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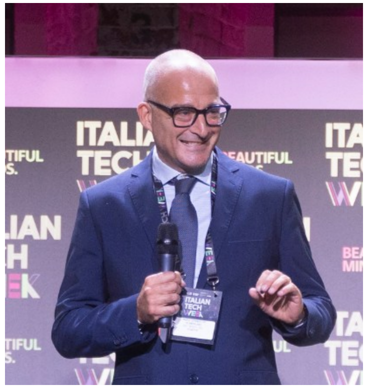
Real-Time Medical Digital Twins: Geometry, Simulation, and Immersive Interaction

Marco Evangelos Biancolini

RBF Morph Company founder

Associate Professor



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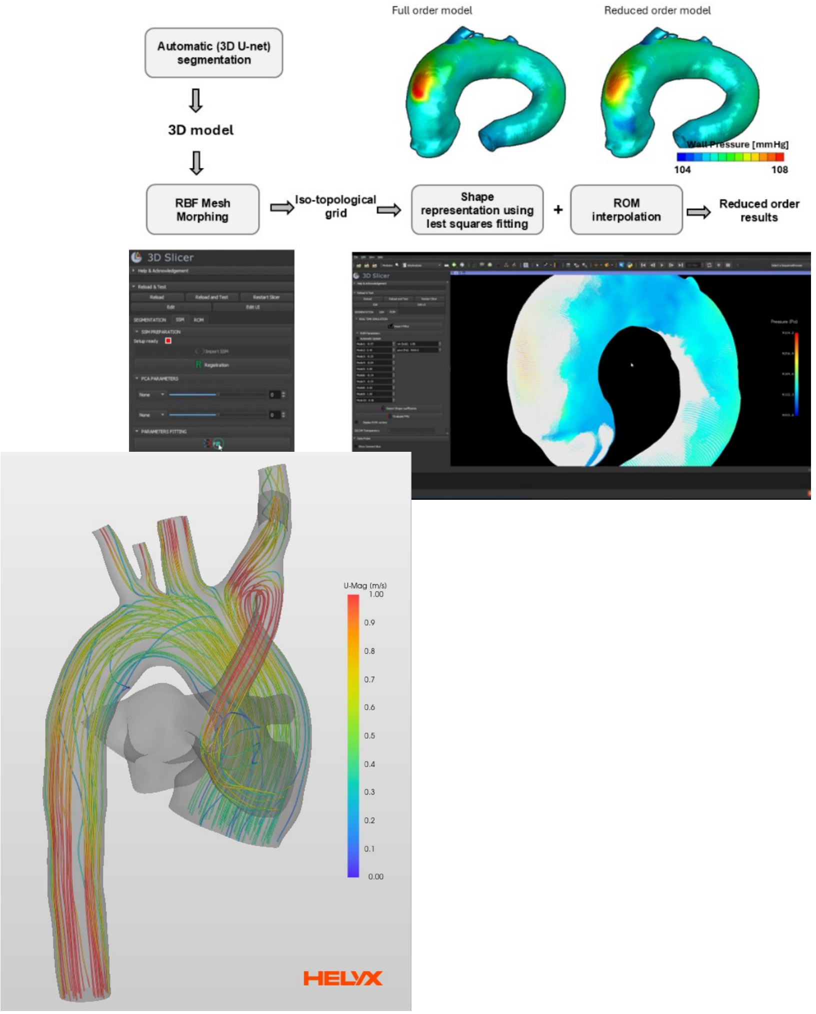
Agenda

- Digital Twins
- Radial Basis Functions
- Reduced order models
- Shape generation
- Interactive Real-Time Design Exploration
- Medical Digital Twins
    - Interactive Medical Digital Twins in 3d Slicer
    - Support to shunting procedures
- RBF Morph technologies
- Conclusions



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Digital Twins

Digital Engineering Applications

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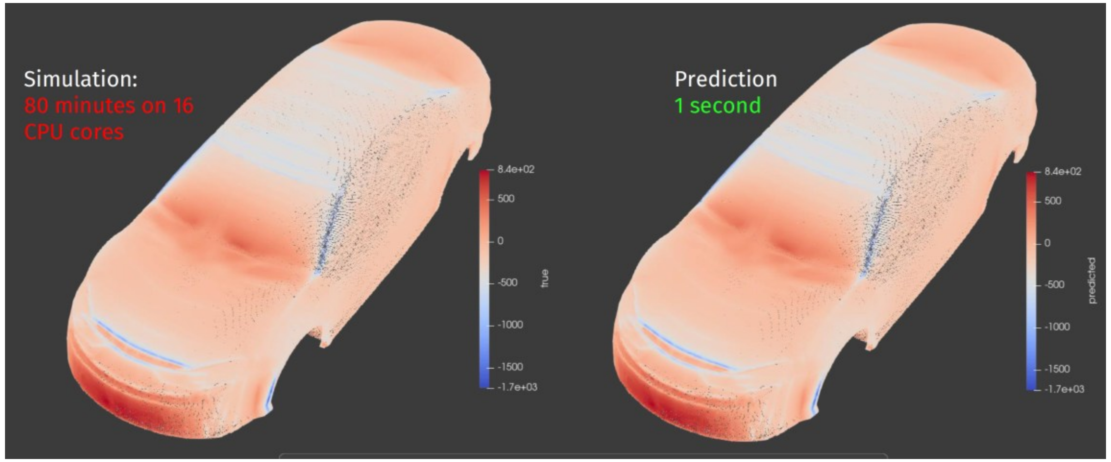
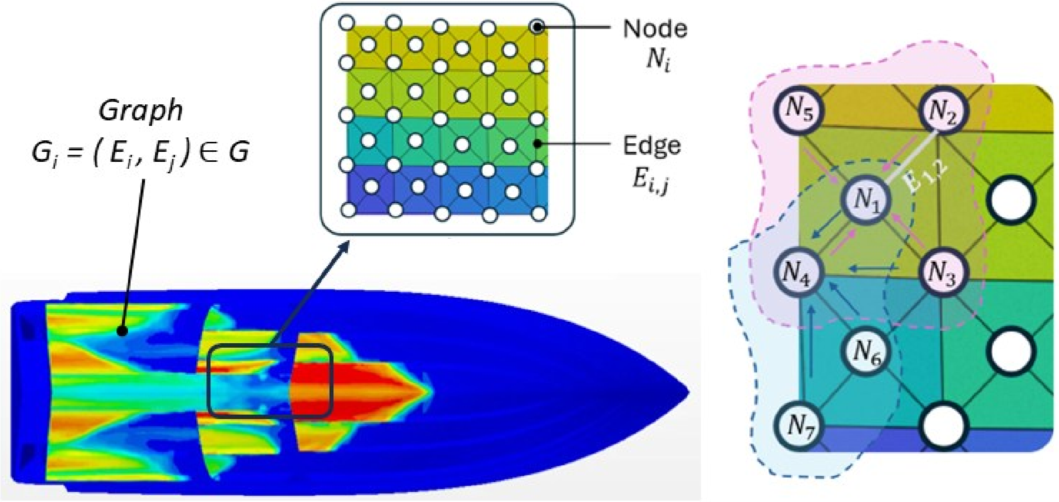
Digital Engineering Applications

- **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**





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Radial Basis Functions

Data Science and Geometrical Intelligence

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The evolution of RBF since their inception

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- Hardy – Multiquadric
- Greengard – Fast Multi Pole
- Powell – generalisation to $\mathbb{R}^n$
- Beatson – thin plate spline
- Wendland - compact support
- Babuška – Partition of Unity
- FGP – fast iterative MQ in $\mathbb{R}^n$
- Jakobsson, de Boer, morphing
- Botsch, interactive morphing
- Biancolini, LCM, first RBF industrial software
- Biancolini, Fast RBF Book

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Radial Basis Functions (RBF) in a nutshell

source points

radial basis

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

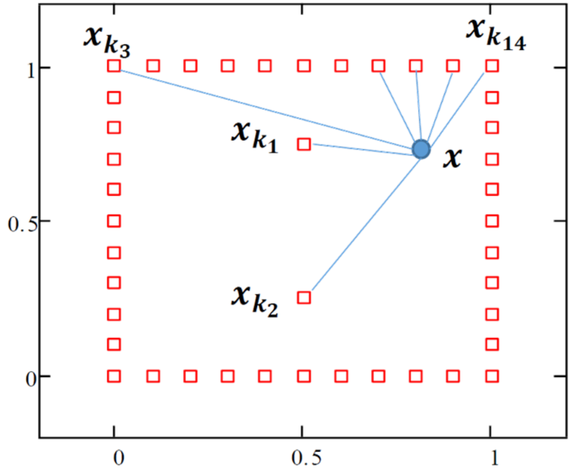
polynomial
e.g. $h(\boldsymbol{x}) = \beta_1 + \beta_2 x + \beta_3 y + \beta_4 z$

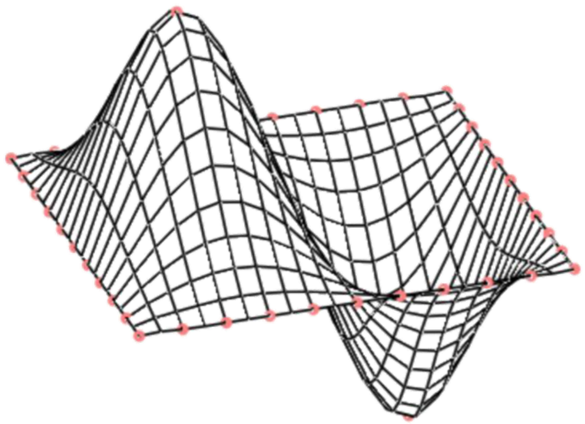
weight

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)	$\sqrt{1+r^2}$

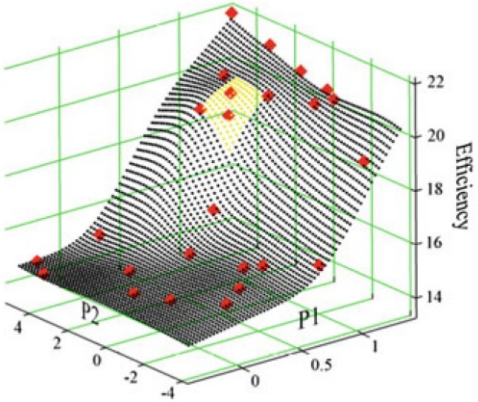
RBF are a very powerful mathematical tool able to interpolate **everywhere** in the $\mathbb{R}^n$ space a function given at scattered **source points**

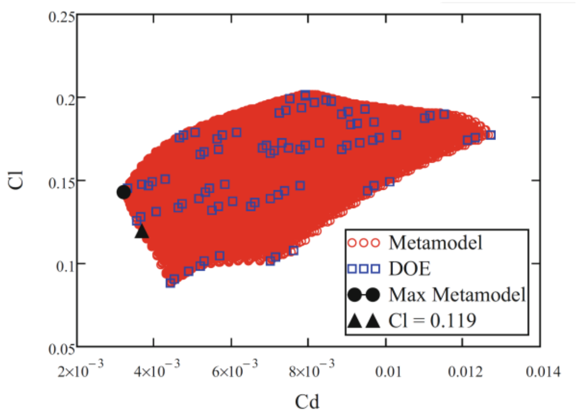




Interpolators in multi-dimensional spaces

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



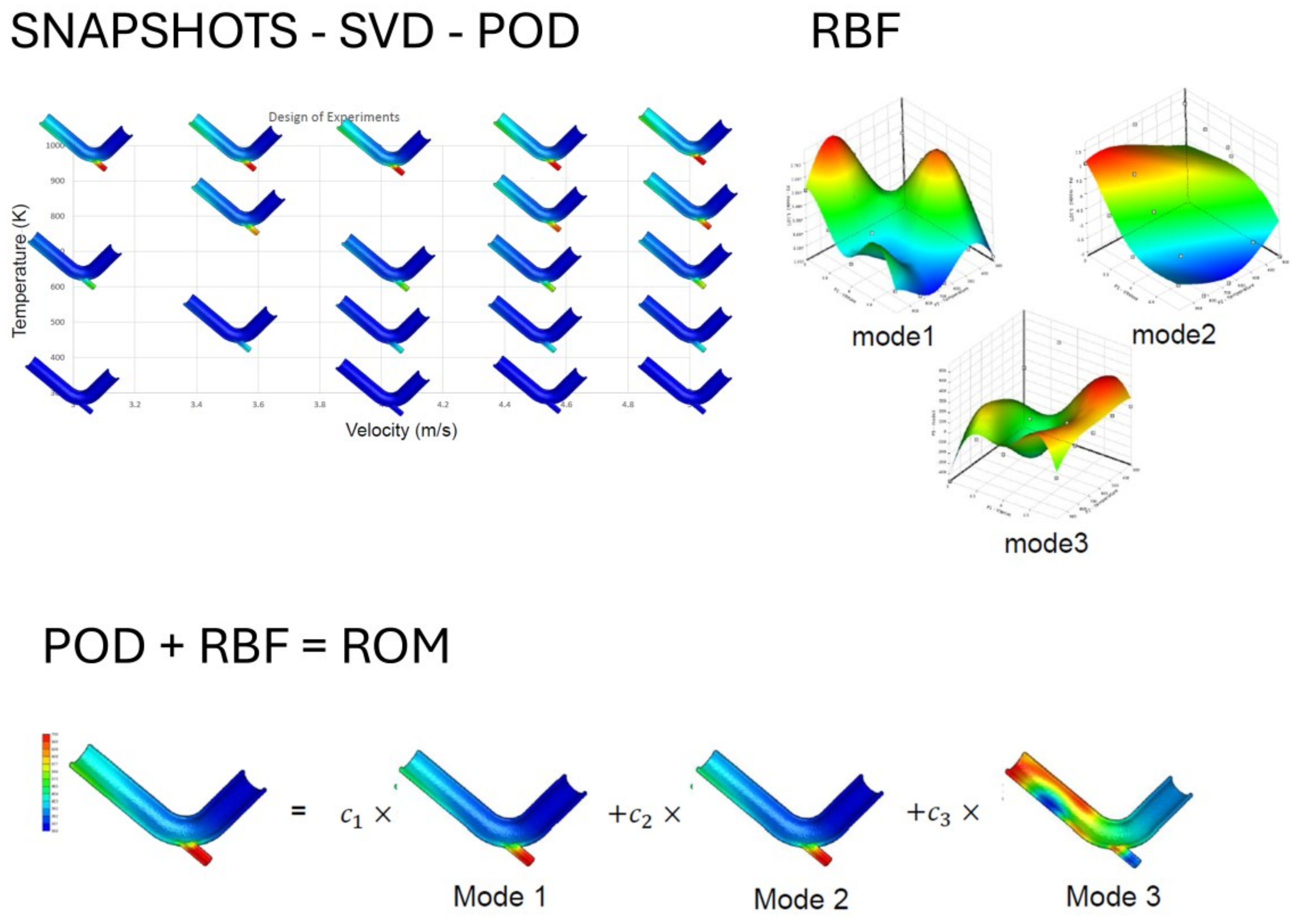


Reduced order models

Singular Value Decomposition and Principal Orthogonal Decomposition

RBF and POD can be combined to get reduced order models (ROM)

- CFD snapshot data are compressed using **Singular Value Decomposition** (SVD) and **Proper Orthogonal Decomposition** (POD).
- AI models are trained in the reduced space using **Radial Basis Functions** (RBFs).
- Full-field solutions are reconstructed via **RBF inference** and modal expansion.



RBF and POD can be combined to get reduced order models (ROM)

- Singular Value Decomposition (Beltrami-Jordan 1873)

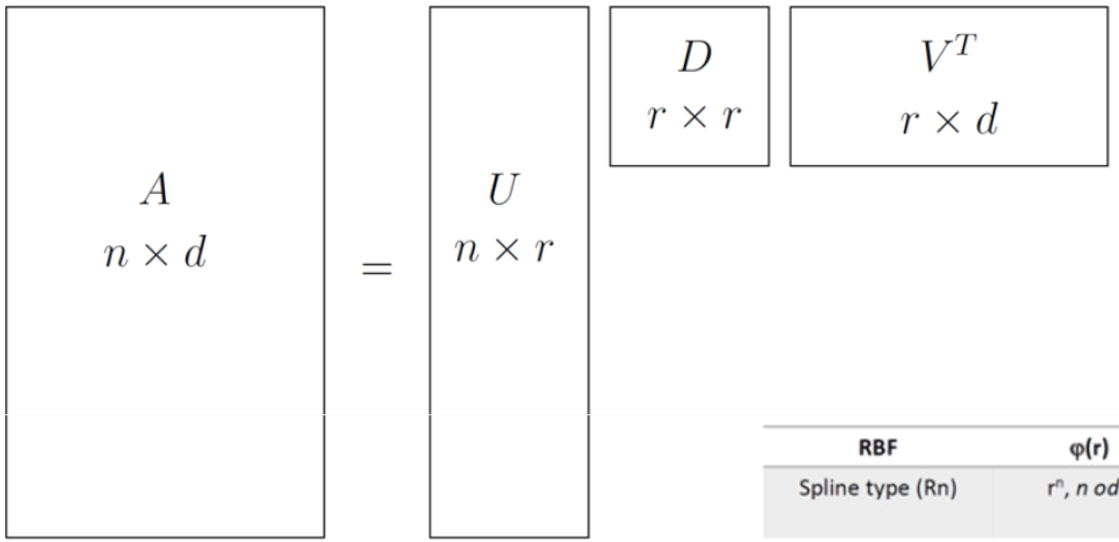
$$\mathbf{X} = \mathbf{U}\,\boldsymbol{\Sigma}\,\mathbf{V}^{\top}$$

- Radial Basis Functions (Hardy 1971)

$$s(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i \, \phi(\|\mathbf{x} - \mathbf{x}_i\|) + p(\mathbf{x})$$

- Reconstruction by modal expansion

$$A = \sum_{i=1}^{d} \sigma_i \, \mathbf{u}_i \mathbf{v}_i^T$$



RBF	φ(r)
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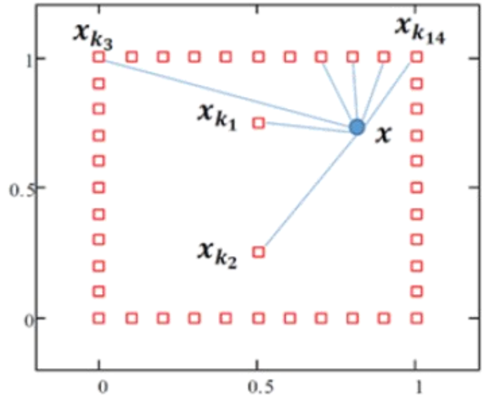
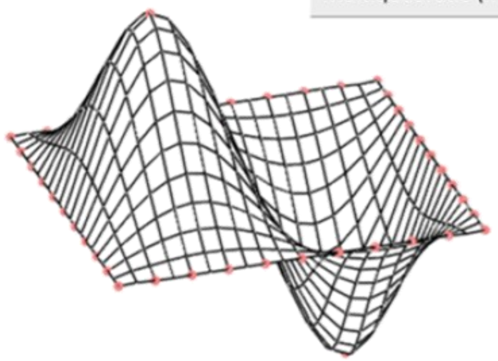




RBF and POD can be combined to get reduced order models (ROM)

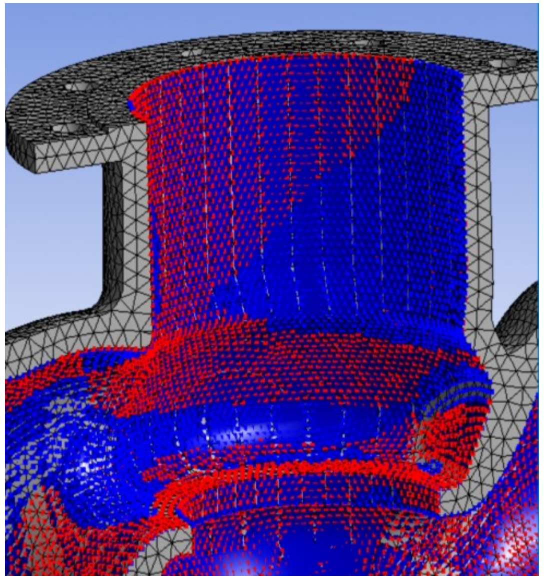
- ROM can be originated by **geometrical and physical parameters**
  - ROM of the shape (**geometrical modes weights**) is trained vs. **input parameters**
  - ROM of the CAE solution (**CAE modes weights**) is trained vs. **input parameters**
- ROM can be originated by **multiple parameter-less snapshots** (statistical shape modeling)
  - ROM of the shape (**geometrical modes weights**) is used to train the ROM of the CAE solution (**CAE modes weights**)
  - A new shape is projected onto the ROM of the shape and the new CAE solution is inferred

Shape generation

Parameter-based and parameter-free workflows

RBF Mesh Morphing

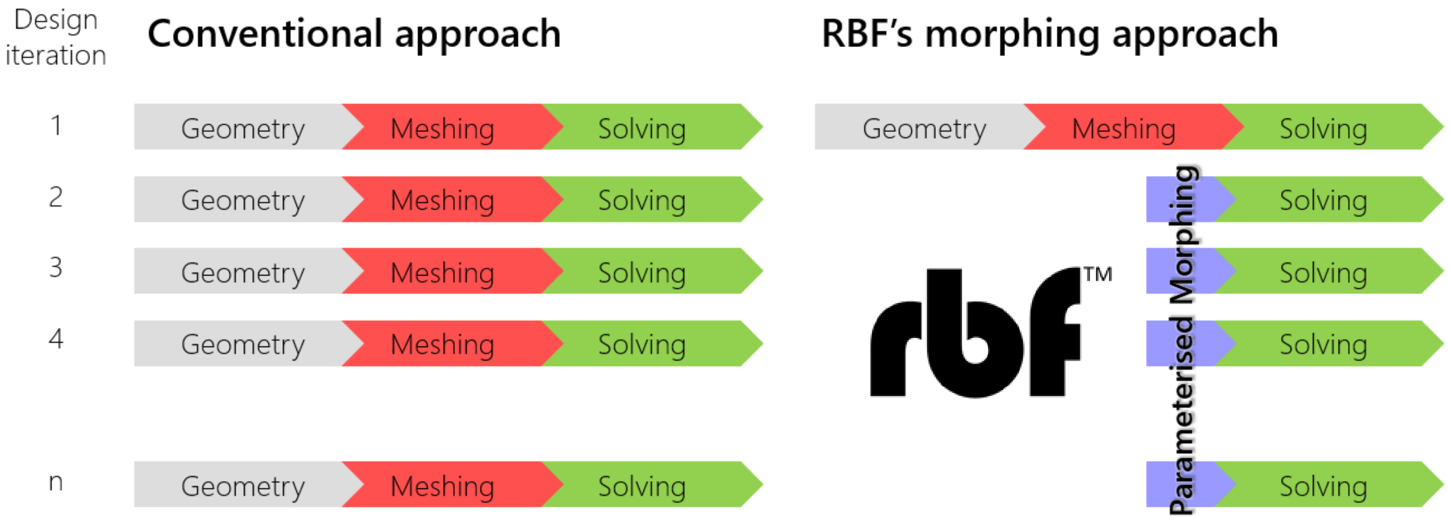
- We adopt **Radial Basis Functions** (RBF) to drive mesh morphing (smoothing) from a list of source points and their displacements
  - o Surface shape changes
  - o Volume mesh smoothing
- RBF are recognized to be one of the **best mathematical tool** for mesh morphing



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

Automated shape generation

- Morphing is a **key enabler** for Digital Twins
- Multiple snapshots can be generated from **shape parameters**
- **Virtual shapes** can be added from SSM
- Synthetic dataset are generated with an high level of **automation**



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Interactive Real-Time Design Exploration

From Advanced Simulation to VR

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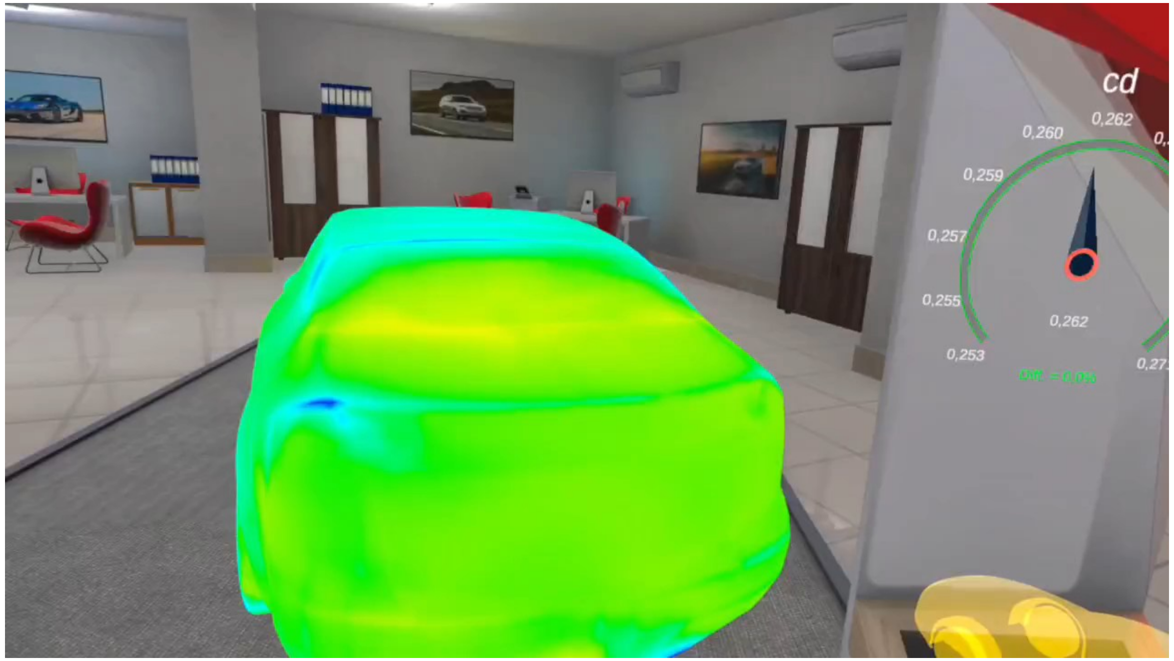
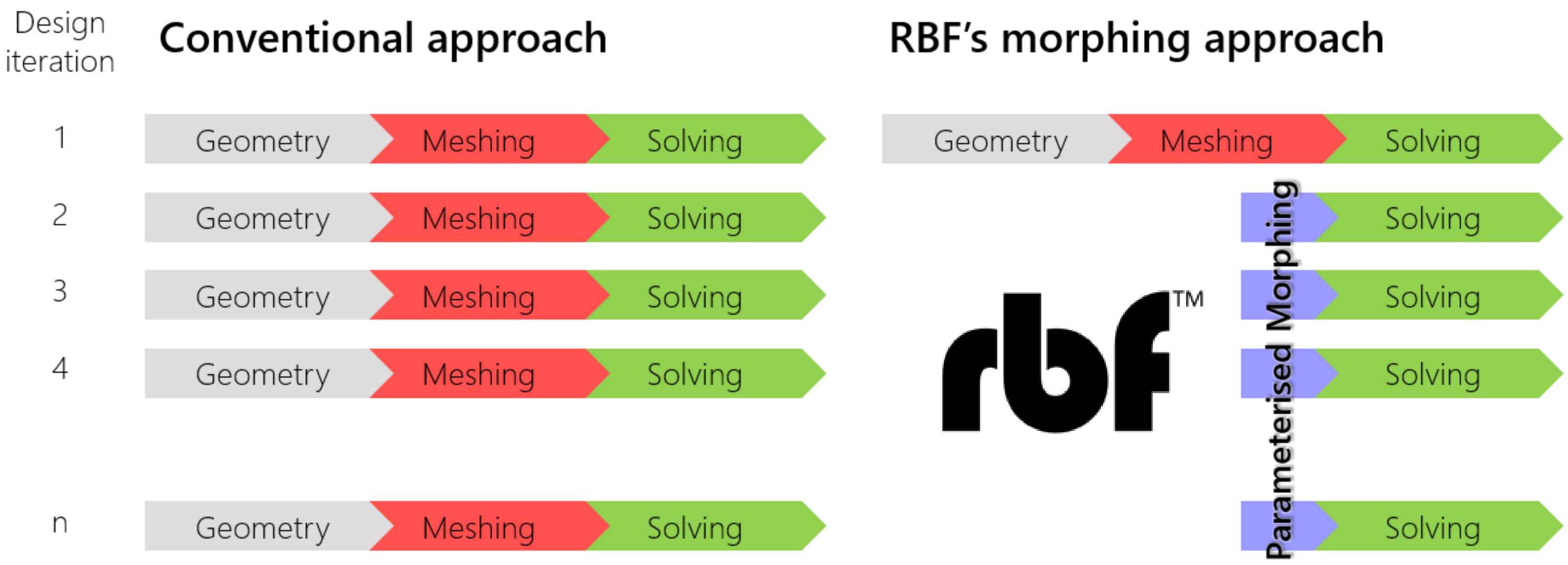
Interactive Digital Twins?

- High-fidelity simulations big data for training AI models:
  - Design stage: steer new projects more effectively
  - Operation stage: **real-time** interactions are key enablers of digital twins
- Challenges:
  - **High level of automation required**
  - **Replicable, easily deployable workflow**
- We present a comprehensive solution powered by **Unity rendering** and exported to **Meta Quest 3** AR/VR



Interactive Digital Twins Challenge #1

- High level of automation to create snapshots is needed
- Geometrical parameters require mesh topology preservation
- **RBF mesh morphing** combined with **CAE solvers**



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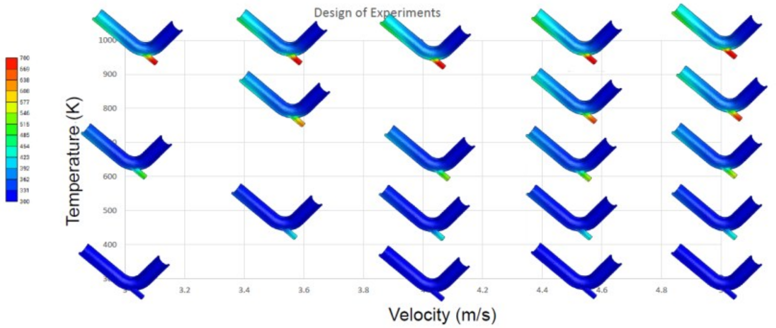
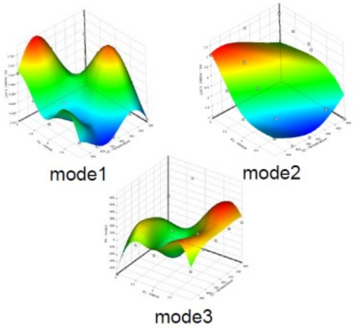
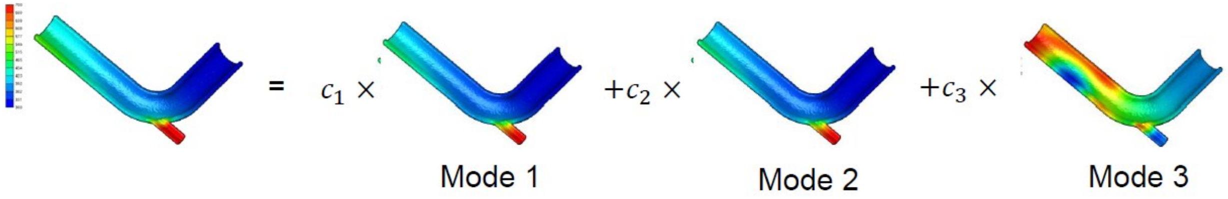
Interactive Digital Twins Challenge #2

- Replicable, easily deployable workflow?
- **Reduced Order Models** (ROM) are compressed (POD) ready to be inferred (GARS or RBF)
- Unity rendering
  - Meta Quest 3 AR/VR
  - Apple VisionPro?
- Portable Functional Mockup Units





POD+GARS = ROM



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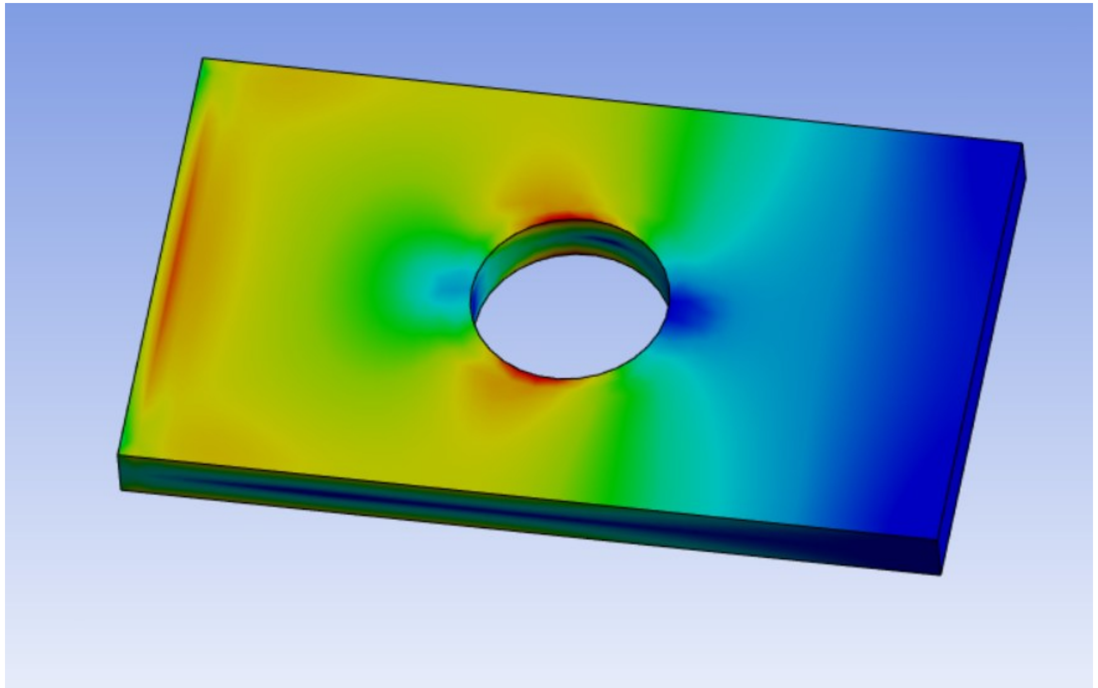
RBF Morph - www.rbf-morph.com

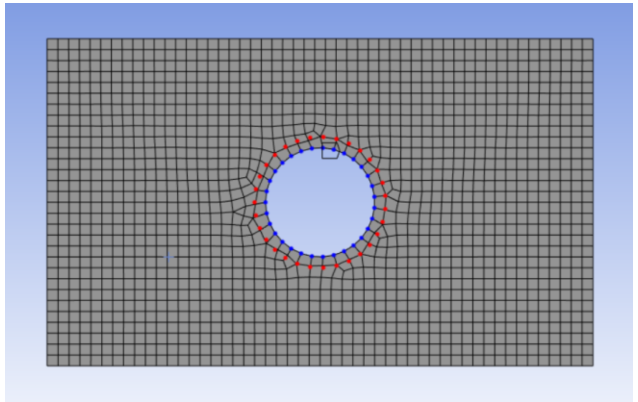
A simple FEA model – ROM - FMU

- Solid model created by CAD
- The notch effect is accurately captured by Mechanical
- RBF morphing allows to create **one geometrical parameter** to change the diameter of the hole
- The applied loads is the **physical parameter**
- Snapshots are exported and the FMU created

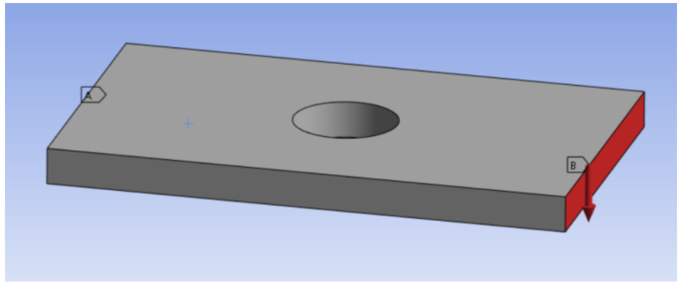


Workflow

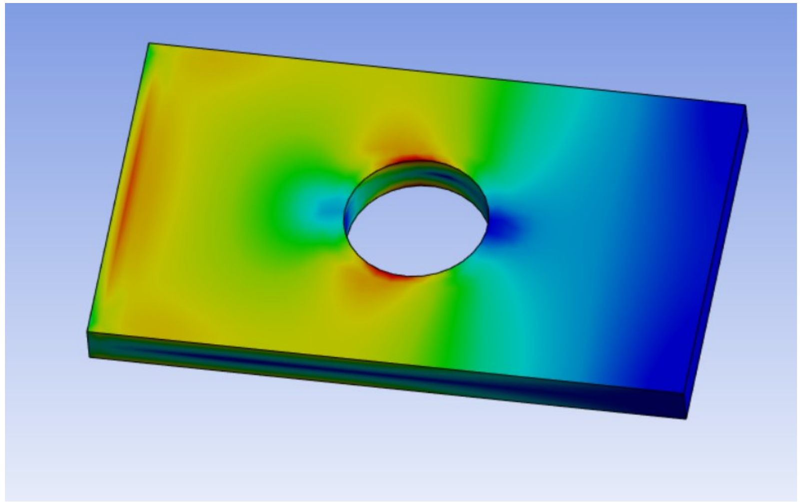
Step 1: Geometry and mesh → Step 2: Setting → Step 3: Parameters → Step 4: DOE: 30 DPs → Step 5: ROM



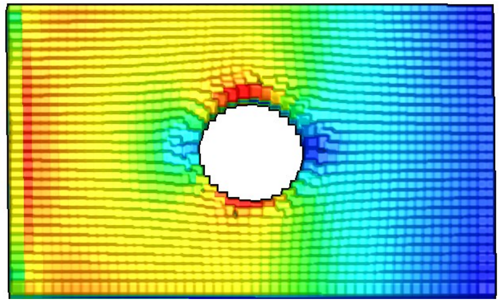
Shape parameter: radius offset

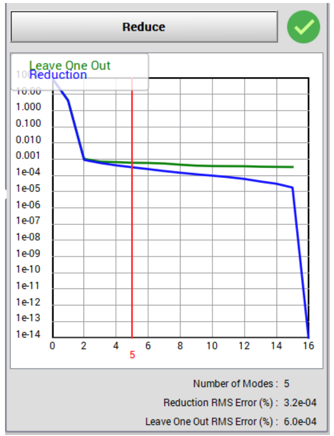


Physical parameter: Force



von Mises stresses

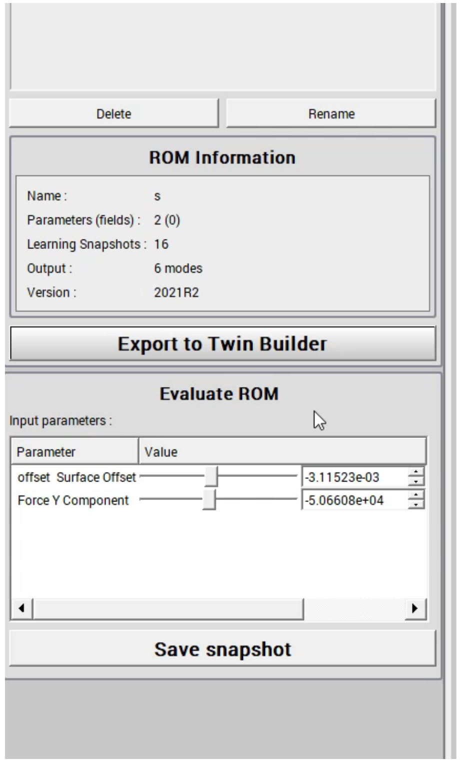


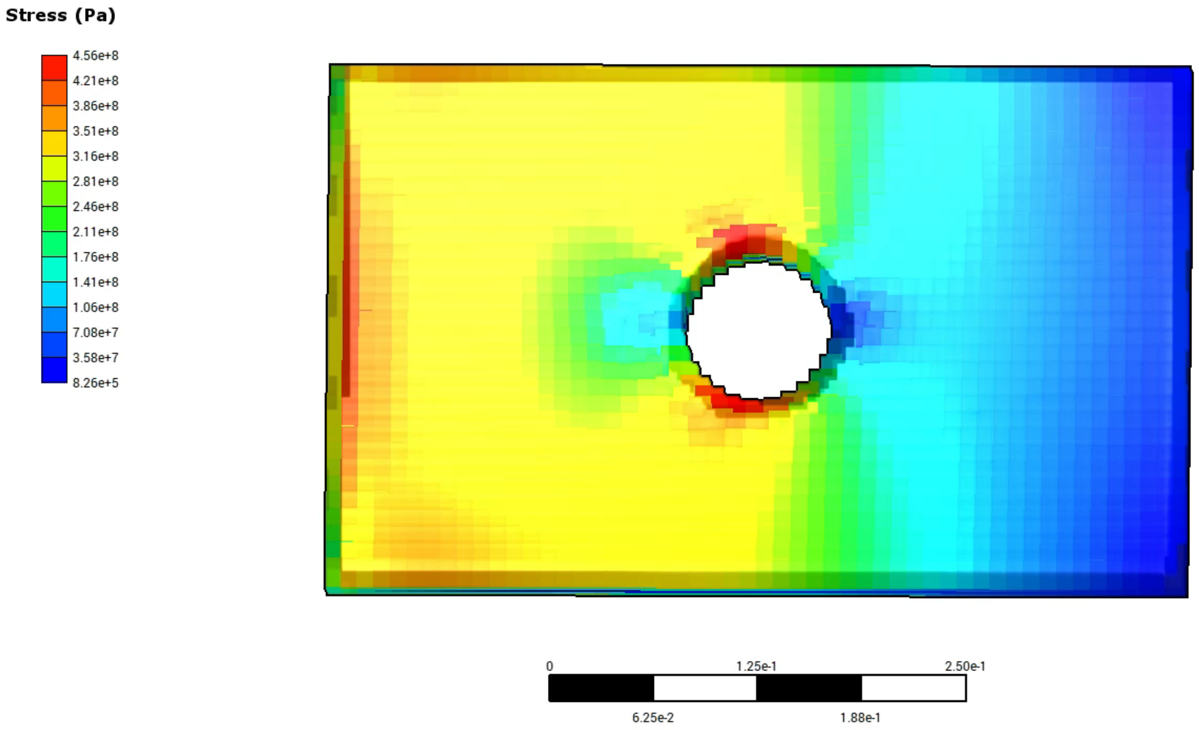


ROM convergence check

Twin Builder

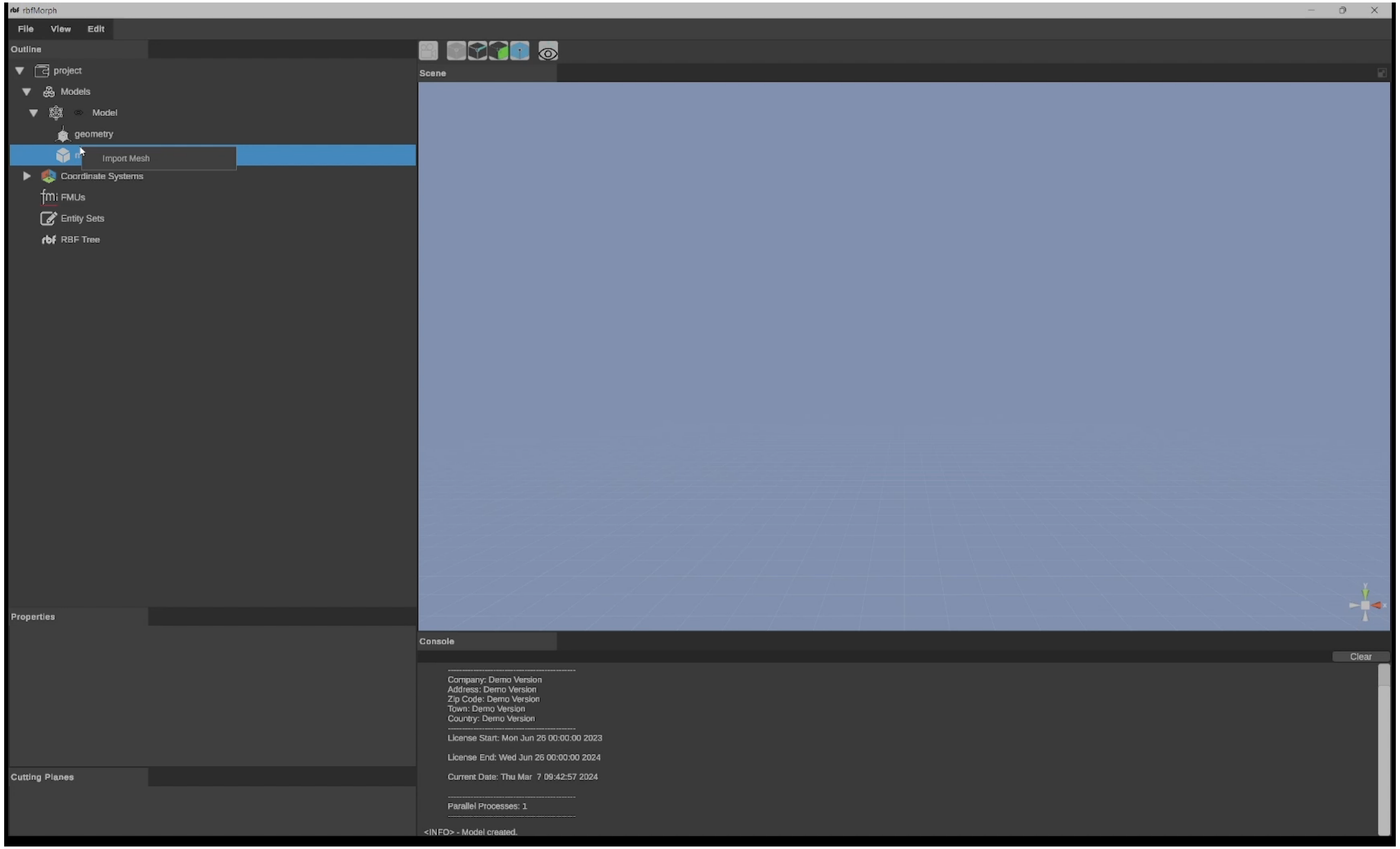
- ROM Builder
- Input parameters are controlled by the sliders
- **Point-based** rendering





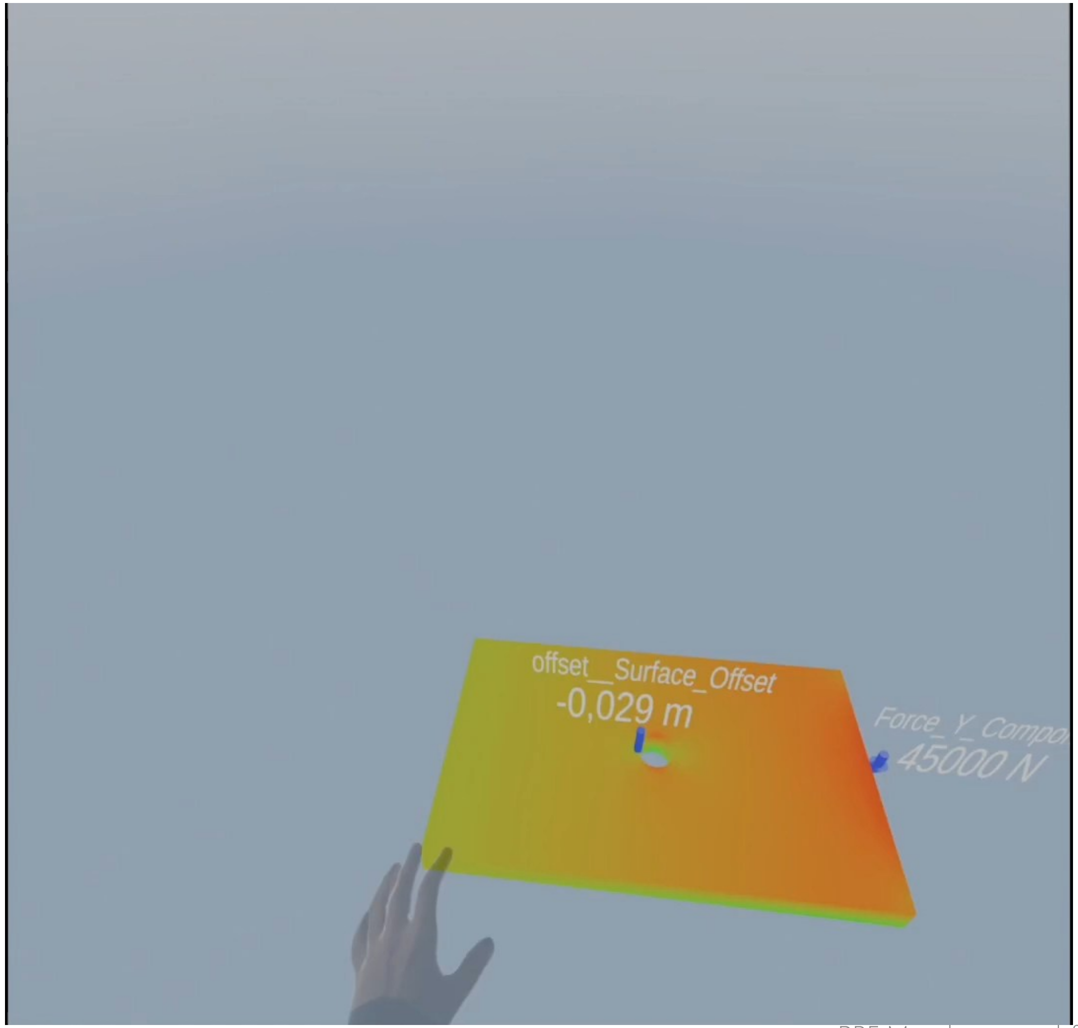
rbfCAE Unity UI

- Unity UI capable to read in **surface** and **FMU**
- Input parameters are controlled by **handles** (json descriptor)
- **Surface-based** rendering



RBF Morph exported VR

- FMU are translated to ARM
- Meta Quest 3
- Input parameters are controlled by hands
- We can add an **immersive scene**
- Wireless AR/VR



CAE agnostic approach

Domain Identification
e.g., automotive, healthcare, aerospace

↓

Specific Need
e.g., aerodynamic efficiency, surgical treatment optimization

↓

End-User Identification
stylists/designers, clinicians, engineering teams

↓

High-Fidelity CAE Response
CFD/FEM/multiphysics; baseline geometry; KPI targets

↓

Parameter Selection
physical and geometric variables

↓

Workflow Execution
parameterization, HPC data, ROM compression, export (FMU/.npy/ONNX)

↓

Deployment
XR/VR, dashboard, software component

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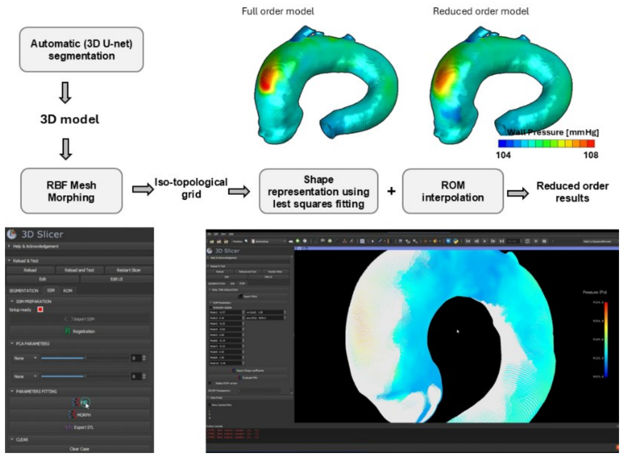
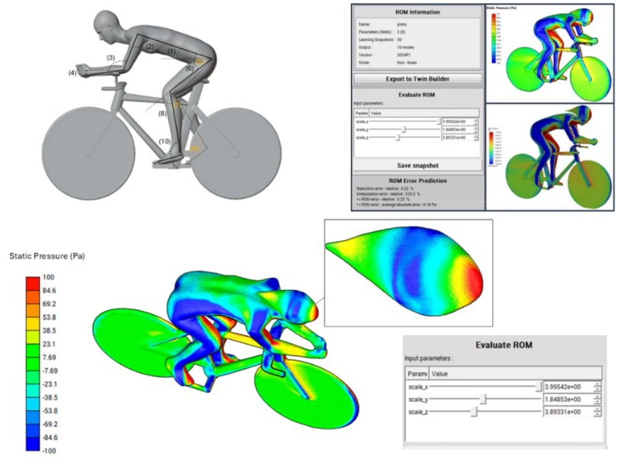
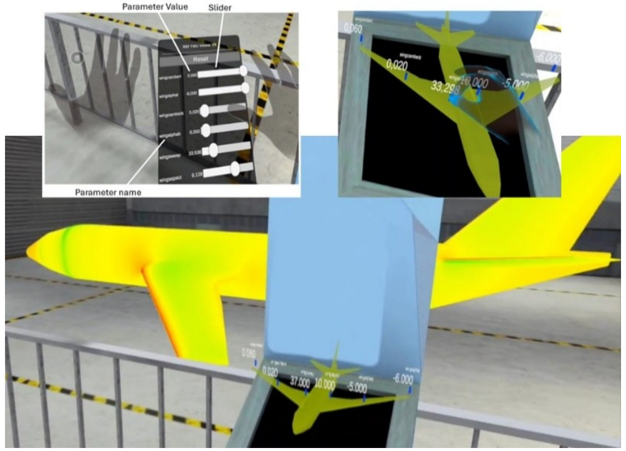
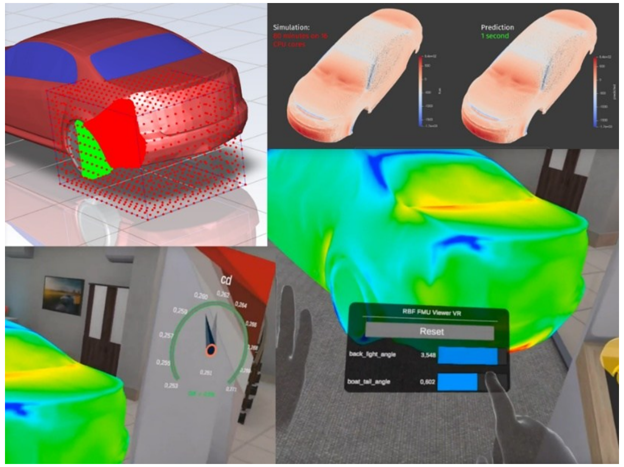
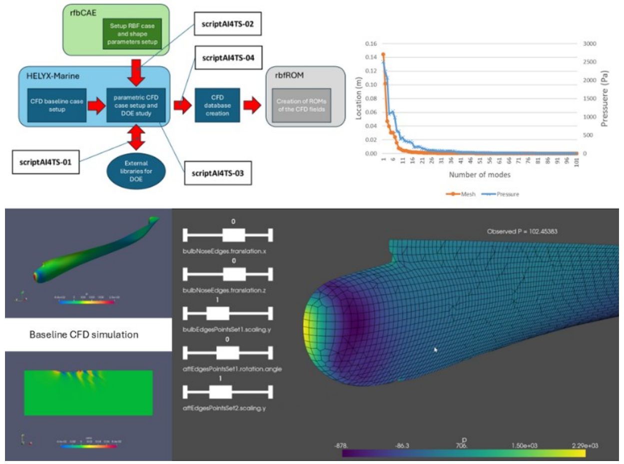
Interactive Real-Time Design Exploration: Applications

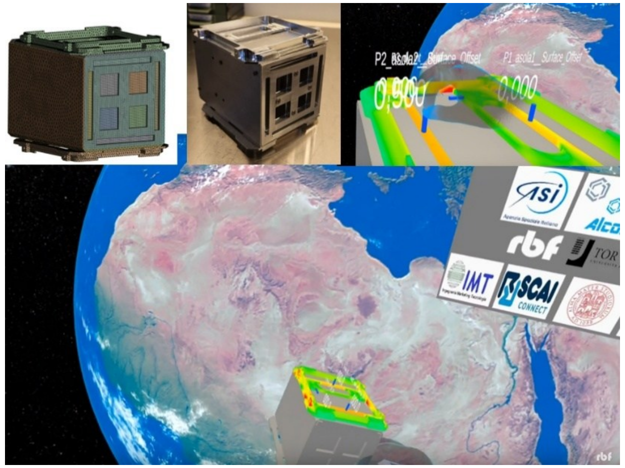








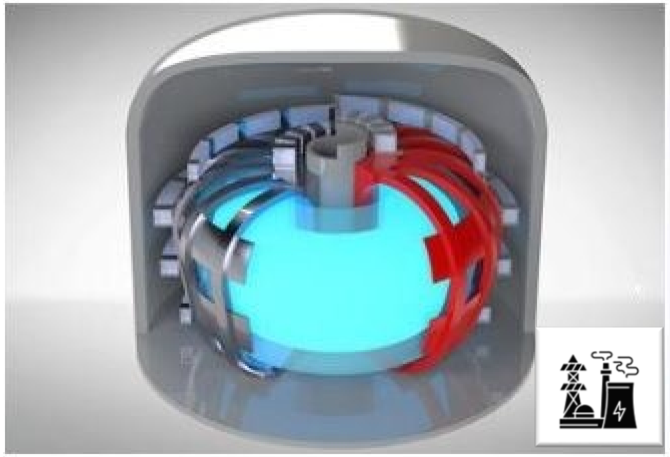


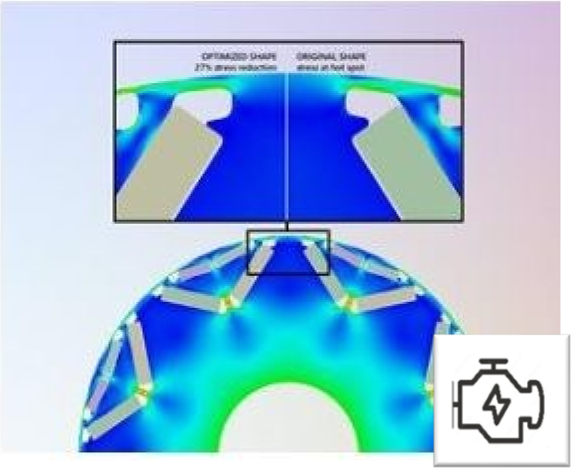


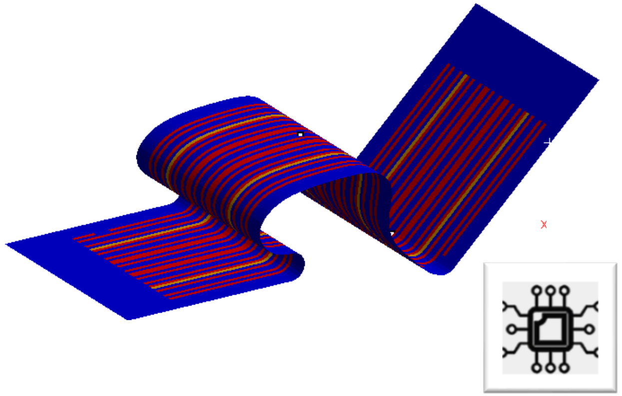
Medical Digital Twins

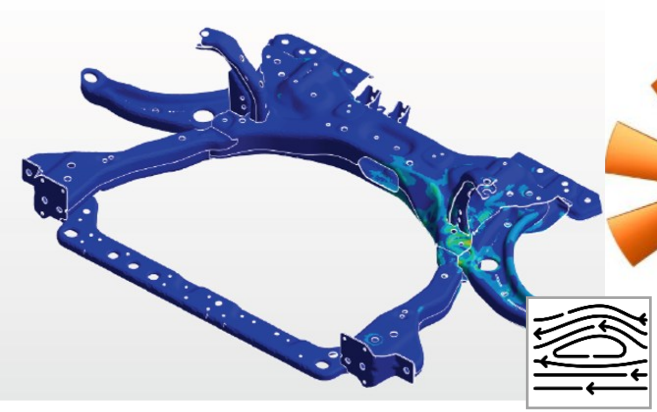
Research Projects and Applications

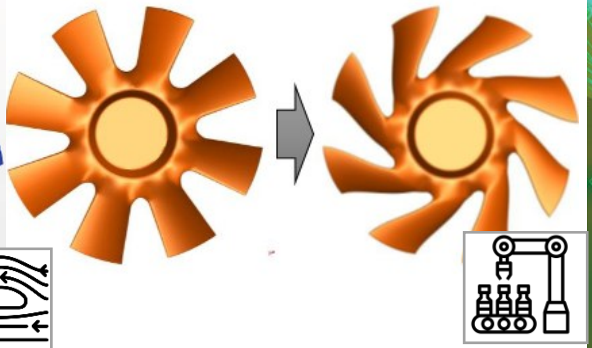
Research and Industrial sectors

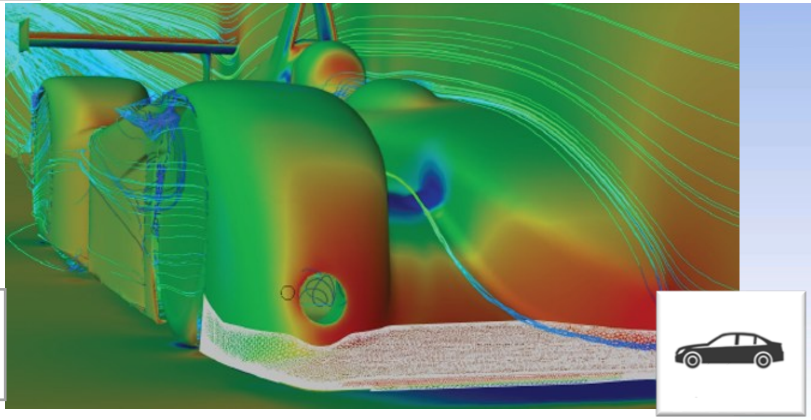


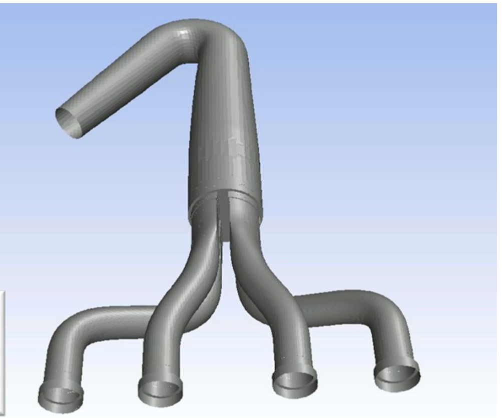












EU-funded research projects 2013-2025

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Running projects on healthcare

- Fortissimo Plus Business Experiment PANDORA - **Pre-operative Assistant Based on Data-Driven Approaches for Vascular Grafts Surgery**
- EU-funded Cyber 4.0 competence center SafeBot4Twin - **A Large Language Model-based Cyber-secure chatbot to control Medical Digital Twins**
- NextGenerationEU - iNEST project ROMed2VR - **Virtual Reality Empowered by Computational Fluid Dynamics Reduced Order Models to Support Pre-Surgery Medical Planning**

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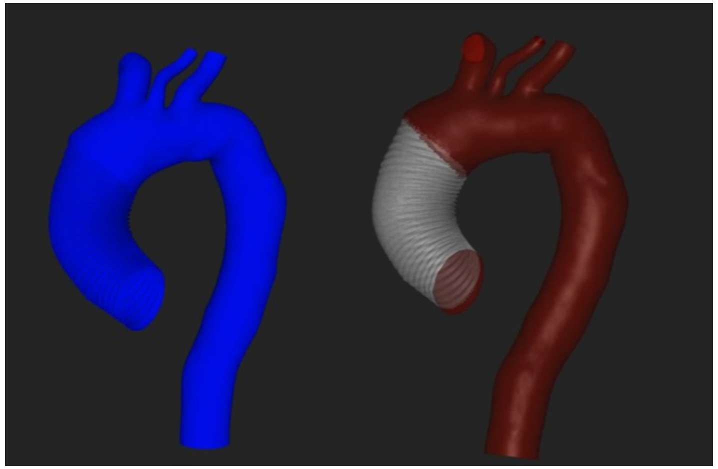
PANDORA

FORTISSIMO
PLUS

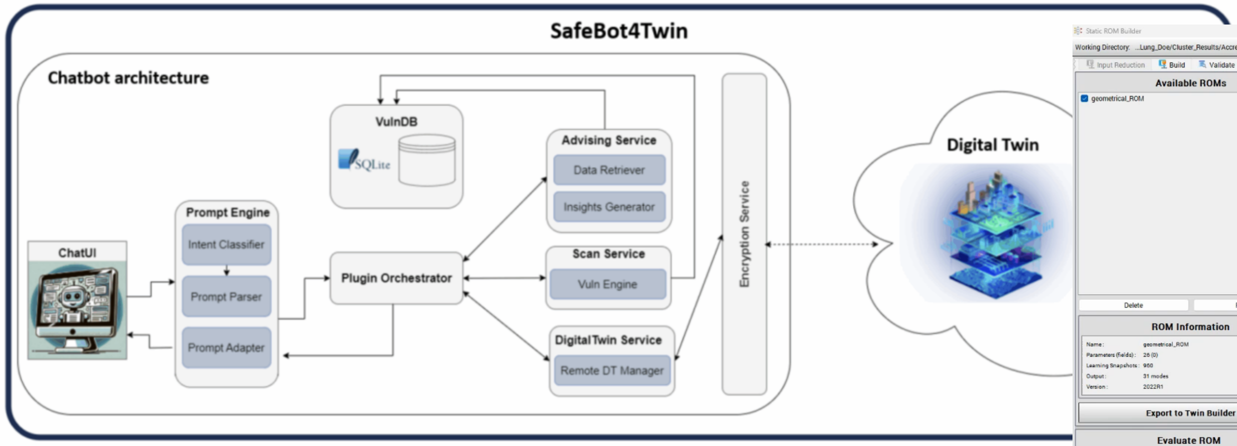


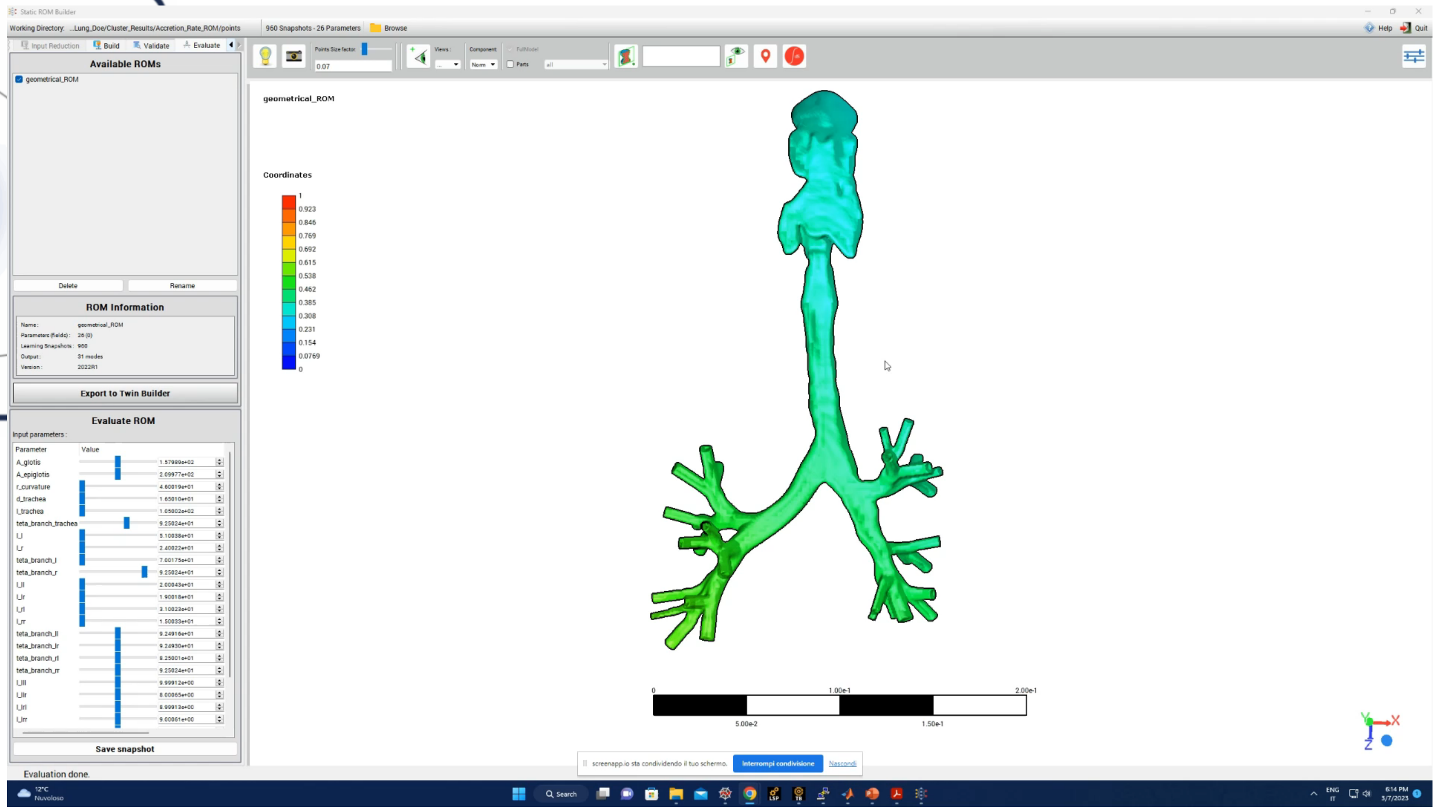
PANDORA

Pre-operative AssistaNt based on Data-driven apprOaches for vasculaR grAft surgery

SafeBot4Twin

CYBER 4.0
CYBERSECURITY COMPETENCE CENTER





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Interactive Medical Digital Twins in 3d Slicer

Meditate ESR02 – Leonardo Geronzi

https://meditate-project.eu/esr-02-leonardo-geronzi/

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Hemodynamic prediction based on surrogate modeling

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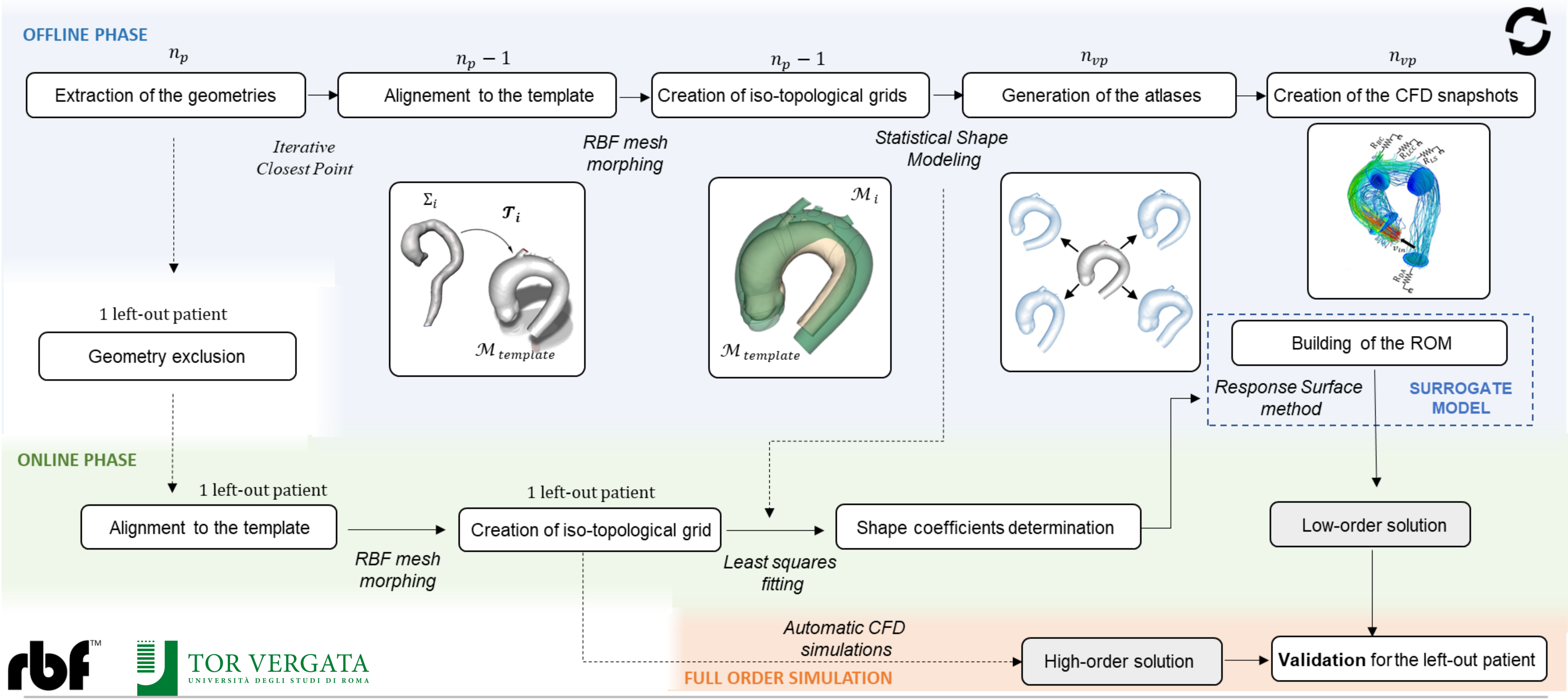
MEDITATE



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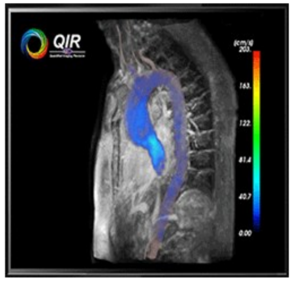
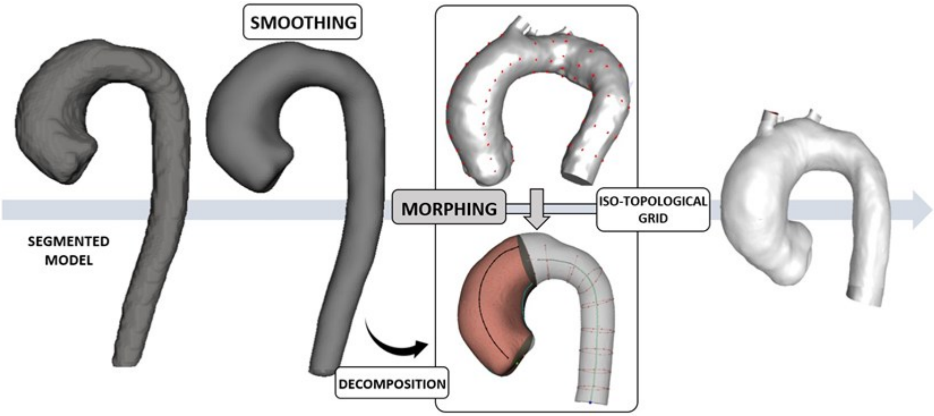
The offline phase

MRI 4D Flow



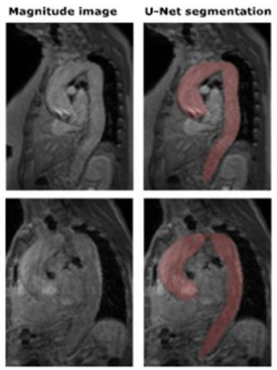


Based on principal component analysis (**PCA**)

Each shape $\widetilde{M_S}^{i}$ can be built combining n_{SM} eigenvalues λ_j and n_{SM} eigenvectors $\boldsymbol{W_j}$

$$\widetilde{\mathrm{M_S}}^{\mathrm{i}} = \mathrm{M_{S_{mean}}} + \sum_{j=1}^{n_{SM}} c_j^i \sqrt{\lambda_j}\,\mathbf{W}_j$$

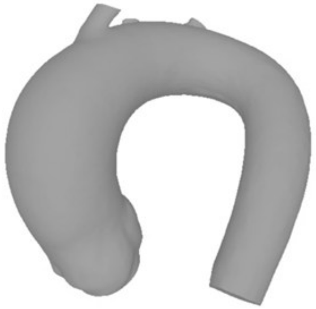
Automatic (3D U-net) segmentation methods developed by Marin-Castrillon et al. [11] ⇨ **3D model** ⇨ **RBF Mesh Morphing** ⇨ **Iso-topological grid** ⇨ **Statistical Shape Modeling** ⇨ **Parametric 3D model**



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

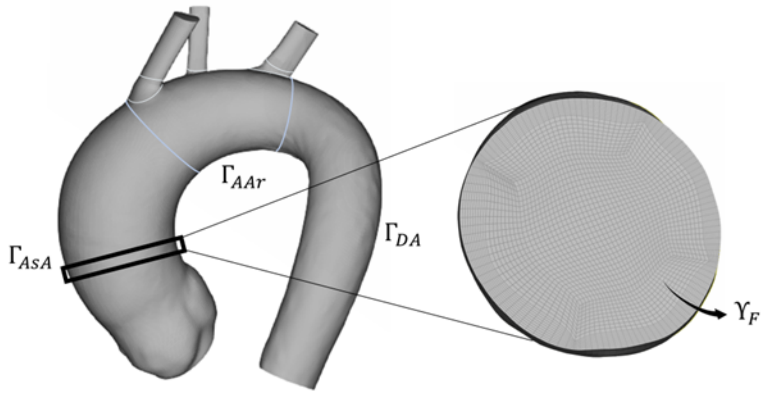
In the 3D space:

$$\mathbf{x}_{\mathbf{node}_{\mathbf{new}}} = \mathbf{x}_{\mathbf{node}} + \begin{bmatrix} s_x(\mathbf{x}_{\mathbf{node}}) \\ s_y(\mathbf{x}_{\mathbf{node}}) \\ s_z(\mathbf{x}_{\mathbf{node}}) \end{bmatrix}$$



[11] Marin-Castrillon et al. *Magnetic Resonance Materials in Physics, Biology and Medicine* (2023): 1-14.

The offline phase

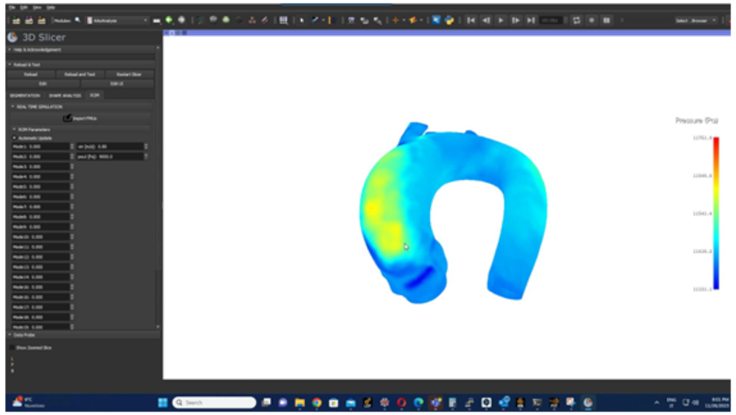


1) DECOMPOSITION

Proper orthogonal decomposition (**POD**) techniques:

$$\boldsymbol{\Omega} = \boldsymbol{U\Sigma V^T}$$

$$\min_{\boldsymbol{\Phi}} \left\| \boldsymbol{\Omega} - \boldsymbol{\Phi\Phi^T} \right\|^2$$



CFD Simulation using the synthetic data created through SSM → **Set of learning snapshots (Wall pressure)** → **Model order reduction techniques** → **Surrogate Model** → **Surrogate model deployment**

Navier-Stokes equations:

$$\mathbf{u} \cdot \nabla\mathbf{u} = -\frac{1}{\rho}\nabla p + \nu \nabla^2\mathbf{u}, \text{in } \Upsilon_F$$

$$\nabla \cdot \mathbf{u} = 0, \text{in } \Upsilon_F$$

SIMPLE pressure-velocity coupling

Parameteric velocity **inlet** – pressure **outlet** BCs

2) INTERPOLATION

Genetic Aggregation Response Surface (**GARS**) technique for the ROM interpolation

19 Geometrical parameters

5 Physical parameters

INPUTS **FMU** OUTPUTS

FMU DEPLOYMENT
Model Exchange 2.0

The online phase

Excluded patient

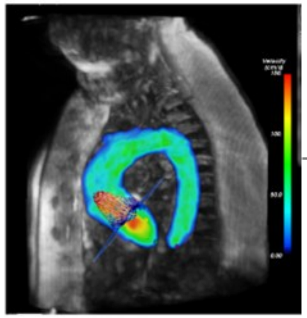
Automatic (3D U-net) segmentation

⇩

3D model

⇩

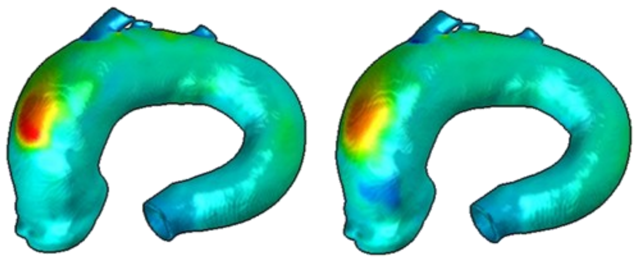
RBF Mesh Morphing ⇨ Iso-topological grid ⇨ Shape representation using lest squares fitting + ROM interpolation ⇨ Reduced order results ⇨ Comparison full order vs reduced order simulation



Inlet BC velocity value from the images →

Full order model

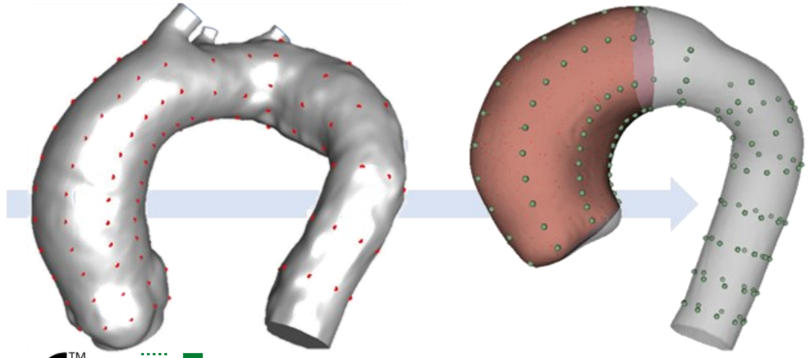
Low order model

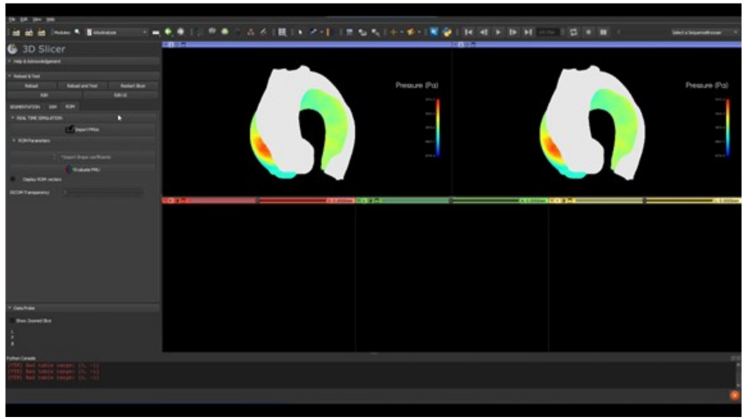


Wall Pressure [mmHg]

104 108

$$\omega^{FOM}(\alpha,\beta) \approx \omega^{ROM}(\alpha,\beta) = \sum_{i=1}^{N_{POD}} w_i \sqrt{\sigma_i(\alpha,\beta)}\,\phi_i(\alpha,\beta)$$

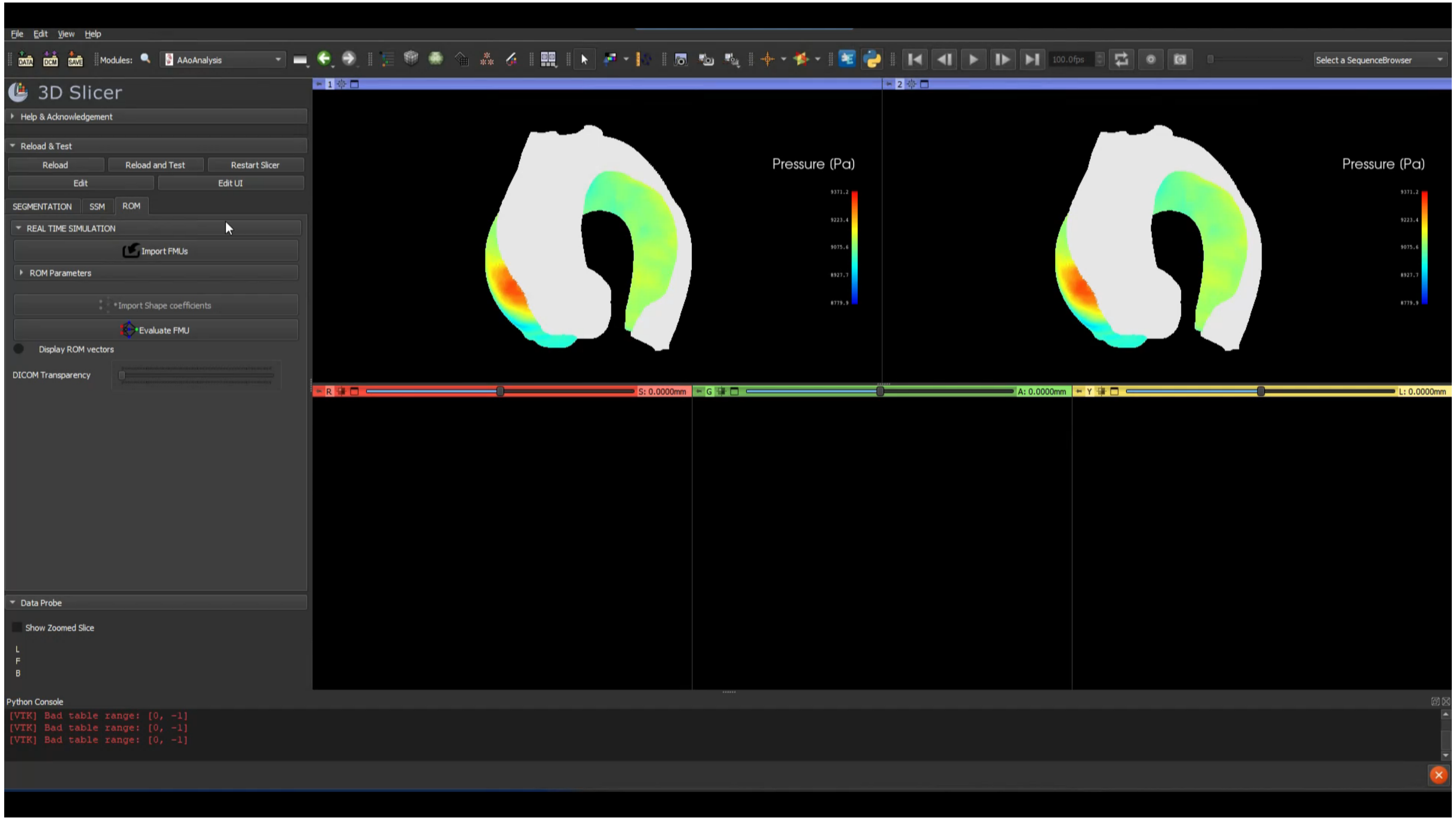




$$e_{ROM}^{rel,i-out} = \frac{\left\|\omega_{i-out}^{FOM} - \omega_{i-out}^{ROM}\right\|}{\left\|\omega_{i-out}^{ROM}\right\|}$$

$$e_{ROM}^{abs,i-out} = \max\left(\left\|\omega_{i-out}^{FOM} - \omega_{i-out}^{ROM}\right\|\right)$$

The online phase

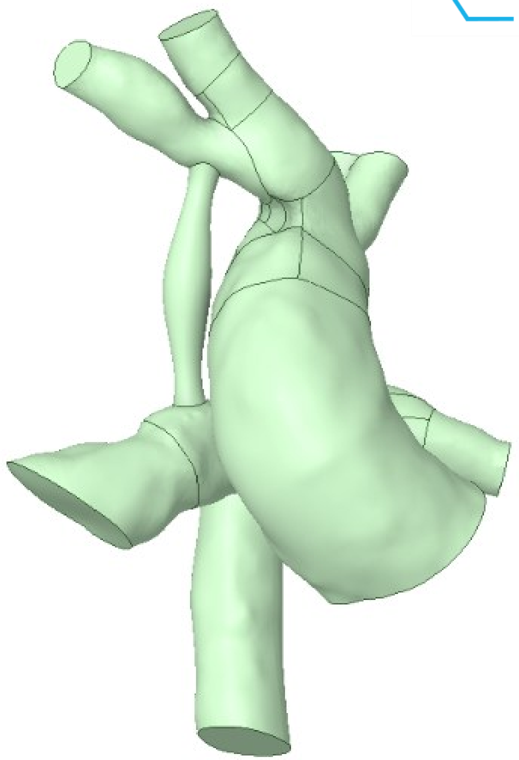


Support to shunting procedures

From Copernicus to ROMed2VR

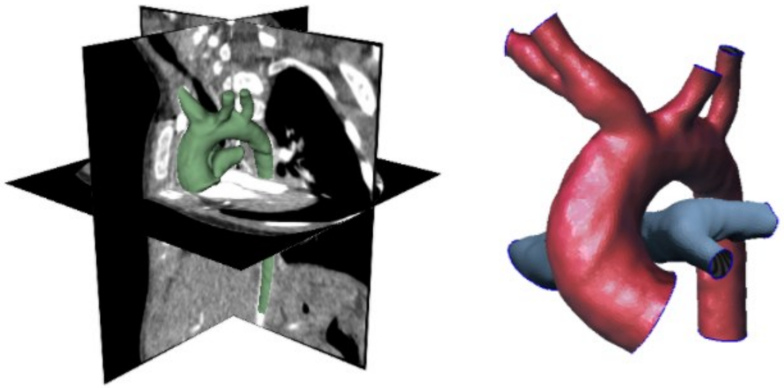
Copernicus

- **Cloud-Based HPC Platform to Support Systemic-Pulmonary Shunting Procedures**
- **Congenital Heart Diseases (CHDs)** = ~⅓ of all birth defects
- **Modified Blalock Taussig Shunt (mBTS)**
- Common palliative surgery for cyanotic CHD
- High risk: **over-shunting** & **shunt thrombosis** - significant mortality
- **Need**: better tools to support surgical planning & improve outcomes



Copernicus

- **Patient-specific** digital twin (MDT) built via advanced **CFD simulations**
- Runs on cloud-based **HPC**: reliable & cost-efficient
- Reduced Order Model (ROM) of vascular district with **shunt parameterization**
- Interactive web interface for medical staff to explore scenarios
- Impact: Affordable **decision-support** tool, safer, tailored mBTS interventions



Medical Digital Twin Copernicus

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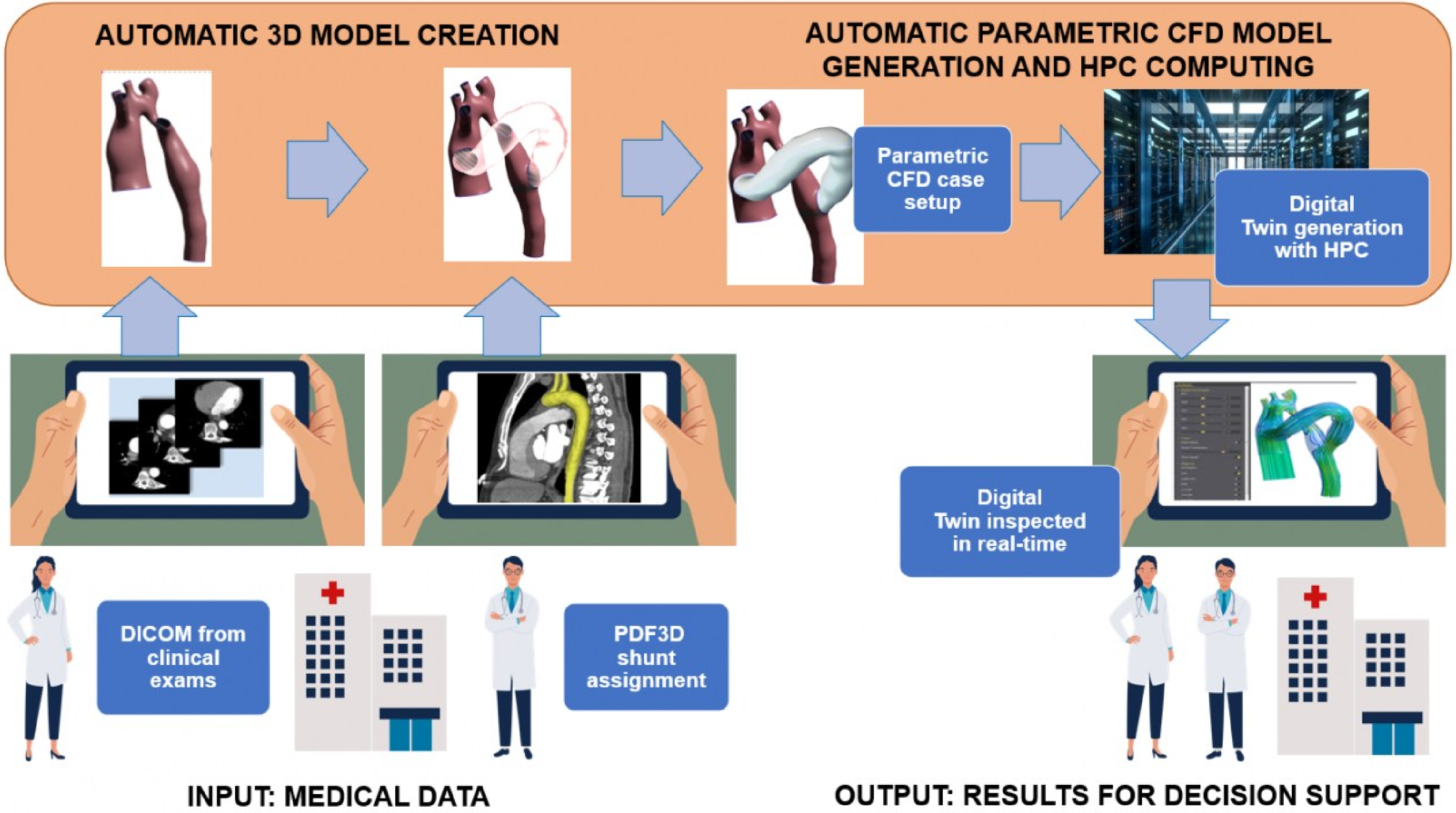
EuroHPC



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Medical Digital Twin Copernicus

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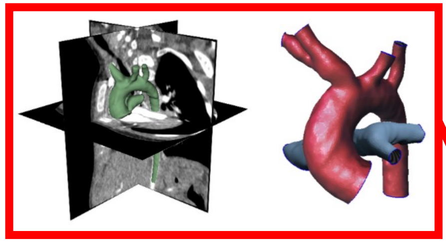
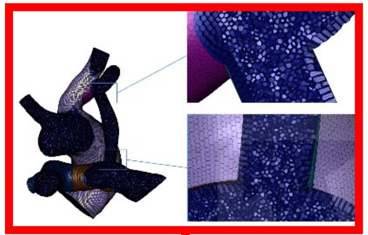
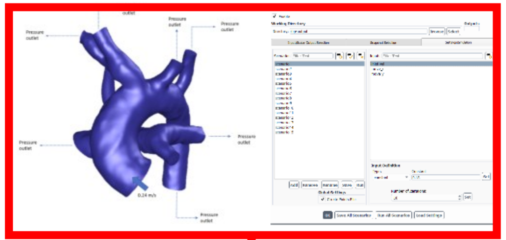
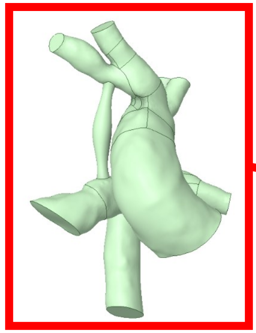








CT Image Segmentation (Python Code)

CAD Reconstruction + Shunt creation (SpaceClaim)

Surface and volume Mesh generation (Fluent – Watertight)

Ansys FLUENT

CFD and Snapshot set-up (Fluent – RBP)

RBF Shape modifiers set-up (Fluent – RBF Morph)

Ansys FLUENT rbf™

Ansys FLUENT rbf™

HPC for Snapshot generation (Fluent – RBF Morph

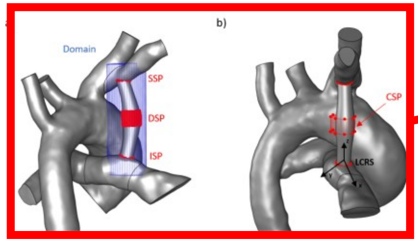
Ansys TWIN BUILDER

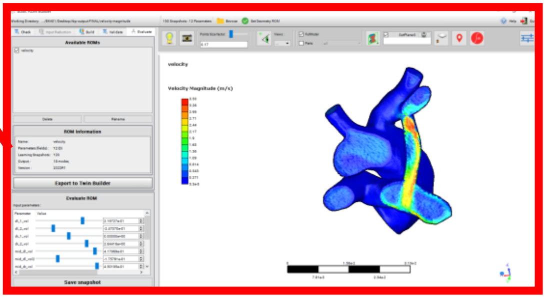
ROM Generation (Twin Builder)

Ansys TWIN BUILDER

ROM Evaluation (Twin Builder)

EuroHPC





Copernicus Pre-Processing

Copernicus Computing

Copernicus Post-Processing

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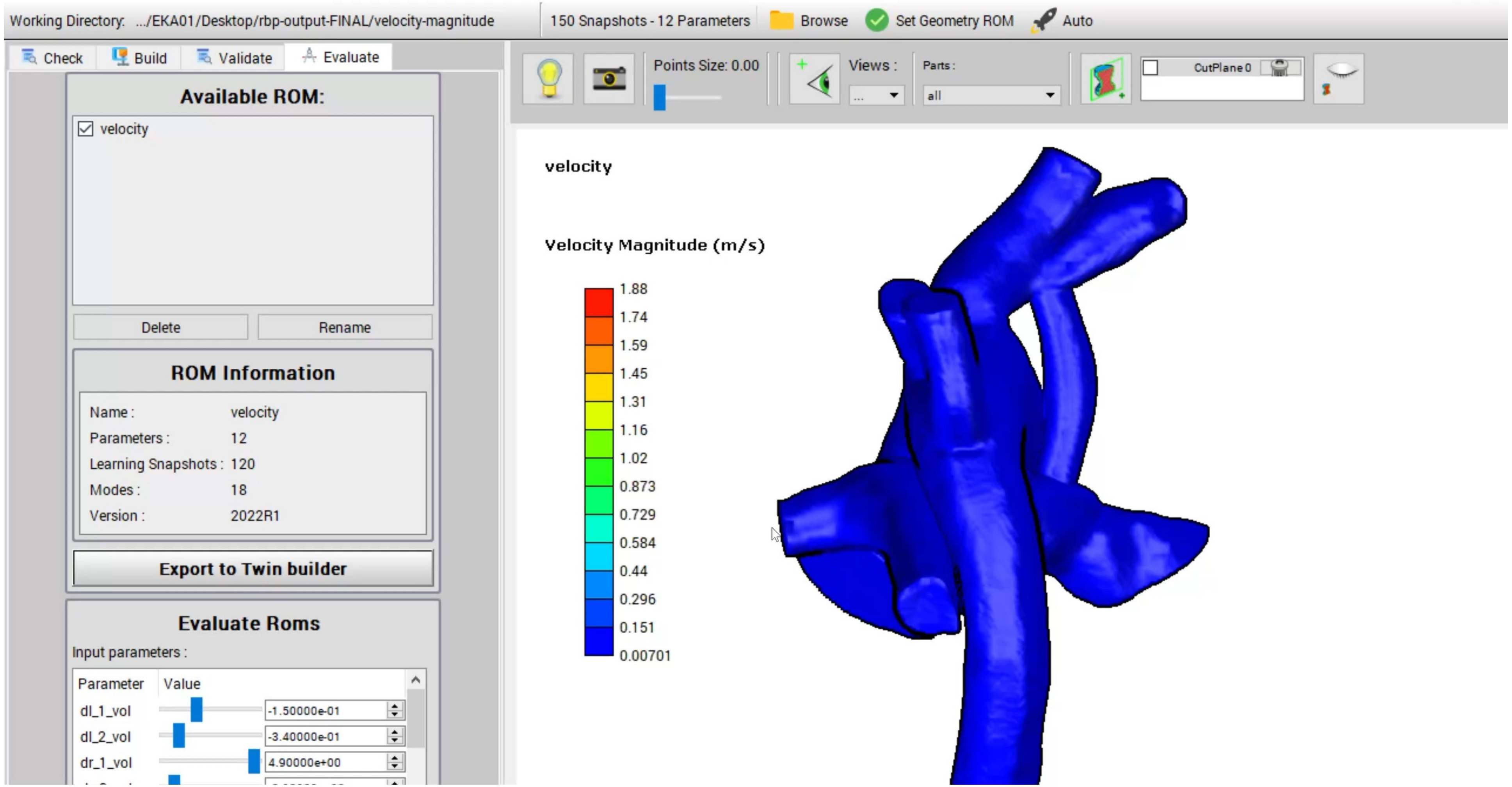
Medical Digital Twin Copernicus



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Next step?

A complete solution to deliver interactive digital twins with AR/VR custom UI

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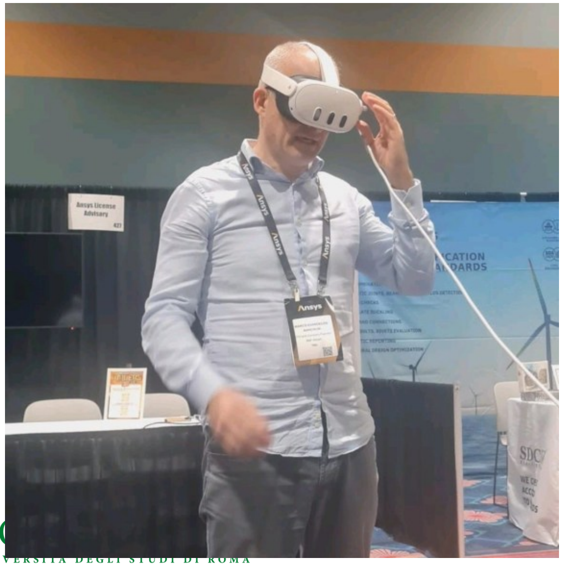
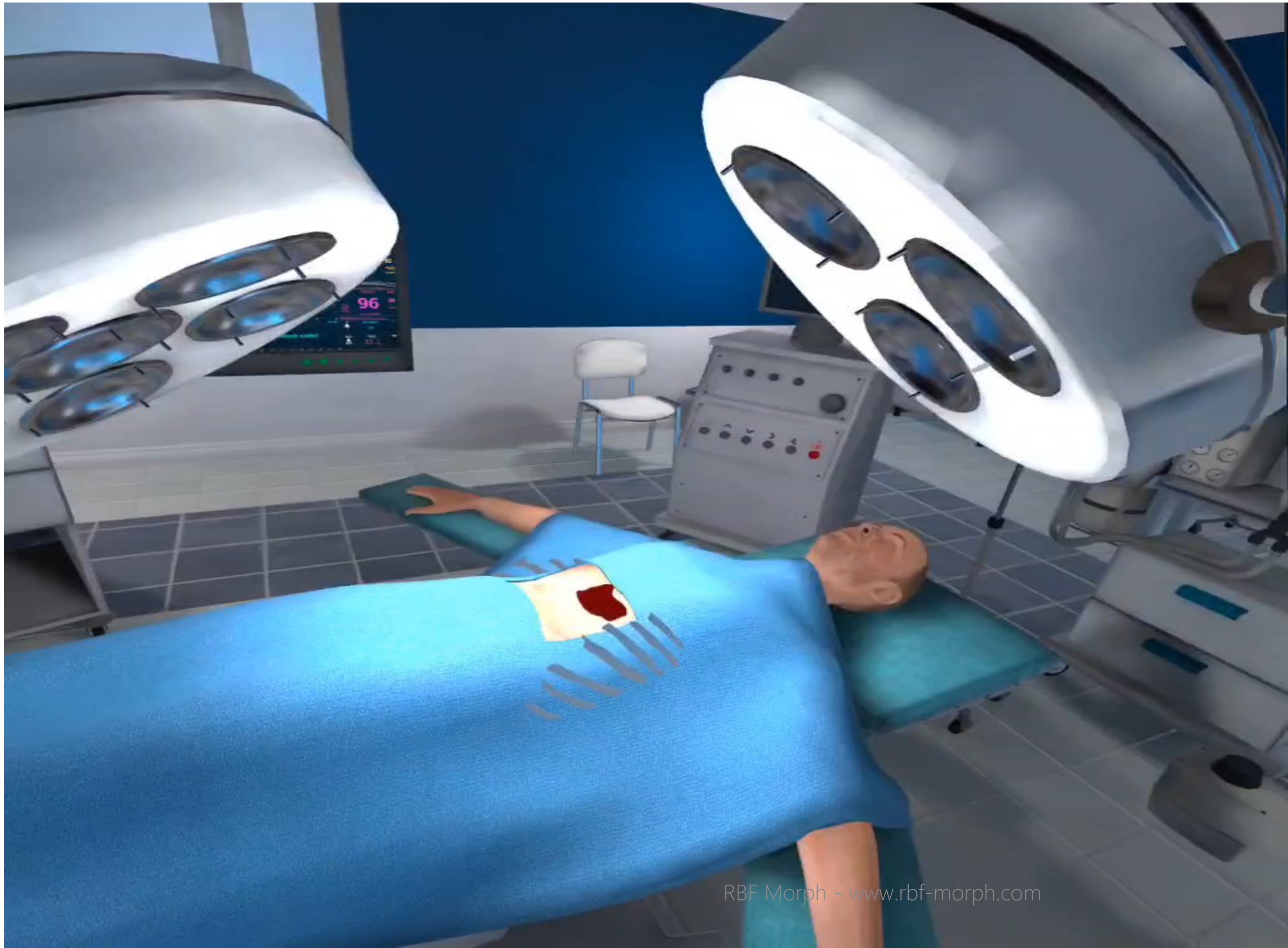
- FMU are translated to ARM
- Meta Quest 3
- Apple Vision Pro (very soon!)
- Input parameters are controlled by hands





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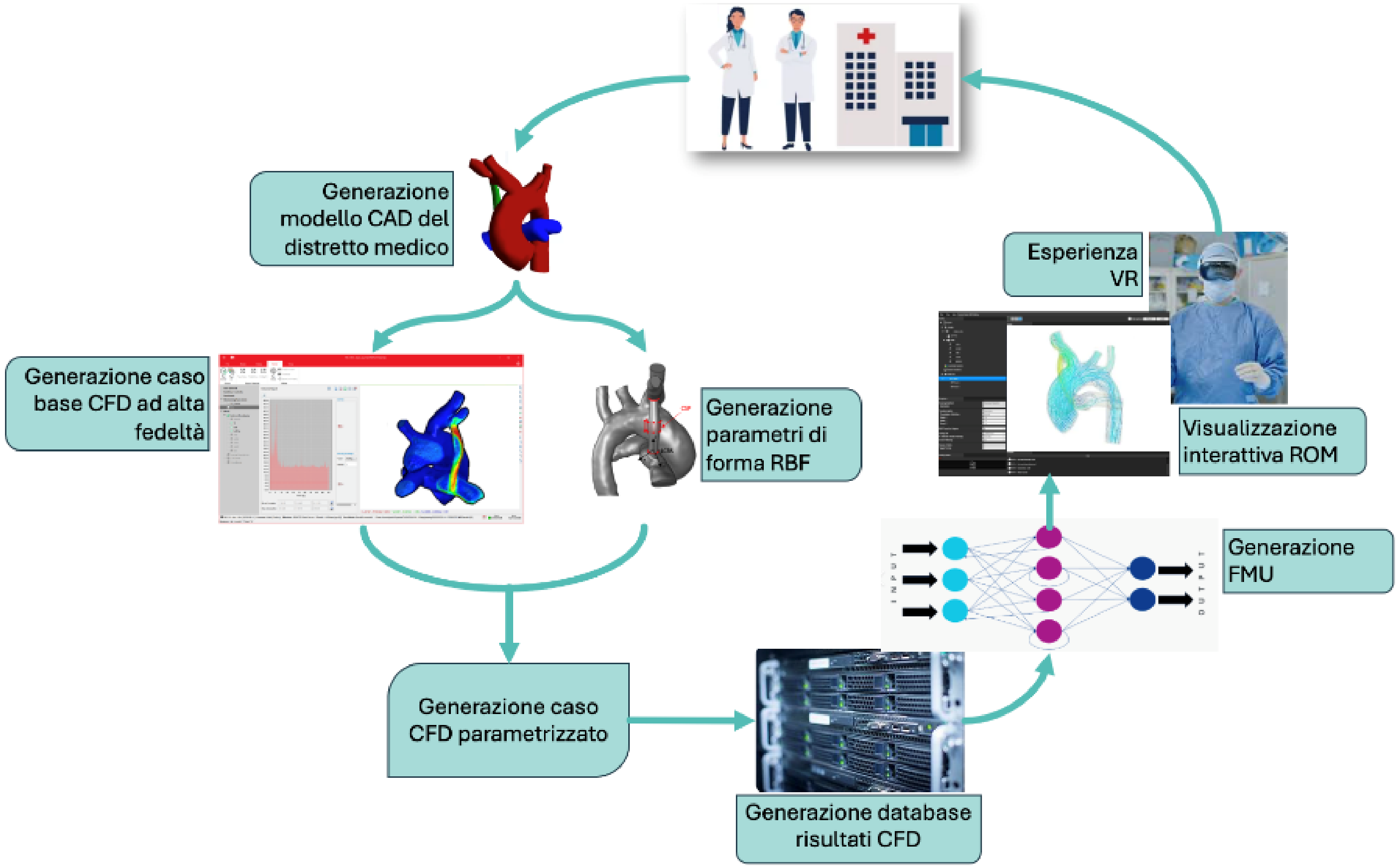
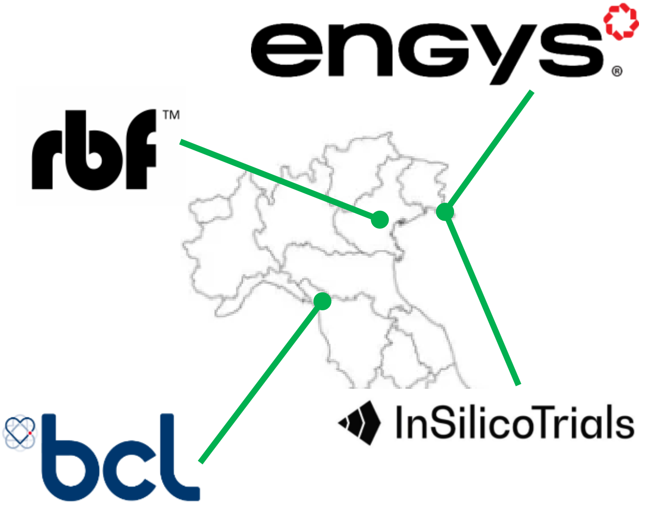
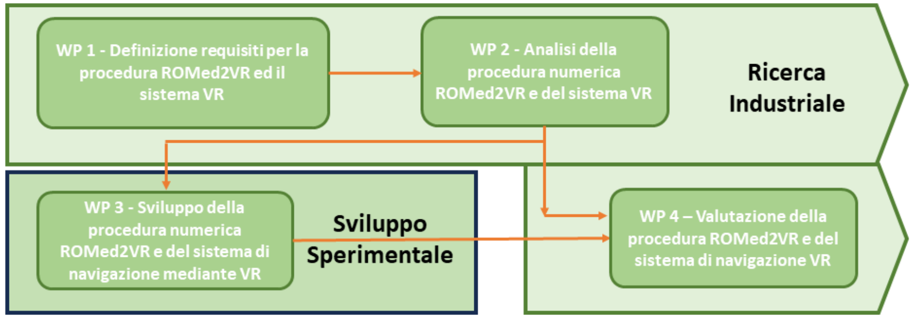
ROMed2VR

iNEST Interconnected Nord-Est Innovation Ecosystem







ROMed2VR

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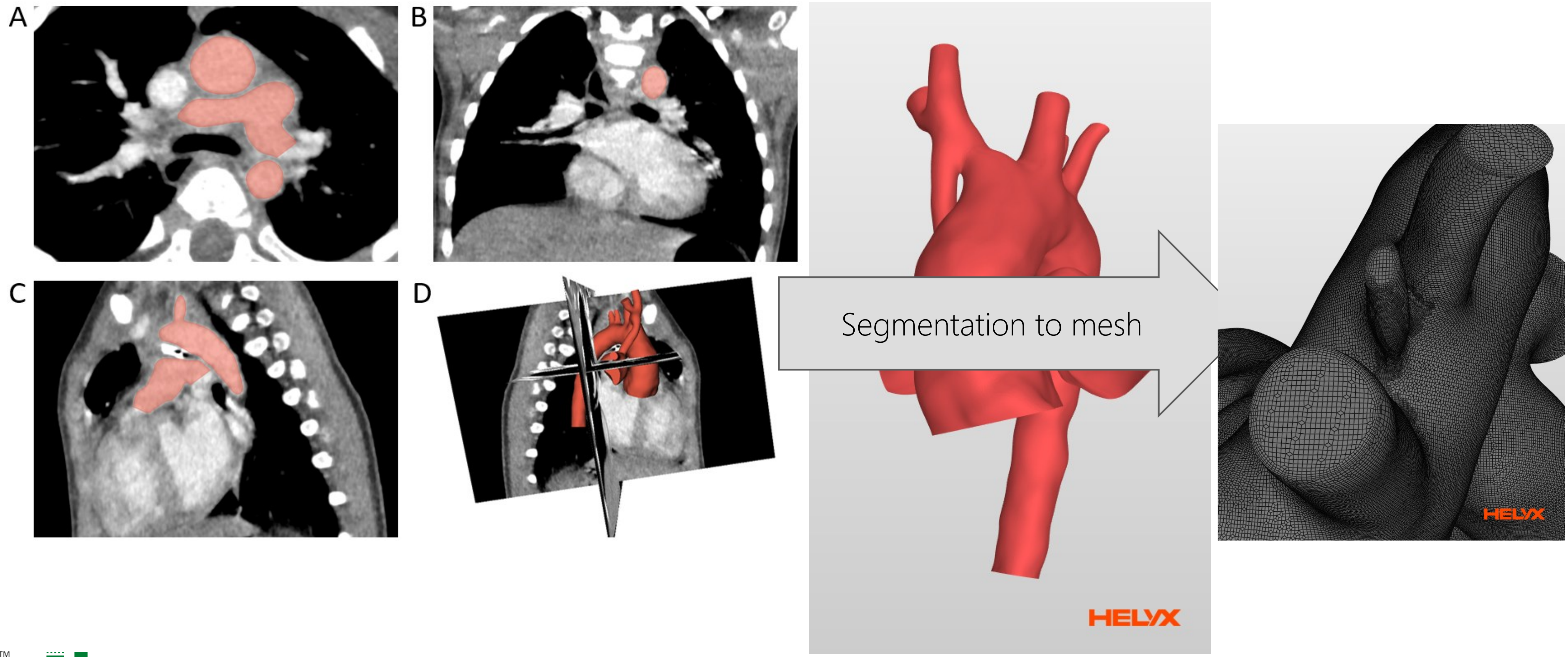

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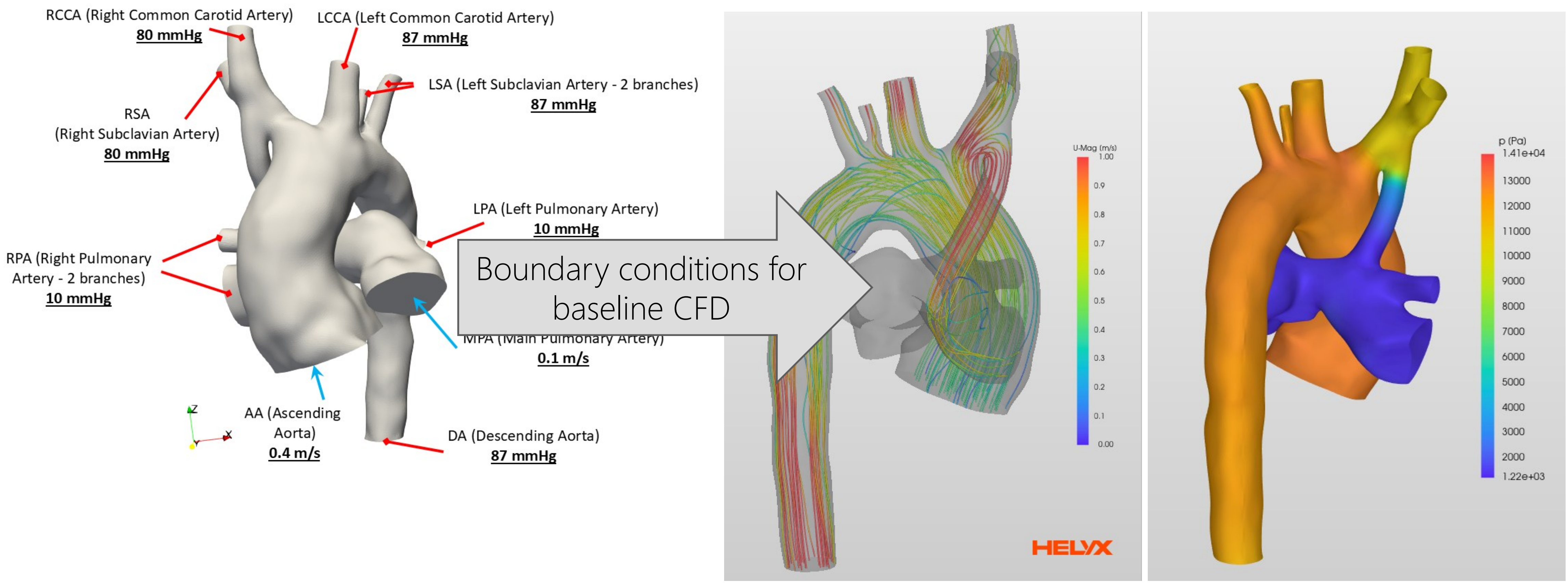

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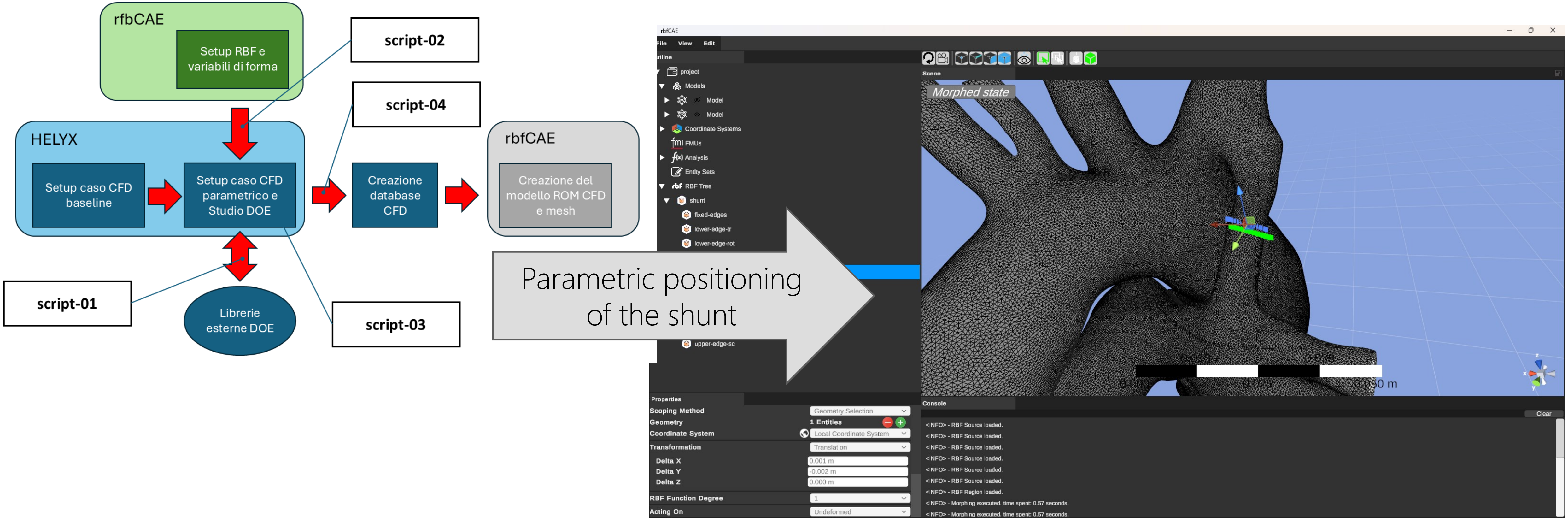

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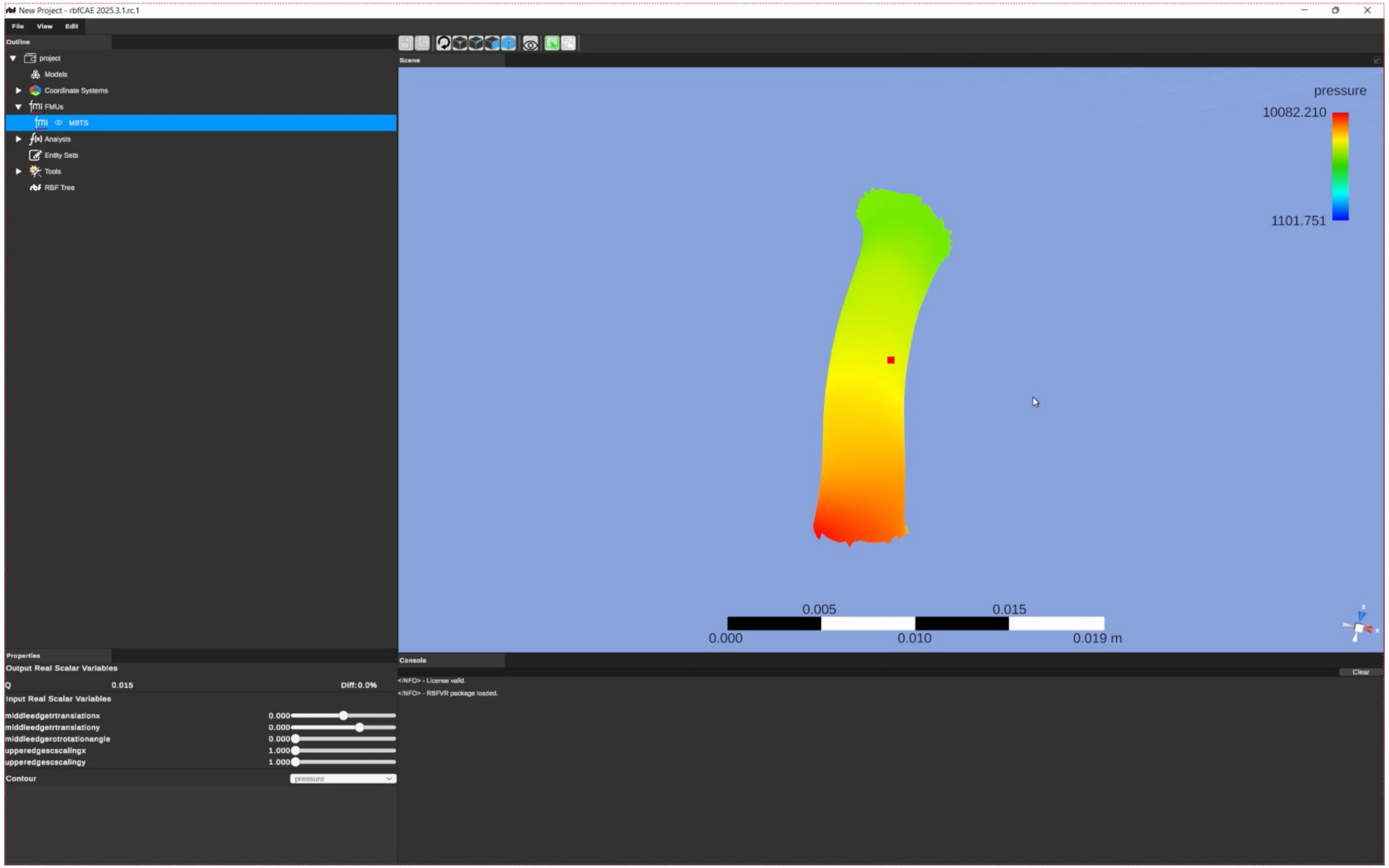

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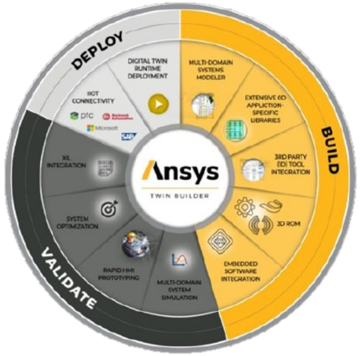
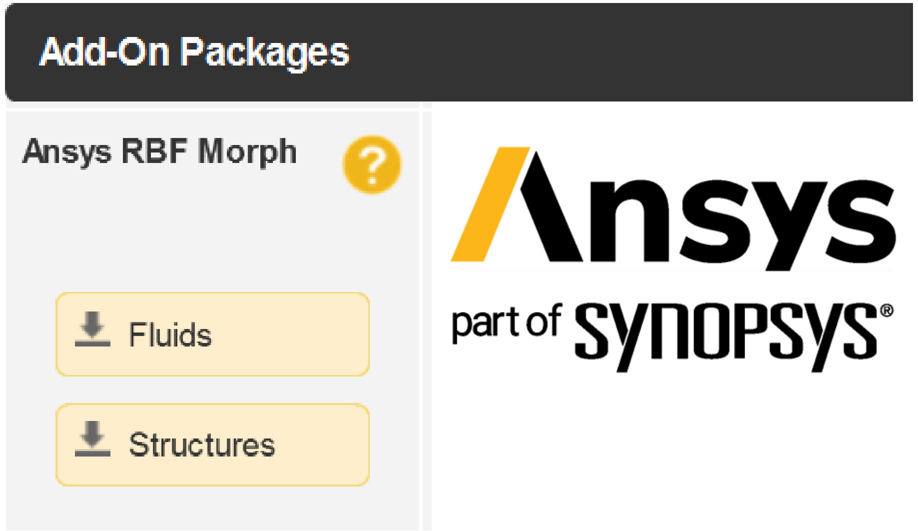
RBF Morph technologies

A complete solution for Medical Digital Twins

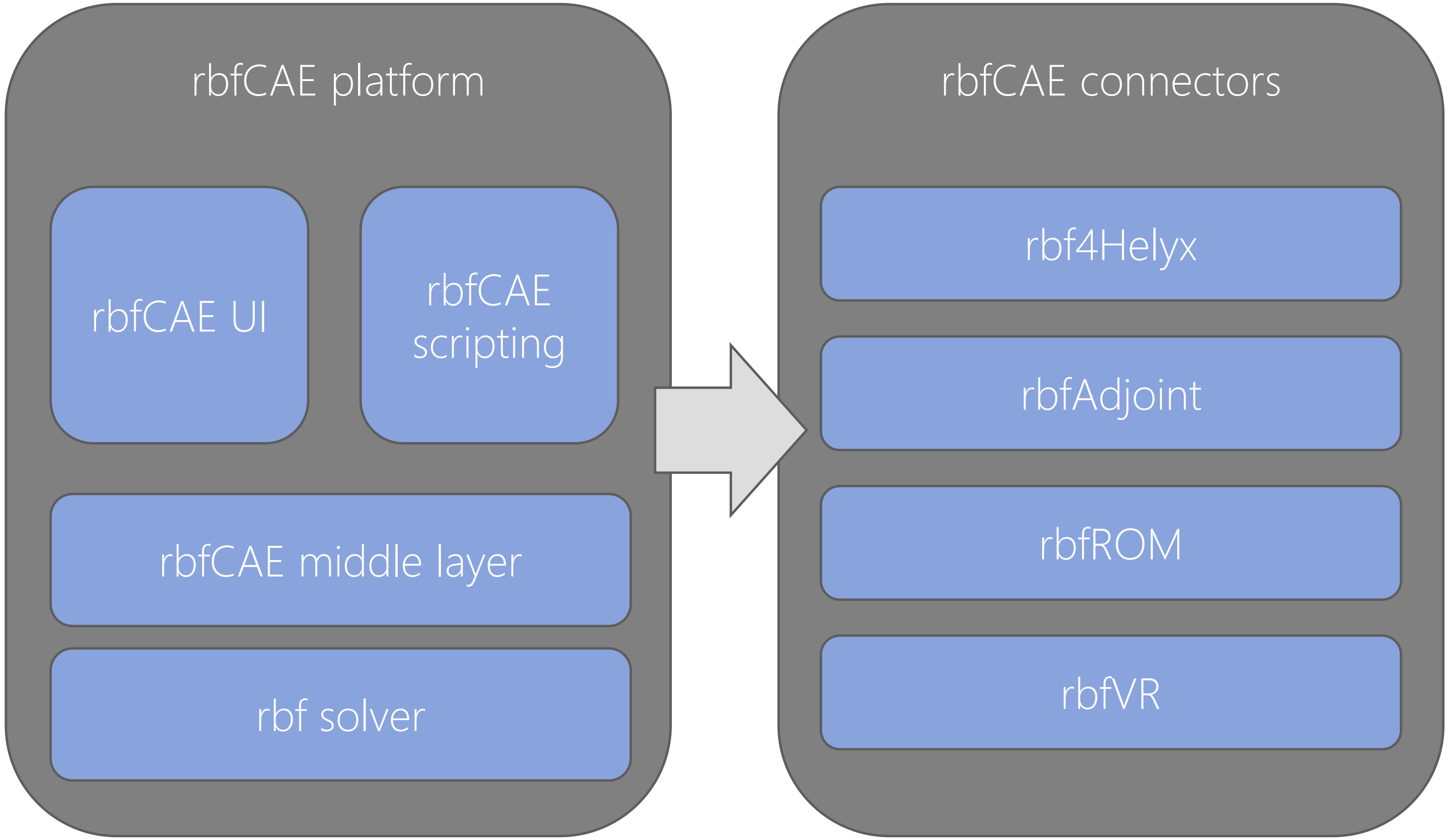
Ansys RBF Morph



- 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**



rbfCAE solution



- Released in 2024
- Read in **STL, STEP**
- **Unity - OpenCascade**
- Solver independent process that supports **many mesh formats**
- **Scriptable** via python

Conclusions

- Interactive Digital Twins? **Yes!**
- We can deploy fast interactive ROM on VR and on custom dashboards
- We use RBF both for the geometrical intelligence and both for the AI inference
- Multiple workflow are supported: a variety of CAE software can be combined to mesh morphing to generate synthetic datasets
- The approach works both for parametric cases (shapes are varied according to specific actions) both for SSM (shapes are collected from a cohort of data)

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Many thanks for your attention!

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