Structural Optimization of Internal Combustion Engines Using RBF Mesh Morphing

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Founder of RBF Morph srl

Agenda

- About us – past and running projects
- Radial Basis Functions – Data Science and Geometrical Intelligence
- Parameter-based and parameter-free shape optimisation
- An industrial example: Internal Combustion Engine Components Fatigue Assessment
- Digital Engineering Applications
- Conclusions

PIAGGIO

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EU-funded research projects 2013-2025

Funded by the European Union

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next generation spine experts

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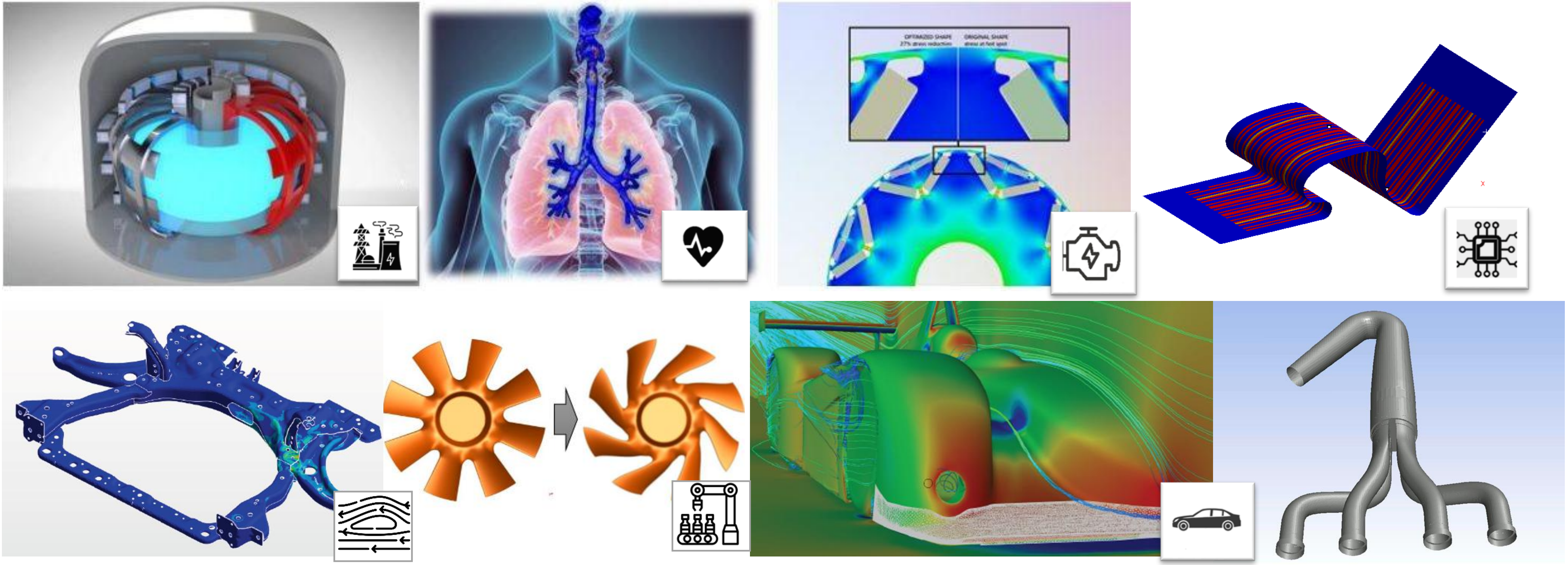
Research and Industrial sectors



Radial Basis Functions

Data Science and Geometrical Intelligence

Radial Basis Functions (RBF) in a nutshell

source points

radial basis

$$s(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i \cdot \varphi\left(\left\|\mathbf{x}-\mathbf{x}_{\mathbf{k_i}}\right\|\right) + h(\mathbf{x})$$

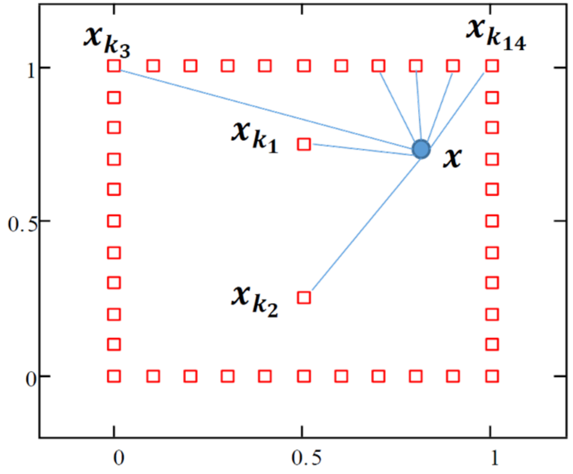
polynomial e.g. $h(\boldsymbol{x}) = \beta_1 + \beta_2 x + \beta_3 y + \beta_4 z$

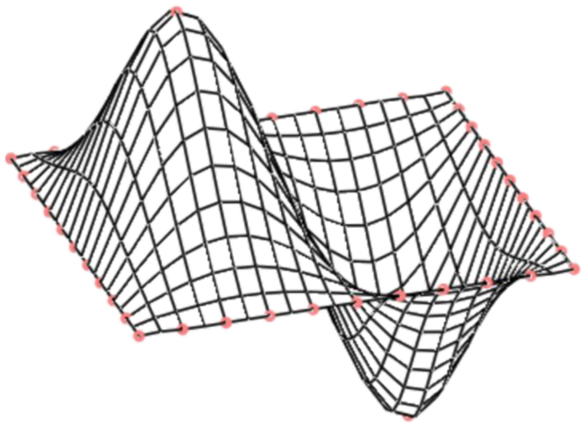
weight

shift of the target point to the i-th data site

RBF	φ(r)
Spline type (Rn)	r^n, *n odd*
Thin plate spline	$r^n \log(r)$ *n even*
Multiquadratic (MQ)	$\sqrt{1+r^2}$

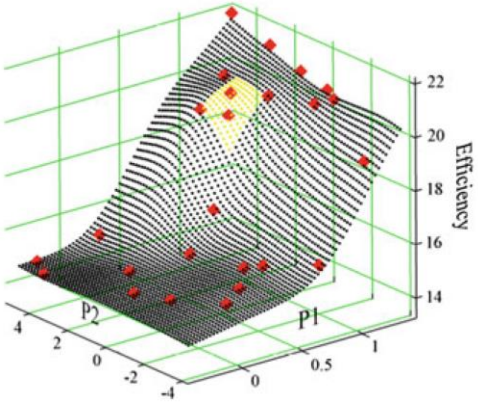
RBF are a very powerful mathematical tool able to interpolate **everywhere** in the $\mathbb{R}^n$ space a function given at scattered **source points**

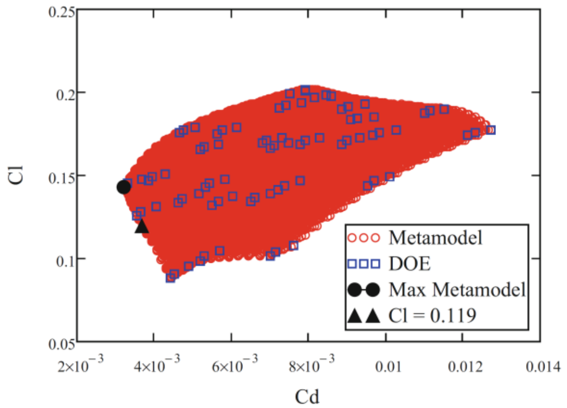




Interpolators in multi-dimensional spaces

- **Data science** problems
  - Inference $\mathbb{R}^n \Rightarrow \mathbb{R}^m$
  - Gaussian RBF is recognized as the "RBF neural network"
  - Useful for **surrogates** in **optimisation**
- 3D space manipulation (shape deformation, data mapping)
  - Field manipulation is a key enabler for **geometric intelligence**
  - Mapping is a key enabler for multi-physics and as a "morphing extender"





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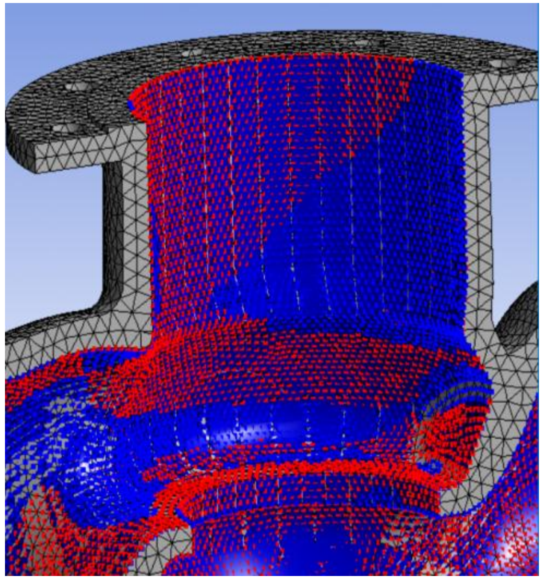
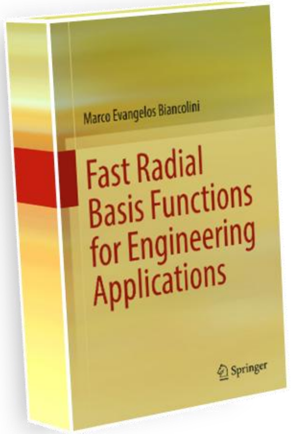
Shape optimisation

Parameter-based and parameter-free workflows

RBF Mesh Morphing



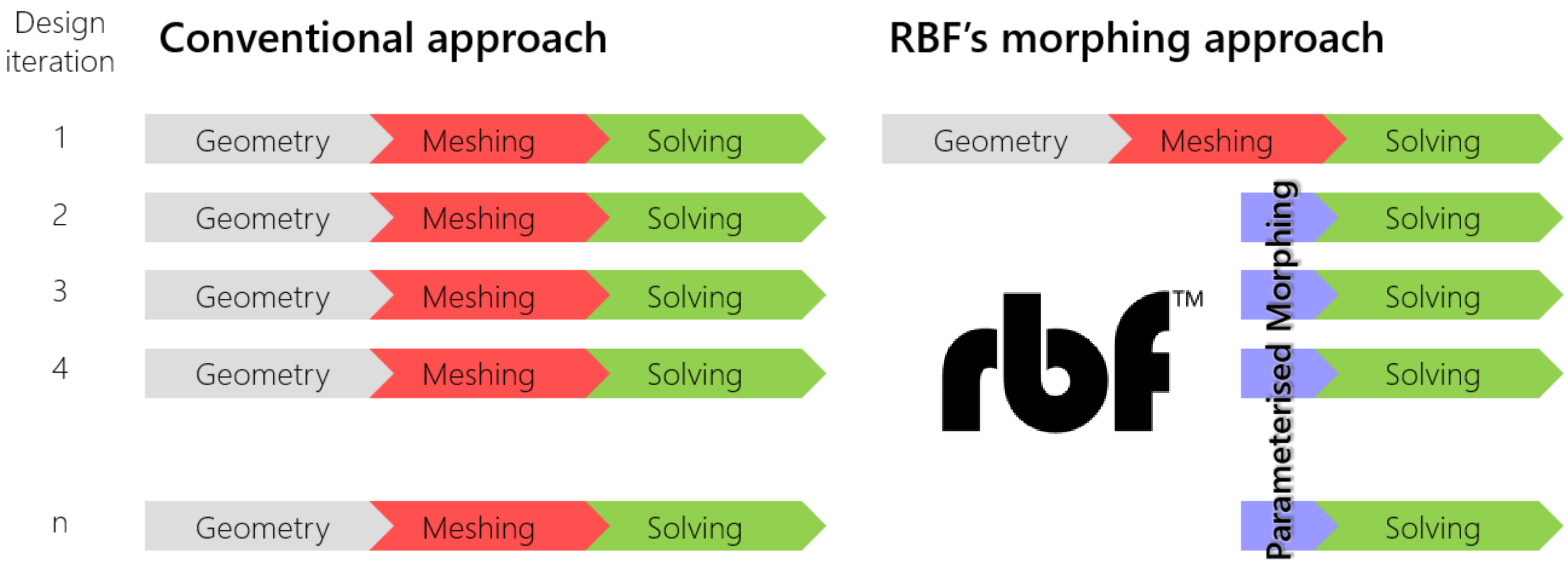
- We adopt **Radial Basis Functions** (RBF) to drive mesh morphing (smoothing) from a list of source points and their displacements
  - Surface shape changes
  - Volume mesh smoothing
- RBF are recognized to be one of the **best mathematical tool** for mesh morphing



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

Parameter-based shape optimization

- Morphing is a **key enabler** for optimization and Digital Twins
- The turnaround time of the optimization is usually **reduced by a factor five** (weeks becomes days)



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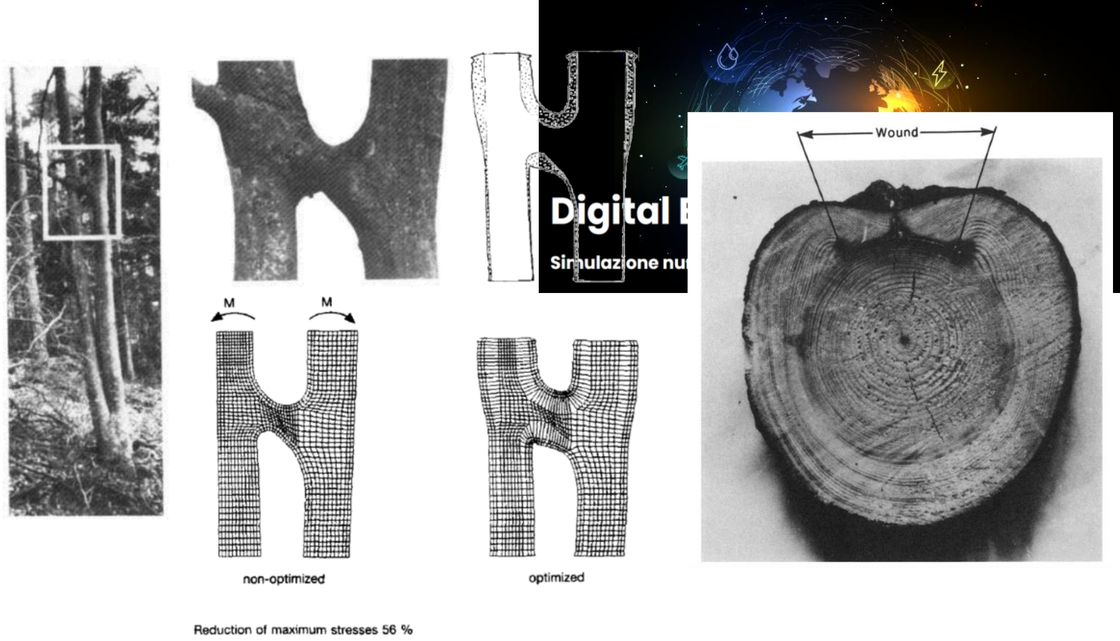
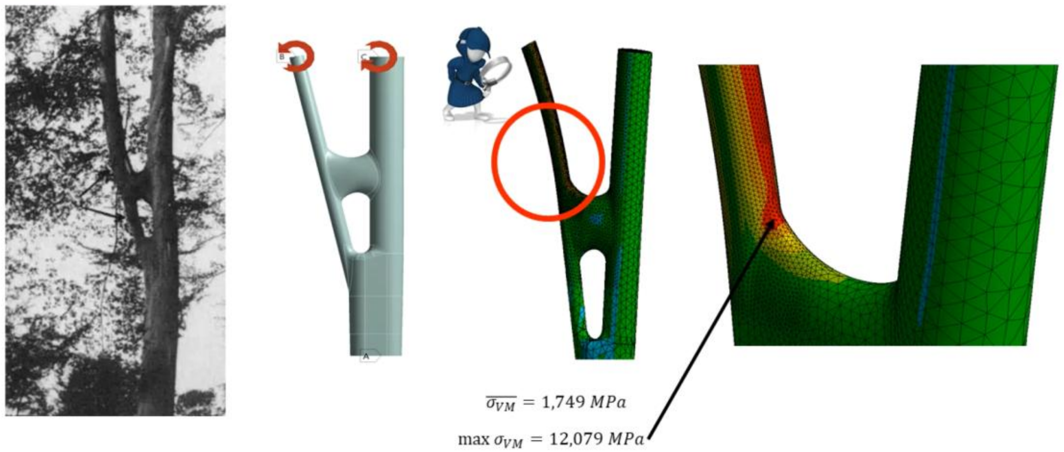
BGM Background

- **BGM** approach is based on the observation that **biological** structures growth is driven by **local** level of **stress**.
- Bones and trees' trunks are able to **adapt the shape** to mitigate the stress level due to external loads.
- The process is driven by stress **value at surfaces**. Material can be **added or removed** according to local values.
- Was proposed by Mattheck & Burkhardt in 1990





Parameter-free shape optimization

- The BGM idea is that surface growth can be expressed as a **linear law** with respect to a given threshold value:

$$\dot{\varepsilon} = k\left(\sigma_{Mises} - \sigma_{ref}\right)$$

- Waldman and Heller refined this first approach proposing a **multi peak** one:

$$d_i^j = \left(\frac{\sigma_i^j - \sigma_i^{th}}{\sigma_i^{th}}\right) \cdot s \cdot c\,, \qquad \sigma_i^{th} = max(\sigma_i^j) \text{ if } \sigma_i^j > 0 \quad \text{or} \quad \sigma_i^{th} = min(\sigma_i^j) \text{ if } \sigma_i^j < 0$$

- A different implementation is present and different **stress types** can be used to modify the surface shape:

$$S_{node} = \frac{\sigma_{node} - \sigma_{th}}{\sigma_{max} - \sigma_{min}} \cdot d$$

An industrial example

Internal Combustion Engine Components Fatigue Assessment

Collaboration Context

- **RBF Morph, Piaggio** and **University of Rome Tor Vergata** supported by **Ansys**
- **Topic**: Structural optimization of a Piaggio 4-stroke engine **connecting rod & piston**
- **Methods**: Parametric mesh morphing + BGM Method within an Ansys-based workflow
- **Outcomes**: A **team project** for the course *Tecnica delle Costruzioni Meccaniche (Advanced Machine Design)* and a **bachelor degree thesis**

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LAUREA TRIENNALE IN INGEGNERIA MECCANICA

Ottimizzazione strutturale della biella di un motore a quattro tempi: dalla simulazione FEM ad alta fedeltà all'intelligenza artificiale

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Candidato:
Danilo Lampasona

A.A. 2023/2024

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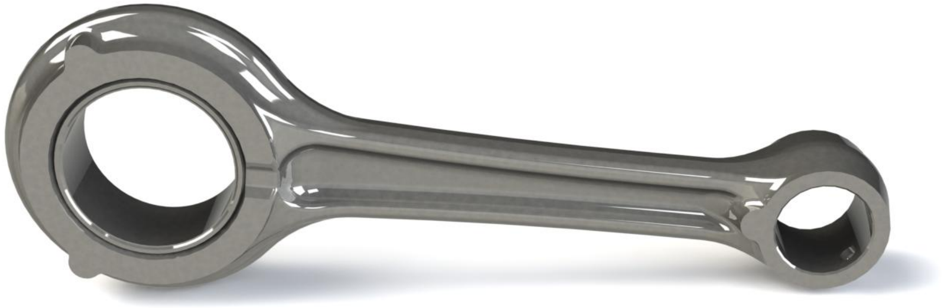
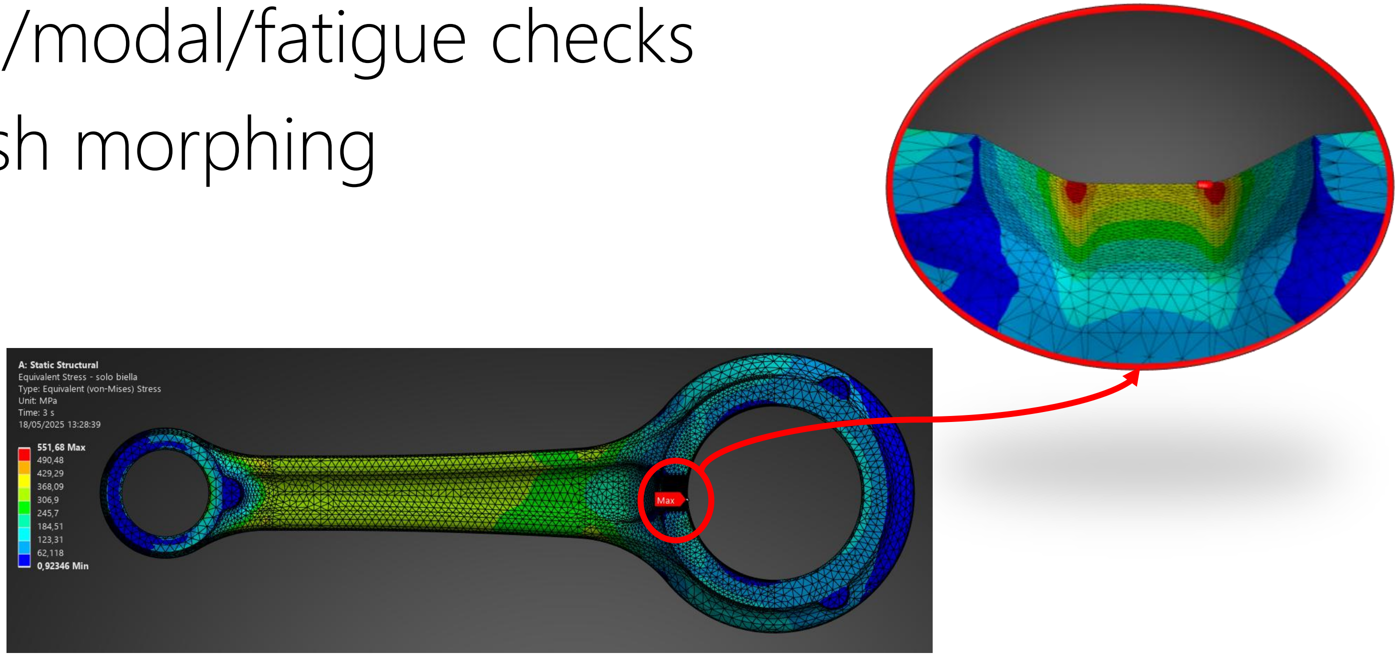
Connecting Rod Optimization

- Lower peak stress at constant mass — or same stress with less mass
- Increase safety factors and fatigue life and getting lower emissions
- Fast, reliable evaluations through a static ROM
- FEA (Ansys Workbench): stress/modal/fatigue checks
- Shape update: RBF-based mesh morphing





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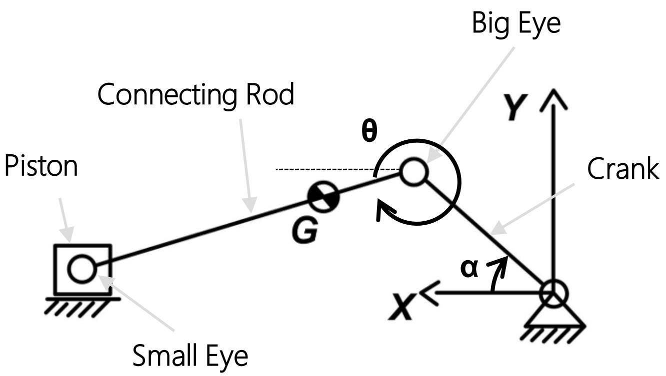
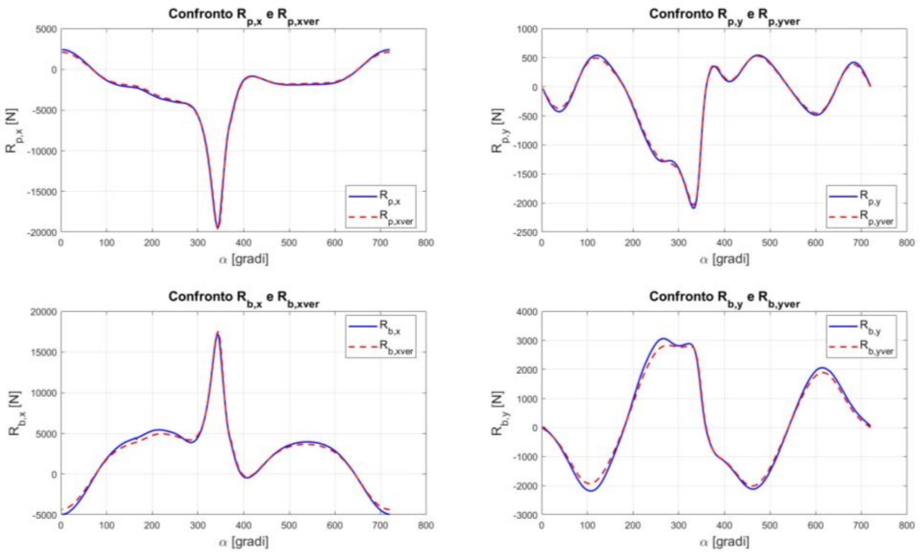
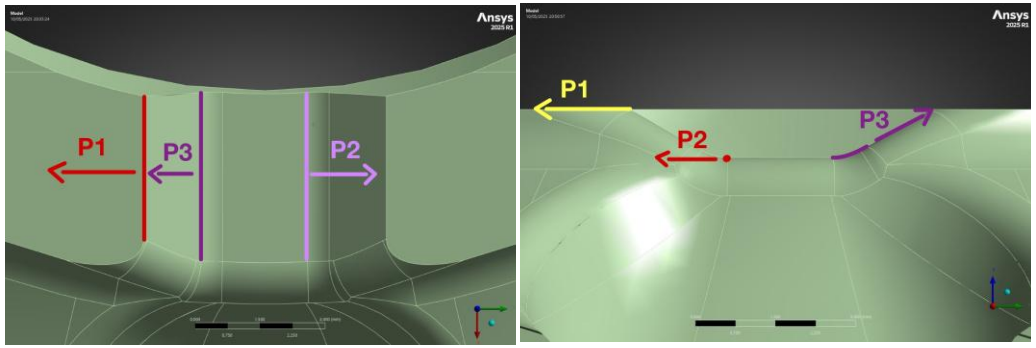
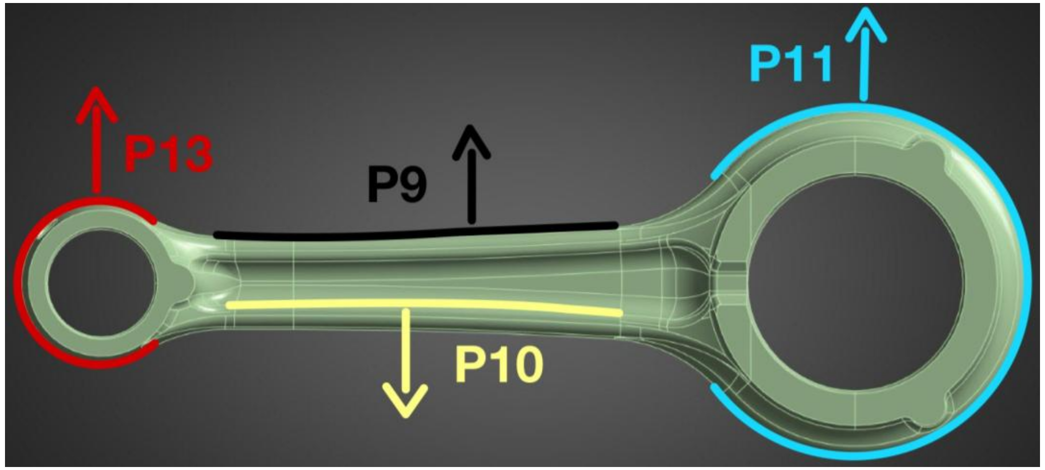
Connecting Rod Optimization







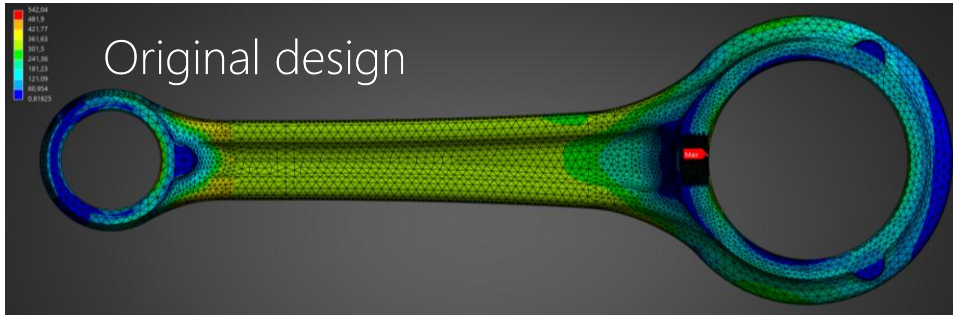


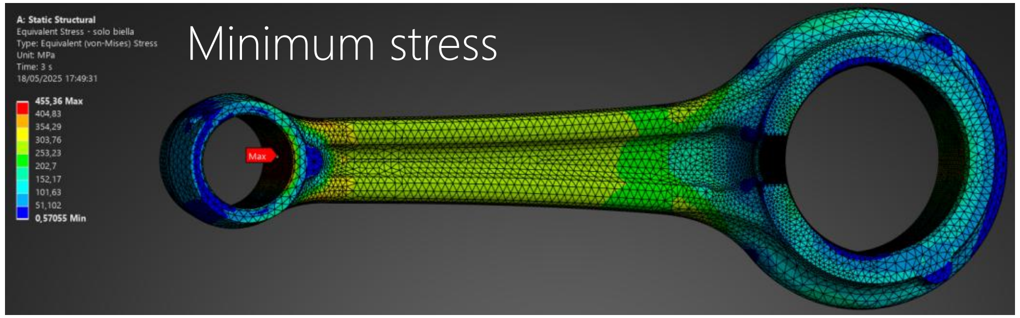
Connecting Rod Optimization

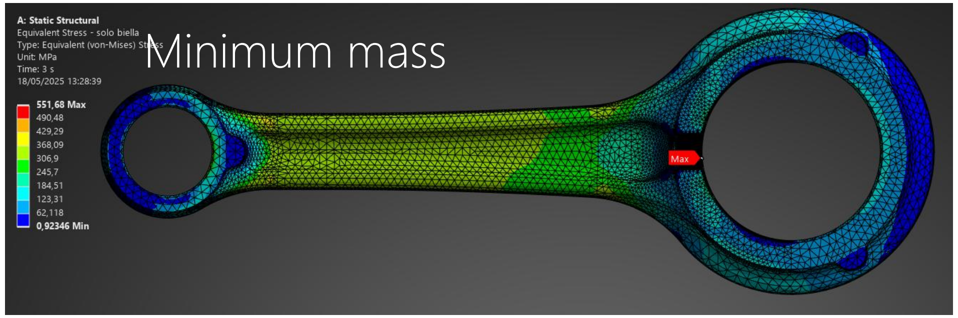
Worst load case:6500 RPM, α=344.7°, θ=-4.5°
DP113: minimum stress (-17,4%)
DP119: minimum mass (-21,0%)

DP	P1	P2	P3	P9	P10	P11	P13
113	1.239	0.787	-0.087	1.102	0.781	0.995	0.954
119	1.218	0.765	-0.146	1.003	0.900	0.903	0.952

DP	$\boldsymbol{\sigma_{VM}}$ [MPa]	V_{tot} [mm^3]	$\Delta\boldsymbol{\sigma}$ [MPa]	$\Delta\boldsymbol{\sigma}$ [%]	ΔV [%]	Δx_G [mm]
113	455.4	18016.4	-95.6	-17.4	0.9	-0.6
119	542.0	14110.9	-9.0	-1.6	-21.0	4.4







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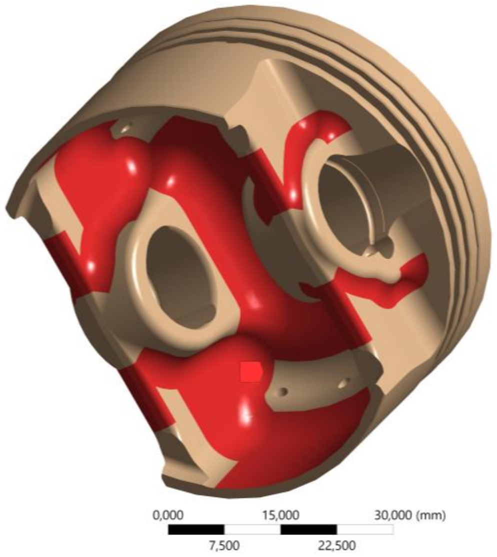
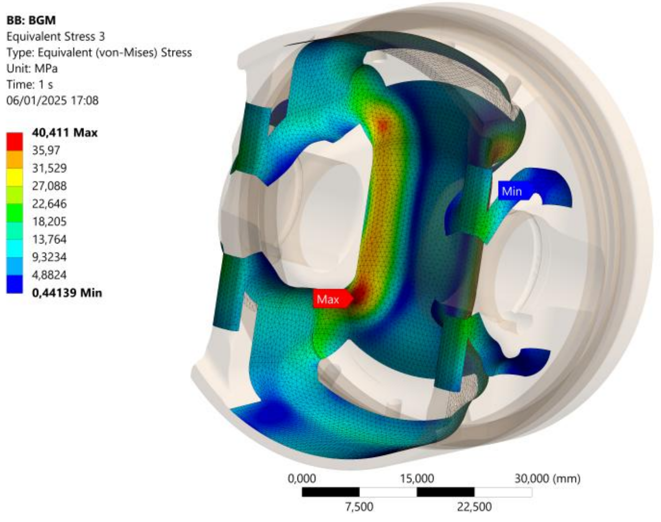
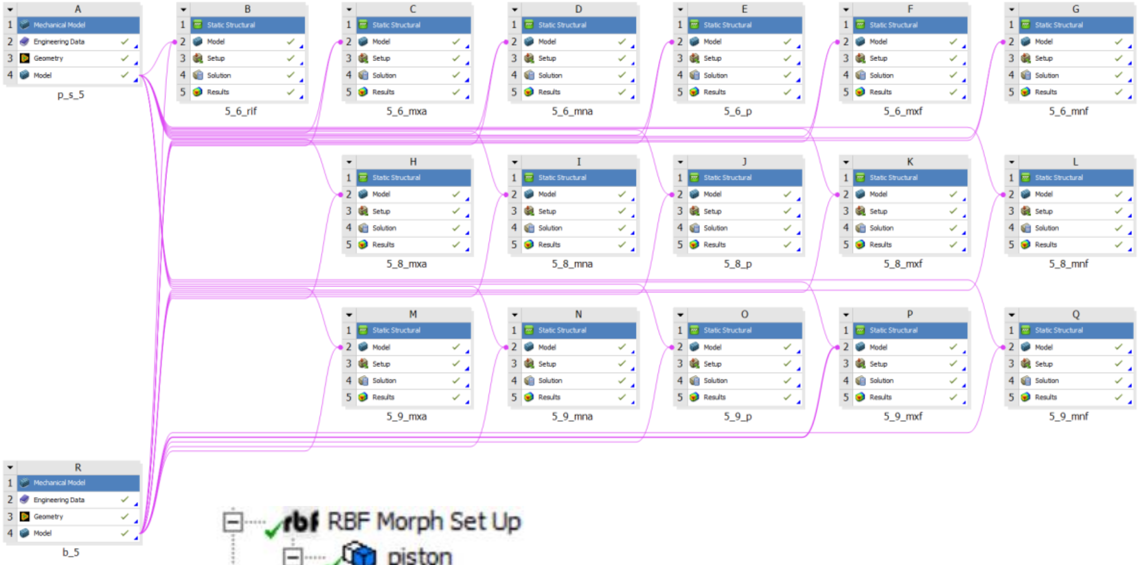
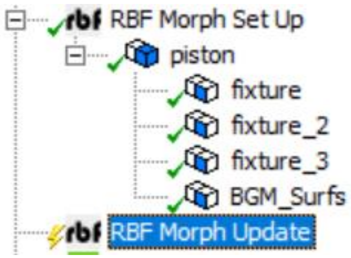
Piston BGM Optimization

- Uniform pressure on the piston crown
- Frictionless contact between the cylinder liner and piston skirt
- Frictional contact between the wrist-pin (gudgeon pin) and the wrist-pin bore
- Fixed constraint on the inner surfaces of the wrist pin









$$s_{node} = \frac{\sigma_{node} - \sigma_{th}}{\sigma_{max} - \sigma_{min}} d$$

Details of "BGM_Surfs"

Node Selection	
Scoping Method	Named Selection
Named Selection	BGM_Surfs(p_s_5)
Definition	
Transformation	Surface Offset
Offset Type	Driven Value
Offset Along	Surface Normal
Auto Offset	Off
Value Type	von Mises Stress
Threshold Value	11 MPa
Max Surf Offset	
Midside Nodes	Keep
Surface Constraint	No

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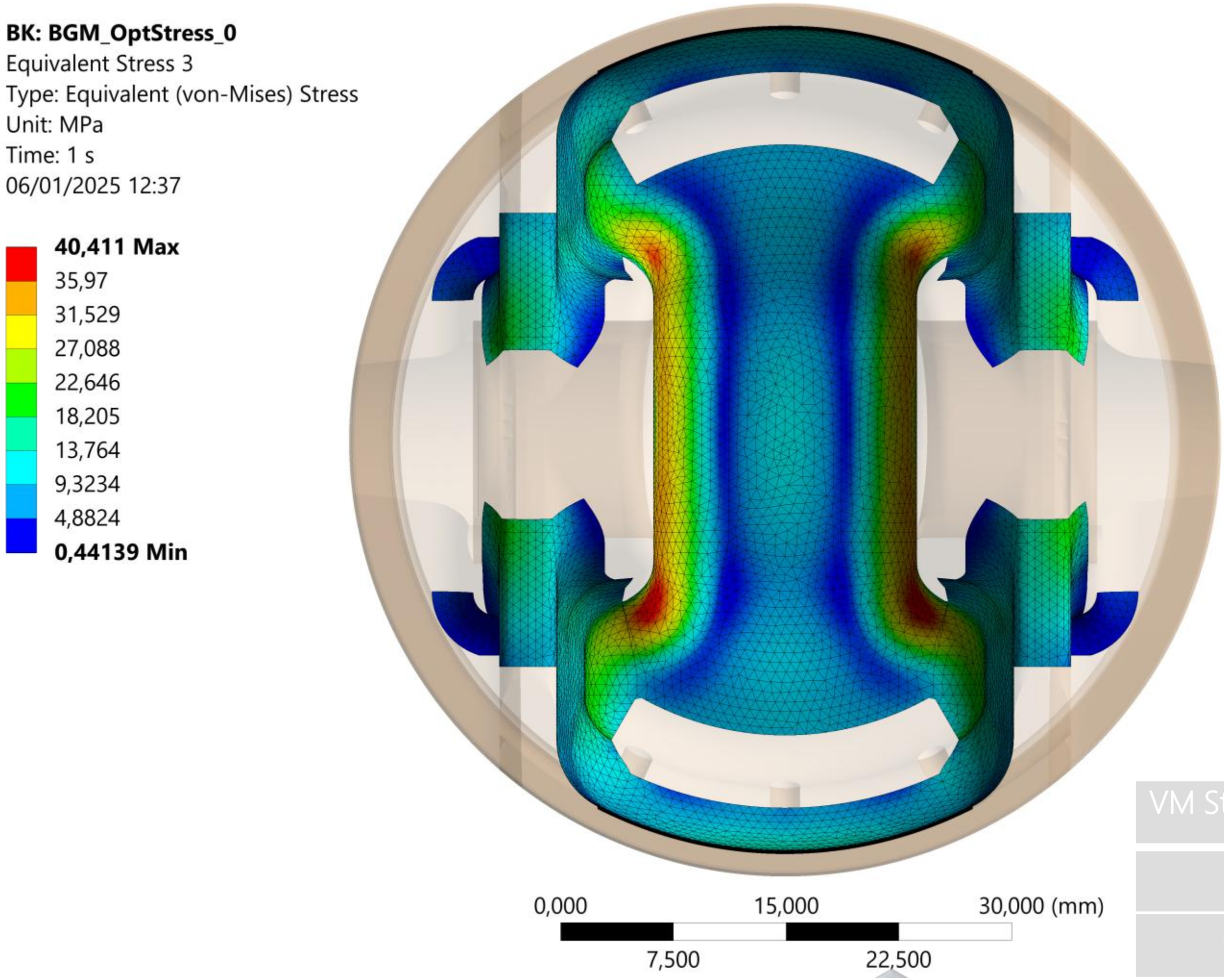
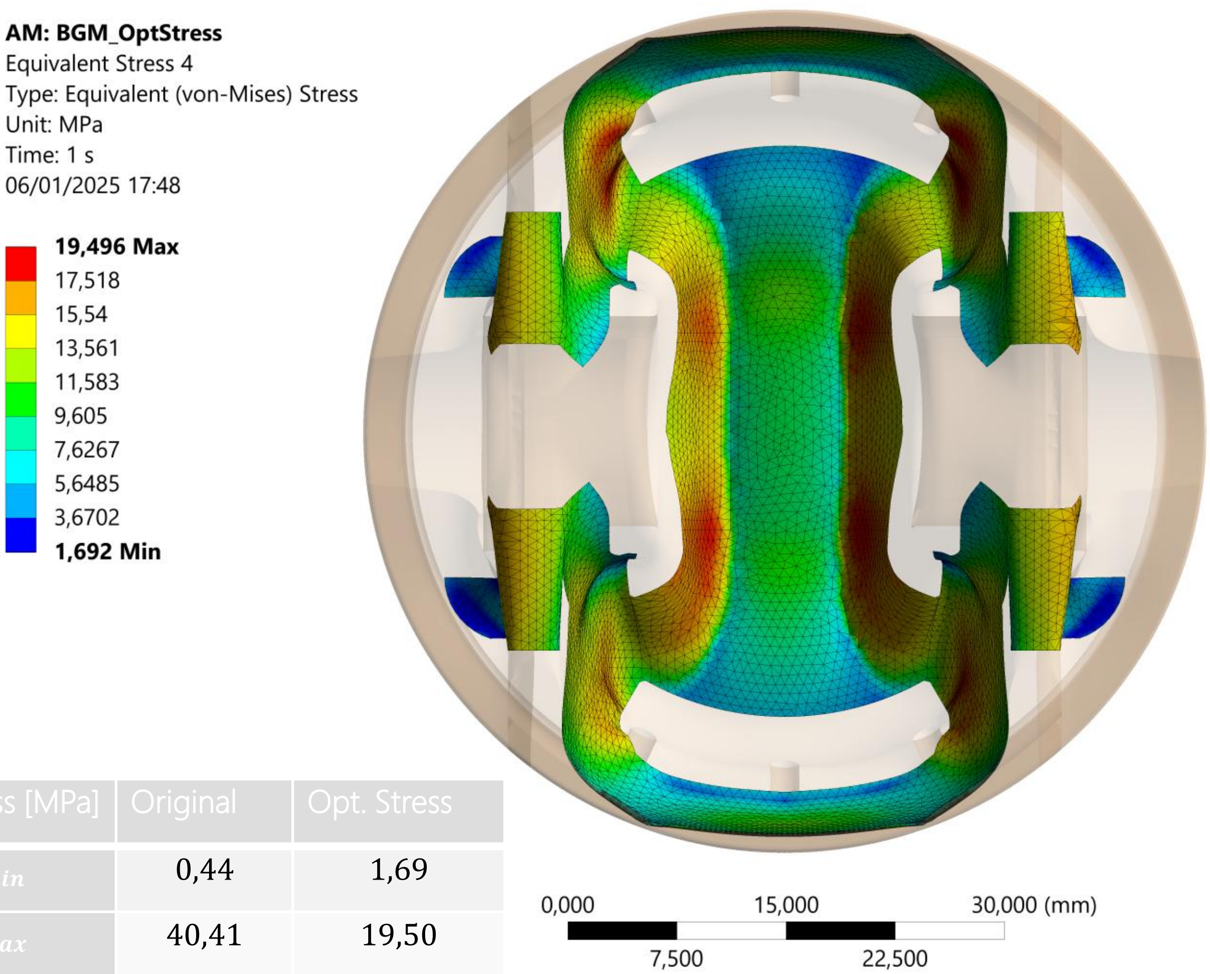
Piston BGM Optimization - Results

Digital Engineering Day Roma
Simulazione numerica: il motore dell'innovazione digitale





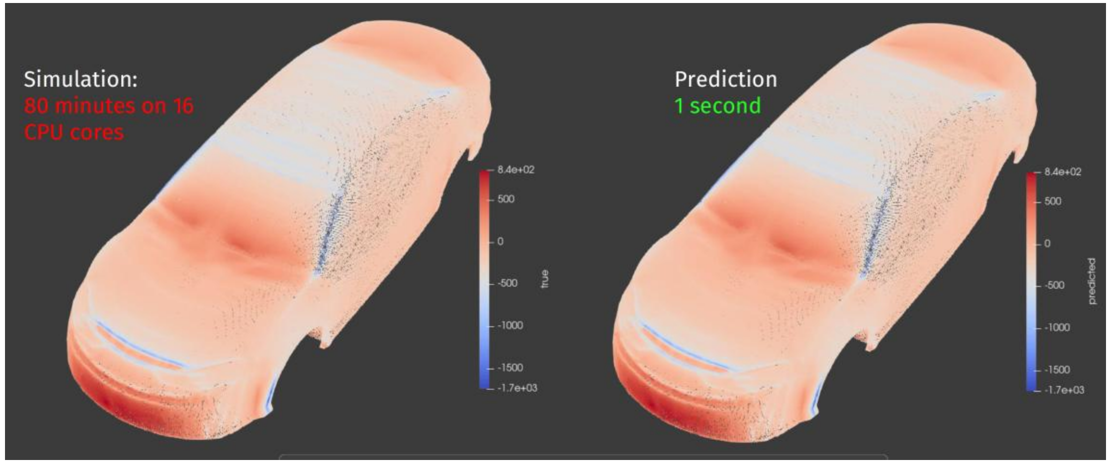
VM Stress [MPa]	Original	Opt. Stress
σ_{min}	0,44	1,69
σ_{max}	40,41	19,50
σ_{med}	11,05	11,13

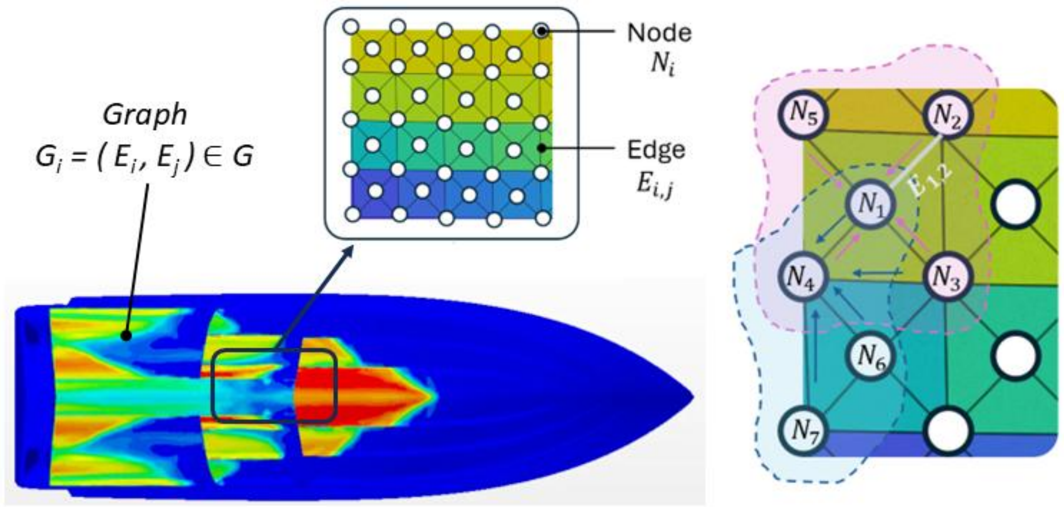
Digital Engineering

Workflows and Applications

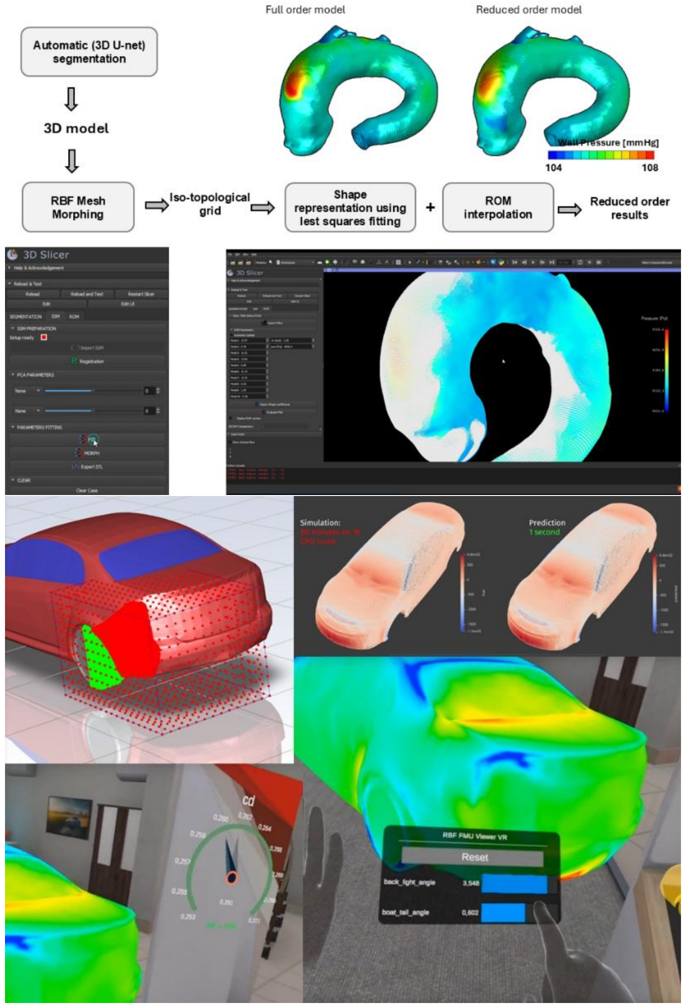
Digital Engineering Applications

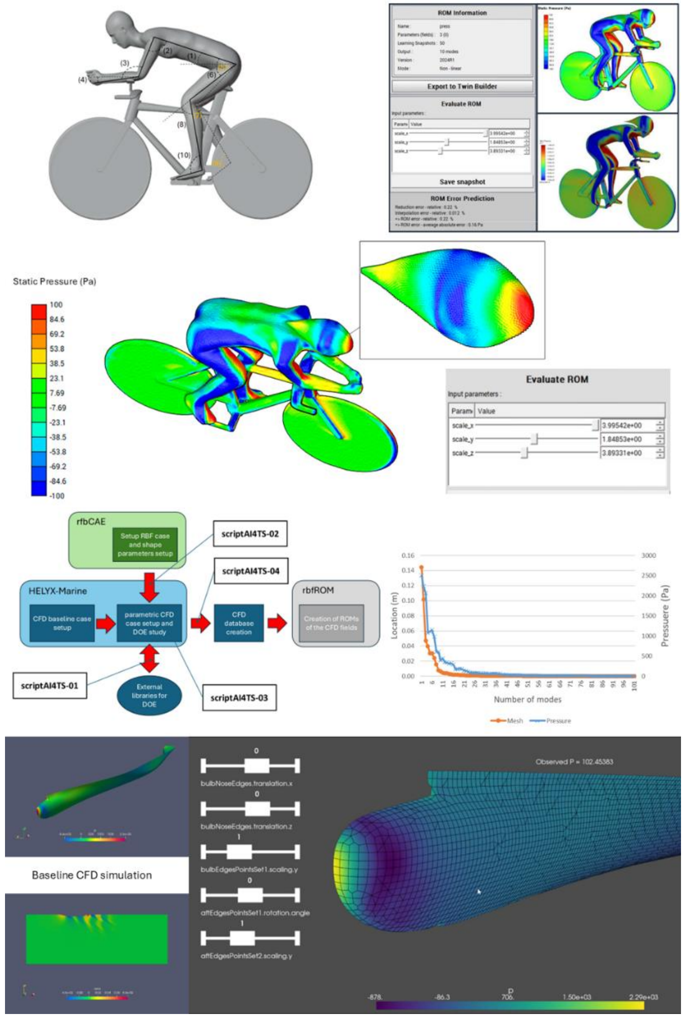
- **Digital Twin** – digital replica of asset useful at design and operation
- CAE adoption is evolving: single verification, design variations, automated optimisation, **parametric space exploration** (snapshots)
- **Machine learning** is the reference for «AI» based approach
- High/medium fidelity simulations allow to generate the training data: **synthetic datasets**

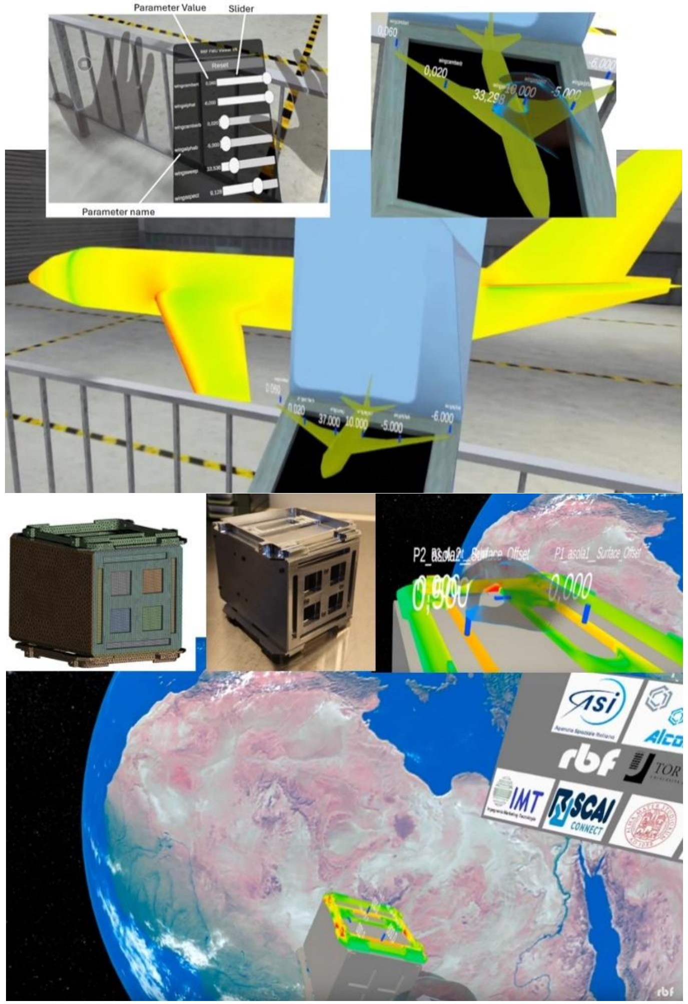




Digital Engineering Applications







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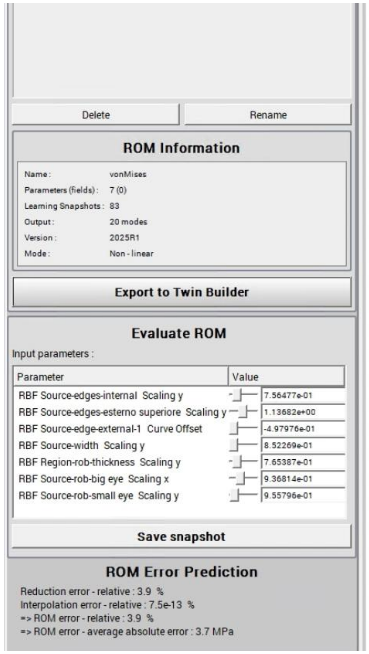
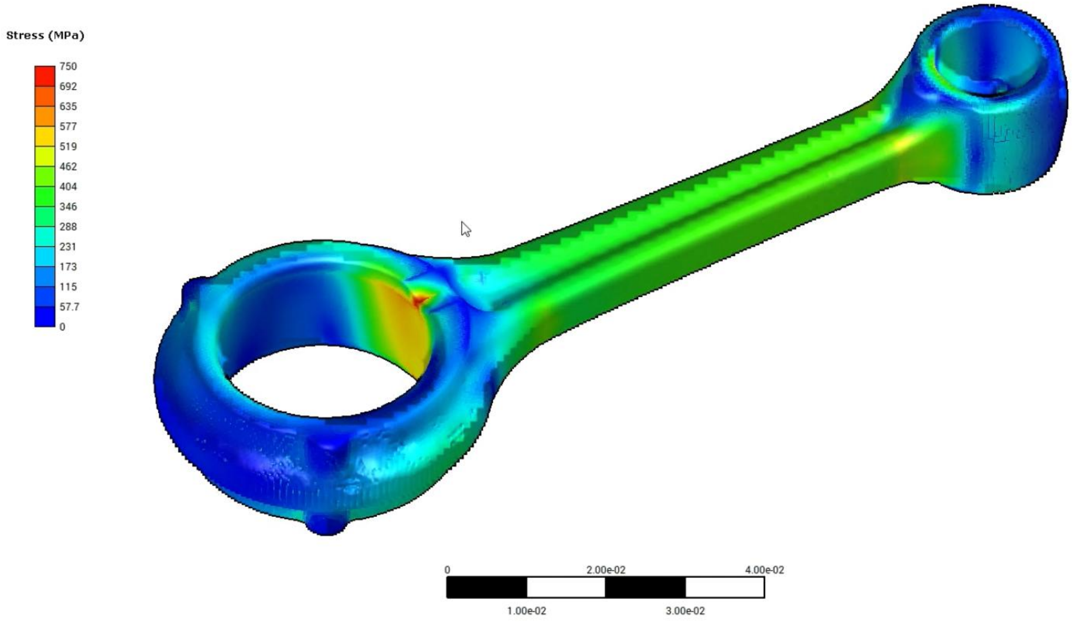
Connecting Rod Interactive

ROM building and validation

- 20 modes
- 80% training set, 20% validation set
- Maximum ROM error: 7%

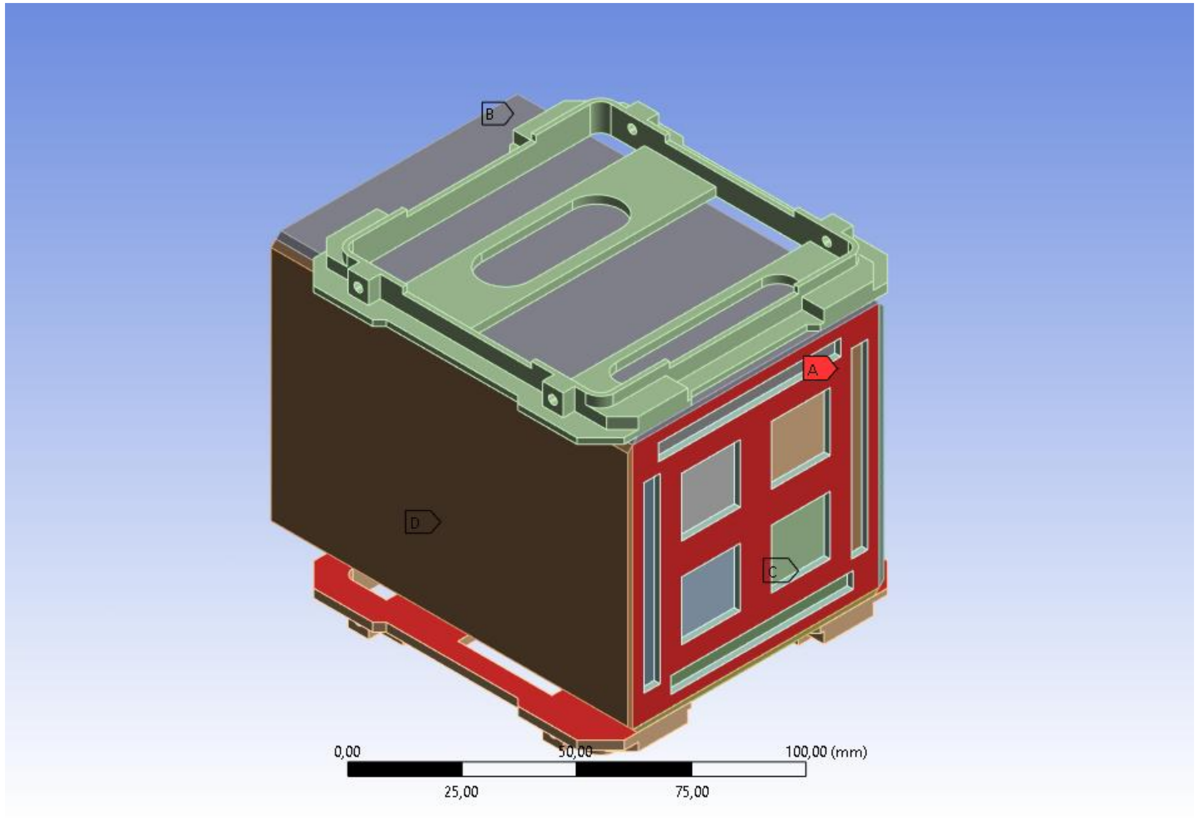
	σ_{VM} FEM (N)	σ_{VM} ROM (N)	$\Delta\sigma_{VM}$ [%]
DP113	455.36	456.52	-0.26
DP119	542.04	566.00	-4.42





Thermo-Mechanical Interactive Optimization

- The **Cubesat** shown in figure is subject to two different **thermo-mechanical** load conditions
- Eyelets and thickness optimization through mesh morphing
- FEA solver: **Ansys Mechanical**



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Thermo-Mechanical Interactive Optimization

- The **Cubesat** shown in figure is subject to two different **thermo-mechanical** load conditions
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Conclusions

- Radial Basis Functions help **Digital Engineering** by providing **geometric intelligence** and an effective **inference** tool
- Parameter-free and parameter-based shape optimisation is possible
- An industrial example, fatigue optimisation of a connecting rod and a piston of a **scooter engine**, has been demonstrated
- Roadmaps toward an **AI based approach** were discussed
- Interactive VR implementation has been shown
- TRL of the solution? Everything is part of Ansys portfolio…

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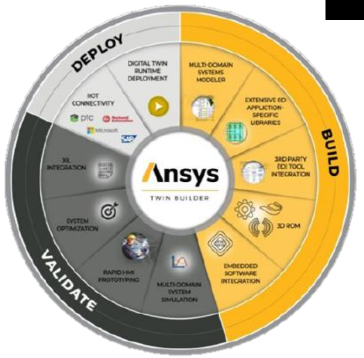
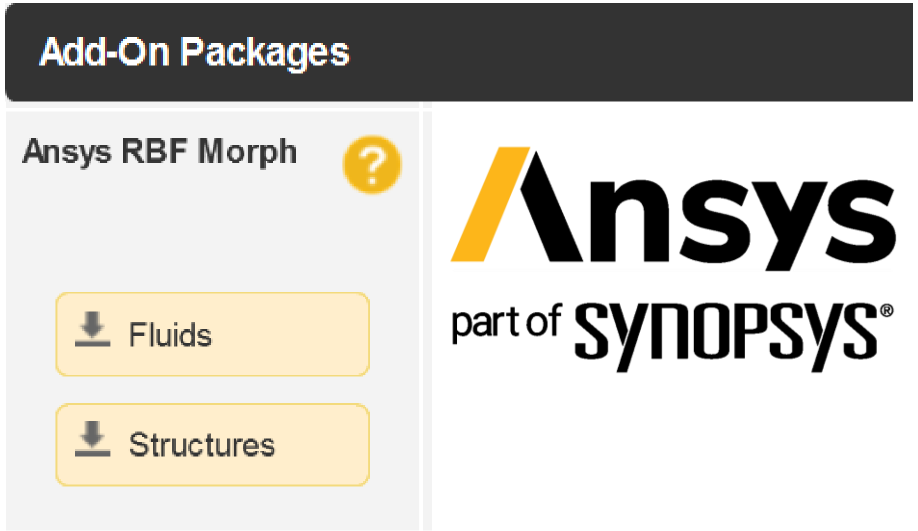
The advanced morphing solution selected by Ansys



- An RBF mesh morphing solution fully embedded in **Ansys**
  - **Ansys RBF Morph Fluids** – an Add On for Fluent
  - **Ansys RBF Morph Structures** – an ACT App for Mechanical
- Full integration with **optiSLang** and **Twin Builder**
- Support for **LS-DYNA** and **APDL**



Many thanks for your attention!

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