



Interactive aerodynamic design based on physics-informed models and immersive visualization

Faculty of Engineering

Degree Course in Mechanical Engineering

Supervisor: Prof. Marco E. Biancolini

Candidate: Helciug Mihai Alin

Co-supervisor: Ing. Emanuele Di Meo

Presentation outline

Introduction: Objectives, case study and methodology

Workflow: Baseline, RBF Mesh Morphing, DoE and generation ROM

Results: Optimization, ROM errors and VR

Conclusions

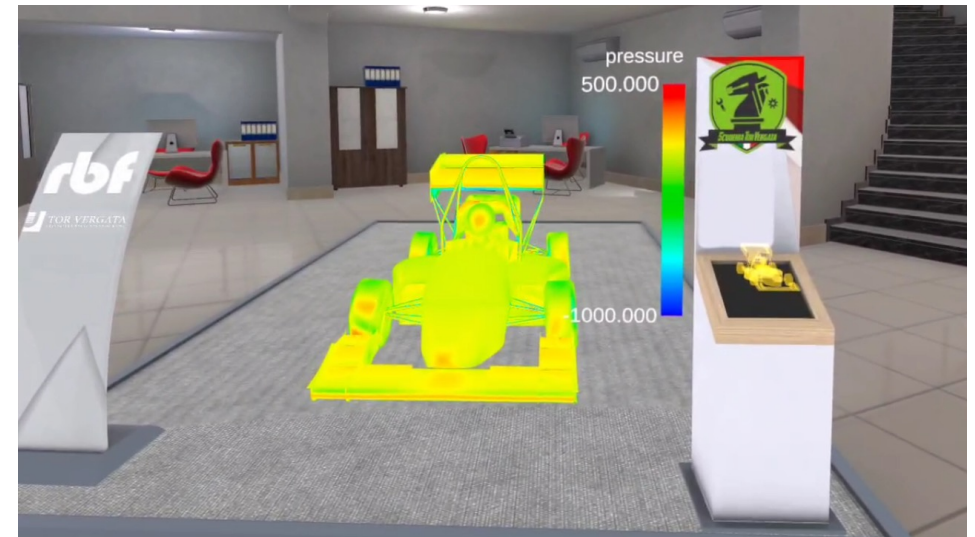




Objectives

The goal of the thesis is to create an interactive **Digital Twin** through a reduced-order model, trained on CFD data, that bypasses the high computational cost of traditional analyses.

Thanks to this approach, optimization becomes an immersive exploration in which every geometry variation **instantly** translates into new pressure maps.



1

Introduction

2

Workflow

3

Results

4

Conclusions

Case study

Formula SAE is an international student motorsport competition in which university teams from around the world participate.

A Formula SAE event consists of:

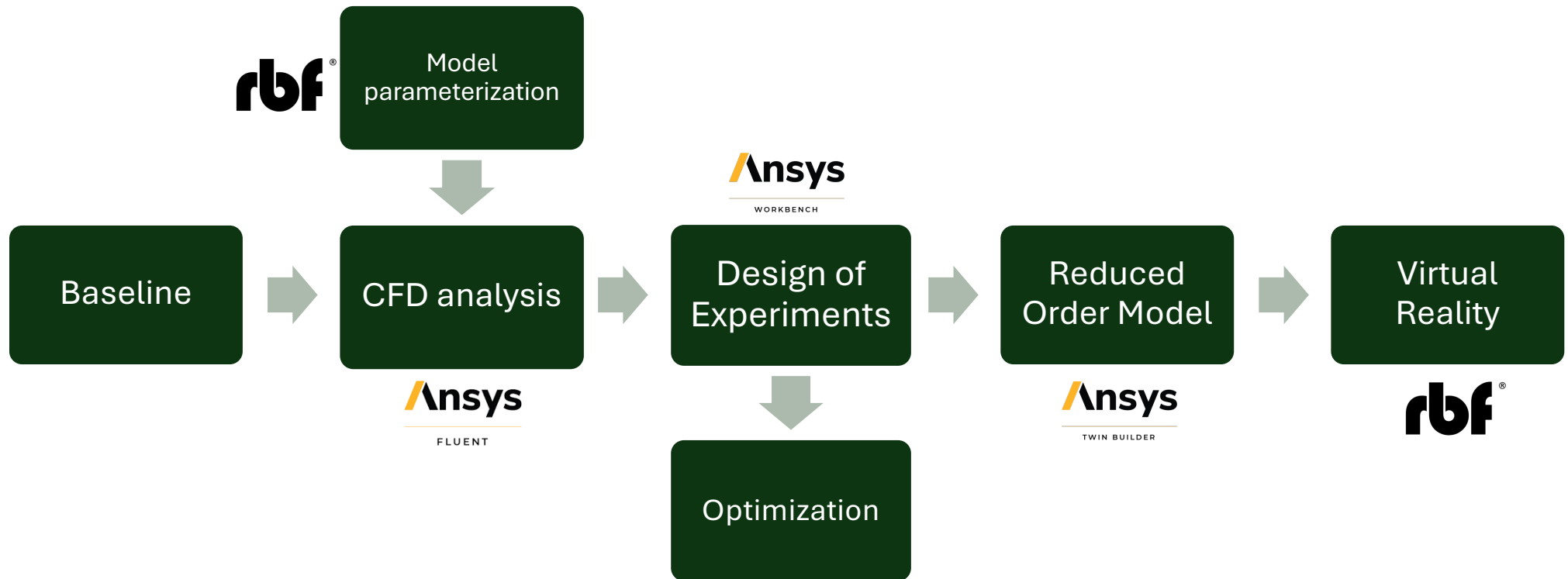
- Static events: Design, Cost and Manufacturing, Business Plan
- Dynamic events: Endurance, Autocross, Acceleration, Skidpad

Aerodynamics plays a decisive role in dynamic events; the goal is to achieve high vehicle efficiency to maximize on-track performance.



TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

Methodology

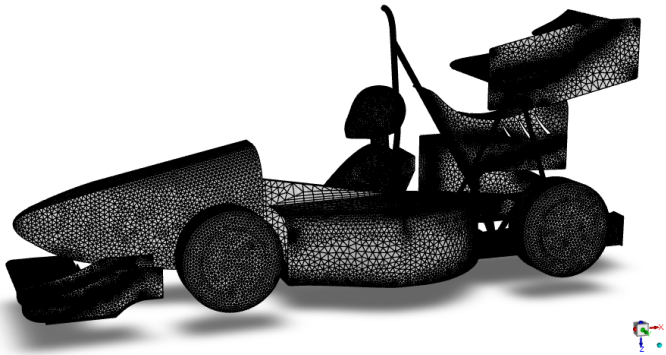




Baseline

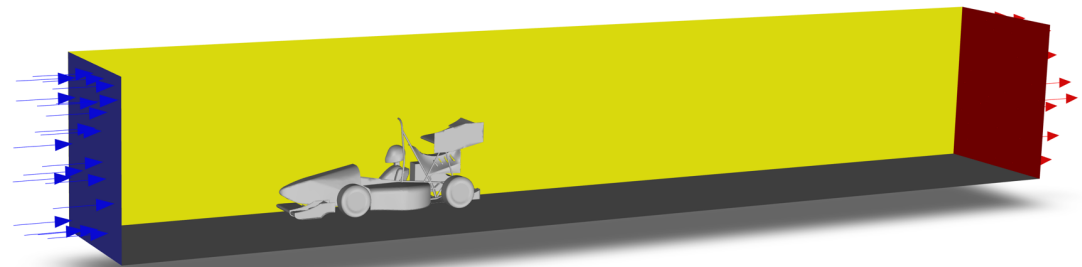
Mesh characteristics:

- Number of cells → 4.841.596
- Number of nodes → 1.233.453
- Number of faces → 10.366.855



Boundary conditions:

- Inlet velocity → 20 m/s
- Outlet relative pressure → 0 Pa
- Turbulence model → $k - \omega \text{ SST}$
- Moving wall for the ground with velocity equal 20 m/s
- Longitudinal symmetry
- 1000 iterations reporting C_d, C_l ed efficiency



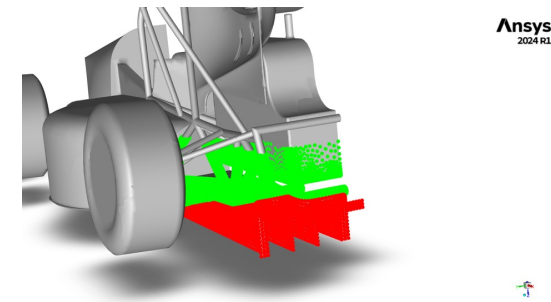
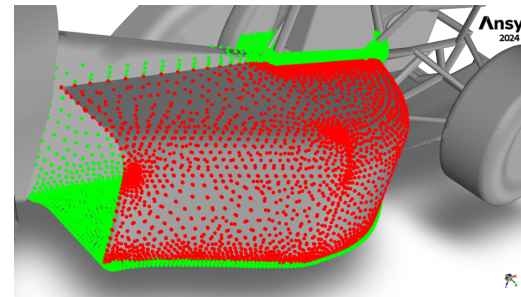
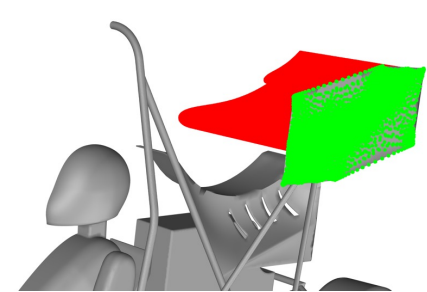
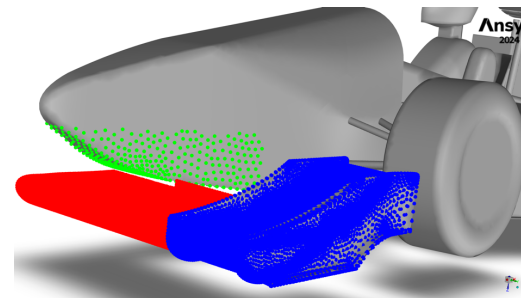
Model parameterization with RBF Mesh Morphing

Radial Basis Functions (RBF) allow the mesh to be modified without needing to rebuild the CAD geometry and without generating a new mesh.

$$s(\vec{x}) = \sum_{i=1}^N \gamma_i \Phi(|\vec{x} - \vec{x}_{k_i}|) + h(\vec{x})$$

Through Mesh Morphing, based on RBF, the surfaces of greatest aerodynamic interest were parameterized:

- **Front and rear wings** → vertical translation and angle of incidence variation
- **Sidepods** → indentations on the lateral and horizontal surfaces
- **Diffuser** → longitudinal translation



1

Introduction

2

Workflow

3

Results

4

Conclusions

Design of Experiments

DoE creation:

- **100 Design Points** using Latin Hypercube Sampling, to obtain a pseudo-random and uniform distribution across the entire design space
- **16 Design Points** located exactly on the domain boundaries, to increase the robustness of the model and the ROM

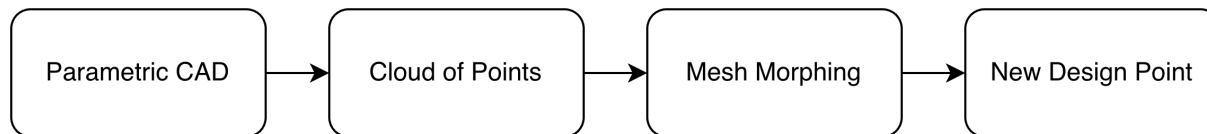
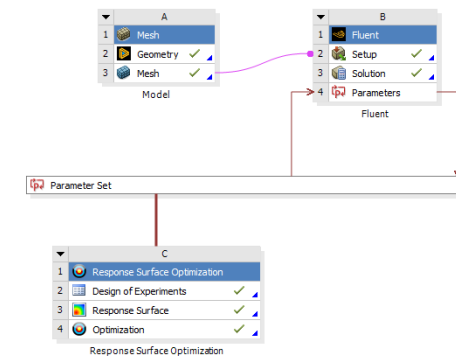


Table of Output A3: Design Points of Design of Experiments		A	B	C	D	E	F	G	H	I	J	K	L
1	2	File	P2 - speedoff	P3 - speedstabil	P20 - realzone_purta_mao	P11 - rotaboot	P12 - speedstabil	P13 - rotaboot	P14 - speedstabil	P15 - rotaboot	P16 - speedstabil	P17 - rotaboot	P18 - speedstabil
81	80	0.0159	-0.03975	-0.00435	-0.057	0.0555	0.89	0.002975	-0.02525	1.4318	1.4211		
82	81	0.0175	0.03025	-0.00945	-0.04945	0.246	0.0003	-0.93	0.000725	-0.01275	0.9899	1.4687	1.4348
83	82	0.0261	-0.00975	-0.00205	-0.261	0.0597	-0.71	7.2615	-0.04975	0.9954	1.4602	1.445	
84	83	0.0093	-0.01435	-0.01035	0.105	0.0133	0.11	0.000325	-0.00375	0.99378	1.4611	1.4519	
85	84	0.0153	-0.05825	0.00945	0.003	0.0099	0.75	0.000375	-0.02475	0.9944	1.4279	1.4385	
86	85	0.0263	0.01975	-0.00435	0.003	0.0099	0.99	0.000325	-0.01375	0.99438	1.4154	1.4073	
87	86	0.0025	0.00525	-0.00175	-0.285	0.0471	-0.65	0.000345	-0.01175	0.9988	1.4435	1.4289	
88	87	0.0115	-0.02775	-0.00235	-0.297	0.0201	-0.91	0.000625	-0.01375	0.9993	1.4602	1.4648	
89	88	0.0073	0.03525	0.01125	-0.246	0.0463	0.63	0.000375	-0.01125	0.99243	1.4638	1.4448	
90	89	0.0013	0.00635	-0.00125	-0.033	0.0039	-0.99	0.000425	-0.01425	0.99628	1.4697	1.4603	
91	90	0.0383	0.01375	-0.00945	-0.219	0.0185	-0.41	0.000375	-0.00225	0.99207	1.4699	1.4588	
92	91	0.0069	-0.00325	0.00465	0.133	0.0463	-0.48	0.000395	-0.00425	0.99333	1.4664	1.4402	
93	92	0.0177	-0.04975	0.00215	0.261	0.0573	0.41	0.000125	-0.01125	0.9881	1.4152	1.3984	
94	93	0.0039	0.01425	-0.00395	0.219	0.0315	-0.95	0.000325	-0.01875	0.98809	1.4638	1.4483	
95	94	0.0063	-0.01175	0.00175	0.197	0.0333	-0.59	0.000425	-0.00375	0.99438	1.4622	1.4393	
96	95	0.0061	0.02475	0.00445	-0.015	0.0239	-0.89	0.000395	-0.00225	0.98705	1.4679	1.4785	
97	96	0.0143	0.00675	-0.00845	0.117	0.0189	0.05	0.000425	-0.00625	0.98542	1.4638	1.4618	
98	97	0.0031	0.00675	-0.00335	0.267	0.0249	0.85	0.000325	-0.00375	0.99284	1.4638	1.4433	
99	98	0.0203	0.00675	-0.00645	-0.231	0.0357	0.95	0.000195	-0.00625	0.99038	1.4577	1.4307	
100	99	0.0137	-0.05025	0.00035	-0.153	0.0369	0.49	0.000275	-0.01225	0.98621	1.4617	1.4415	
101	100	0.0095	0.01125	-0.00025	0.139	0.0375	-0.17	2.3610	-0.04975	0.99077	1.4793	1.4617	
102	101	0.0059	0.04925	-0.00245	0.173	0.0496	-0.57	0.000395	-0.01325	0.98879	1.4678	1.4599	
103	102	0.0207	-0.02035	-0.00485	-0.177	0.0177	-0.73	0.000875	-0.00775	0.992	1.4694	1.4578	
104	103	0.0003	0.00675	-0.00075	0.087	0.0091	0.67	0.000225	-0.01225	0.98824	1.4694	1.4523	
105	104	0.0081	0.01315	-0.00205	0.207	0.0491	-0.15	0.001175	-0.01975	0.99665	1.4638	1.4746	
106	105	0.0009	-0.05475	0.00185	-0.045	0.0585	-0.85	0.001825	-0.00825	0.98763	1.4691	1.4509	
107	106	0.0187	0.00975	0.00385	-0.003	0.0147	0.71	0.000225	-0.00225	0.99122	1.458	1.4451	
108	107	0.0073	0.00975	0.00295	0.099	0.0511	0.85	0.000195	-0.01975	0.98747	1.458	1.4502	
109	108	0.0185	-0.07425	-0.00385	0.159	0.0513	-0.29	0.000475	-0.00825	0.99017	1.4694	1.4549	
110	109	0.0027	-0.03825	-0.00095	0.111	0.0097	0.77	0.000475	-0.01425	0.98817	1.4738	1.4584	
111	110	0.0017	-0.04925	0.00275	0.287	0.0396	-0.48	0.000375	-0.01525	0.99037	1.4699	1.4647	
112	111	0.0045	-0.06525	-0.00205	0.153	0.0183	0.21	0.000425	-0.00875	0.98864	1.4294	1.4131	
113	112	0.0015	-0.01375	0.00335	-0.099	0.0579	0.31	0.000725	-0.01225	0.98723	1.4295	1.4073	
114	113	0.0053	-0.02675	0.00295	0.135	0.0267	-0.21	0.000195	-0.00825	0.99033	1.4763	1.4657	
115	114	0.0119	-0.01225	0.00075	0.141	0.0417	0.13	0.000625	-0.01925	0.99026	1.4735	1.4589	
116	115	0.0037	0.01745	-0.00425	-0.267	0.0587	-0.31	0.000625	-0.00375	0.98964	1.469	1.4538	
117	116	0.0151	0.00945	-0.00295	0.189	0.0287	0.35	0.000125	-0.00975	0.99003	1.4669	1.4531	



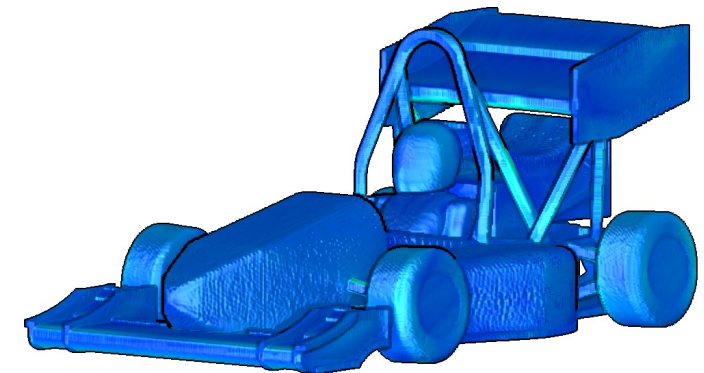
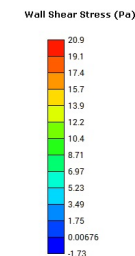
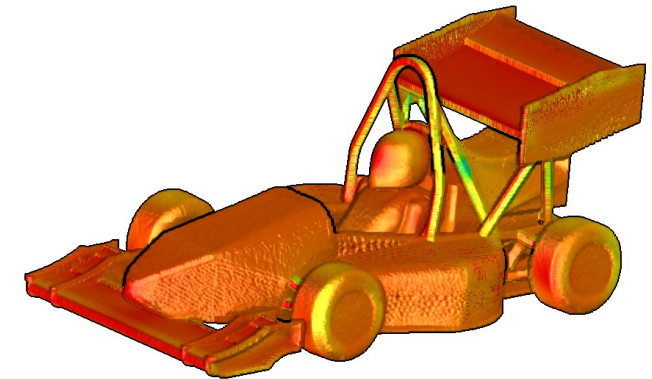
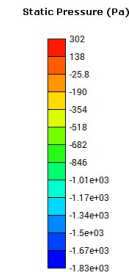
Reduced Order Model

Two ROMs were created:

- **Static pressure**
- **Wall shear stress**

To build the ROM, snapshots were used, i.e., the results of the fluid dynamics fields obtained from each CFD simulation.

Out of a total of 116 snapshots, 80% (93) were employed to train the model: on these we apply Singular Value Decomposition (SVD) to extract the dominant spatial modes.



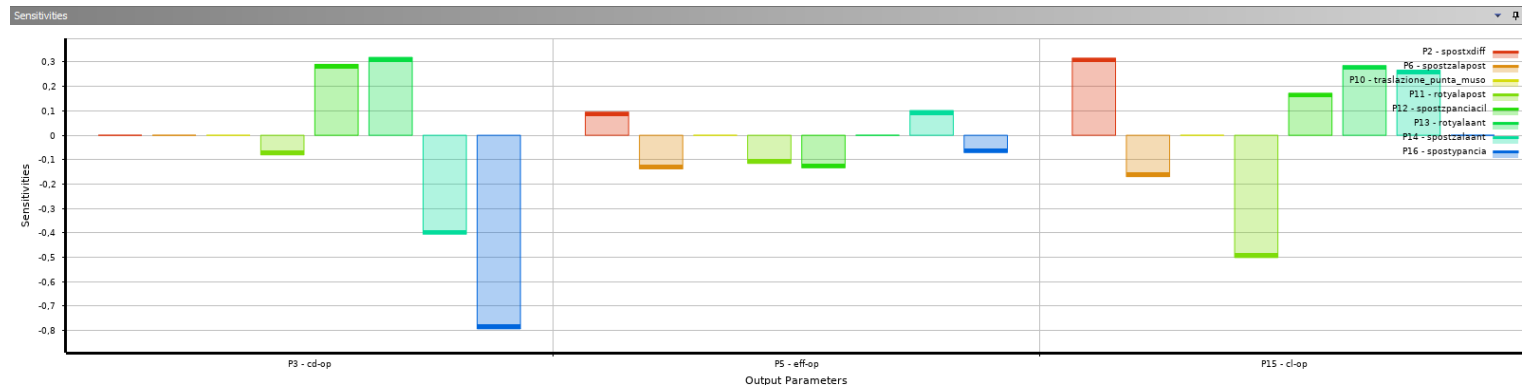
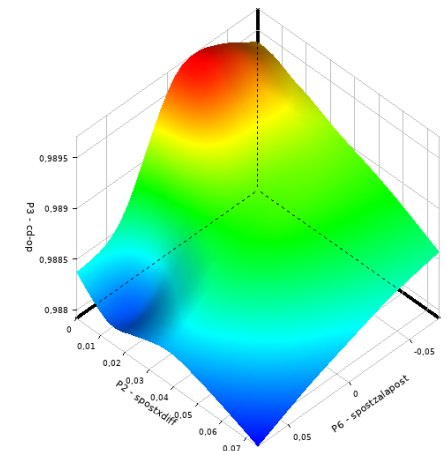
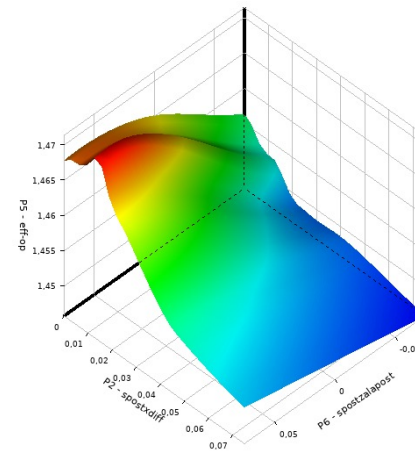


Analysis of results and optimization

Optimization via **response surfaces**

Drag coefficient: from 1 to 0.95 (-5%)

The **sensitivity** analysis made it possible to define the most influential parameters.



1

Introduction

2

Workflow

3

Results

4

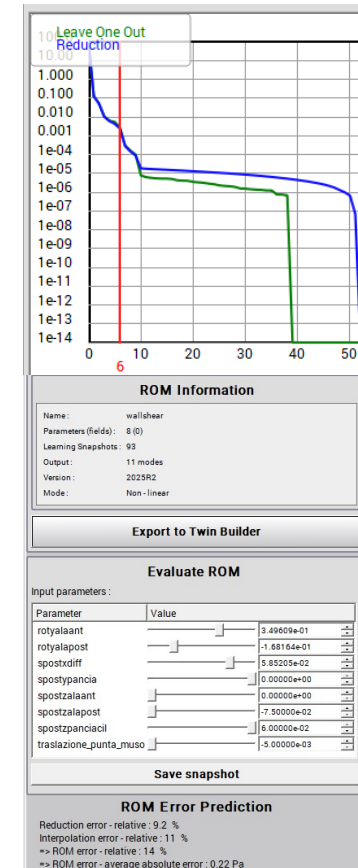
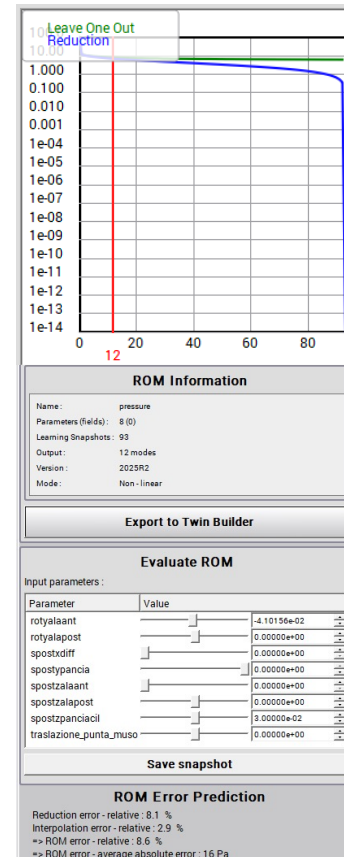
Conclusions

ROM and reduction errors

The static pressure ROM retained 12 modes, achieving a relative error of **8.6%** with an average deviation of 16 Pa.

For the wall shear stress, with 11 modes, the error rises to **14%**.

id	rotlyalaant	rotlyalapost	spostdiff	spostpancia	spostzalaant	spostzalapost	spostz	ROM Error - Relative (%)
1	0	0	0	0	0	0	0	6.4021
2	1	0.300	0.020	-0.050	5.000e-03	0.075	0.050	6.7591
3	0	0	0	0.075	0	0	0	7.7441
4	0	0	0	0	0	0	0	7.5181
5	0	-0.300	0	0	0	0	0	6.0791
6	0	0	0	0	0	0	0	6.5741
7	1	0	0	0	0	0	0	7.0001
8	0	0	0	0	5.000e-03	0	0	6.9701
9	0	0	0	-0.050	0	0	0	10.2181
10	-1	0	0	0	0	0	0	7.7691
11	0	-0.300	0	0	0	0	0	7.0211
12	0	0.300	0	0	0	0.075	0	7.5561
13	1	0	0	0	5.000e-03	0	0	7.0631
14	0	0	0	0	0.050	0	0	6.7441
15	0	-0.300	0.020	0	0	-0.075	0	7.8921
16	-1	-0.300	0.020	-0.050	5.000e-03	-0.075	0.050	6.9351
17	-0.110	-0.165	0.015	-0.043	4.725e-03	-0.049	0.024	11.0001
18	0.570	-0.027	9.900e-03	-0.027	2.375e-03	0.043	7.500	7.3961
19	0.030	0.183	1.100e-03	-0.030	1.750e-04	-3.750e-03	0.043	7.2411
20	-0.810	-0.021	7.000e-04	-0.017	1.475e-04	0.029	0.042	6.9001
21	-0.250	0.051	5.100e-03	-6.750e-03	2.475e-03	-9.750e-03	0.051	5.0801
22	-0.230	0.093	0.015	0.022	3.125e-03	0.023	2.100	6.7151
23	-0.030	0.147	0.019	-1.750e-03	1.775e-03	0.037	0.041	7.0001
24	0.830	0.069	2.100e-03	-0.048	2.425e-03	-0.032	0.033	7.3521
25	-0.690	-0.225	0.013	-0.044	4.475e-03	-0.055	0.030	6.9521
26	0.410	0.027	9.700e-03	-0.016	8.250e-04	1.250e-03	0.015	6.7901
27	-0.790	-0.261	0.014	-0.023	3.525e-03	0.019	0.035	6.6751
28	0.970	0.177	0.012	-2.750e-03	1.125e-03	-0.043	0.048	5.9161
29	0.470	0.291	0.020	-0.031	1.225e-03	-0.073	0.045	6.8061
30	0.790	-0.255	4.700e-03	-0.028	2.025e-03	2.250e-03	0.021	7.5241
31	0.070	0.063	0.013	-0.015	4.225e-03	0.034	0.011	9.0241
32	0.390	-0.213	0.015	-2.500e-04	3.675e-03	-0.064	0.020	6.5721
33	0.530	-0.075	6.500e-03	-0.033	4.925e-03	8.250e-03	0.024	6.5381

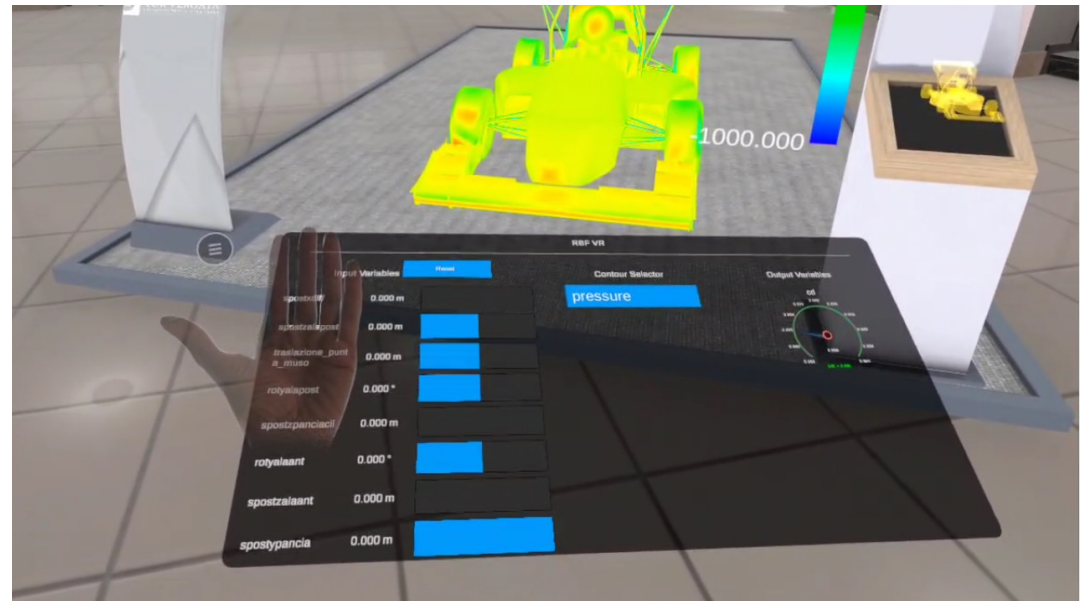


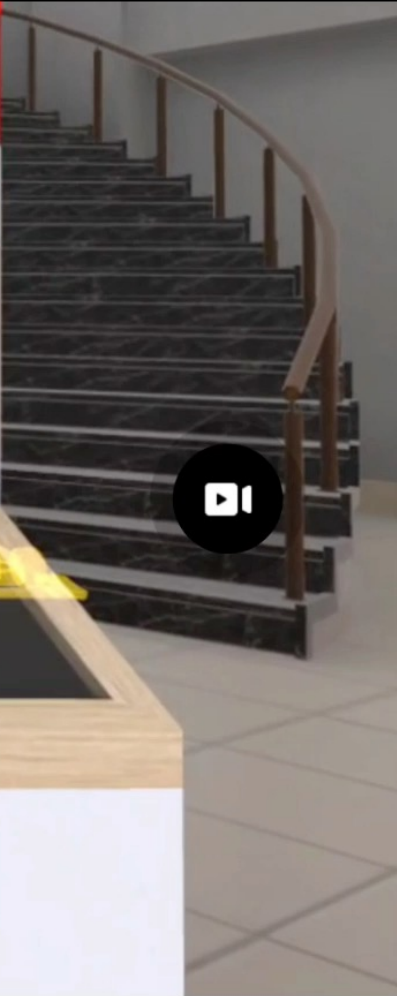
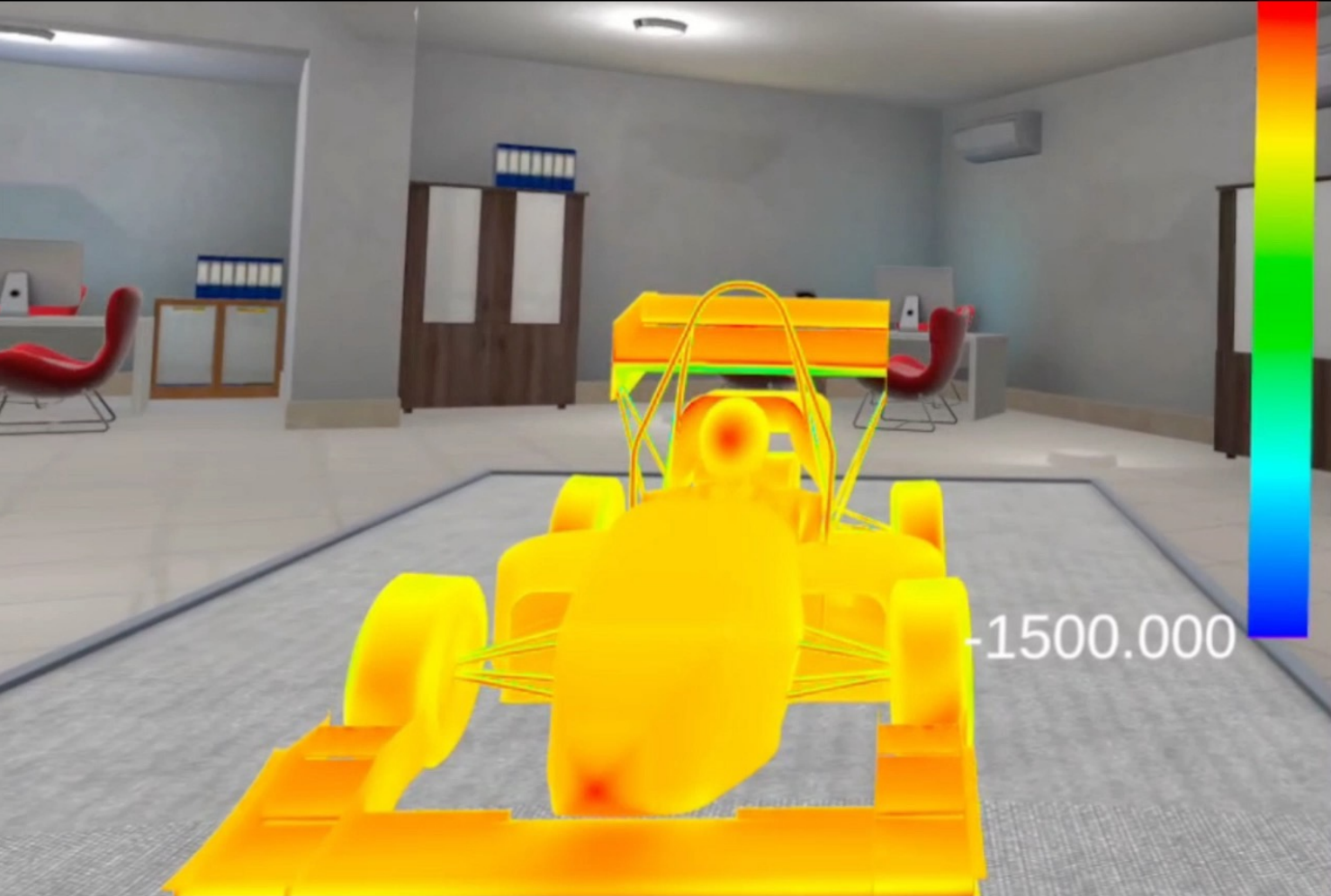


VR experience

The static pressure model was exported as an FMU and integrated into a VR environment on Meta Quest 3, with rendering at **60 fps**.

Virtual **sliders** allow real-time modification of the wings, sidepods, and diffuser, instantly updating the pressure maps for immediate and **immersive** aerodynamic optimization.







Conclusions and future developments

Conclusions

- The aerodynamic optimization reduced the drag coefficient by 5% while keeping the vertical load constant.
- Static pressure ROM: **8.6%** error (average deviation 16 Pa)
- Interactive **Digital Twin** in VR on Meta Quest 3, with real-time modification of wings, sidepods, and diffuser.

Possible future developments

- Enrich the snapshot database to reduce interpolation error
- Increase mesh resolution
- Include dynamic parameters (yaw, variable setup, ride height)
- Extend the analysis to structural and thermal elements



TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA



Thank you for your attention!

Helciug Mihai Alin