Fast and cost efficient CFD optimization by means of adjoint and RBF mesh morphing: a perspective from Dallara

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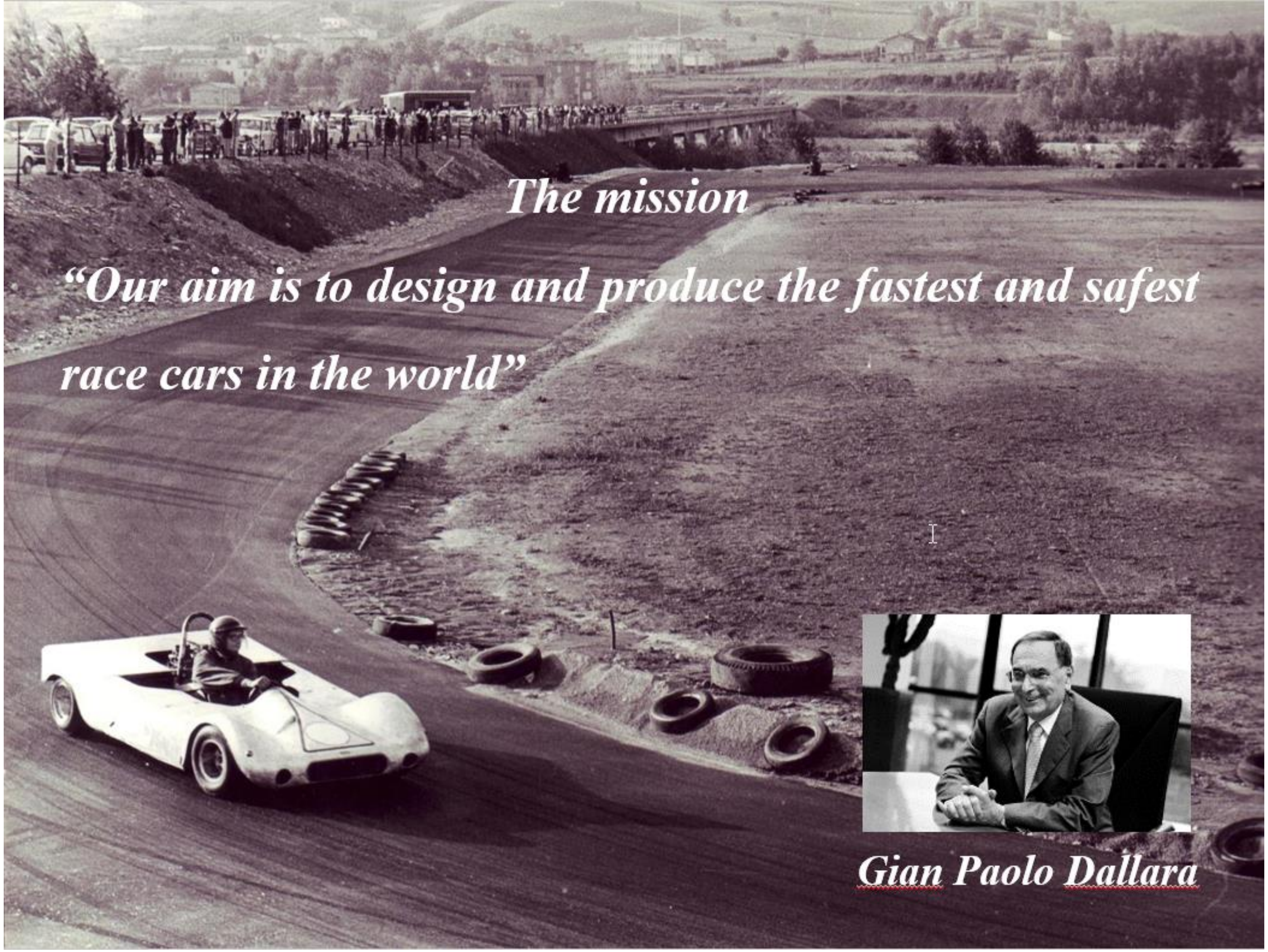
[b] University of Rome «Tor Vergata», Roma, italy



The mission

"Our aim is to design and produce the fastest and safest race cars in the world"

Gian Paolo Dallara

Dallara Group

Dallara
Varano de' Melegari, Parma

Dallara Compositi
Collecchio, Parma

Dallara Indycar Factory
Speedway, Indiana

Products

Championships

IndyCar

LMP1

LMP2

Formula 2

Indy Lights

Formula 3

Formula E

Super Formula

GP3

RS01

Services

Consultancy

Haas Formula 1 Team

Cadillac DPi

Bugatti Chiron

Lamborghini Aventador

Lamborghini Huracan GT3

Lamborghini Huracan Supertrofeo

Bugatti Vision Gran Turismo

Alfa Romeo 4C

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Products

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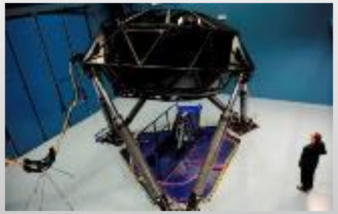
Core Competencies

Concept/Regulations

1. Advanced Composite Materials

2. Aerodynamics



3. Vehicle Dynamics

4. Prototyping and Production

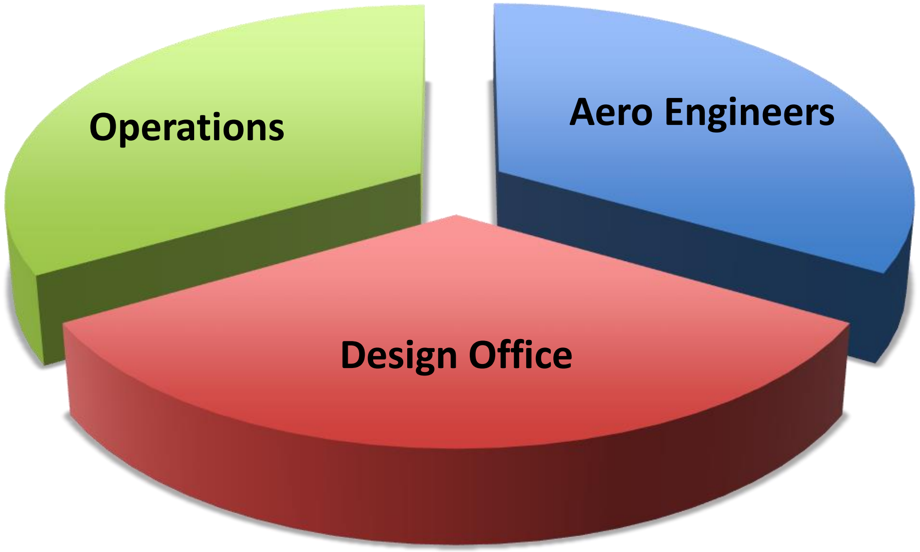
Aerodynamics

Over 30 years of experience & Mostly on consultancies for third parties

EFFICIENT & FLEXIBLE AERODYNAMIC DEVELOPMENT PROCESS

Applying advantages of the motorsport process to any project
Tailoring the budget to the clients’ expectations

Dallara’s aerodynamic department is composed by a highly specialized team of over 100 people:



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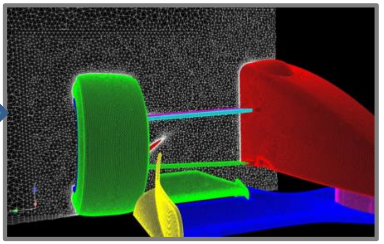
Aerodynamics

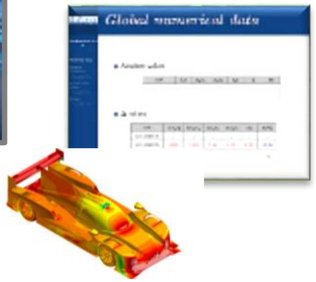
CFD PROCESS

PRE-PROCESSING



CALCULATION

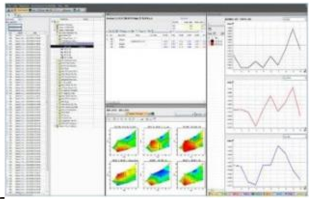
POST-PROCESSING



CONCEPT &DESIGN

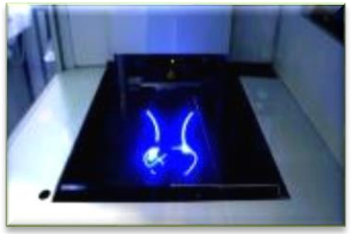
DALLARA AERODYNAMIC PROCESS

DATA ANALYSIS



WT PROCESS

PRODUCTION



PREFITTING

TESTING

Aerodynamic Development

CFD Department

The CFD tools are deeply involved in the aerodynamic application for racing car and motorcycles development, combining a great potential related to the HPC innovation and mathematical models evolution with time and cost control.

- Over **40 Teraflops** of CFD computational capacity
- **Over >2500** complete car CFD runs / year
- Typical straight line car simulation with **350M cells / CFD run**
- Different car configurations tested (Mapping)

PRODUCT

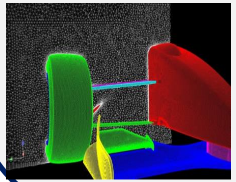
Vehicle performance and cooling development

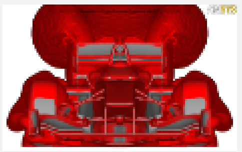
PROCESS

Implementation of new methodologies and tools aimed at improving the CFD process and product simulations performances.

AUTOMATED PROCESS PHASES

PRE-PROCESSING (volume mesh)	RUN	POST-PROCESSING
TGRID ANSYS	FLUENT SOLVER	FIELDVIEW/ENSIGHT





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CFD workflow

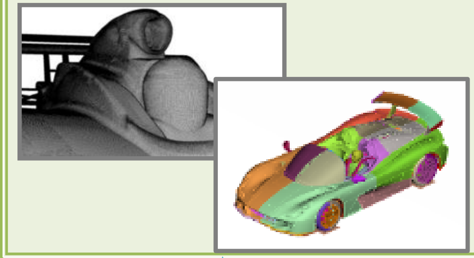
CFD automated process phases

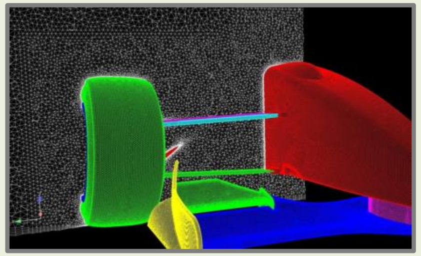
PRE – PROCESSING
(batch surface mesh and morphing)
ANSA BETA CAE

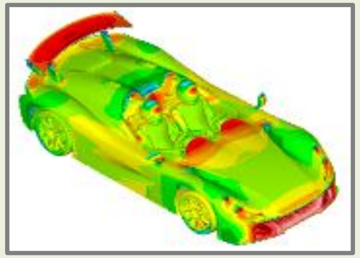
PRE – PROCESSING
(volume mesh)
TGRID

RUN
(CFD solver)
FLUENT

POST – PROCESSING
FIELDVIEW/ENSIGHT



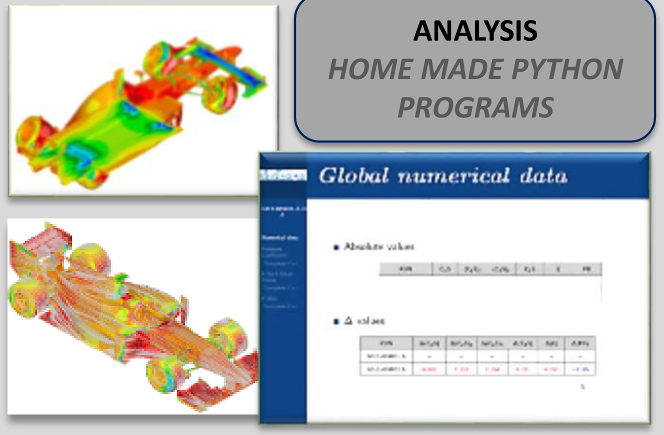




CFD human process phases

CONCEPT AND DESIGN
CREO PTC and PID splitting

ANALYSIS
HOME MADE PYTHON PROGRAMS



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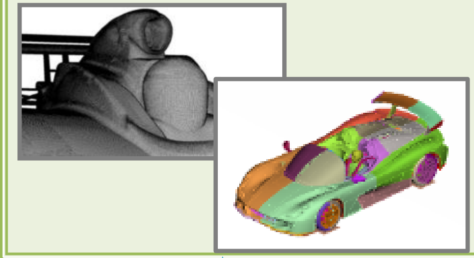
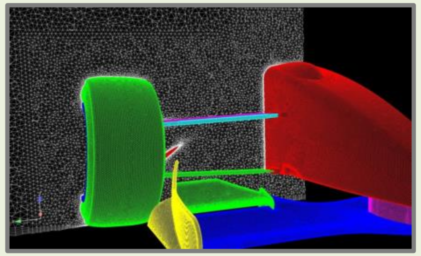
CFD workflow

CFD automated process phases

PRE – PROCESSING
(batch surface mesh and morphing)
ANSA BETA CAE

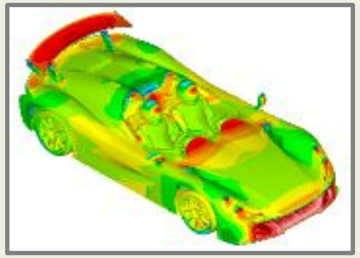


PRE – PROCESSING
(volume mesh)
TGRID



RUN
(CFD adjoint solver, volume mesh morphing)
FLUENT + RBF MORPH

POST – PROCESSING
FIELDVIEW/ENSIGHT



CFD human process phases

CONCEPT AND DESIGN
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ANALYSIS
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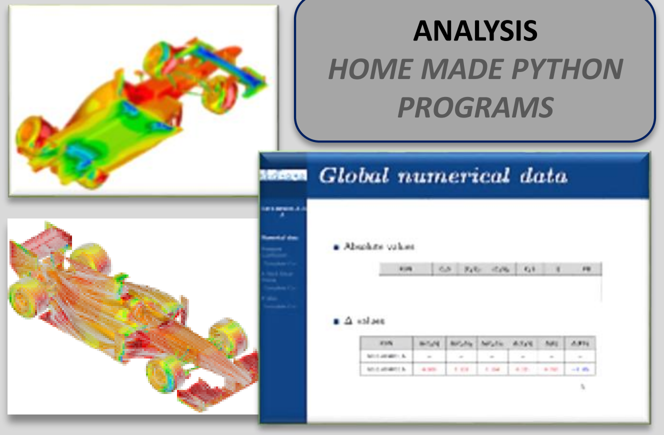

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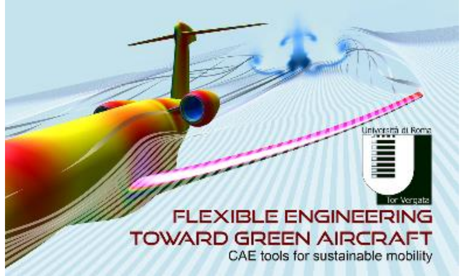
University of Rome Tor Vergata

Department of Enterprise Engineering composed by 90 full time employees, 80 contract researchers. Research team, from Machine Design Group, involved in **several national and international research projects**.

- Structural and fluid dynamic shape optimization (**automotive**, nautical, aerospace, biomedical, energy).
- Static and dynamic **F**luid **S**tructure **I**nteraction.
- Advanced use of **R**adial **B**asis **F**unctions coupled with **Adjoint** sensitivities.
- Large-scale **high-fidelity** numerical simulations of flows in complex geometric configurations.
- **R**educed **O**rder **M**odels and Digital Twin.



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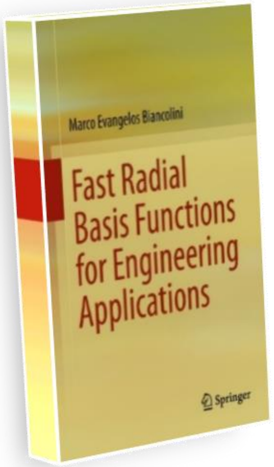
Radial Basis Functions mesh Morphing

Radial Basis Functions (RBF) drive mesh morphing (smoothing) from a list of source points and their displacements.

- Surface shape changes
- Volume mesh smoothing.

RBF are recognized to be one of the **best mathematical tool** for mesh morphing.

$$\begin{cases} s_x(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^x \varphi\left(\left\|\boldsymbol{x} - \boldsymbol{x}_{s_i}\right\|\right) + \beta_1^x + \beta_2^x x + \beta_3^x y + \beta_4^x z \\ s_y(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^y \varphi\left(\left\|\boldsymbol{x} - \boldsymbol{x}_{s_i}\right\|\right) + \beta_1^y + \beta_2^y x + \beta_3^y y + \beta_4^y z \\ s_z(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^z \varphi\left(\left\|\boldsymbol{x} - \boldsymbol{x}_{s_i}\right\|\right) + \beta_1^z + \beta_2^z x + \beta_3^z y + \beta_4^z z \end{cases}$$



Biancolini, M. E. (2017). Fast radial basis functions for engineering applications. Springer International Publishing.

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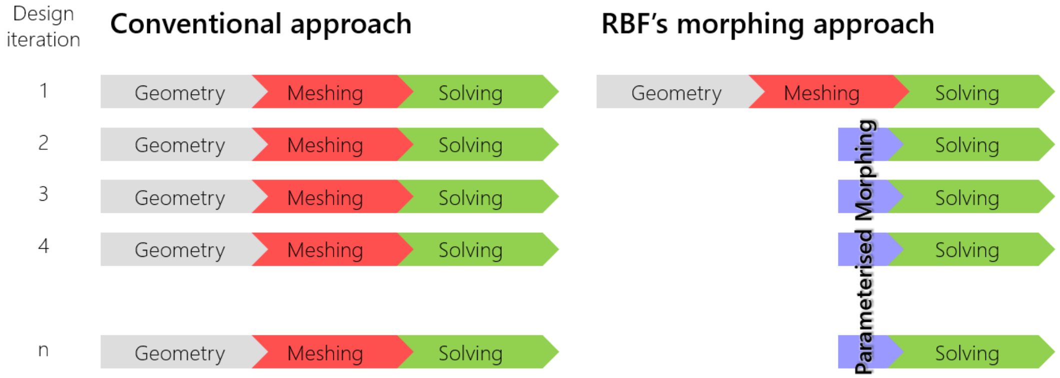
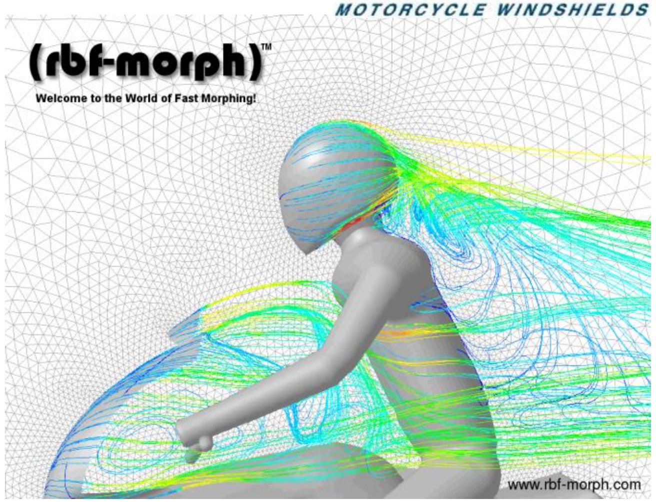
Parametric CAE models

CAE models supported includes flow analysis (CFD) and structural analysis (FEM)

RBF Morph makes the CAE model parametric with respect to the shape.





Works for any size of the mesh.

It's **easy and fast**: shape parameters are defined in the CAE GUI. No need to iterate the CAD.

Shape parameters can be steered with the optimizer of choice.

The turnaround time of the optimization is usually **reduced by a factor five** (weeks become days)

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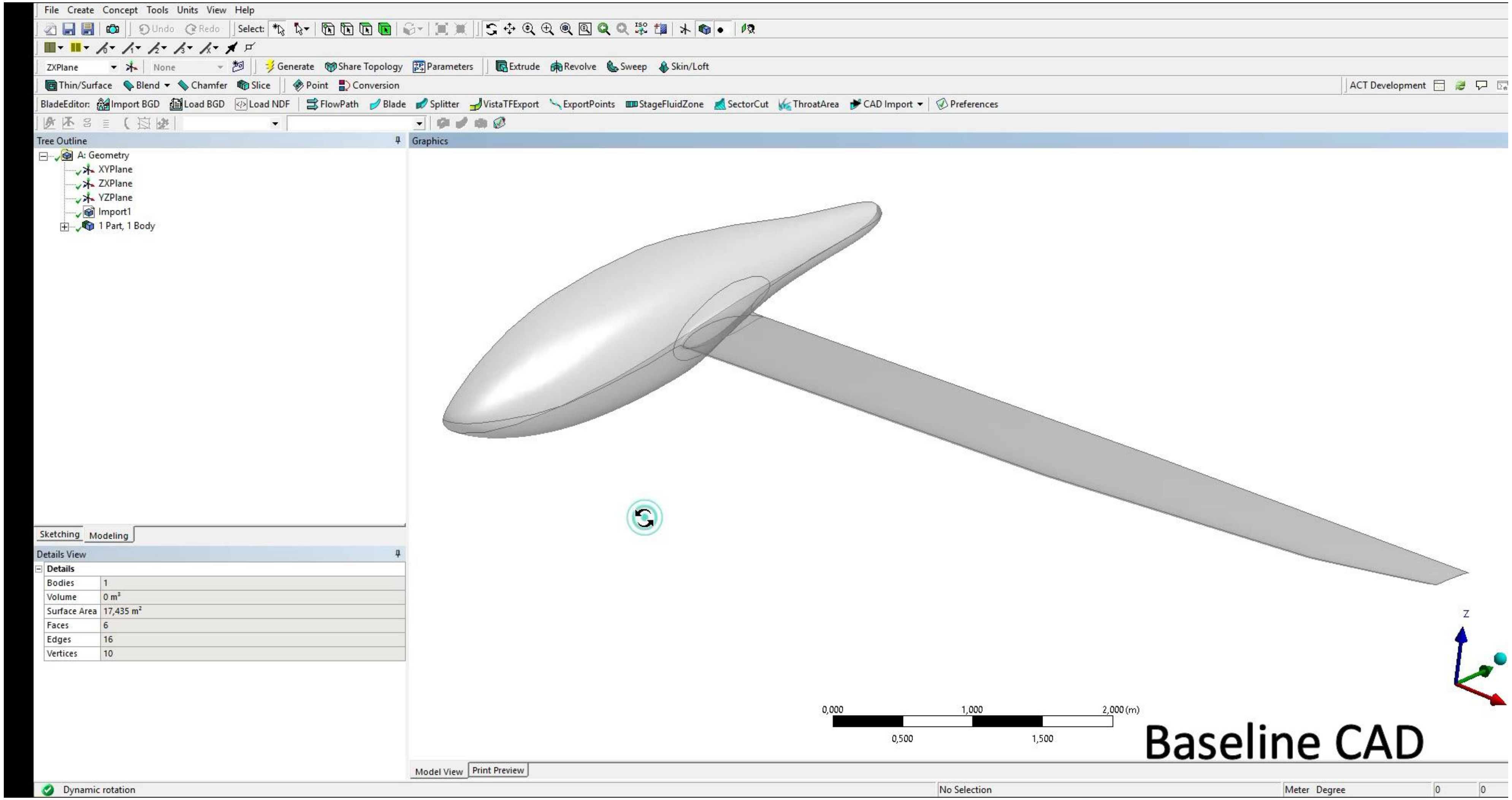
MOTORCYCLE WINDSHIELDS

RBF Morph Fluent Module

https://youtu.be/EWsigyqByRg



Fluent module

Add on fully integrated within Fluent (GUI, TUI & solving stage), **Workbench** and **Adjoint Solver**

Mesh-independent RBF fit used for **surface** mesh morphing and **volume** mesh smoothing

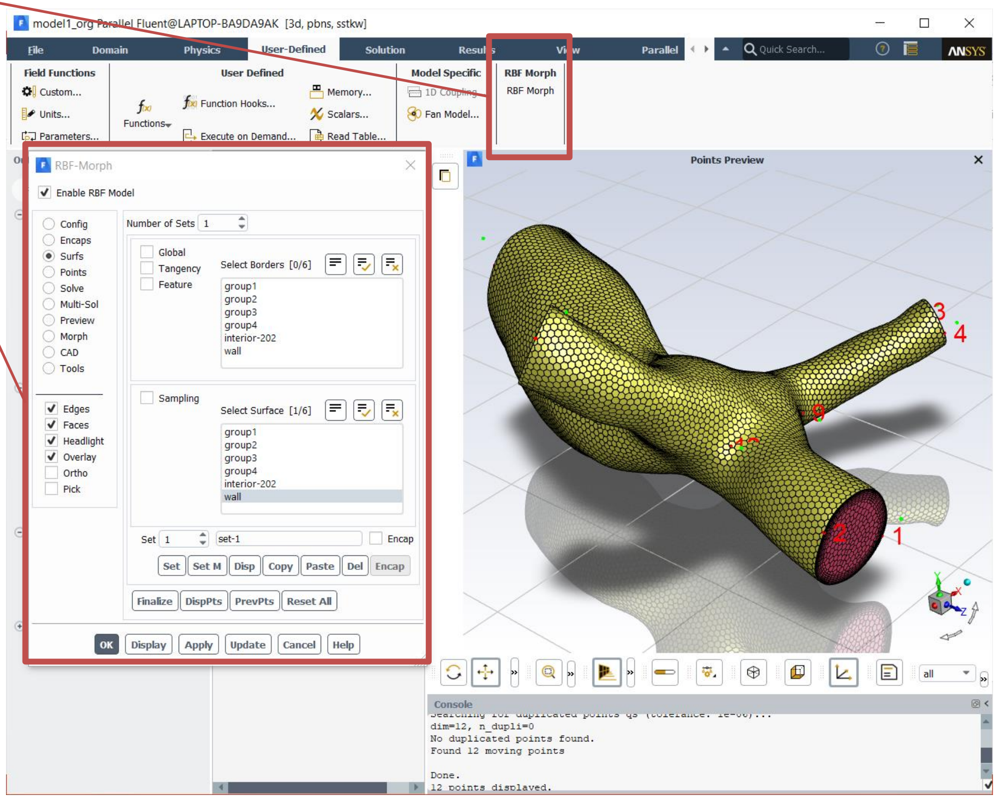
Parallel calculation allows to morph large size models (many millions of cells) in a short time

Management of **every kind of mesh** element type (tetrahedral, hexahedral, polyhedral, etc.)

Support of the **CAD** re-design of the morphed surfaces

Multi fit makes the Fluent case **truly parametric** (only 1 mesh is stored)

Precision: exact nodal movement and exact feature preservation (**RBF are better than FFD**)



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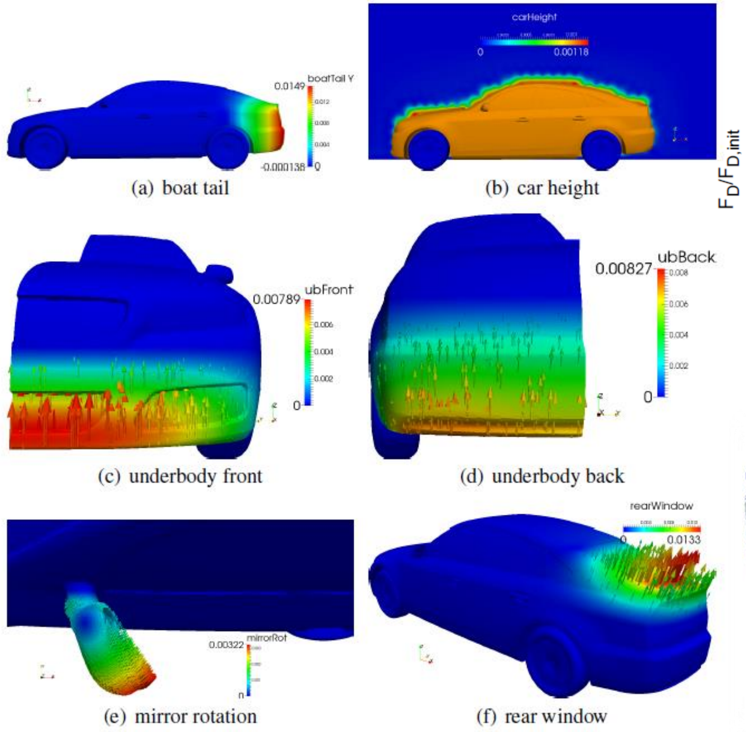
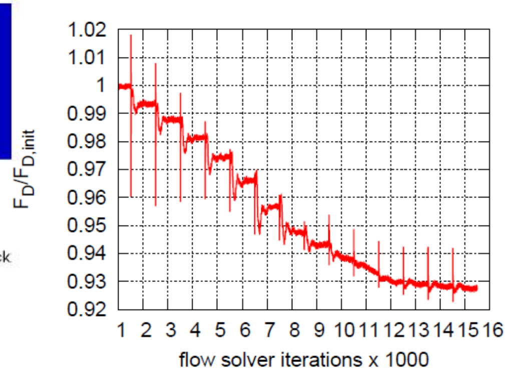
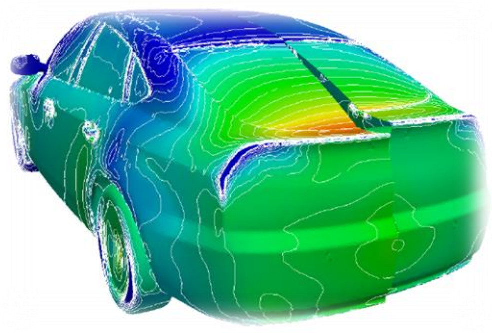
Gradient-based optimization (adjoint)







The adjoint formulation provides the **gradient** of an aerodynamic objective function **with respect to surface displacements**.

$$\frac{\delta F}{\delta \vec{b}} = \frac{\delta F}{\delta x_\kappa} \frac{\delta x_\kappa}{\delta \vec{b}}$$

RBF Morph provides the **deformation velocity** (adjoint preview).

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Beyond optimization: advanced adjoint based post-processing

High fidelity CAE solver adopted in this study is **Ansys Fluent** (CFD+adjoint)

Advanced mesh morphing is provided by combining the CFD solver with the **RBF Morph Fluent module**

A new **interactive custom feature** defined to quickly explore new shapes without any additional solver calculations

```
(rbf-adjoint-interactive)
```

Beyond optimization: advanced adjoint based post-processing

Ansys FLUENT rbf™

(rbf-adjoint-interactive)

1. Inspect flow solution and **adjoint sensitivity**
2. Decide the **regions** to be modified
3. Create desired **shape modifications** (design parameters, FEA deflections, sculpted shapes)
4. Explore how shape modifications combines and get a (gradient based) **estimation of the performance**

Drag analysis of a Formula 3 car

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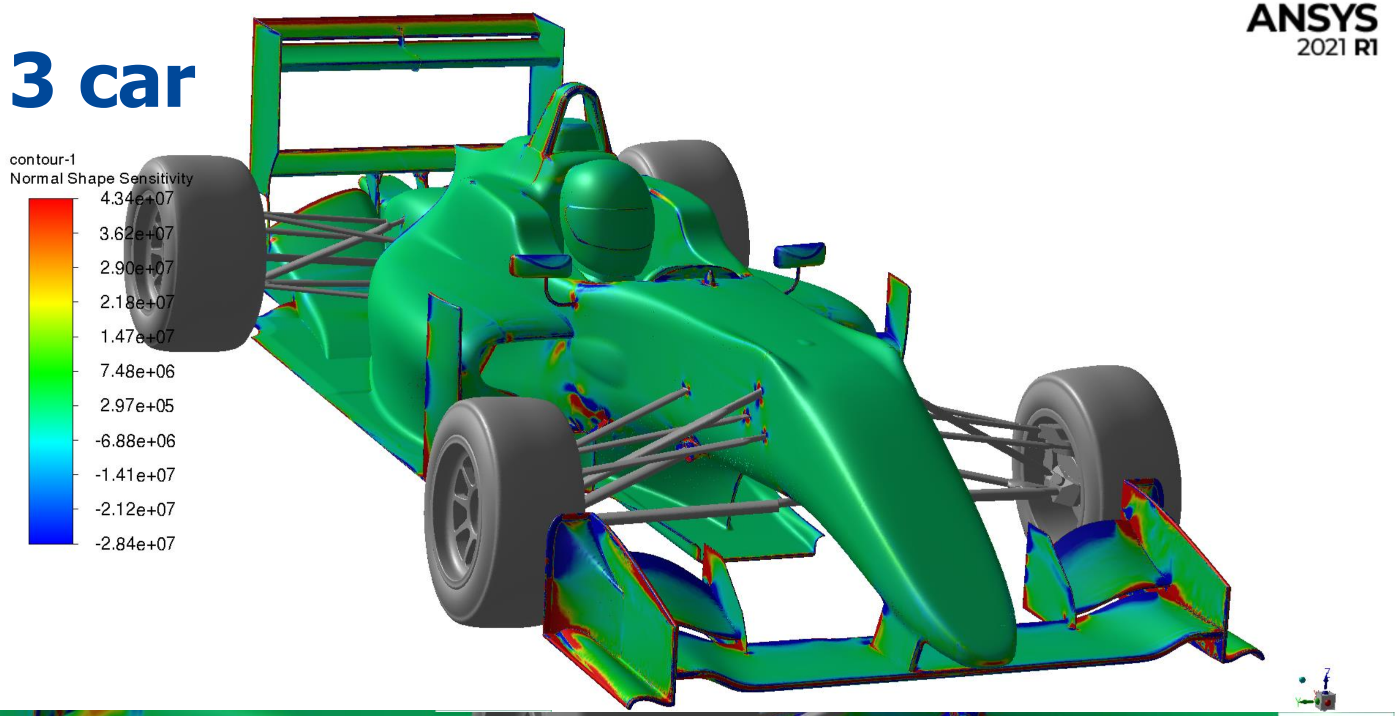
Drag analysis of a Formula 3 car

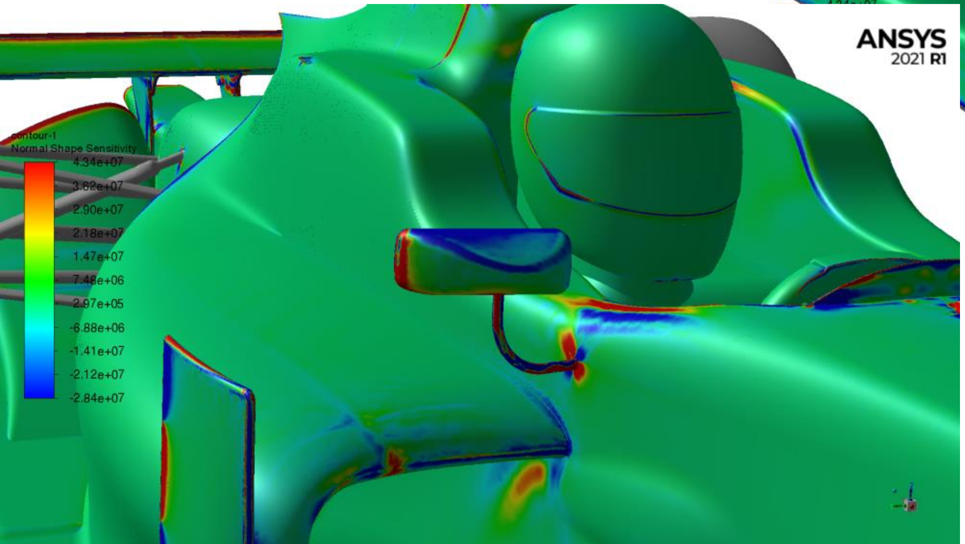
Half car model mosaic mesh comprised of about 50 millions cells

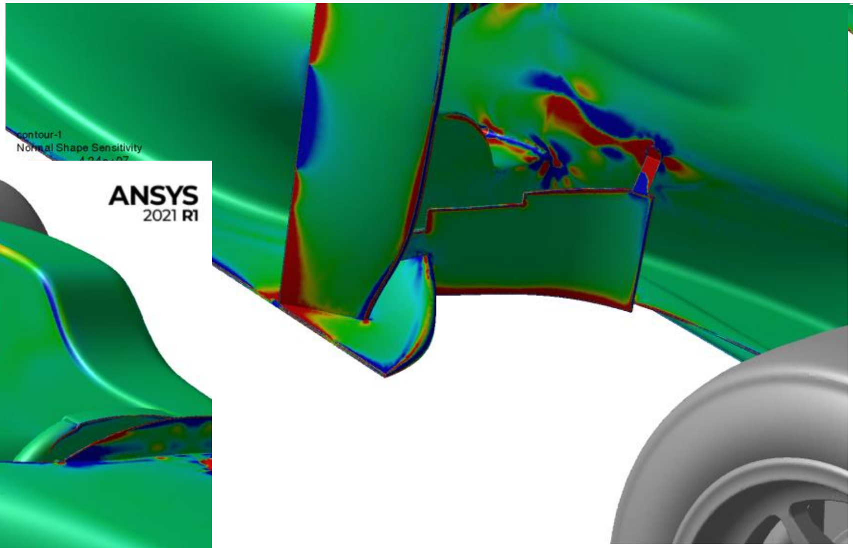
Drag sensitivity computed with adjoint solver

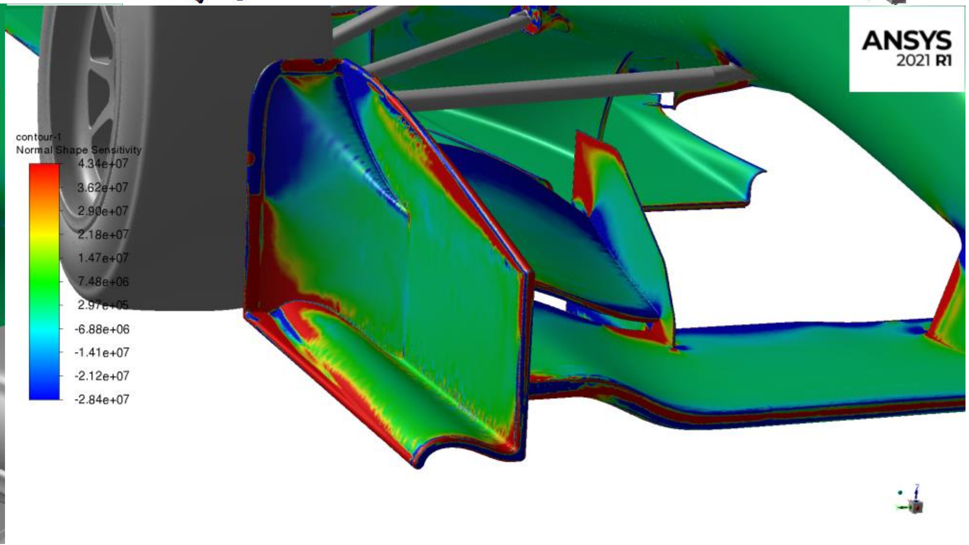
Regions of interest:

- Rearview mirror
- Bargeboard
- Front wing end plate









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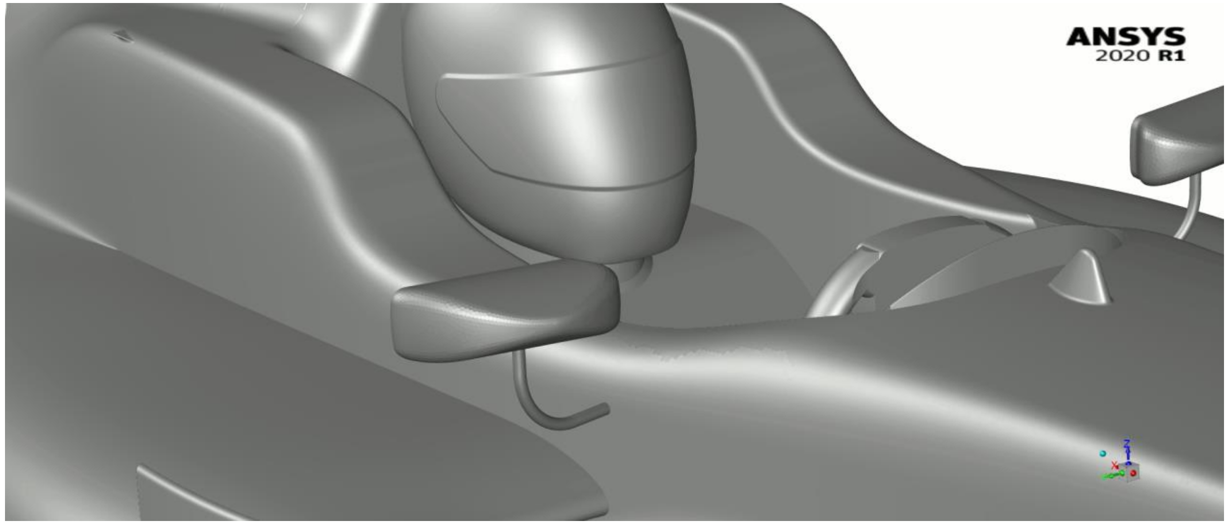
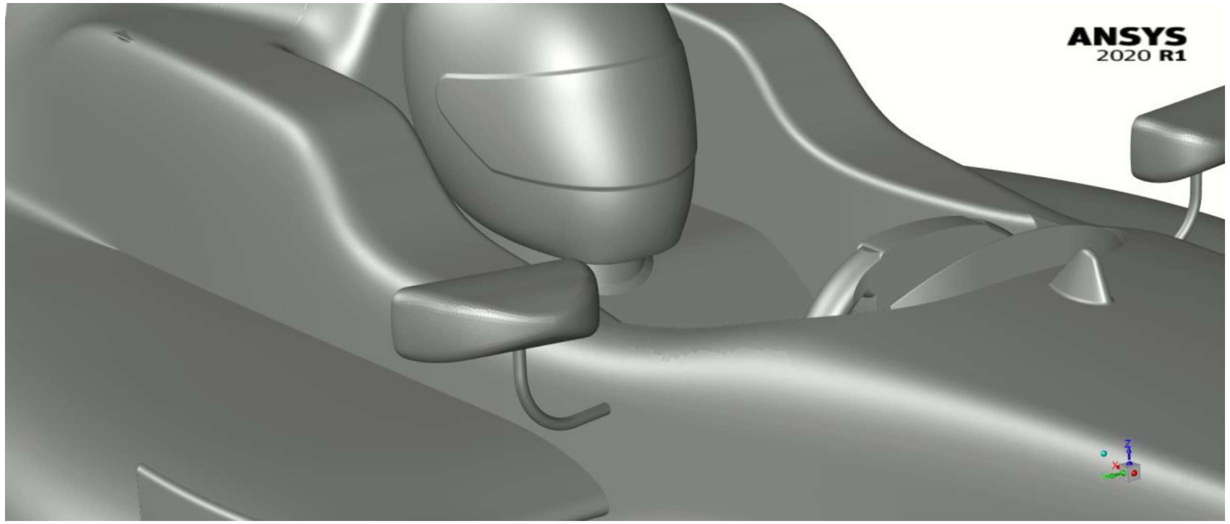
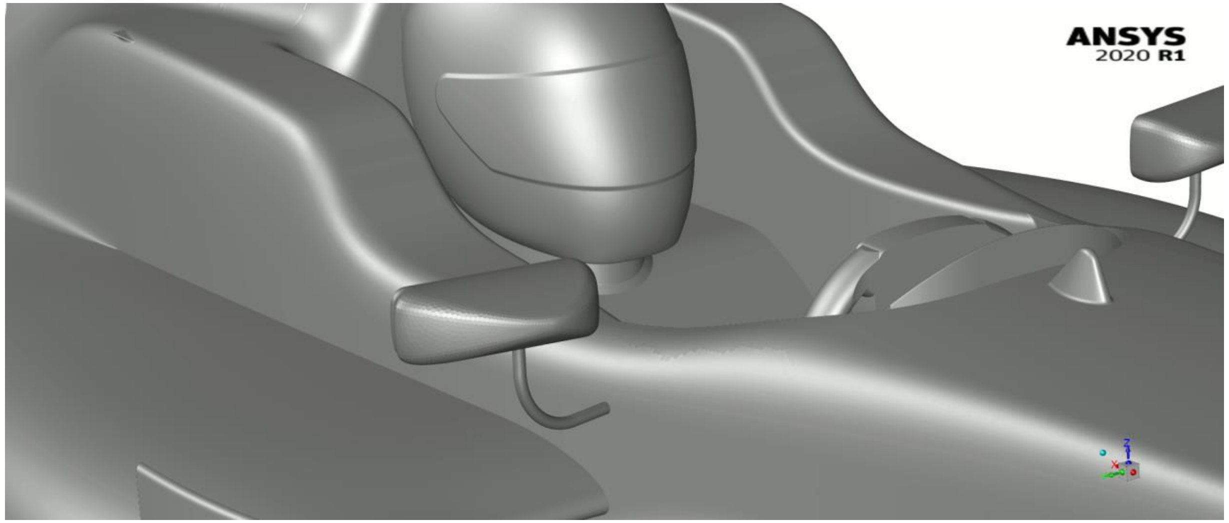
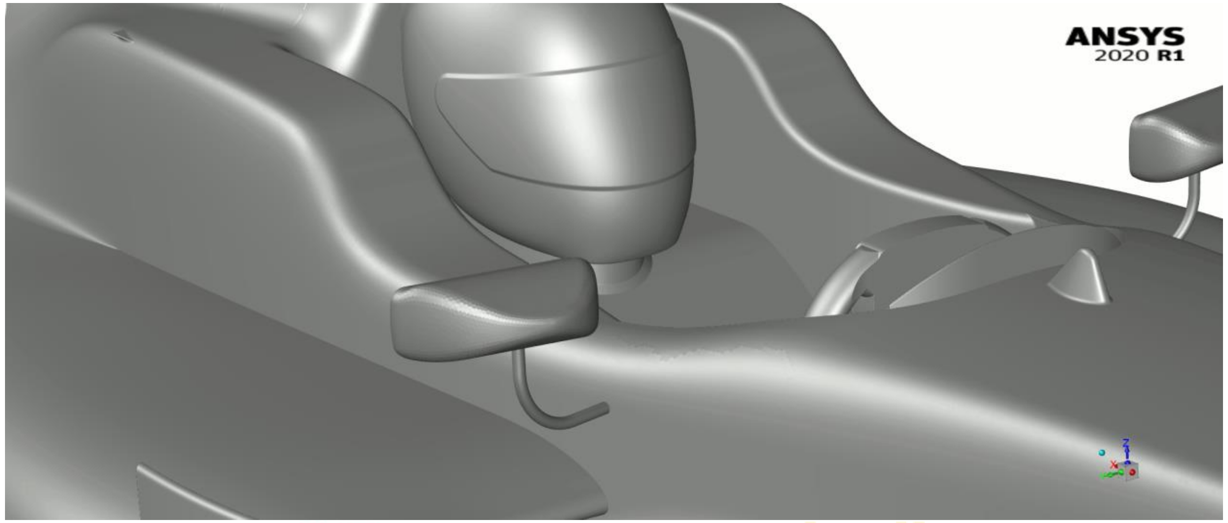
Mesh morphing – rearview mirror (4 parameters)

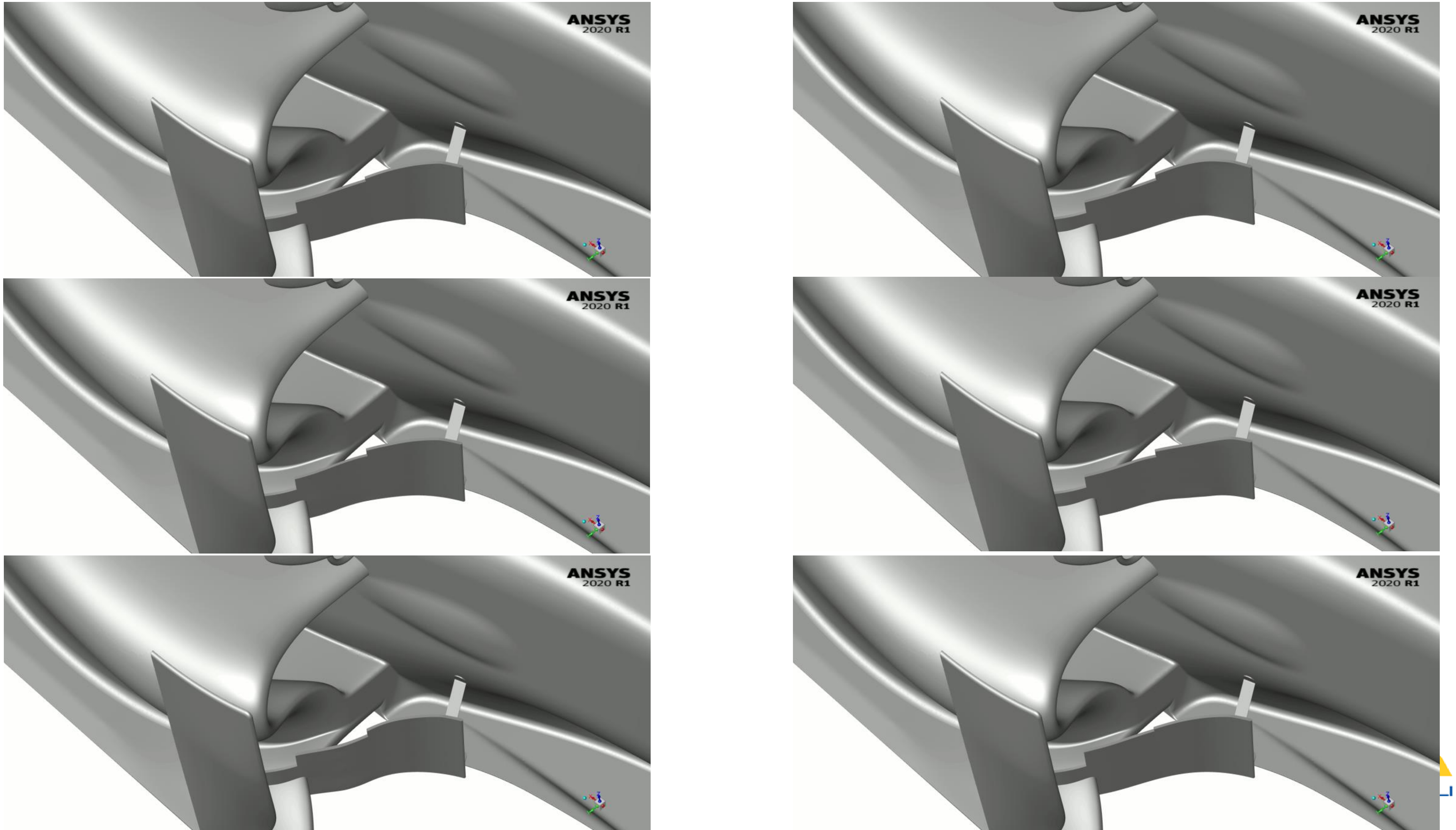




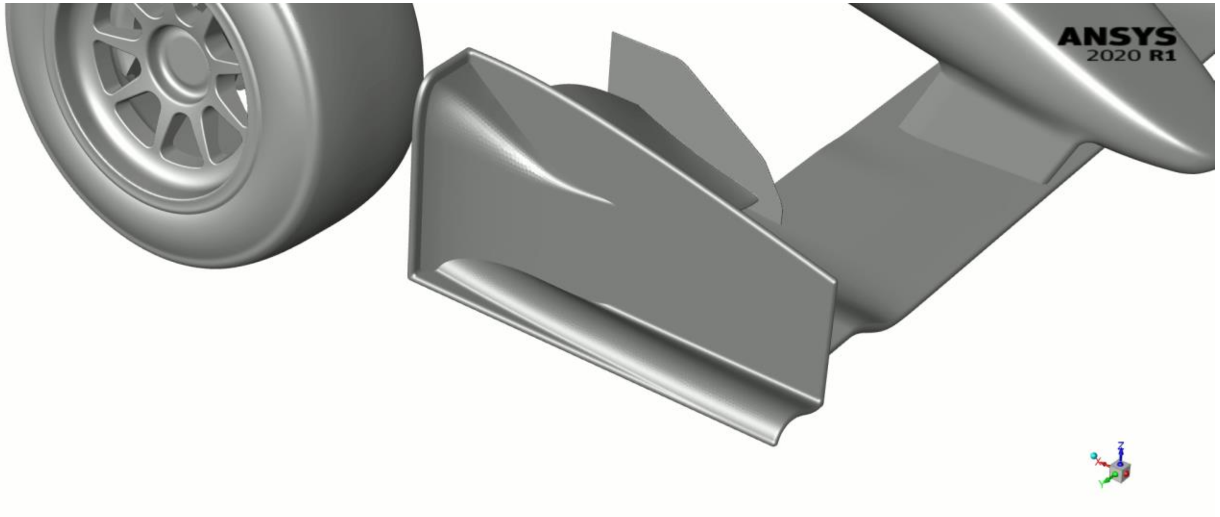


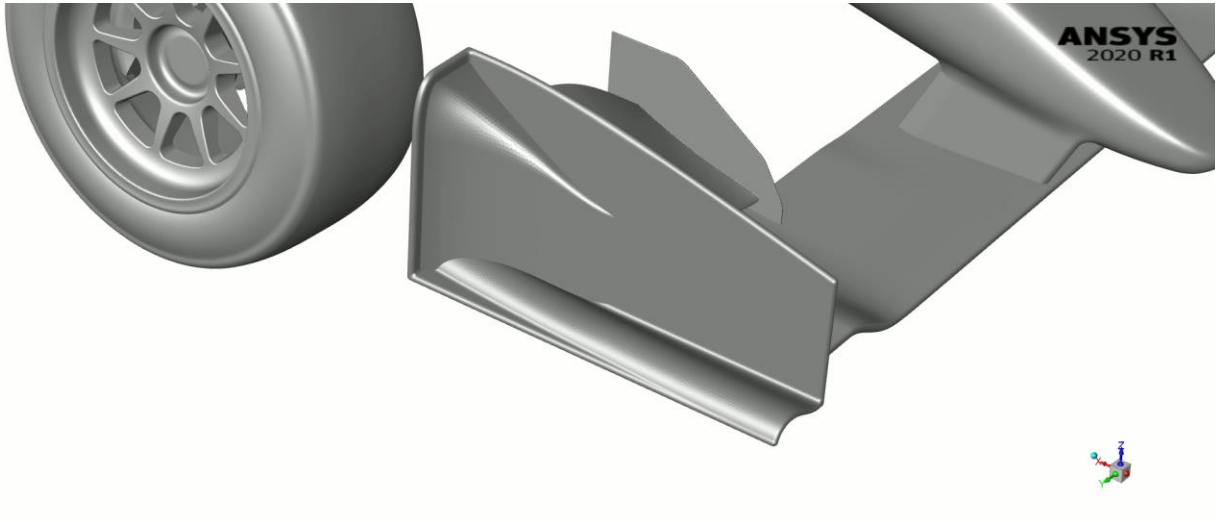


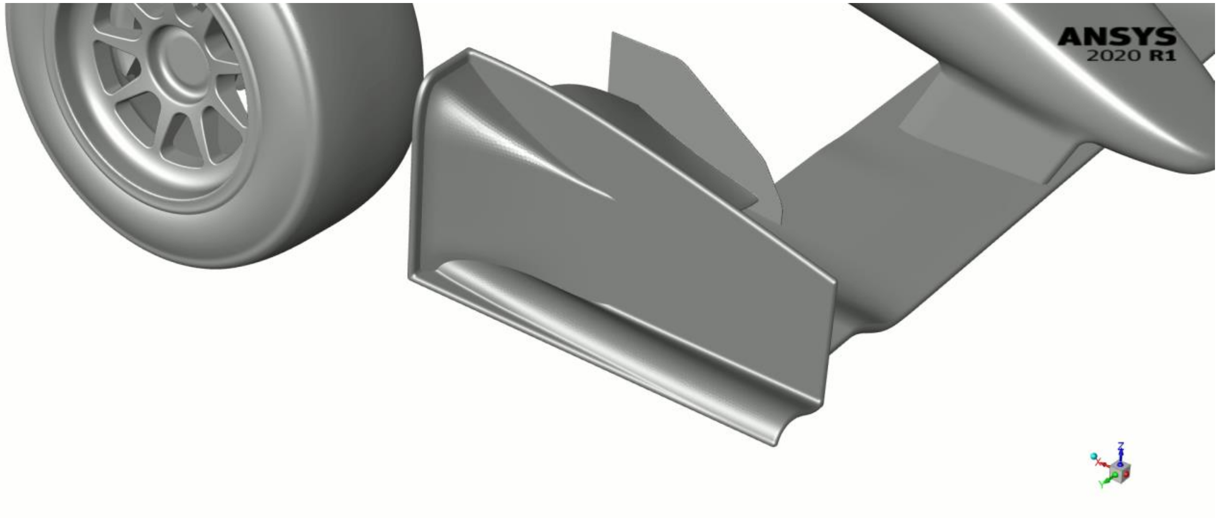
Mesh morphing – bargeboard (6 parameters)

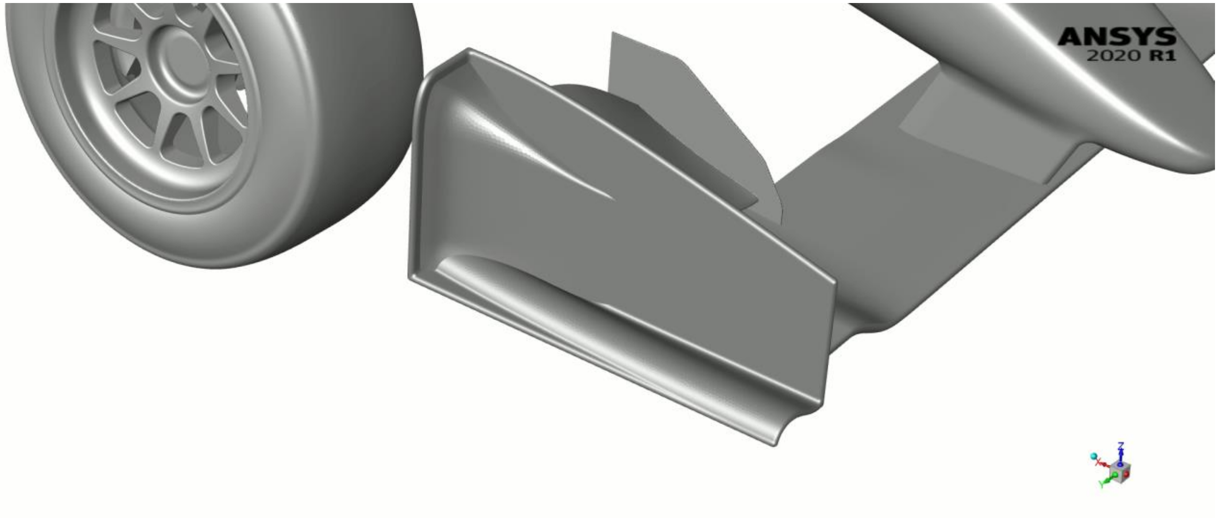


Mesh morphing – front wing end plate (4 parameters)









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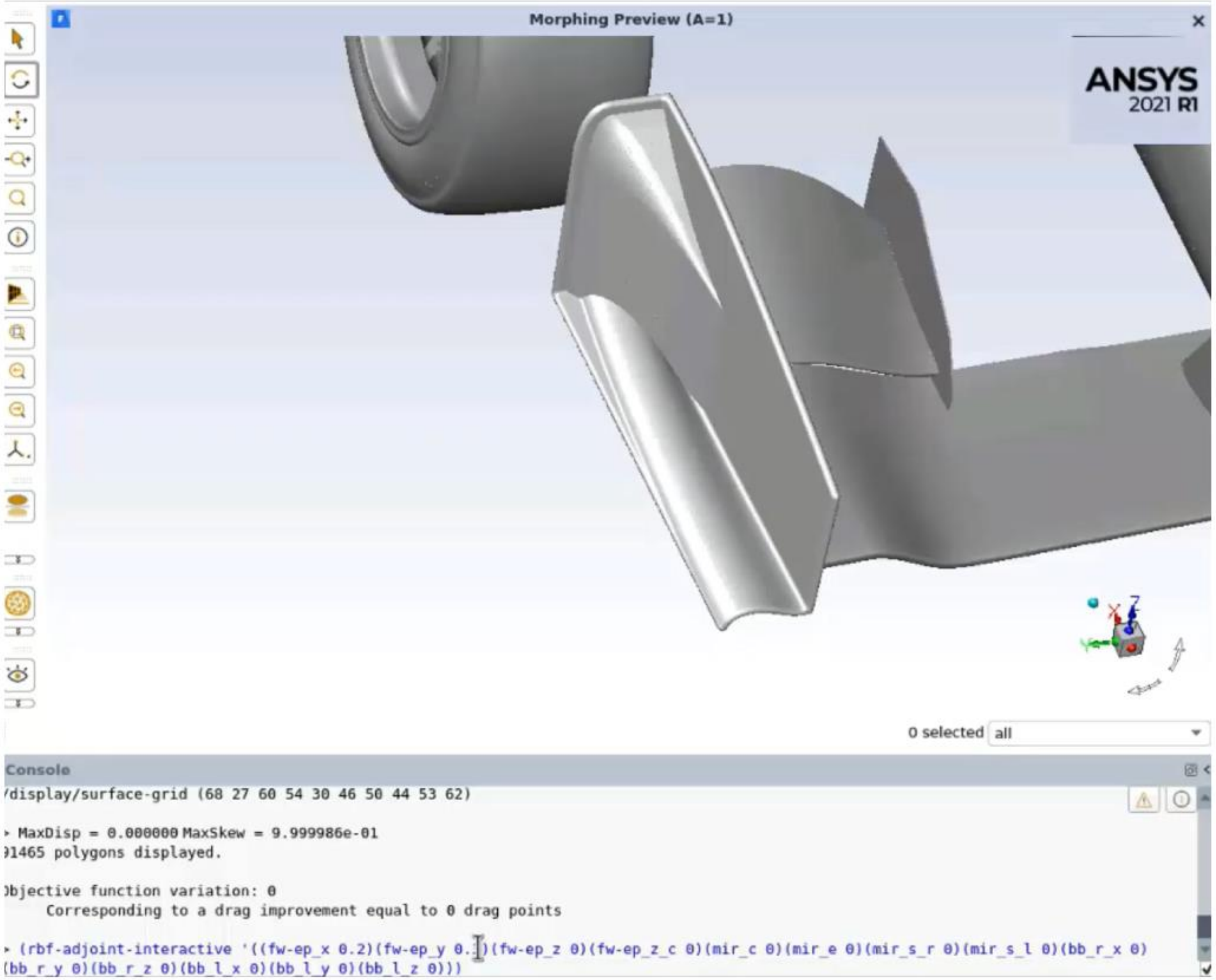
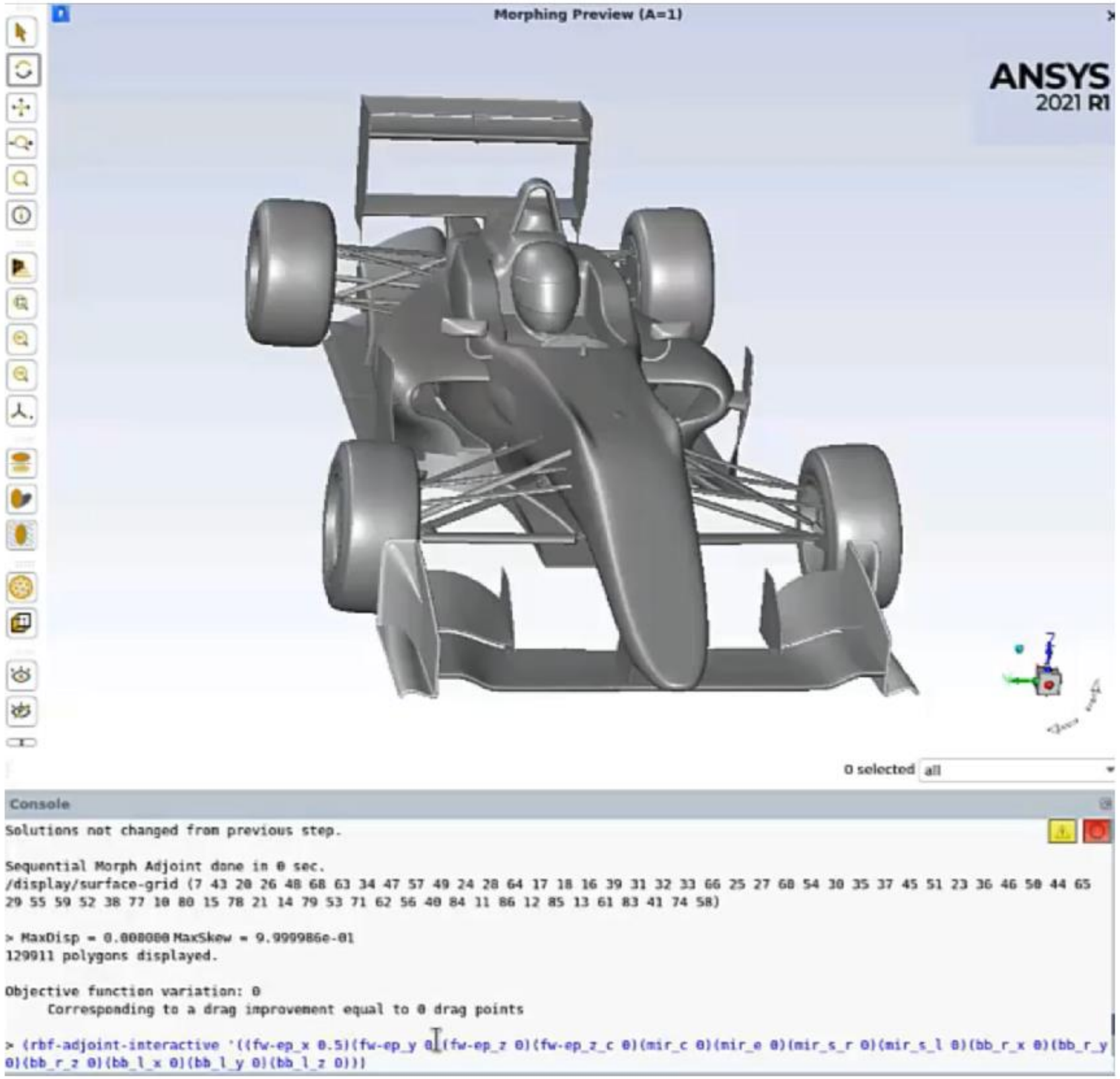
RBF adjoint interactive





What can be achieved in a single shot after inspecting the adjoint sensitivities?

Well, now we have a quantitative estimation of the effect of shape parameters

Automatic methods are based on the gradient and can converge toward an optimum

Can the engineer get a better shape in a single shot?...

...to answer it is important to be aware that:

Sensitivities are valid only around the baseline

Too much variation could be risky

A small variation is safer… but predicts a small gain!

(challenge posed on Friday to get the answer after the week end)

Obtained result

The new shape was defined by combining 8 parameters (4 on the mirror, 4 on the front wing end plate) that show most promising results

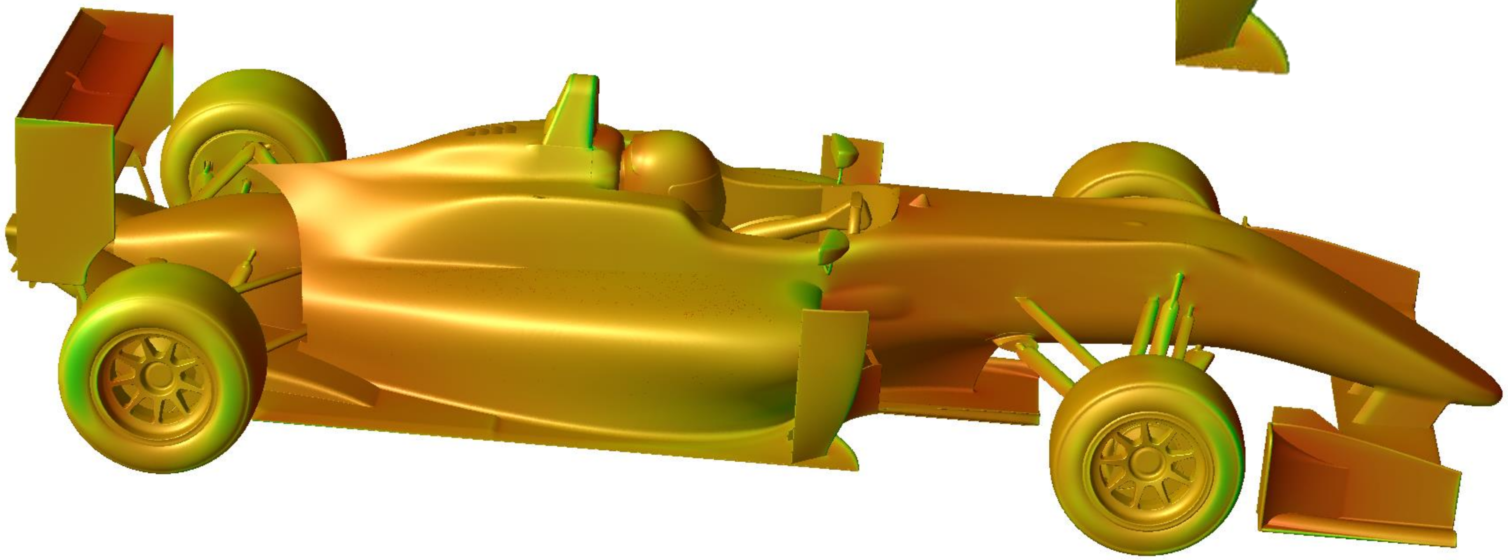
A 0.6% reduction of the drag force has been obtained

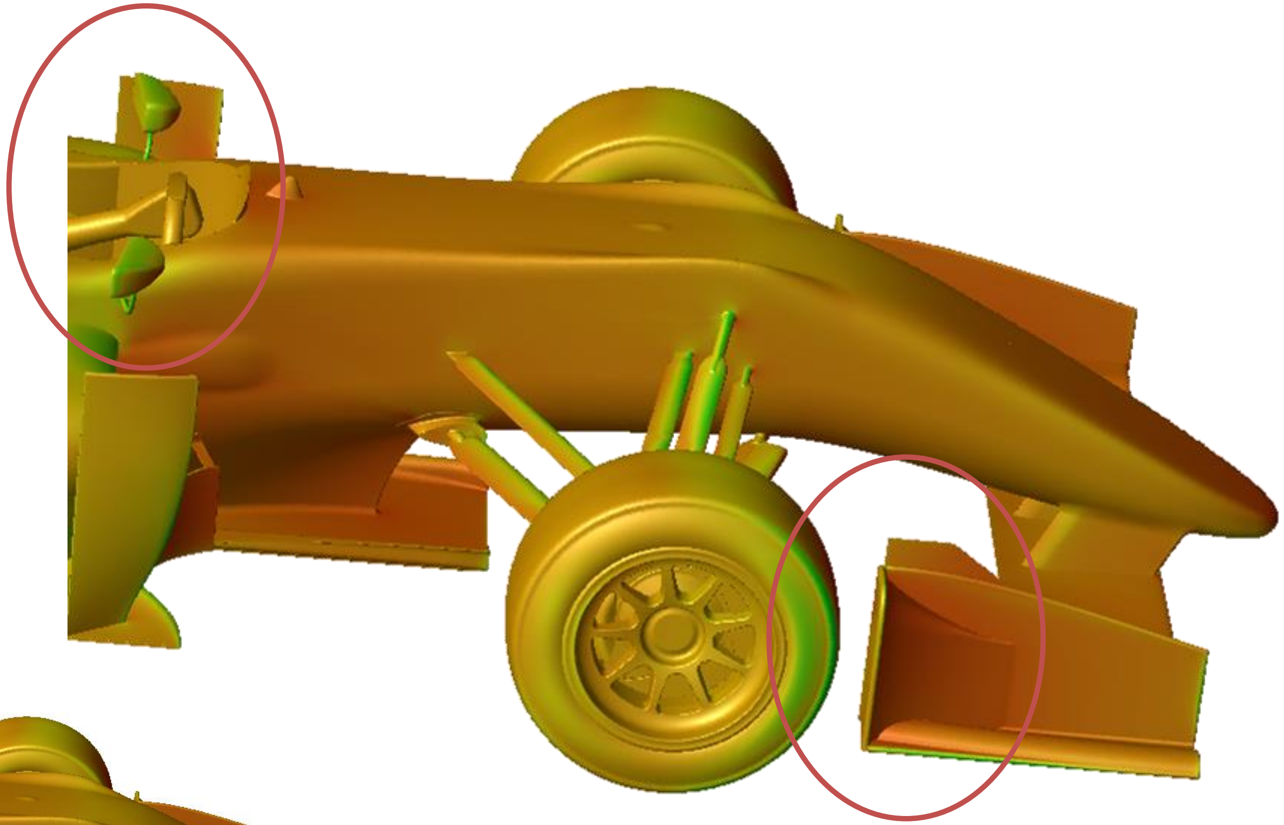
A 0.43 drag points reduction achieved

zone	Cd baseline	Cd modified	difference
w01aa-bw-chassis	0.050395574	0.049522977	-0.0008726
w01aa-bw-driver	-0.028866122	-0.027914999	0.00095112
w01aa-bw-engine-cover	0.00513905	0.005075394	-6.366E-05
w01aa-bw-side			
w01ab-mech-er			
w01ab-mech-ex			
w01ab-mech-ra			
w01ab-mech-ra			
w01ab-mech-ra			
w01ba-fuw-skic			
w01ba-fuw-ster			
w01bb-ruw-diff			
w01bb-ruw-skic			
w01bb-ruw-top			
w01bb-ruw-tyre			
w02-fw-endplat			
w02-fw-main			
w03-rw-endplat			
w03-rw-main			
w03-rw-pylon			
w04-fs-inf			
w04-fs-pull			
w04-fs-sup			
w04-fs-track			
w05-rs-drivesha			
w05-rs-inf			
w05-rs-push			
w05-rs-sup			
w05-rs-track			
w06a-fwls-plate			
w06b-fwlr-rim			
w06b-fwlr-tyre-			
w06b-fwlr-tyre-			
w07a-rwls-plate			
w07b-rwlr-rim			
w07b-rwlr-tyre-			
w07b-rwlr-tyre-			
total			

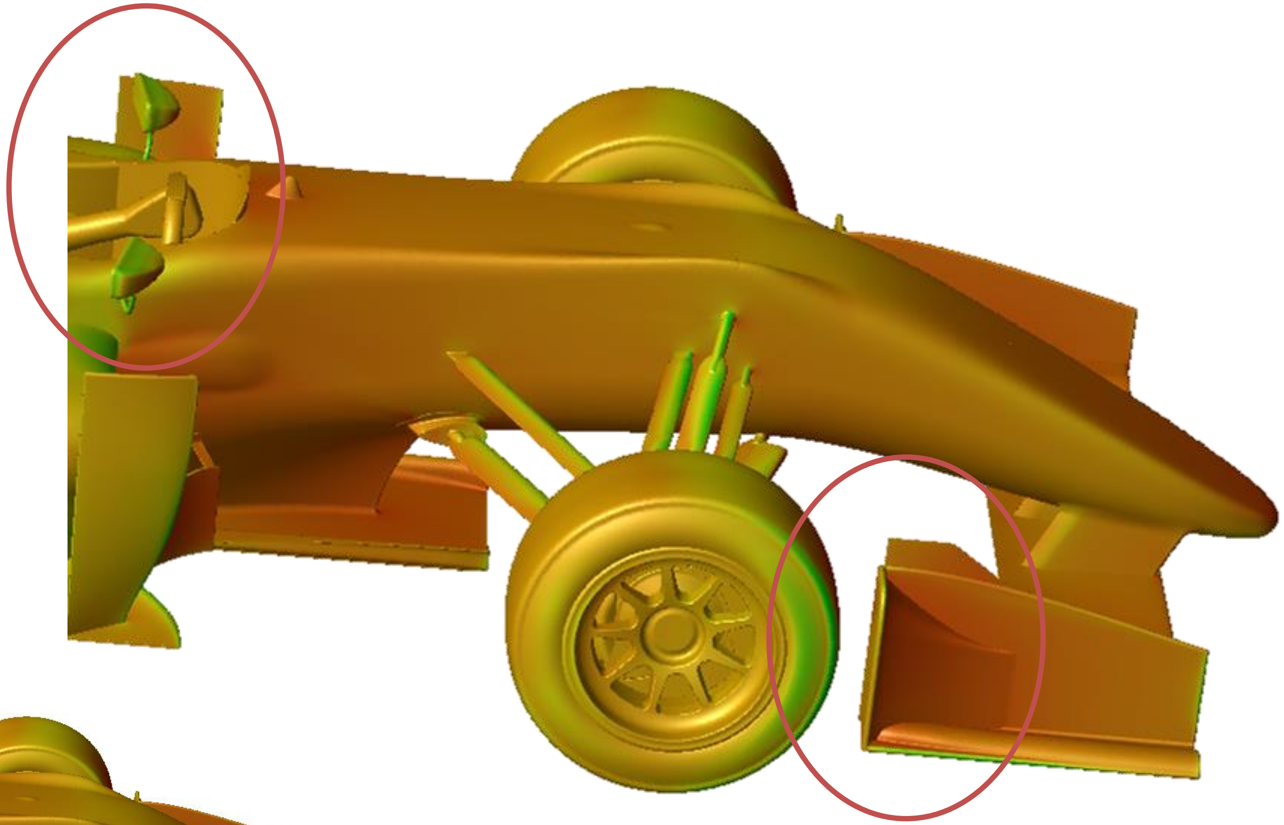
zone	Cd baseline	Cd modified	difference
w01aa-bw-chassis	0.050395574	0.049522977	-0.0008726
w01aa-bw-driver	-0.028866122	-0.027914999	0.00095112
w01aa-bw-engine-cover	0.00513905	0.005075394	-6.366E-05
w01aa-bw-sidepod	-0.001937374	-0.006622437	-0.0046851
…	0.036997341	0.038567107	0.00156977
…	…	…	…
total	0.5391928	0.53432232	-0.0042989

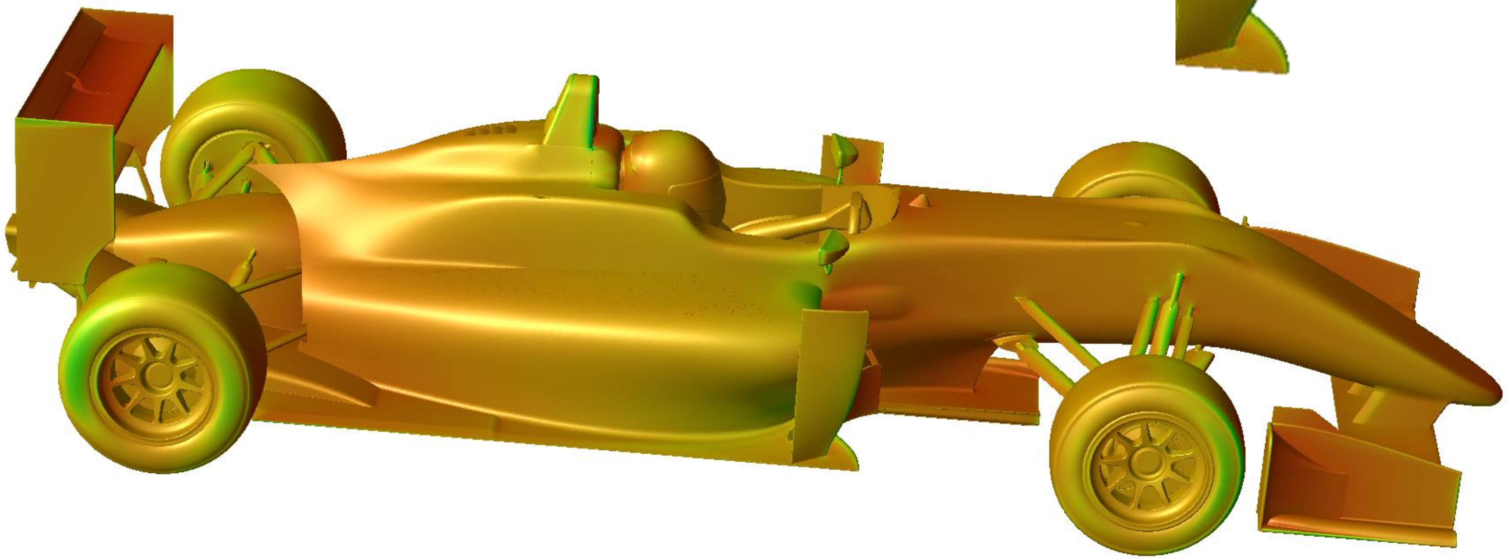
Original design





Optimized design
(-0.43 drag points)





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Conclusions

There is a need for advanced tools to get as more information as possible from high fidelity CFD

When **shape sensitivities** are available (adjoint solution) we can compute derivatives of performance vs. parameters

In this study we presented **(rbf-adjoint-interactive)** a new tool based on Ansys Fluent, and RBF Morph that allows to predict the effect of shape on performance **without** the need of a new **CFD computation**

The proposed method was applied to reduce the aerodynamic drag of a **Formula 3 Car** acting on the mirror and the front wing end plate gaining a **0.43 drag points**

Many thanks for your kind attention!

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