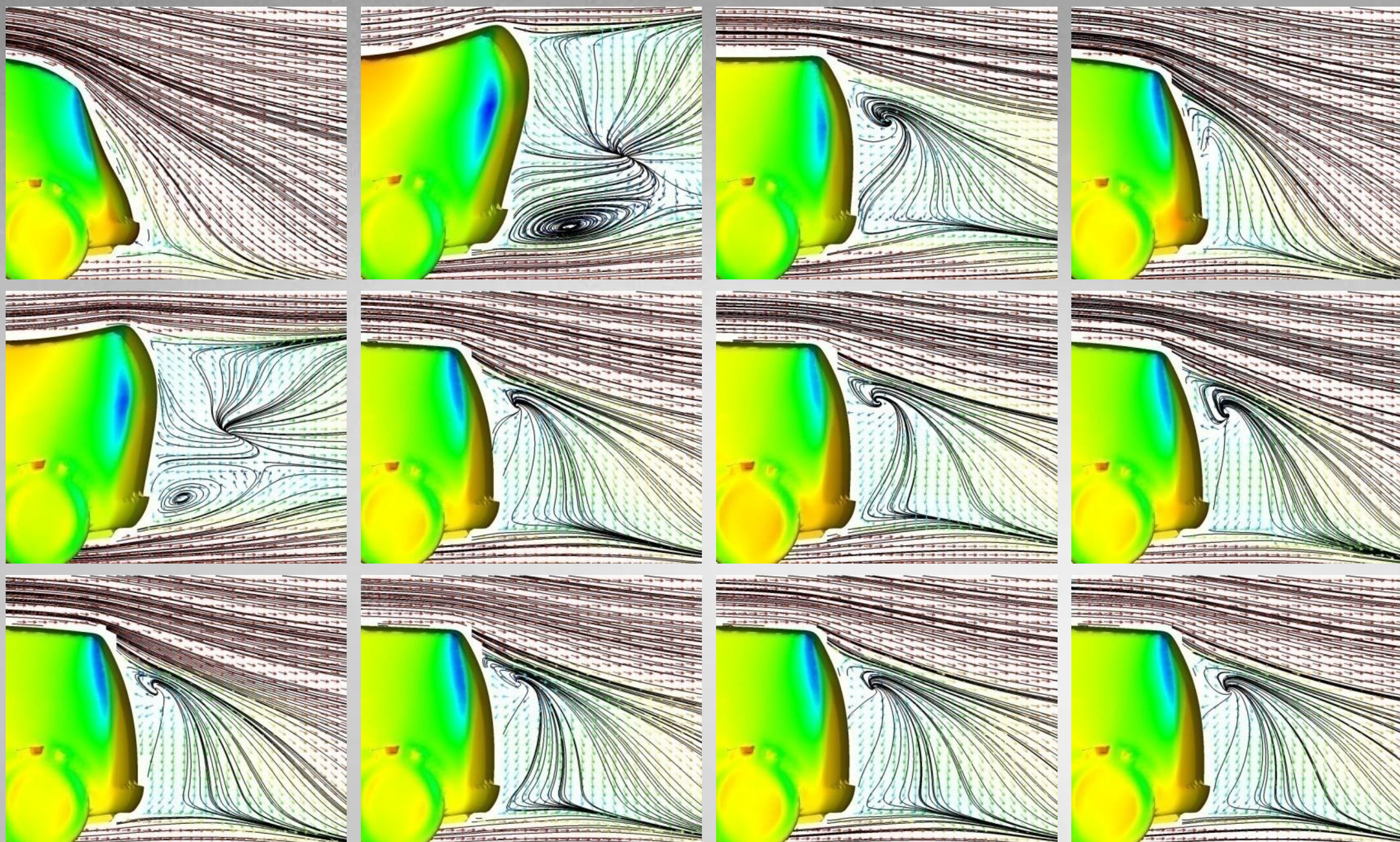
Results from modeFrontier

- Automatic Optimization with SIMPLEX algorithm using steady k-e turbulence model with inlet velocity of 10 m/s.
- Using course mesh with approx 300.000 cells
- Each simulation runs from t=0.

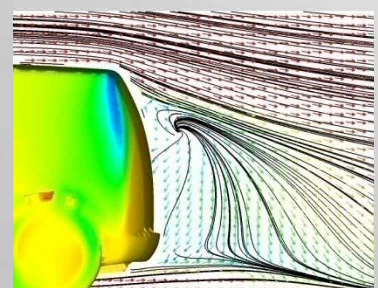


The control variable Rear_r = 0, corresponds to the original car

Flow visualization

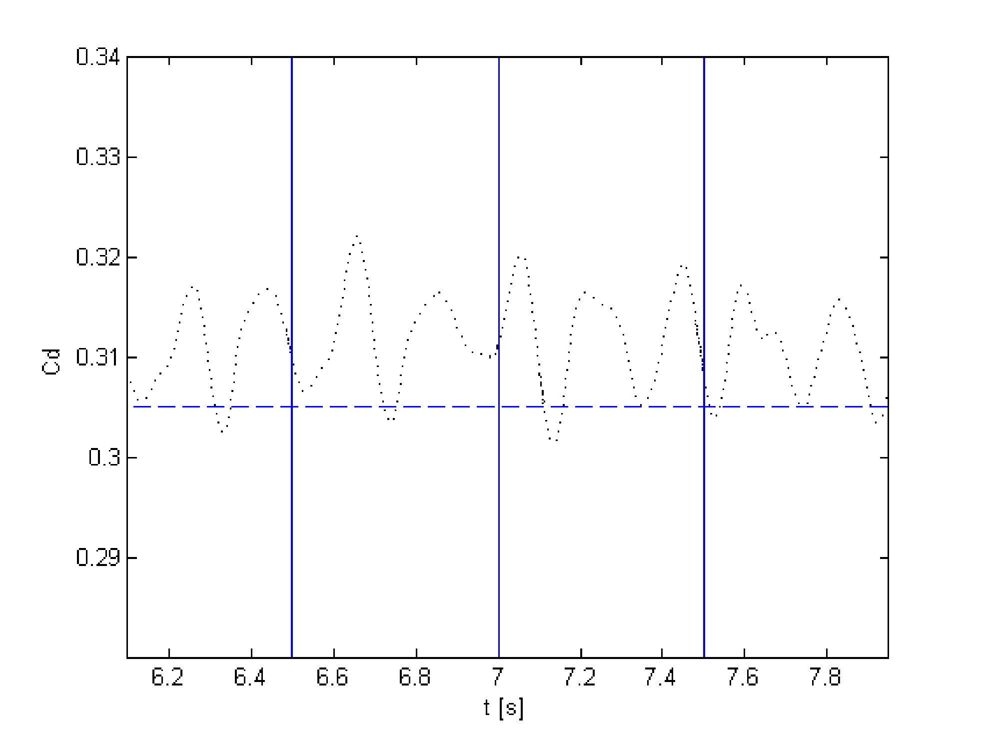


- $U_\infty = 10$ m/s



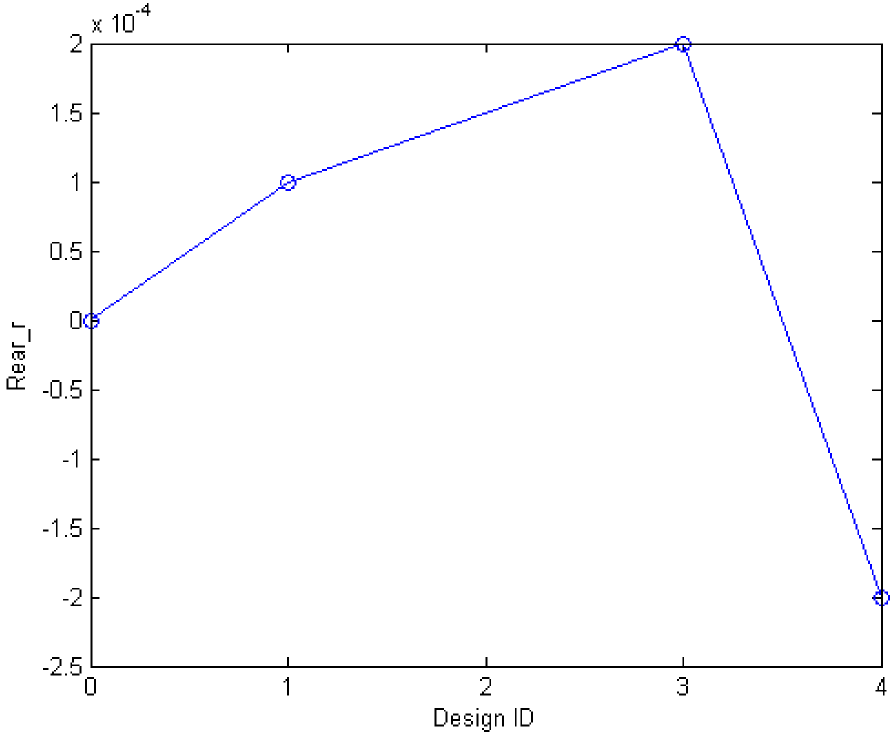
Automatic Optimization with the NLPQLP algorithm using unsteady k-z-f turbulence model with inlet velocity of 140 km/h

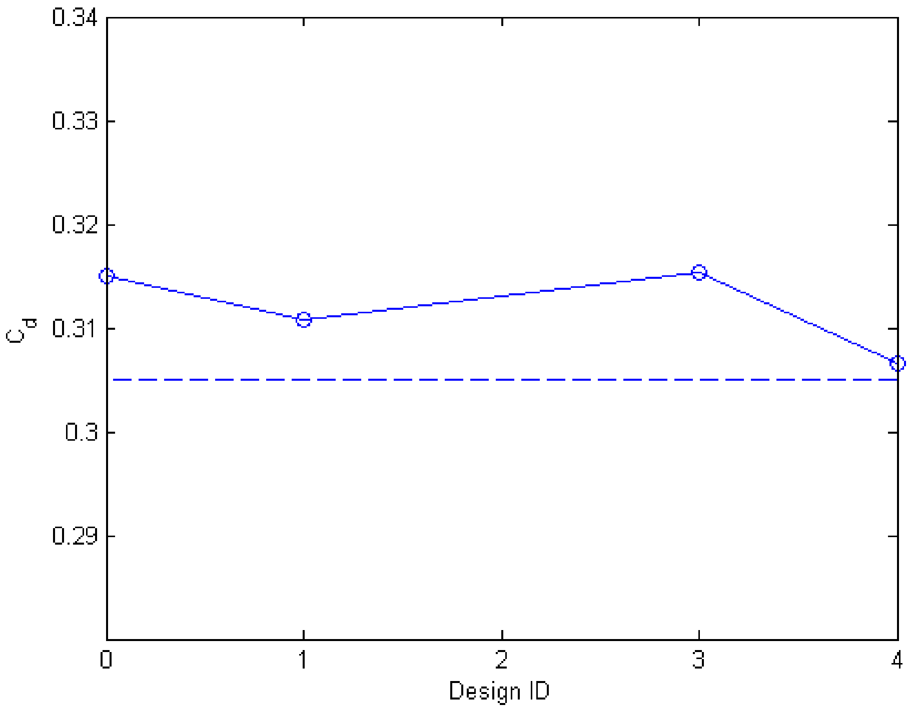
- Using finer mesh with boundary layers, approx 3.000.000 cells
- First run is the original VRAK
- Small modifications are made on the surface and the simulation is restarted with results from previous simulation
- Each modification runs for 0.5s
- Last 0.1s gives average Cd
- Horizontal dotted line represents experimental value of the drag coefficient for orginal VRAK
- Cd-exp = 3.05
- Vertical lines emphasize at what time simulation is restarted with new deformed geometry



Results from ModeFRONTIER

- Cd is reduced by 3% in four simulations.



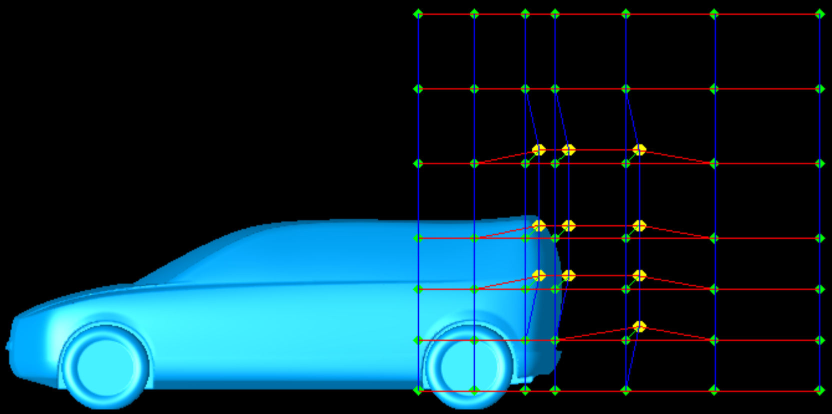


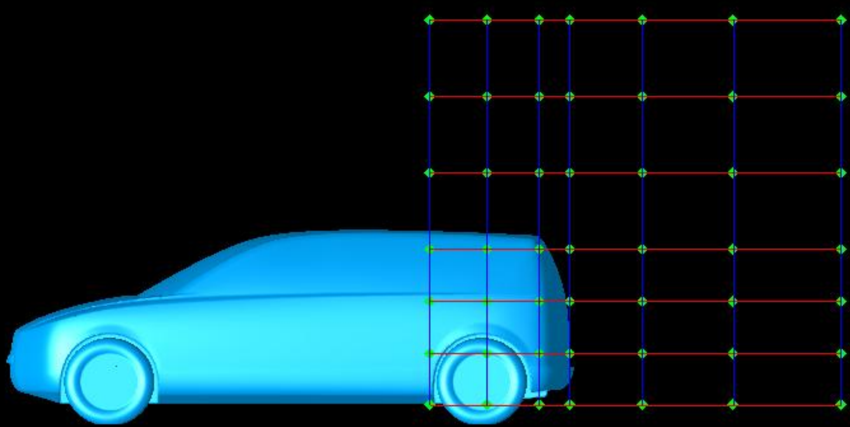
Modifying the car surface in Sculptor

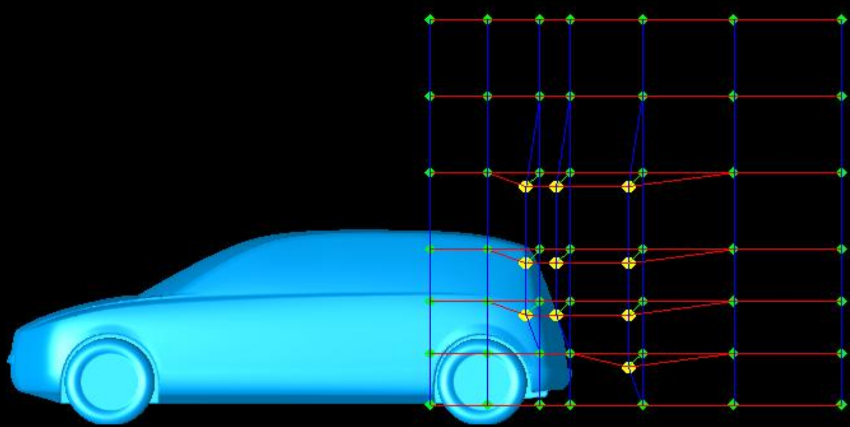
Upper right fig: Upper limit of the Deformation parameter, Rear_r = 0.1

Lower left fig: Undeformed car, Rear_r = 0.0

Lower right fig: Lower limit of the deformation Paramater, Rear_r = -0.1

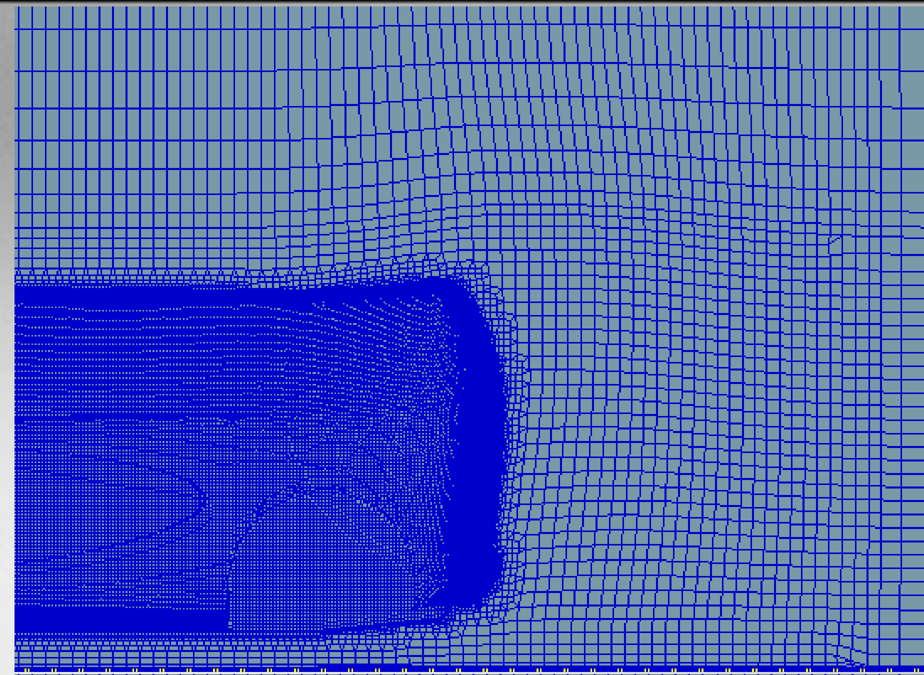


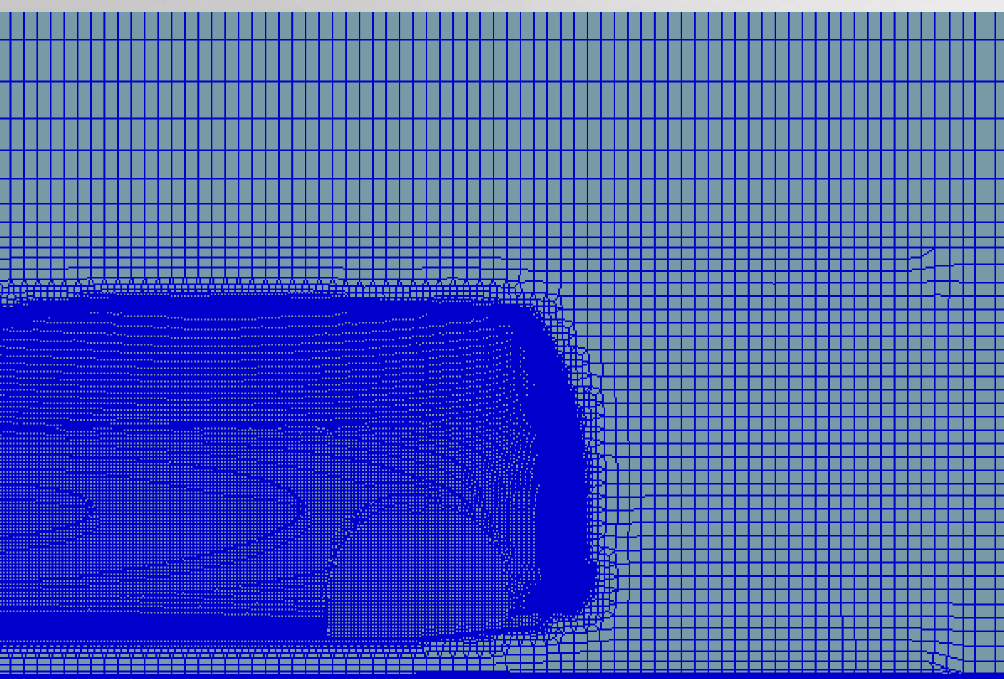


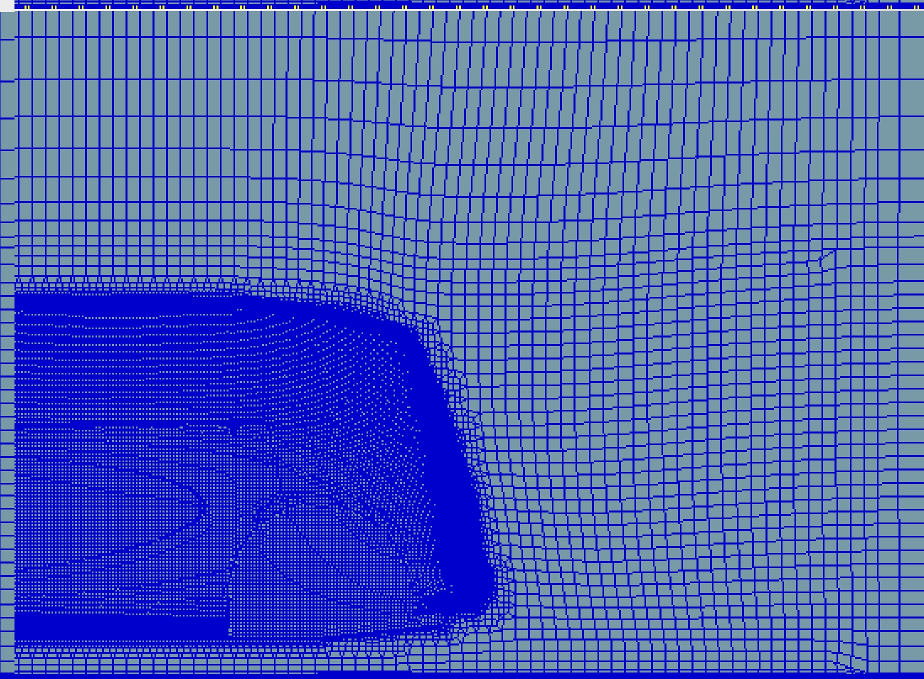


Deformed mesh

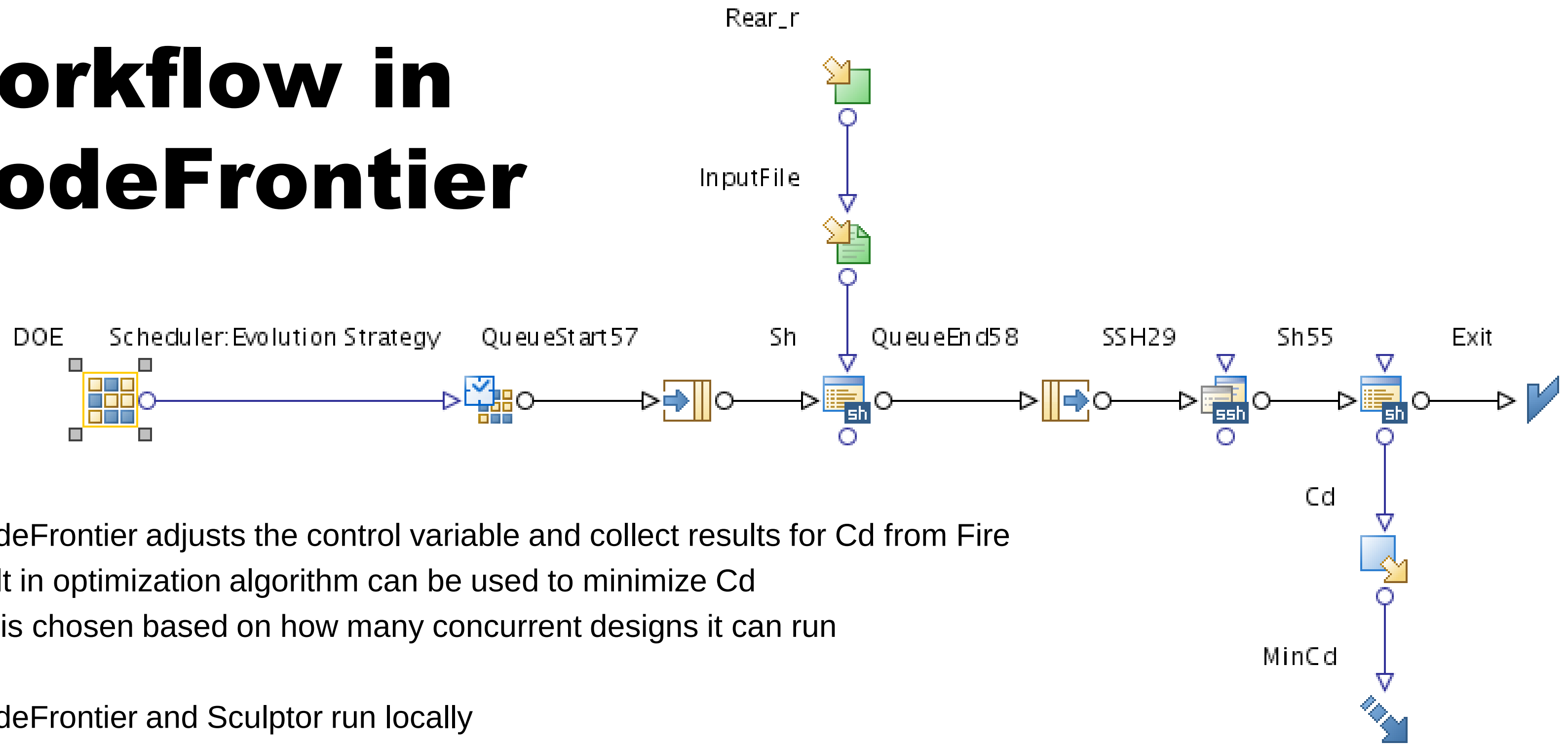
Upper right fig: Upper limit of the Deformation parameter, Rear_r = 0.1
Lower left fig: Undeformed car, Rear_r = 0.0
Lower right fig: Lower limit of the deformation Paramater, Rear_r = -0.1







Workflow in ModeFrontier



- modeFrontier adjusts the control variable and collect results for Cd from Fire
- Built in optimization algorithm can be used to minimize Cd
- ES is chosen based on how many concurrent designs it can run

- modeFrontier and Sculptor run locally
- One deformation is performed at a time
- The mesh is transferred to the cluster
- CFD calculations are restarted using the new mesh
- Each design takes ~ 22 h
- All flow results for each design can be obtained from the cluster

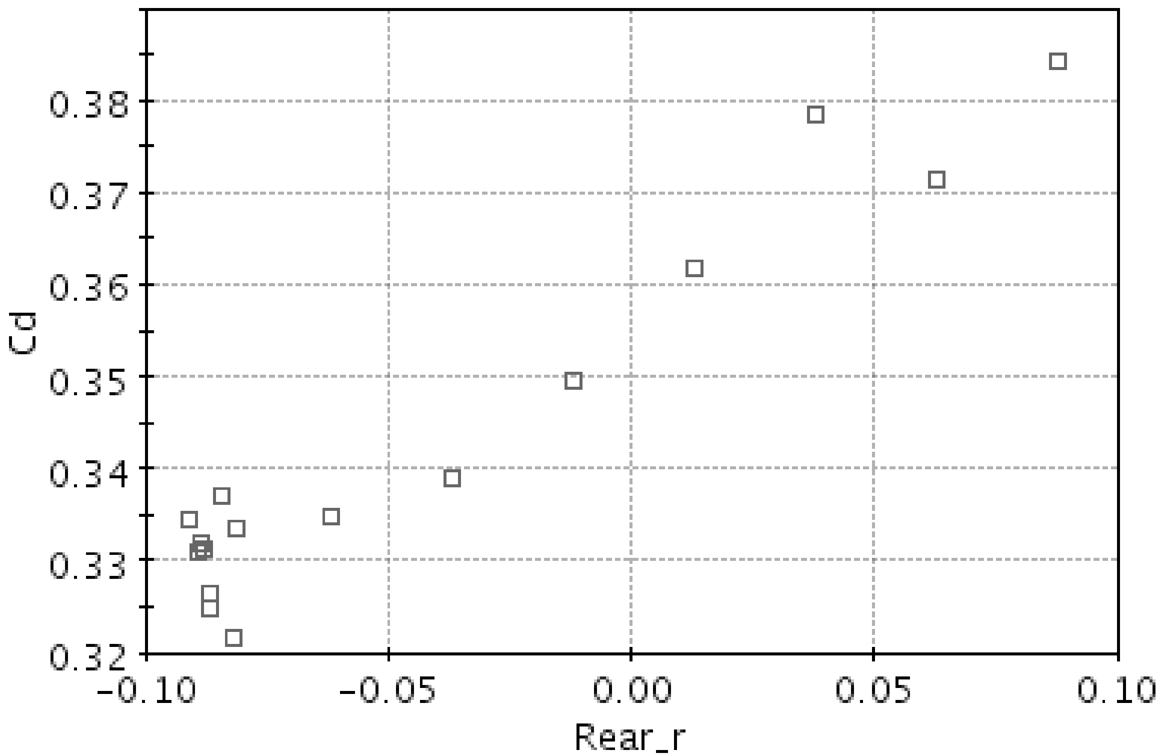
System specs

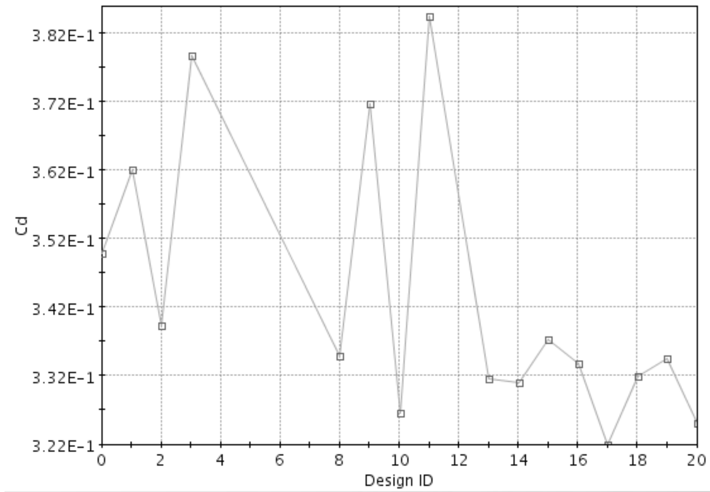
- Computer cluster: Neolith NSC Linköping 6440 cores
- Processor: Intel Xeon E5345 Quad Core Processor 2.33 GHz, 4MB Level cache
- Interconnect: Infiniband ConnectX interconnect
- Node memory: 16 GiB

- Computer resources at C3SE at Chalmers in Göteborg

- Number of cells $\approx 4.0 \cdot 10^6$
- Simulation runs on 48 CPUs
- Time step execution time ~ 80s
- Time step $\Delta T = 0.001$s
- Time for simulation to run 1.0s ~ 22h
- A particle will pass the car 10 times during 1.0s

Results from modeFrontier





Cd is decreased by 8.8%

- Four concurrent simulations are made each time.
- 8 DOE points are equally distributed over the design space.
- Optimization algorithm (ES) is used locally around the best point found in the DOE sequence.

Introduction

Task

- Minimize rolling and yawing moments of a train

Programs

- AVL FIRE® – Mesh creation and CFD simulations
- Sculptor – Mesh deformation
- modeFrontier - Optimization

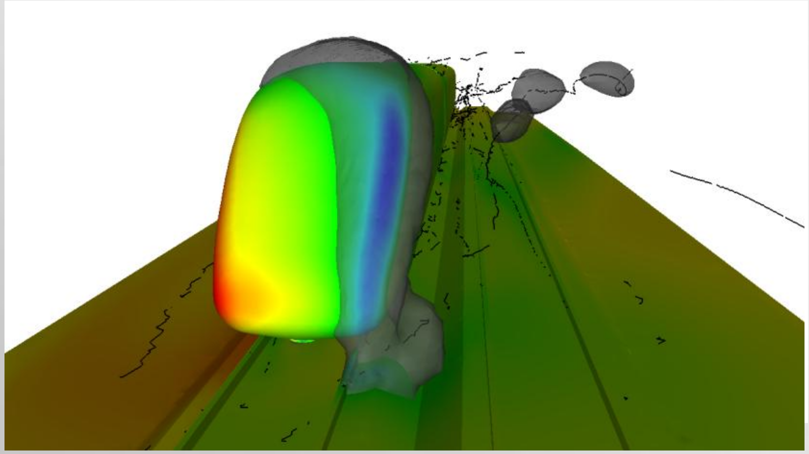
The Optimization Process

Mesh Generation → Optimization → Mesh Deformation

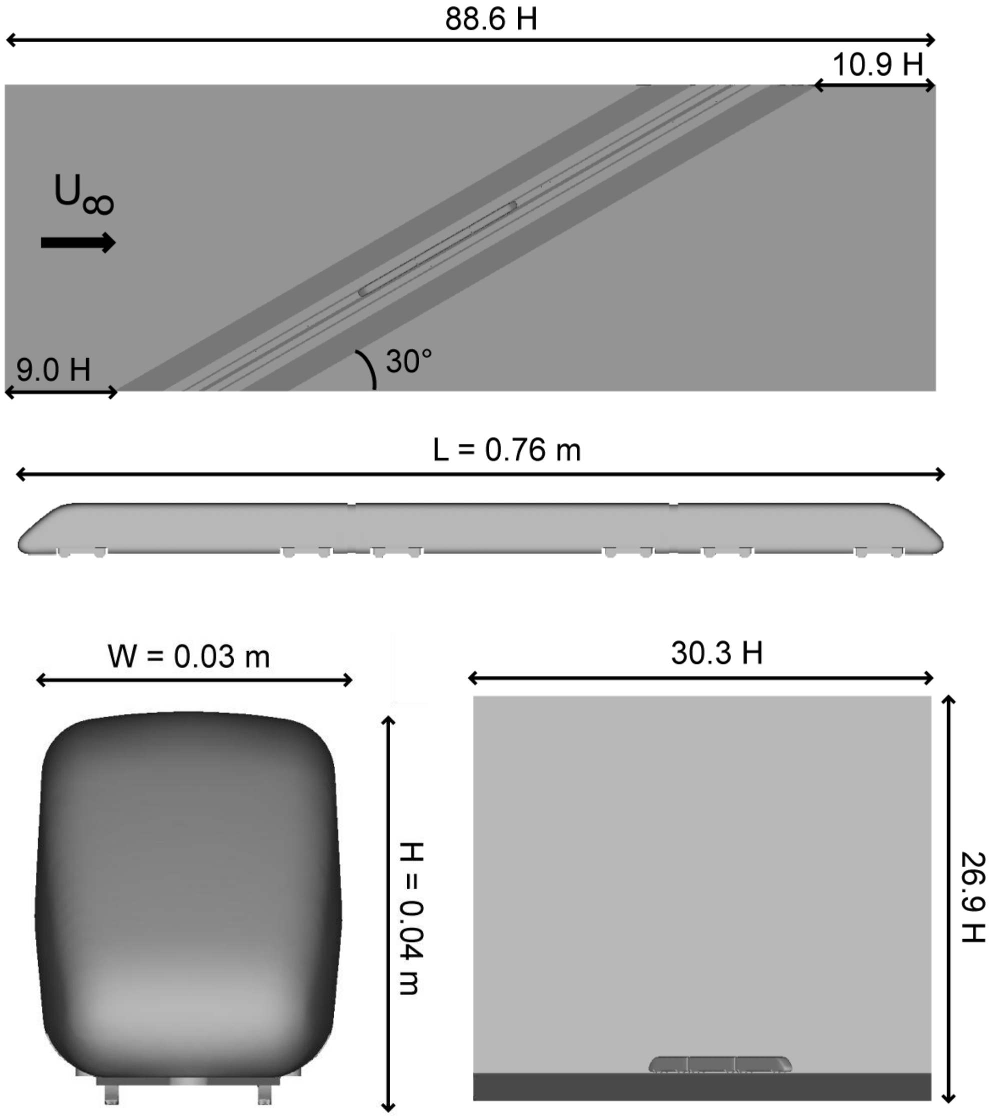
AVL fire™ → modeFRONTIER (the multi-objective optimization and design environment) → SCULPTOR (OPTIMAL SOLUTIONS)

↓

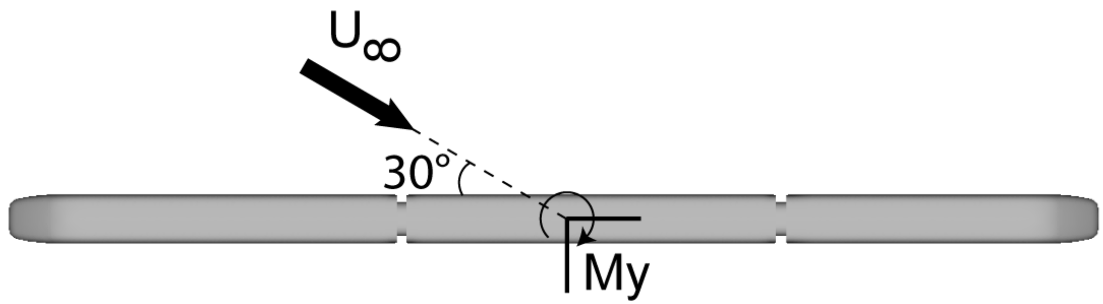
CFD Simulation — AVL fire™ → ↑ Optimization

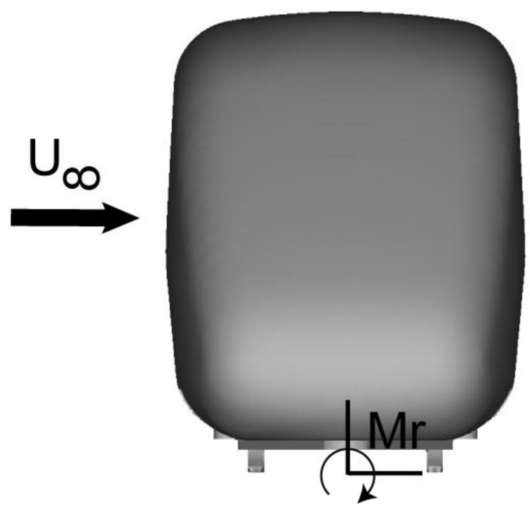


Computational Domain

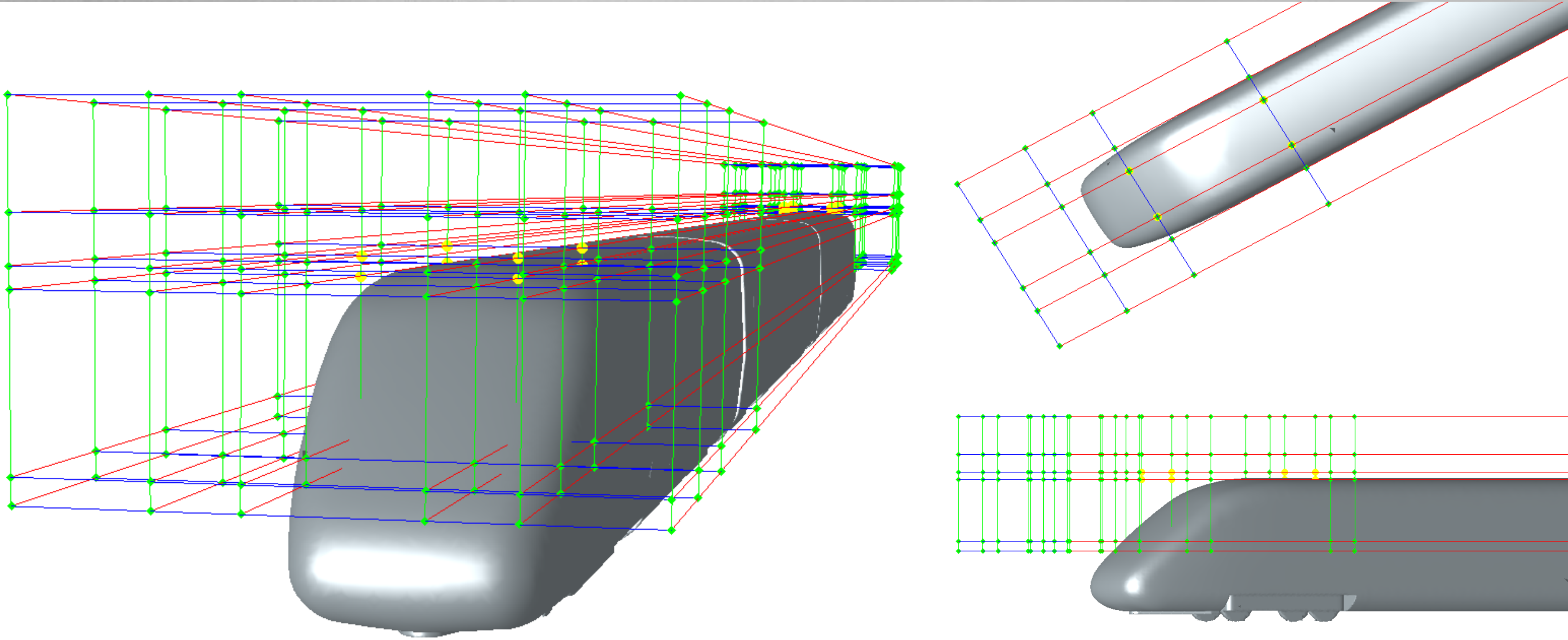


30 side wind
$U_\infty = 30$ m/s



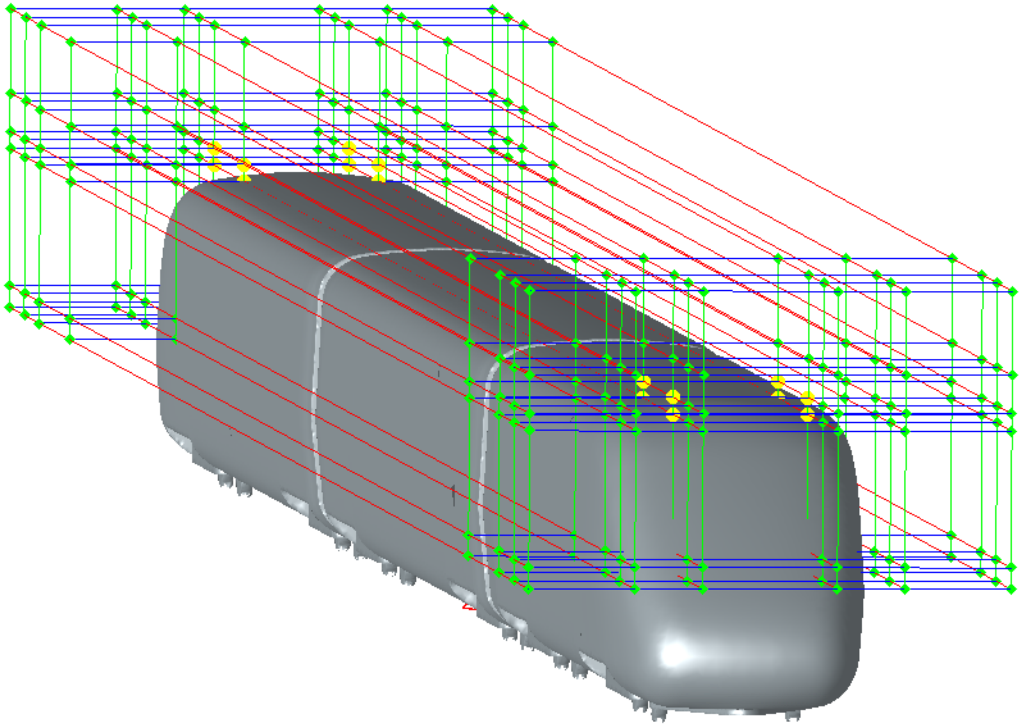


Mesh deformation in Sculptor



Creation of ASD volume

Deforming the train surface in Sculptor



Deformation parameter

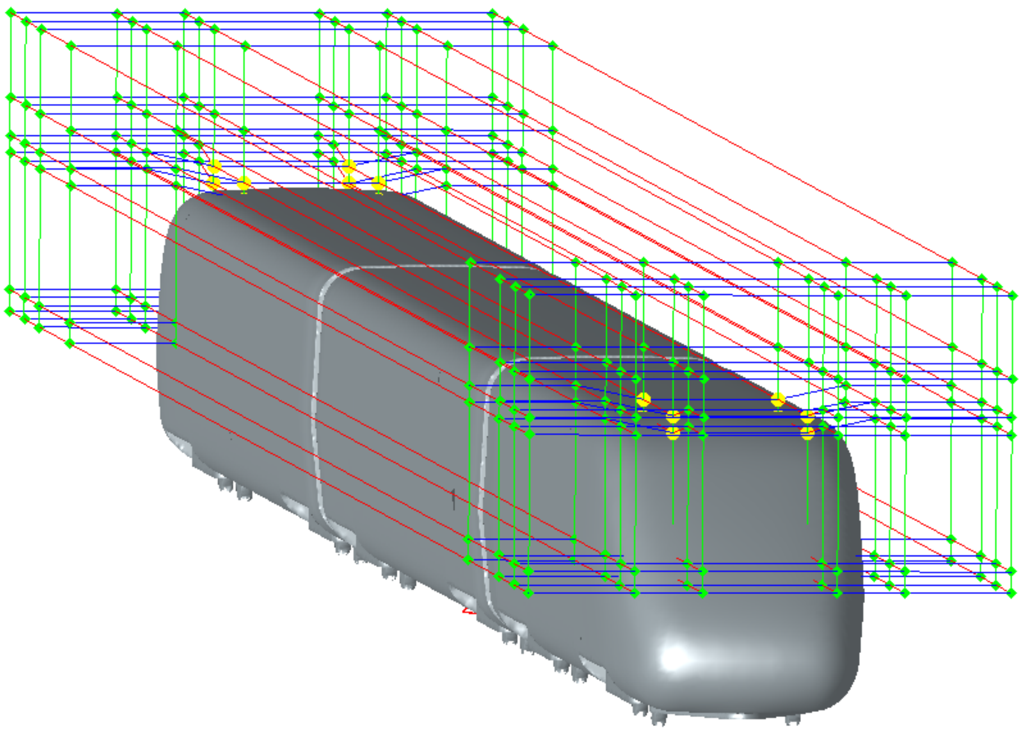
$\Delta_1 \in$ [-0.002,0.004]

$\Delta_2 \in$ [-0.004,0.004]

$\Delta_1 = 0.000$

$\Delta_2 = 0.000$

Deforming the train surface in Sculptor



Deformation parameter

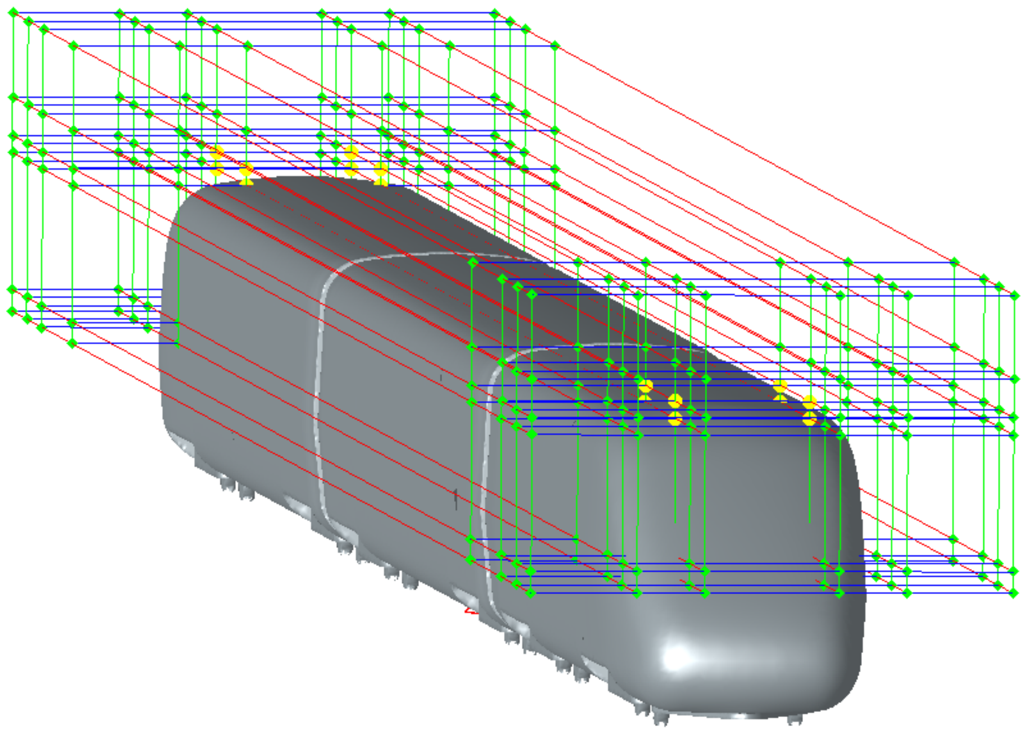
$\Delta_1 \in [-0.002, 0.004]$

$\Delta_2 \in [-0.004, 0.004]$

$\Delta_1 = -0.002$

$\Delta_2 = 0.000$

Deforming the train surface in Sculptor



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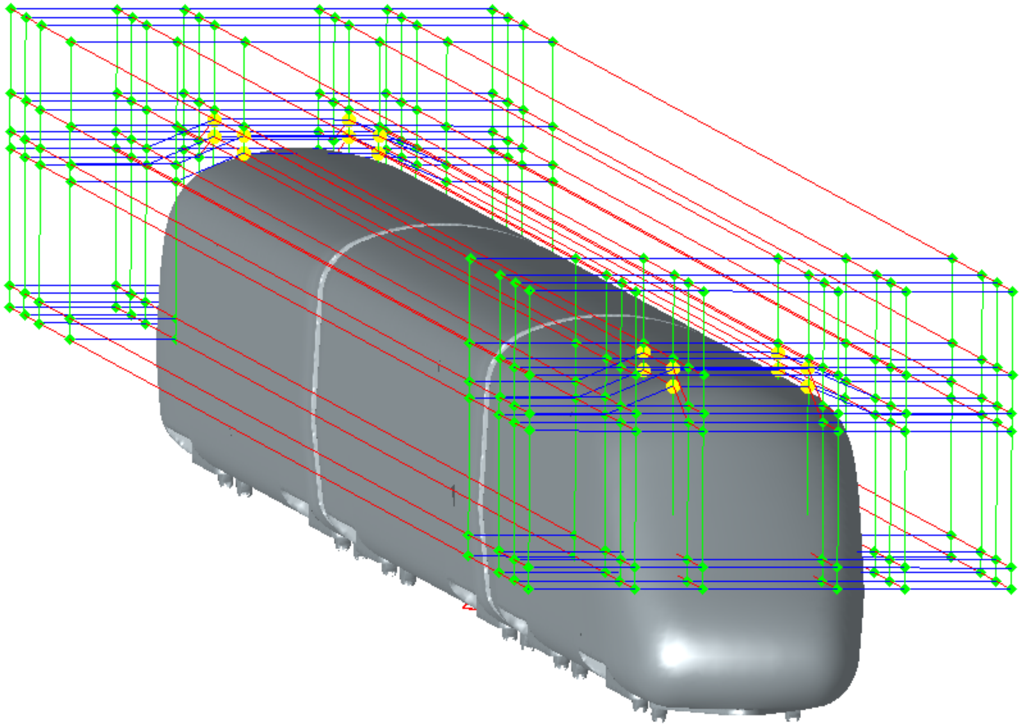

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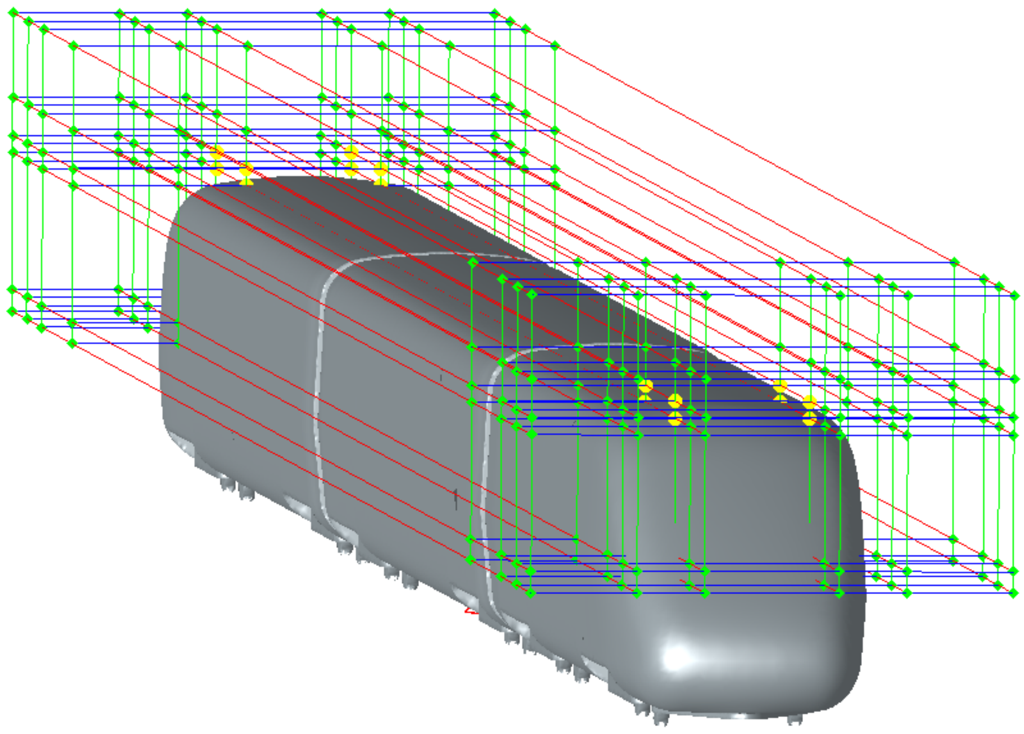

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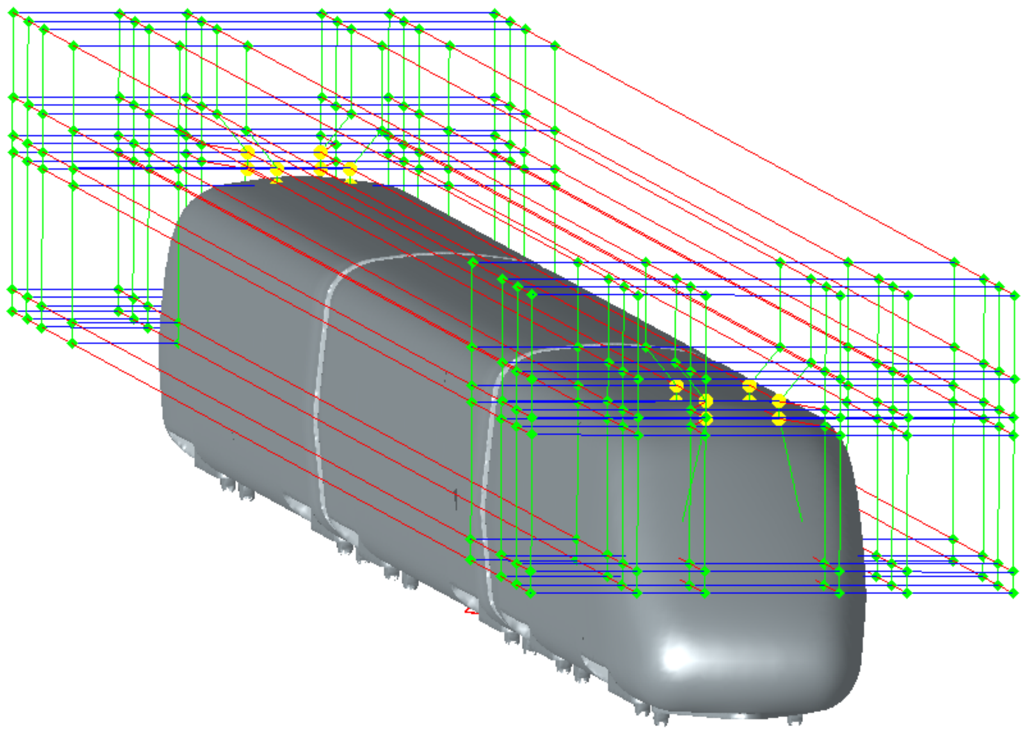
Deforming the train surface in Sculptor



Deformation parameter

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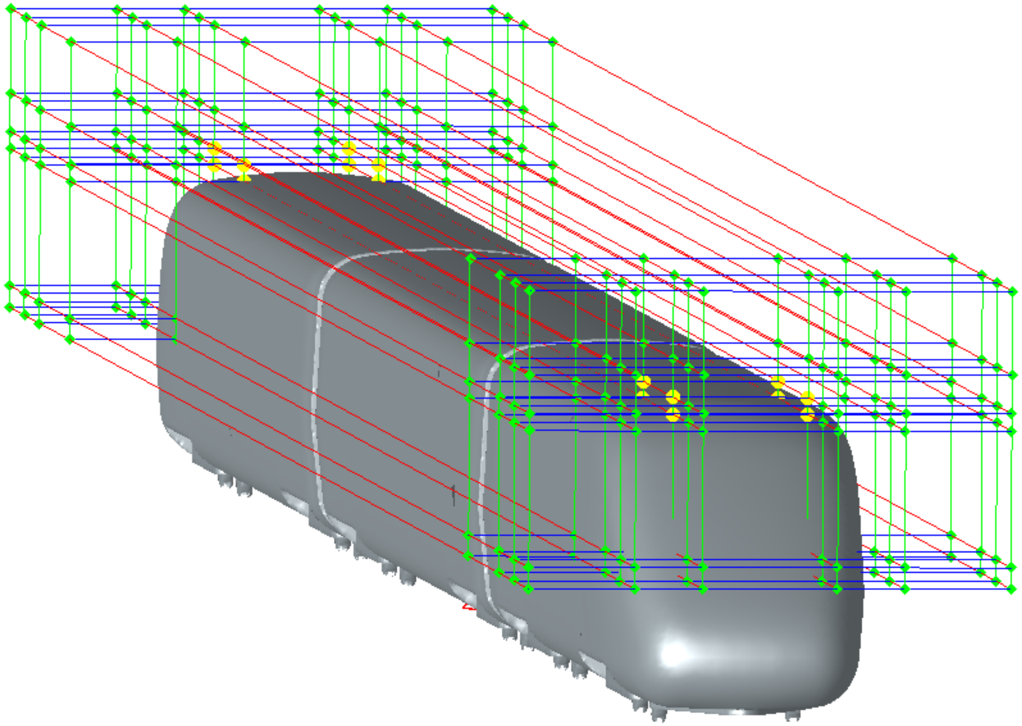

Deformation parameter

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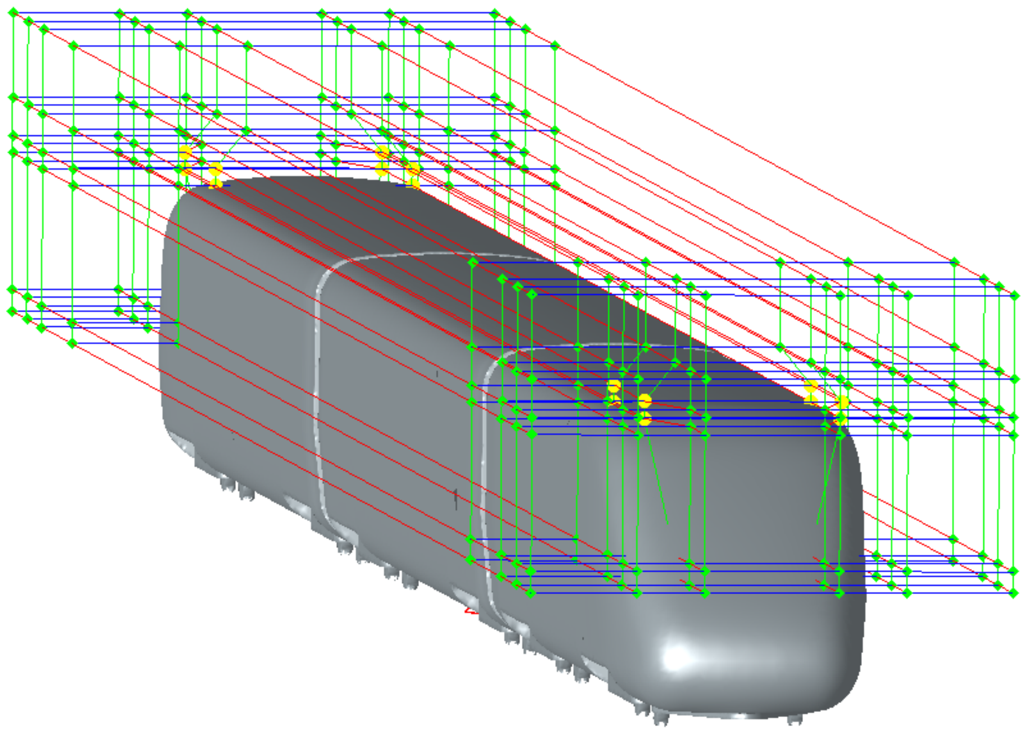

Deformation parameter

$\Delta_1 \in$ [-0.002,0.004]

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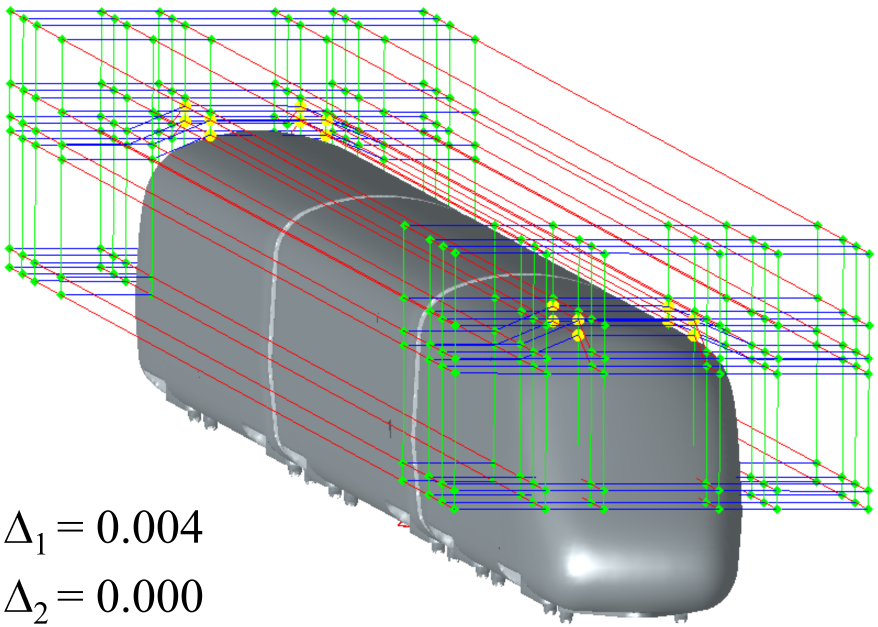
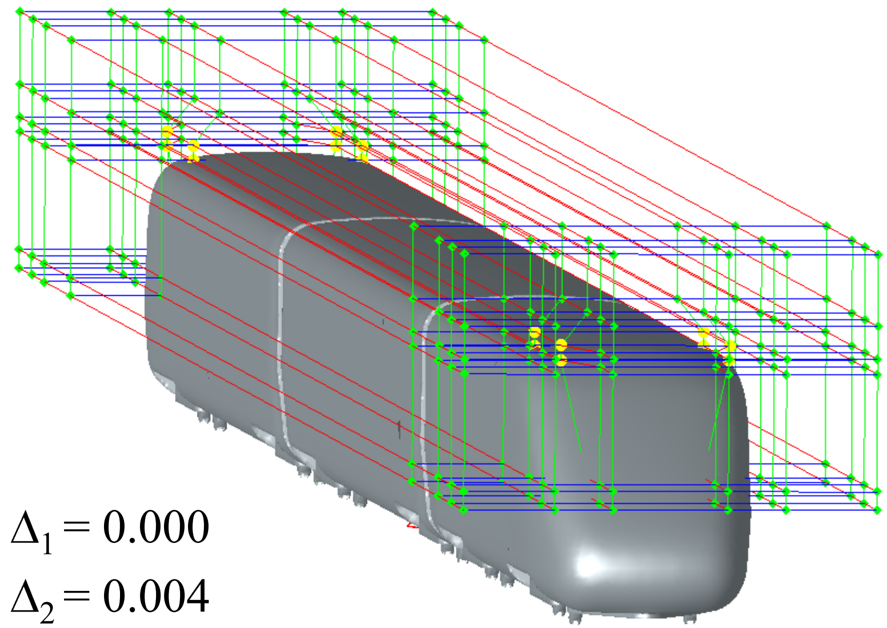
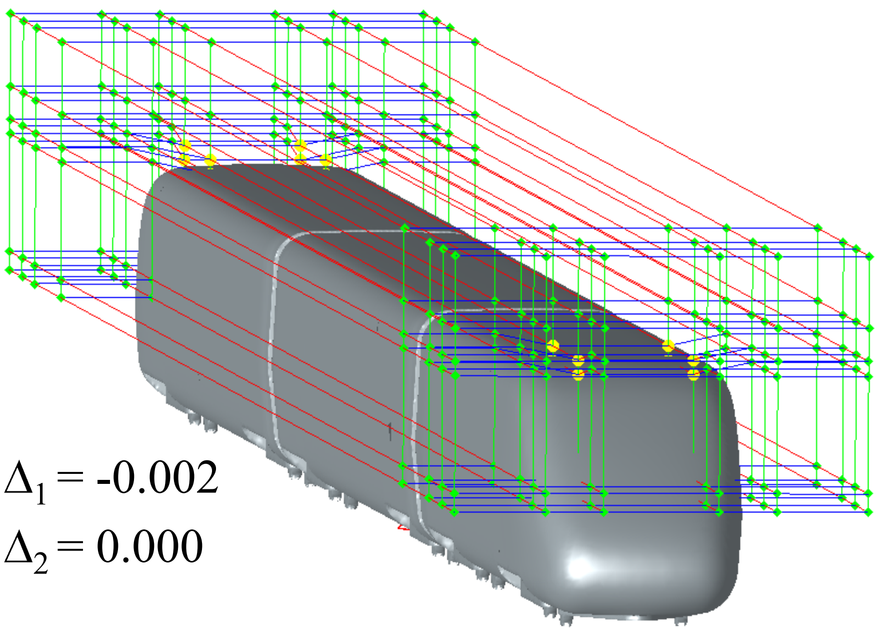
$\Delta_2 = 0.004$



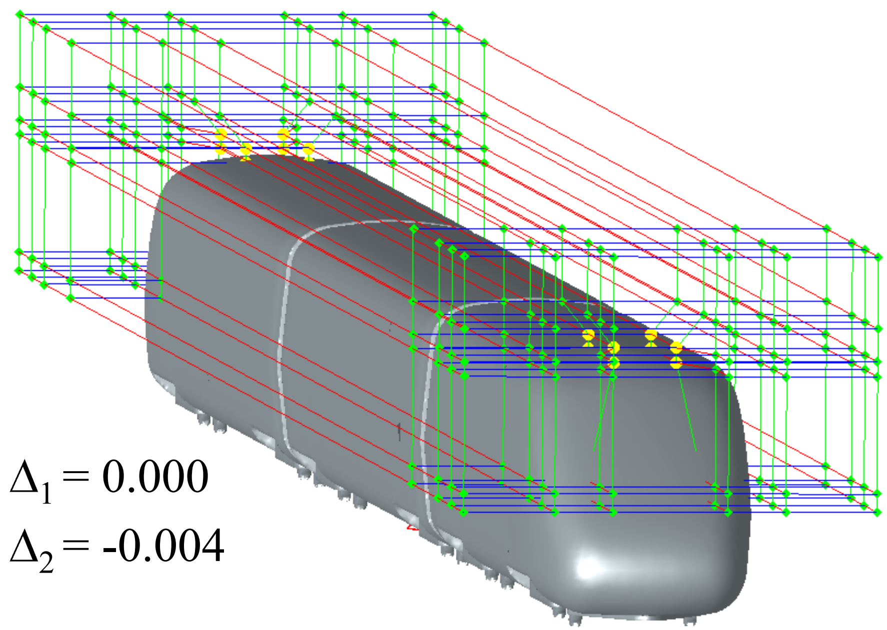
$\Delta_1 = 0.004$
$\Delta_2 = 0.000$



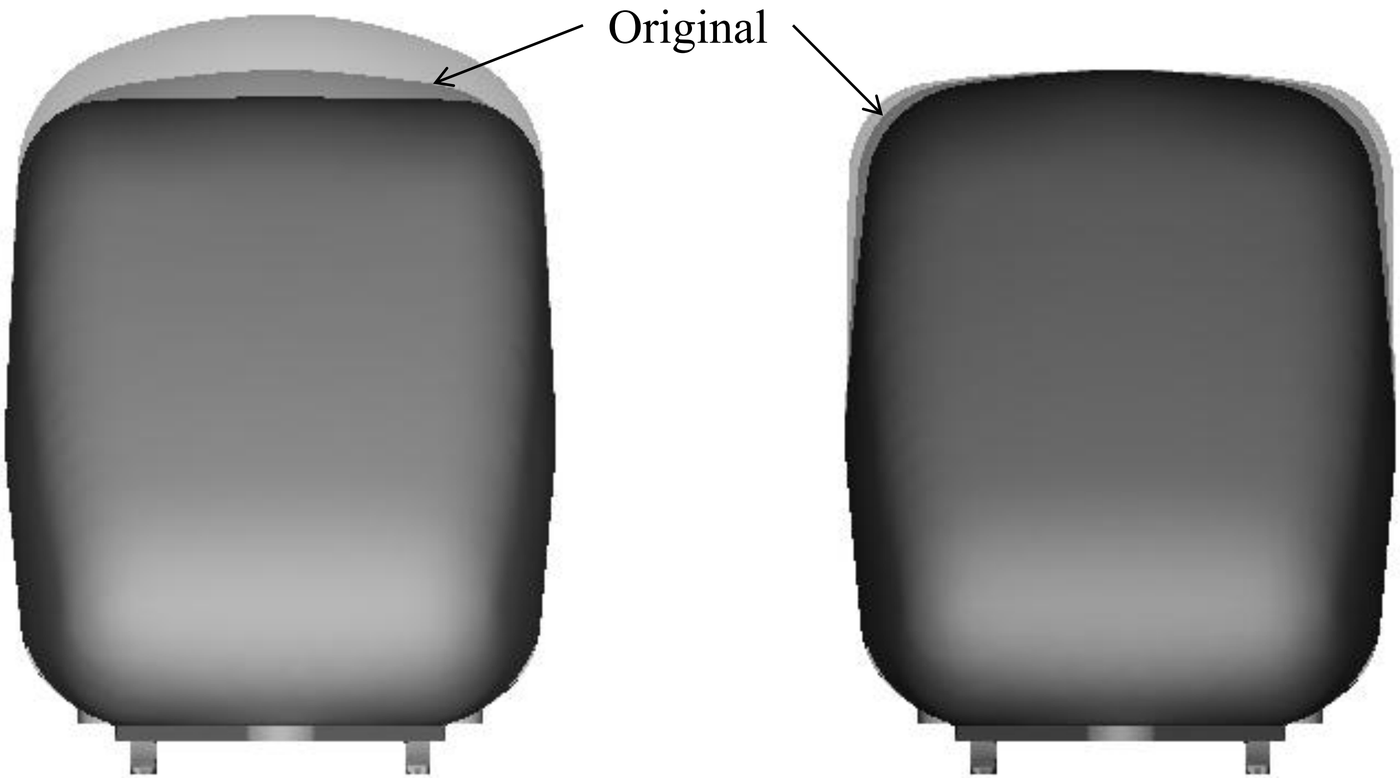
$\Delta_1 = 0.000$
$\Delta_2 = 0.004$



$\Delta_1 = -0.002$
$\Delta_2 = 0.000$



$\Delta_1 = 0.000$
$\Delta_2 = -0.004$



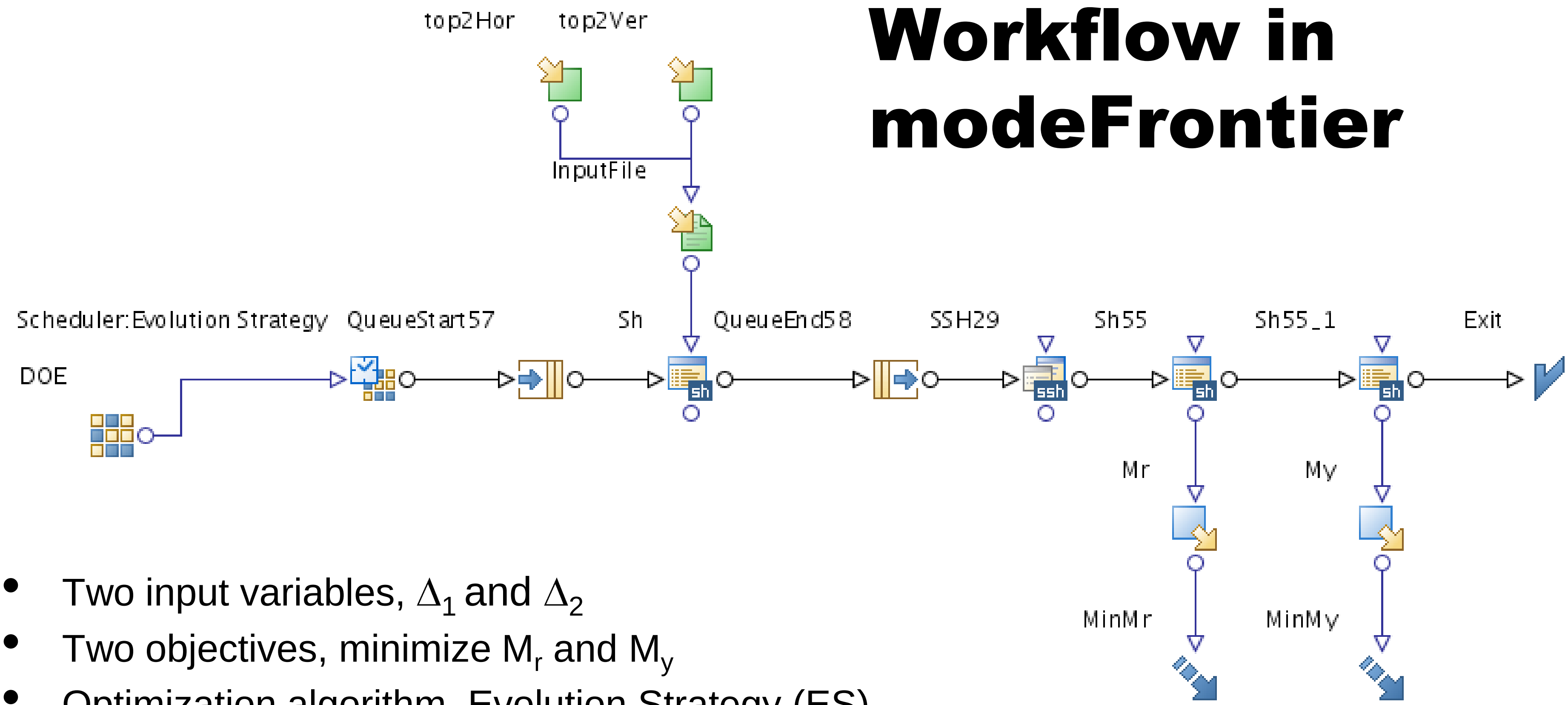
$\Delta_1 \in [-0.002, 0.004]$

$\Delta_2 \in [-0.004, 0.004]$

Optimization

Turb. Model	U_∞ [m/s]	Num. Cells	Deform. Par.	Objective	Opt. Alg
steady k-z-f	30	5 700 000	2	min M_r, M_y	ES

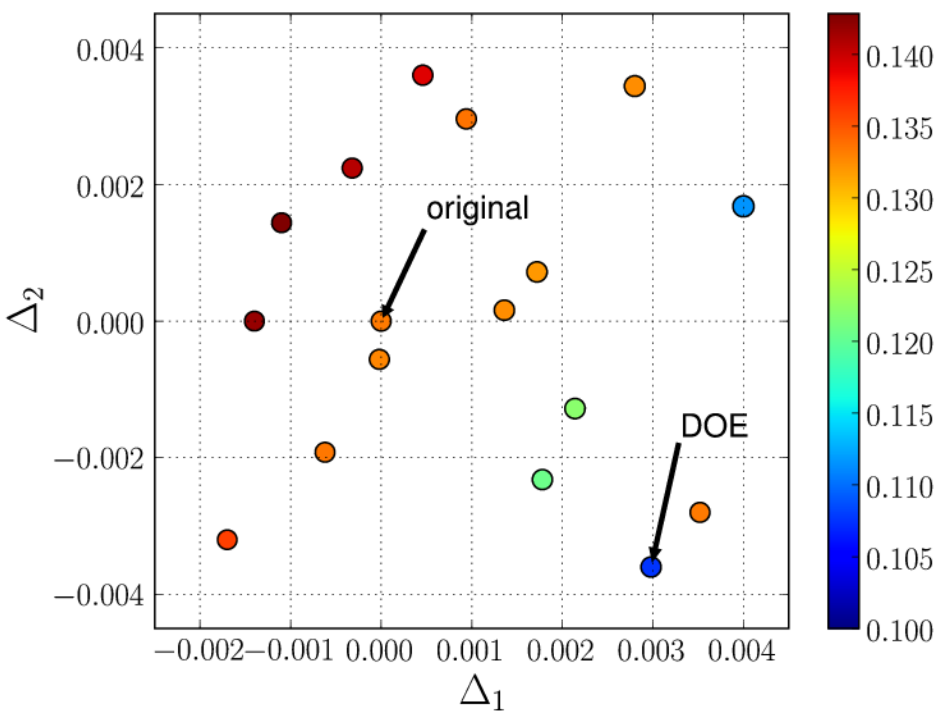
Workflow in modeFrontier

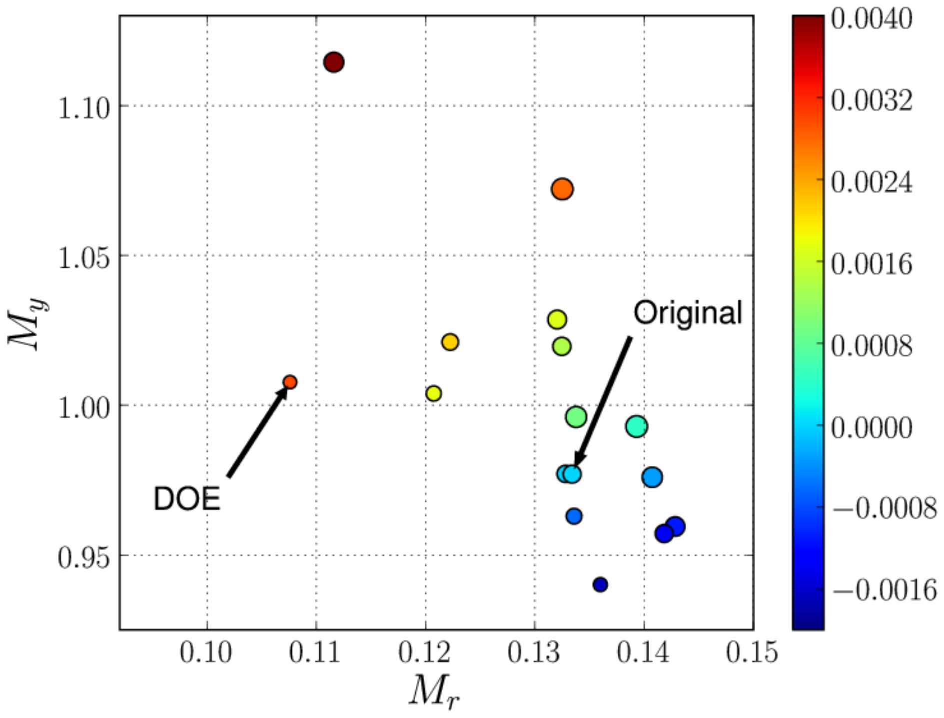


- Two input variables, Δ_1 and Δ_2
- Two objectives, minimize M_r and M_y
- Optimization algorithm, Evolution Strategy (ES)
- modeFrontier and Sculptor run locally
- AVL FIRE® runs on cluster
- Each design is restarted from original train

DOE Points	Concurrent Designs	Size of Generation	Generations	Simulation Time [h]	CPU´s	Total CPU Time [h]
16	8	16	5	5	48	18 000

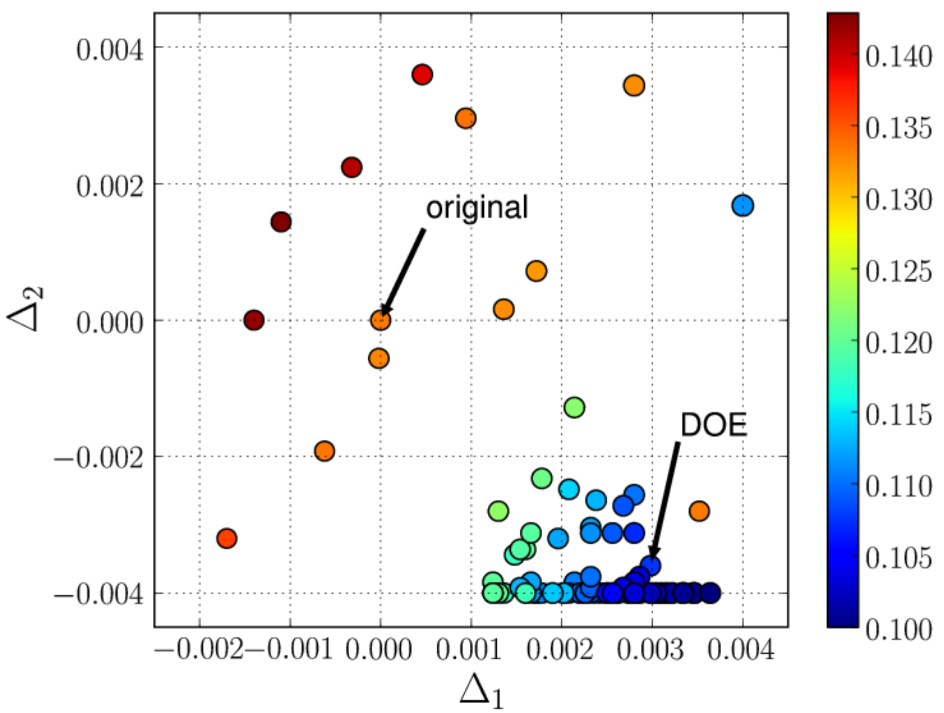
Results

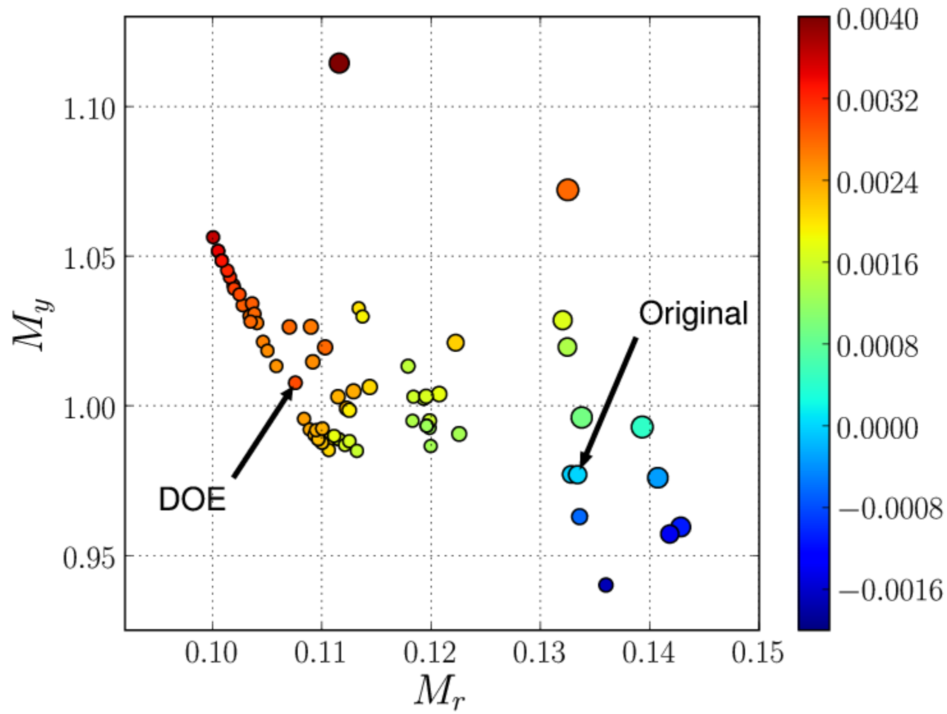




	Δ_1	Δ_2	My [Nm]	%	Mr [Nm]	%
Original			0.98		0.13	
DOE	0.00298	-0.0036	1.01	3.3	0.11	-21.3

Results

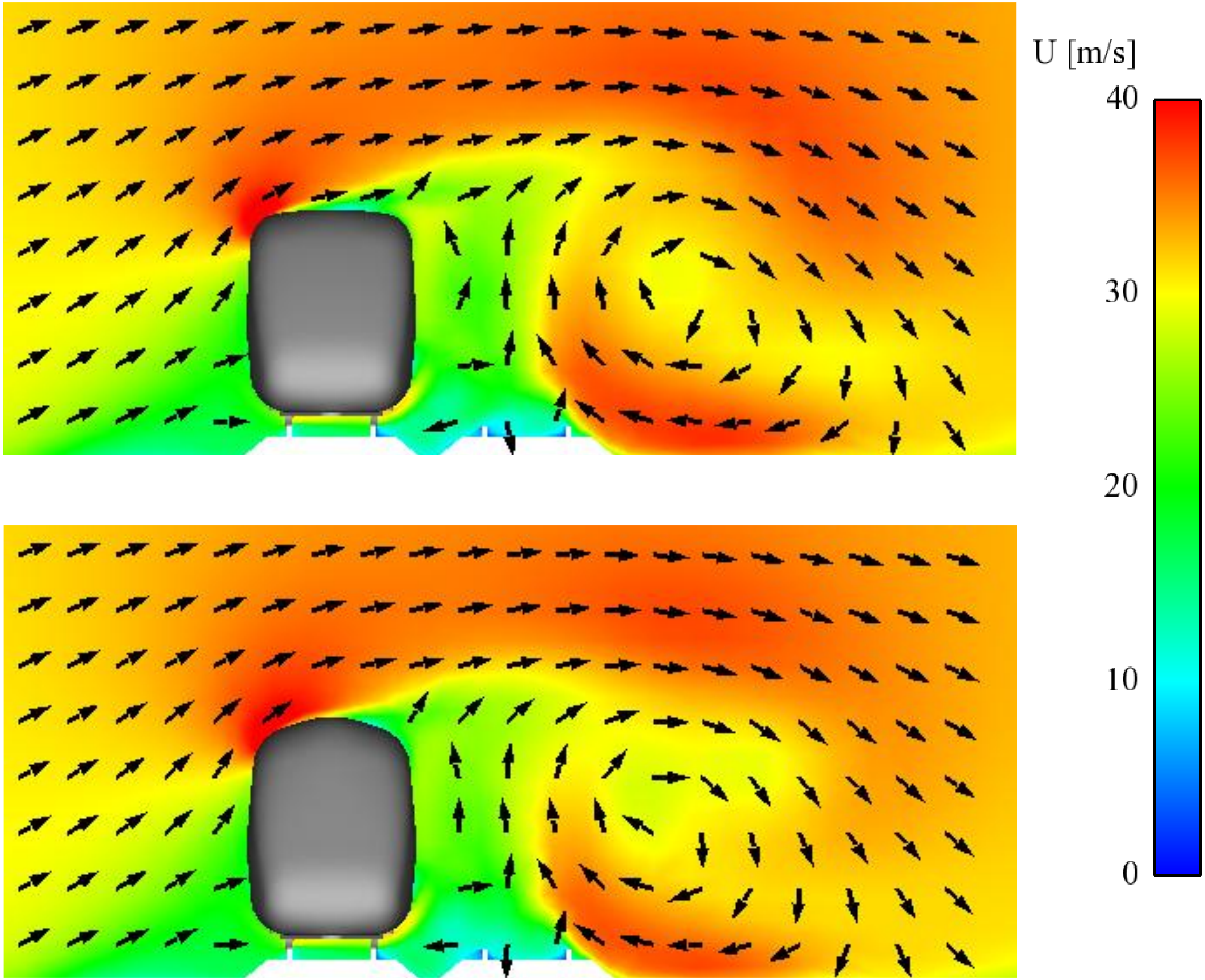




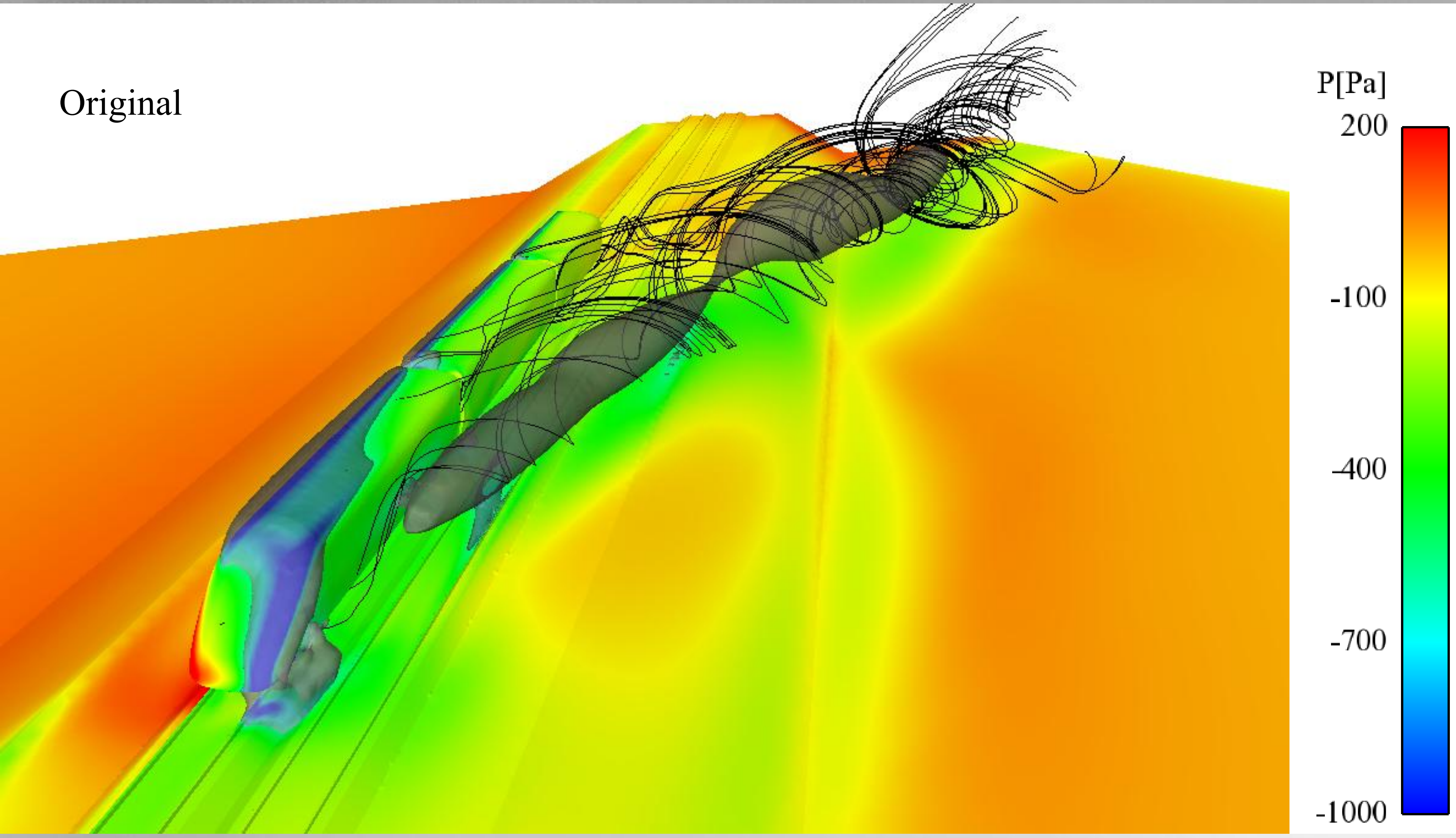
	Δ_1	Δ_2	My [Nm]	%	Mr [Nm]	%
Original			0.98		0.13	
DOE	0.00298	-0.0036	1.01	3.3	0.11	-21.3
ES	0.00364	-0.004	1.06	7.8	0.10	-33.4

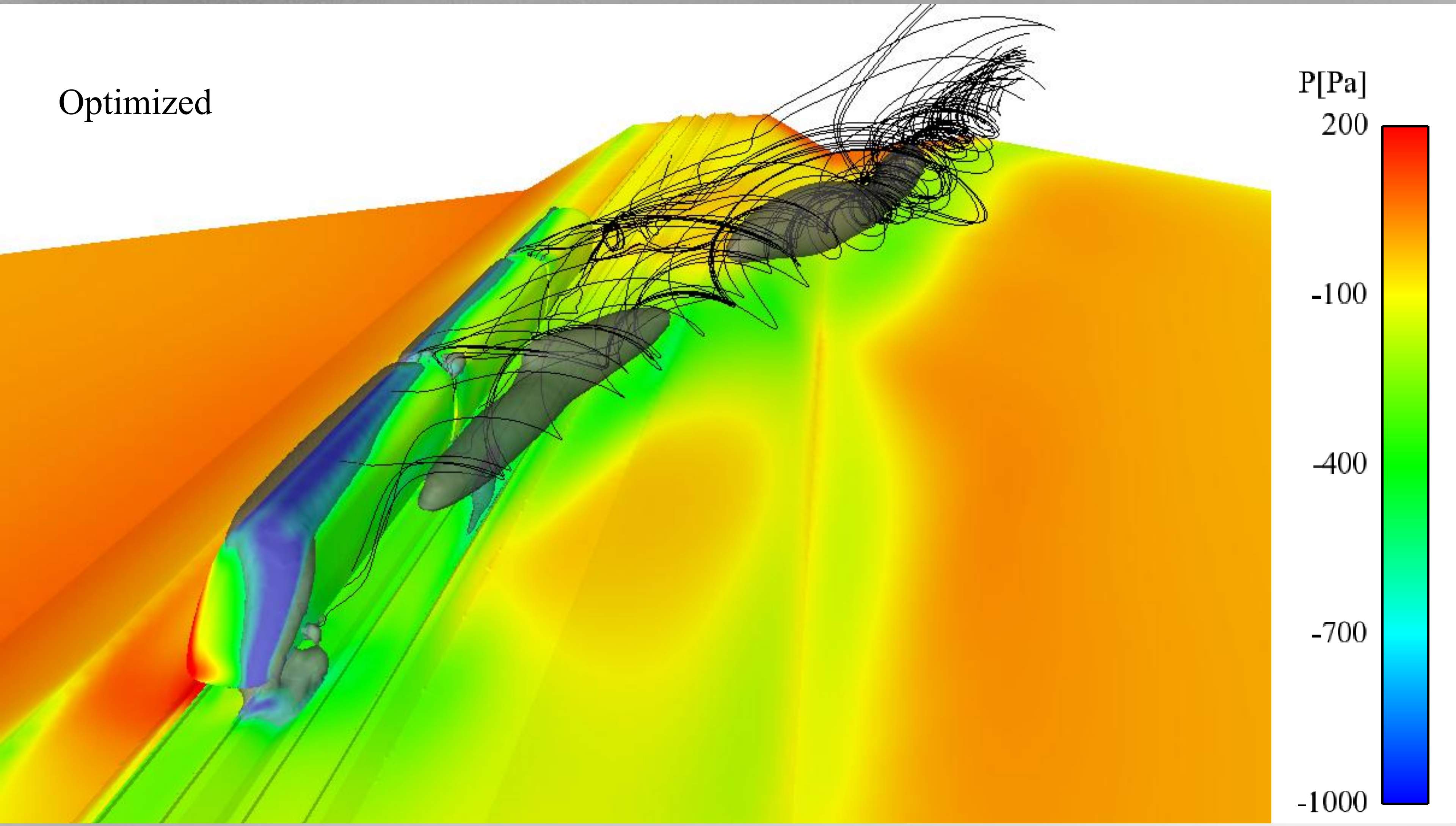
Original

Optimized



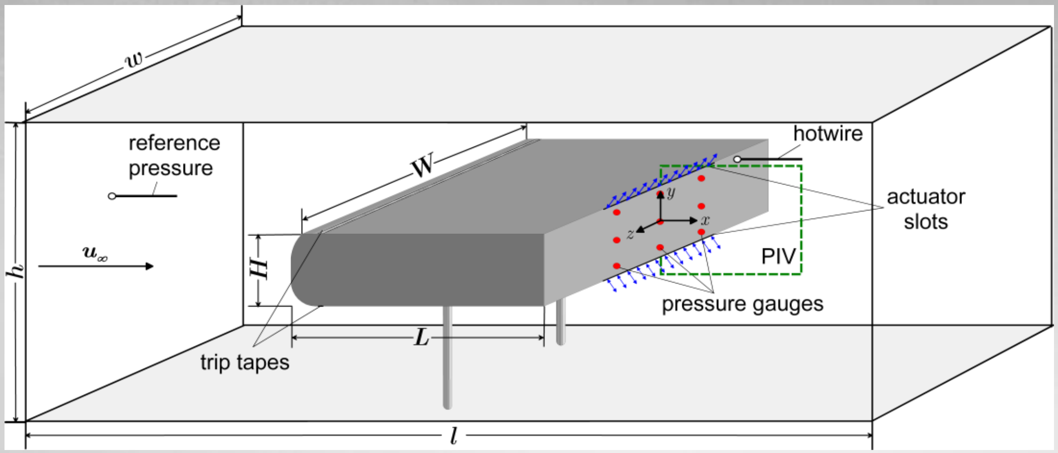
Original




Optimized
P[Pa]
200
-100
-400
-700
-1000

The active flow control problem

1. Reference experimental work

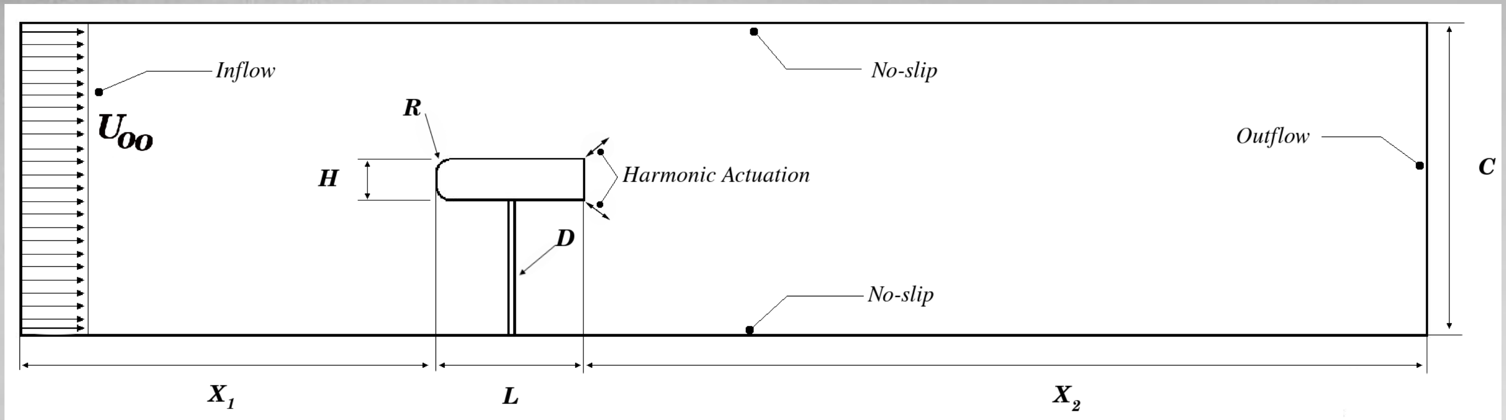


[1] Henning et al. Feedback control applied to the bluff-body wake. In King R. (ed.), *Active Flow Control*, Springer-Verlag, 369-390. 2007.

- Open and closed-loop control;
- Re_h in the range of 2.0 10^4 – 7.0 10^4;
- Harmonic actuation in time through two spanwise slots at 45º with the streamwise direction;
- Drag reduction of ≈15% at St_A=0.17, in-phase actuation.

Model and computational details

3. Boundary conditions:



• At the slots, oscillatory forcing is implemented as:

$$\vec{u}_{slot} = u_A sin(\omega_A t)(cos(\phi)\hat{i} + sin(\phi)\hat{j})$$

•The actuation amplitude follows from momentum coefficient:

$$C_\mu = \frac{4s}{H}\frac{u_A^2}{U_\infty}$$

Model and computational details

4. Resolution and numerical details:

	$y^+ = yu^*/\nu$	$\Delta z^+ = \Delta z u^*/\nu$	$\Delta x^+ = \Delta x u^*/\nu$
Mean	1.06	30.02	13.78
Maximum	4.78	146.63	146.32

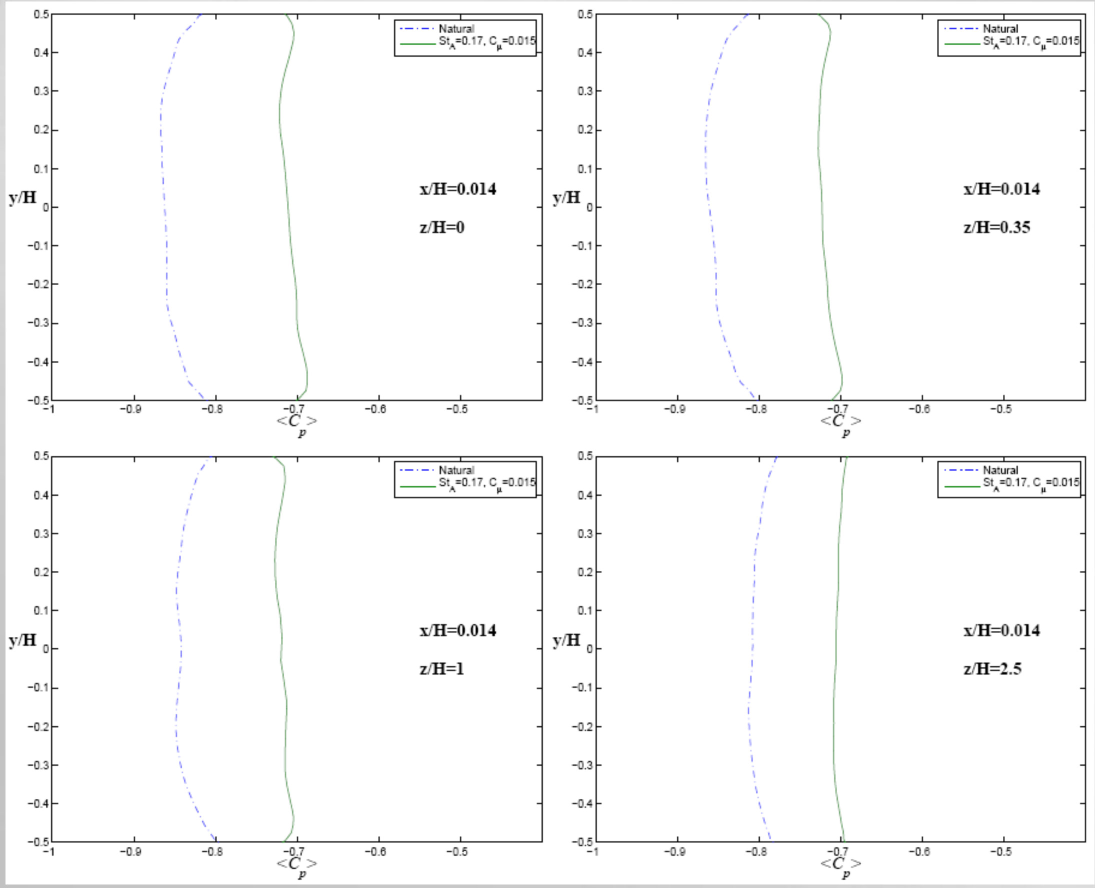
Table 4.1: Spatial resolution in the LES at $Re_h = 2 \times 10^4$.

- Total number of nodes ≈ 5.5 10^6;
- Spatial resolution acording to $y^+ < 2,\ \Delta z^+ \approx 15 - 40 \text{ and } \Delta x^+ \approx 50 - 150$
- Physical time step = 1.0 10^{-4};
- 96.5% of the cells with CFL < 1;
- Space discretization: 2nd order central differences;
- Temporal discretization: Three-time-level Scheme (implicit second order scheme);
- Solution algorithm: SIMPLE;
- Turbulence model: LES – Smagorinsky Model; C_s=0.1.

Drag control results

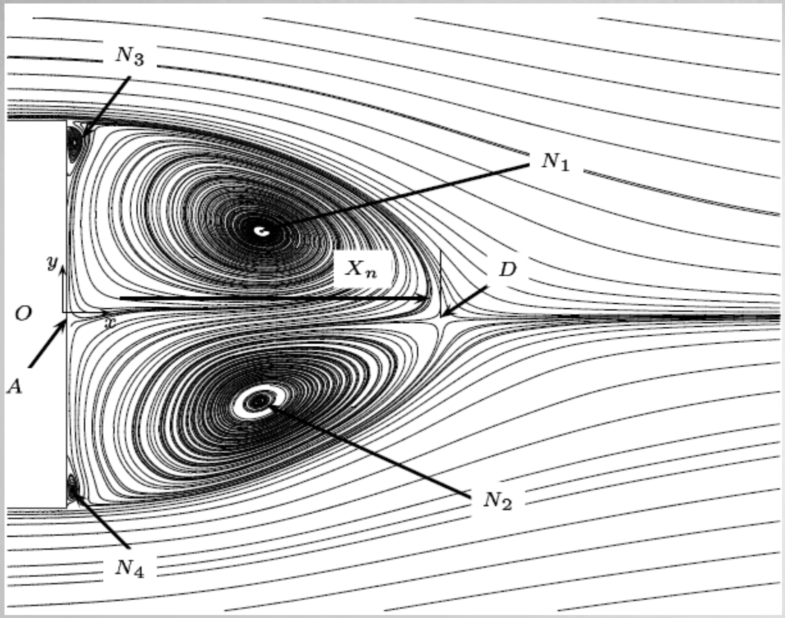
Drag control results from the LES at $Re_h=2\ 10^4$, $St_A=0.17$ and $C_\mu=0.015$:

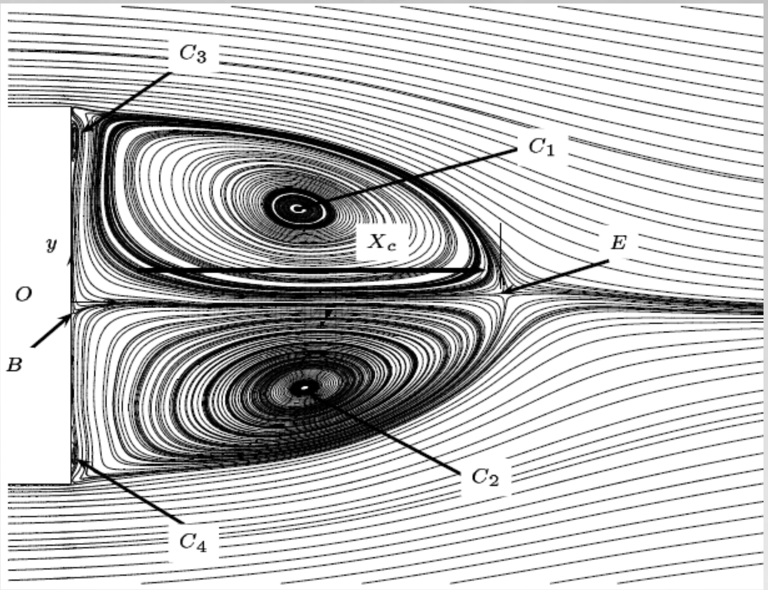
- 11% drag reduction achieved;
- 20% pressure recovery in the near-wake region;



Exploring the flow

The time-averaged flow:

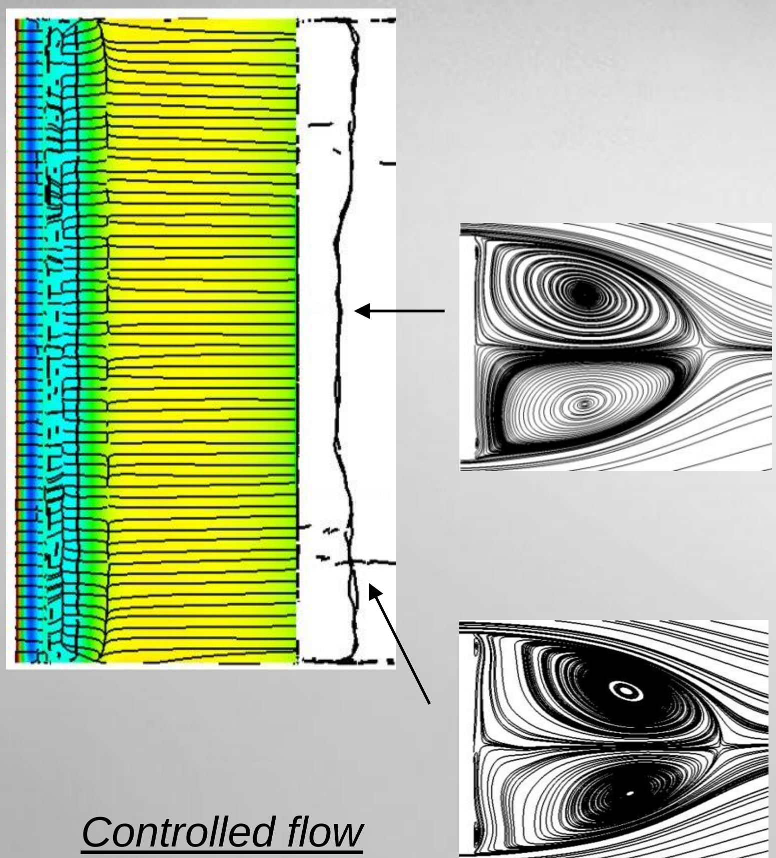




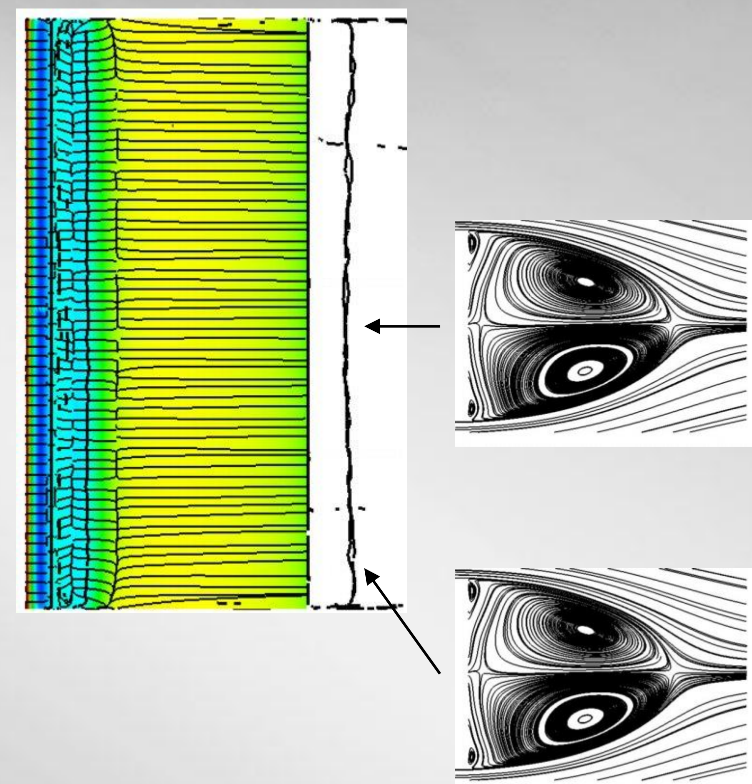
Natural flow *Controlled flow*

- Reduction of the thickness of the upper and lower edge thin vortices;
- Foci C_1/C_2 and the saddle point are displaced further downstream by 20% from their streamwise locations in the natural case.

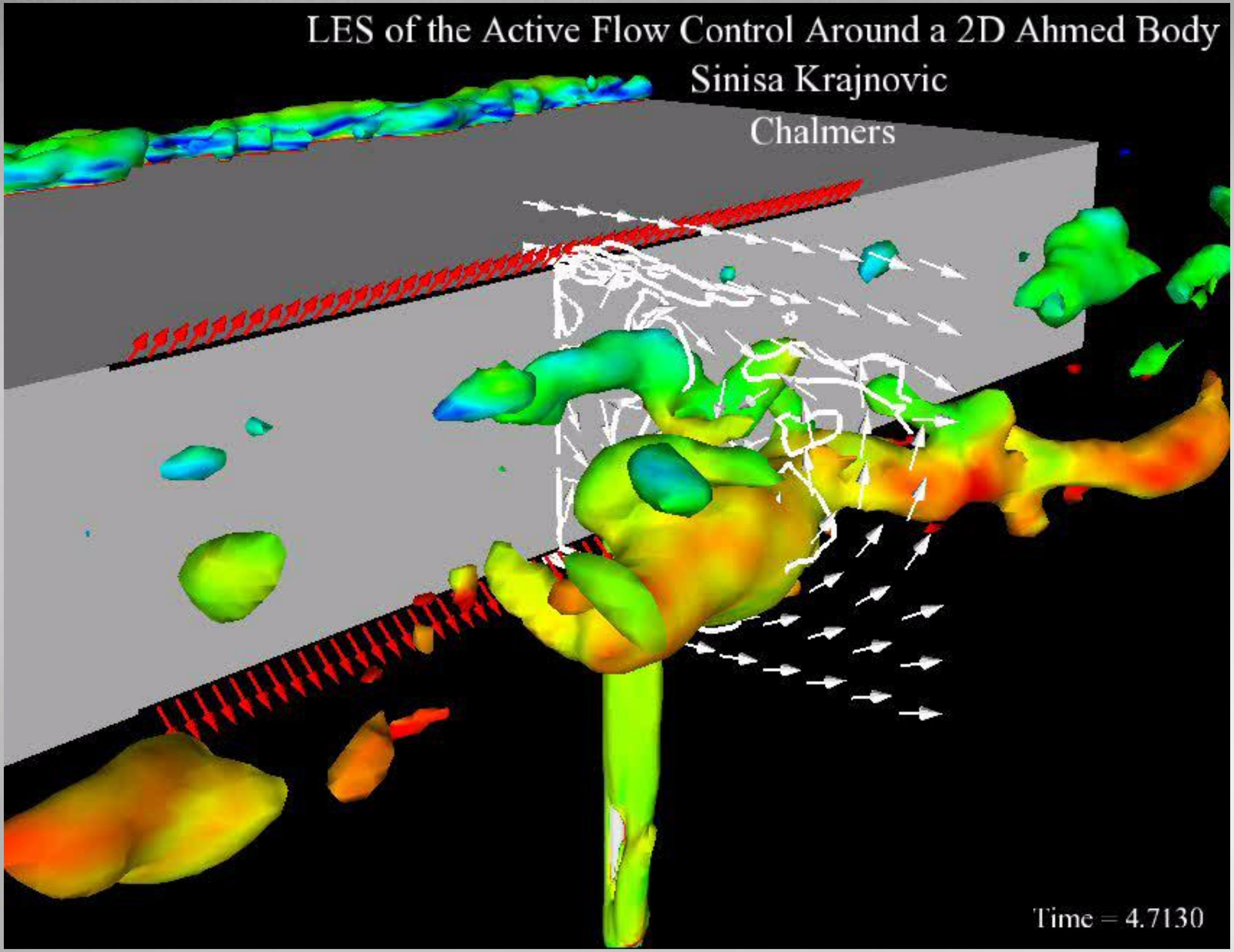
Comparison of time-averaged flows



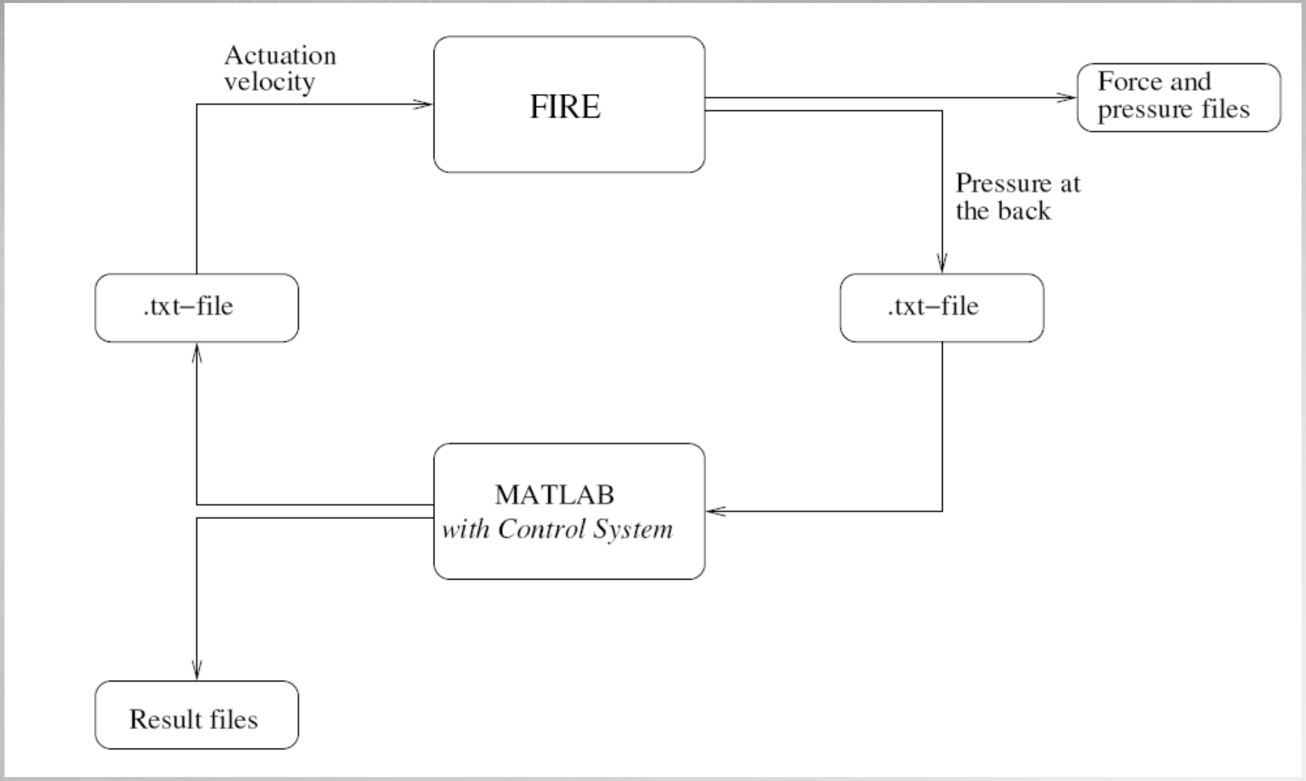
Controlled flow



Natural flow


LES of the Active Flow Control Around a 2D Ahmed Body
Sinisa Krajnovic
Chalmers
Time = 4.7130

How the communication beetween Matlab and Fire works



Phase control