# CAE$^{Up}$ - Update of CAE models on actual manufactured shapes

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# Summary

- Introduction – robust design concepts
- Cluodifacturing project
- CAE$^{Up}$ Experiment
- Radial Basis Functions mesh morphing and projection
- Test case
- Conclusions

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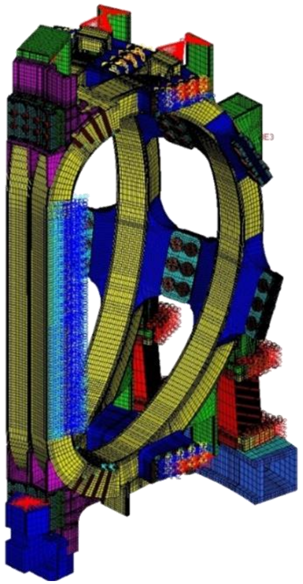
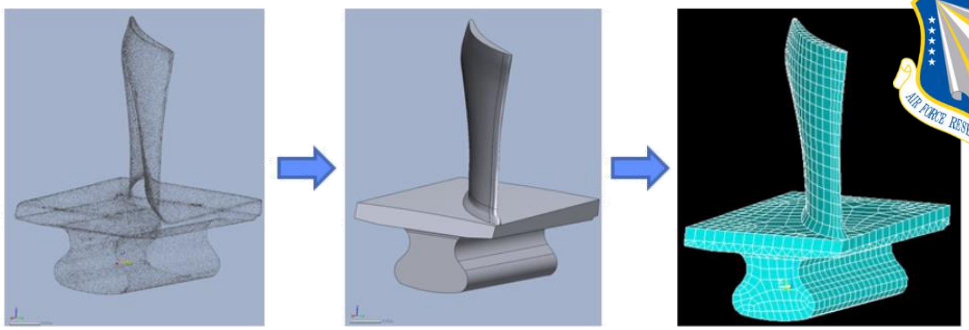
# Introduction - Robust design concepts

- The actual **manufactured shapes** represent the nominal geometry within a prescribed tolerance
- The effect on performances can be **predicted** in advance (mesh morphing and RS method are typically adopted)
- The effect on performances can be **evaluated after manufacturing** (an update of CAE models is required!)
- The same concepts can be applied to parts that passed QA (i.e. deviations within prescribed tolerances) as well to **off-design parts** (for instance repaired ones)
- According to the **Digital Twin** concept we want the CAE model to be individual part specific

# Introduction - Robust design concepts

- A. Portone, A. Formisano, G. D’Amico, M. Jimenez, B. Bellesia Results on error fields simulation in ITER from the first EU TF coil manufacturing. 33rd Meeting of ITPA MHD 1-3 April 2019, Daejeon, South Korea.
- Biancolini, M.E., Cella, U., 2019. Radial basis functions update of digital models on actual manufactured shapes. Journal of Computational and Nonlinear Dynamics 14, 021013.
- Kaszynski, A. A., Beck, J. A., & Brown, J. M. (2014, June). Automated finite element model mesh updating scheme applicable to mistuning analysis. In ASME Turbo Expo 2014: Turbine Technical Conference and Exposition. American Society of Mechanical Engineers Digital Collection.





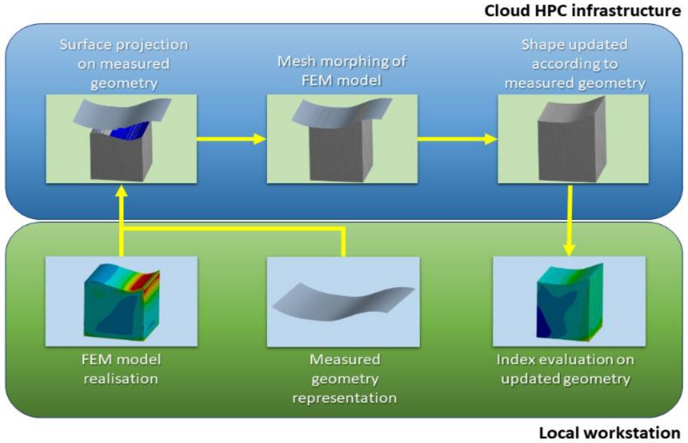
# Cloudifacturing project (https://www.cloudifacturing.eu)

- The mission of **Cloudifacturing*** is to optimize production processes and producibility using **Cloud/HPC-based** modelling and simulation. By leveraging online factory data and advanced data analytics, the project contributes to the competitiveness and resource efficiency of **manufacturing SMES**, ultimately fostering the vision of **Factories 4.0** and the **circular economy**.


(*) The project Cloudifacturing receives funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement no. 768892.

# CAE$^{Up}$ Experiment – Overview

- **CAE$^{Up}$** succeeded the II call and aims to solve an important need of industrial design and optimization in a reliable and cost-effective way
- The need consists of the **verification** of the actual geometry of manufactured parts, adopting the **Digital Twin** approach
- The digital representation consists in **updating the numerical models** in the respect of the real shape of the manufactured products using **RBF mesh morphing**

# CAE$^{Up}$ Experiment – Consortium



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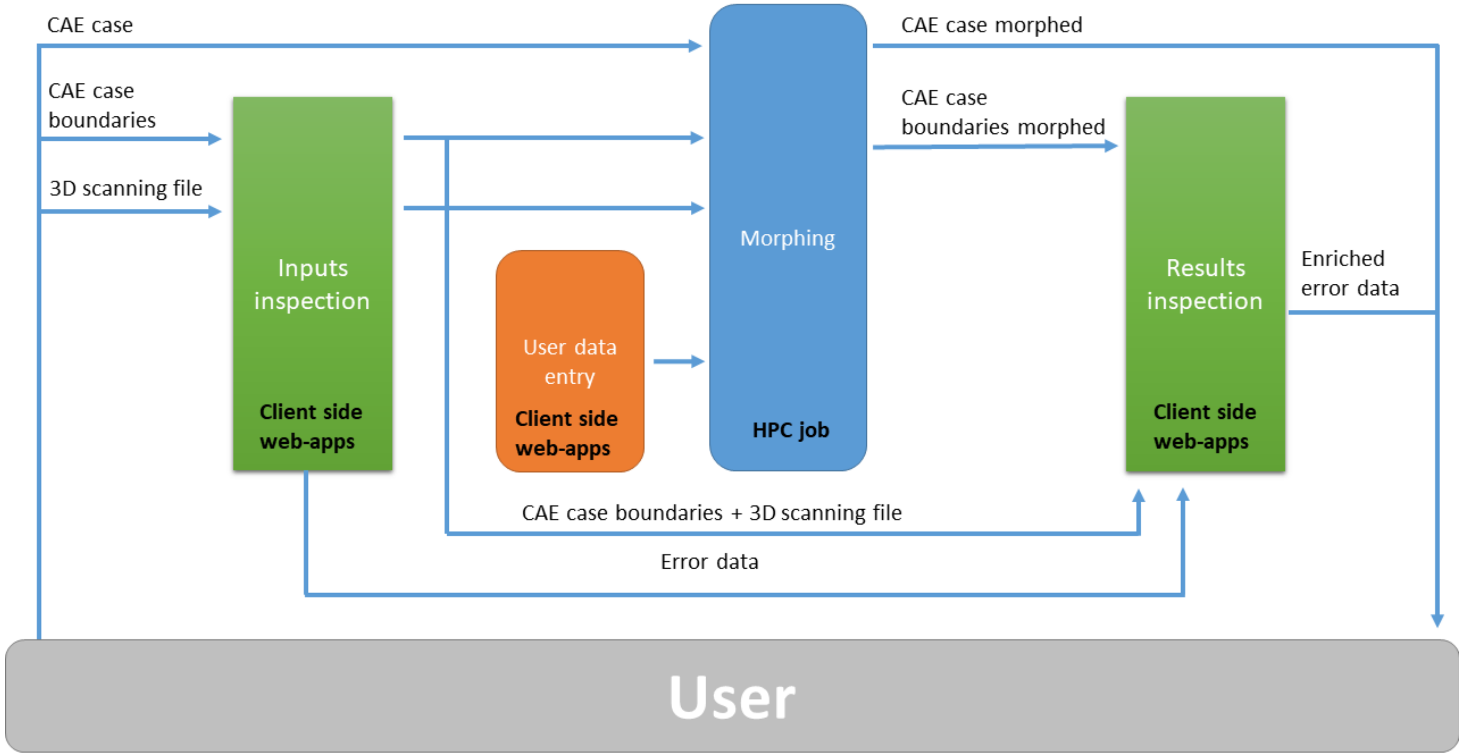
# CAE$^{Up}$ Experiment – Service benefits and features

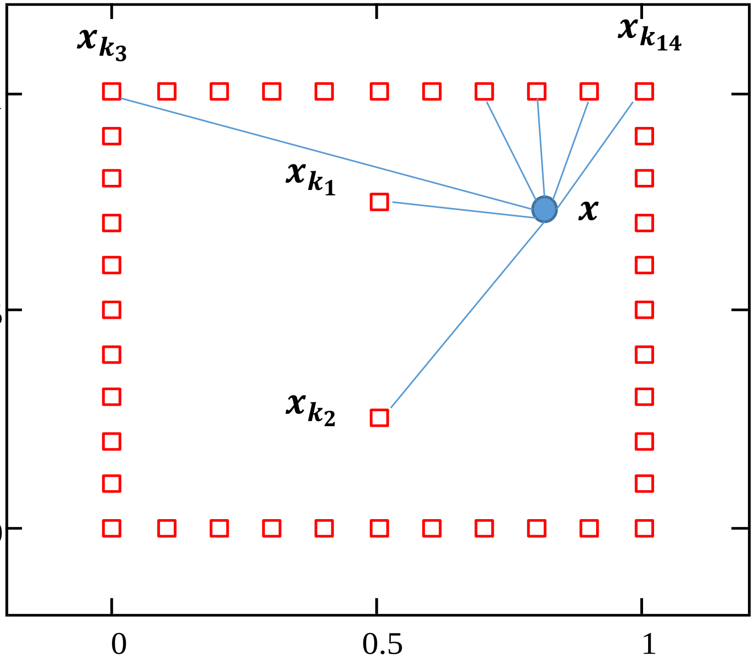
- **effective tool**, that can be run through web, characterized by a high level of automation;
- **increased accuracy** in numerical prediction through CAE computing;
- **reduced production costs** obtained by quality assessment related to actual local shape;
- **high level of security** for the data.

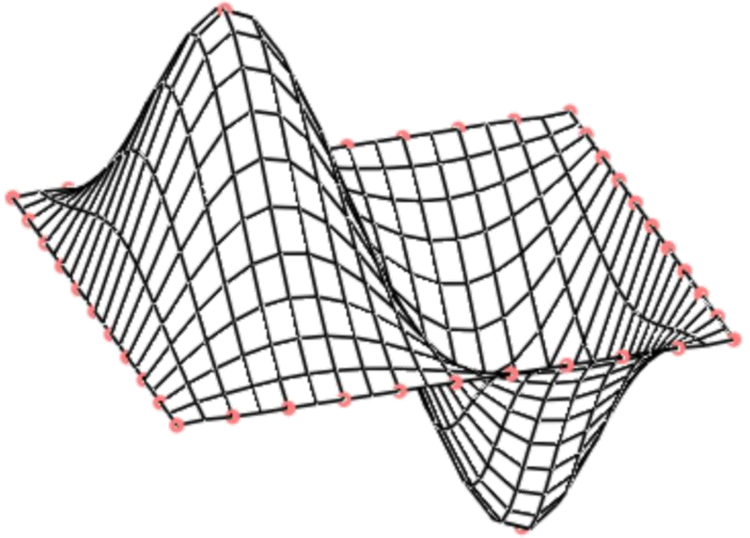


# RBF Background

- RBFs are a mathematical tool capable to **interpolate** in a generic point in the space a function **known** in a discrete set of points (**source points**).
- The interpolating function is composed by a **radial basis** and by a **polynomial**:

$$s(\mathbf{x}) = \overbrace{\sum_{i=1}^{N} \gamma_i \varphi\left(\underbrace{\left\|\mathbf{x}-\mathbf{x}_{k_i}\right\|}_{\text{distance from the i-th source point}}\right)}^{\text{radial basis}} + \overbrace{h(\mathbf{x})}^{\text{polynomial}}$$



# RBF Background

- If evaluated on the source points, the interpolating function gives exactly the input values:

$$s(\boldsymbol{x}_{k_i}) = g_i \qquad h(\boldsymbol{x}_{k_i}) = 0 \qquad 1 \le i \le N$$

- The RBF problem (evaluation of coefficients γ and β) is associated to the solution of the linear system, in which **M** is the interpolation matrix, **P** is a constraint matrix, **g** is the vector of known values on the source points:

$$\begin{bmatrix} \mathbf{M} & \mathbf{P} \\ \mathbf{P}^{\mathrm{T}} & 0 \end{bmatrix} \begin{pmatrix} \boldsymbol{\gamma} \\ \boldsymbol{\beta} \end{pmatrix} = \begin{pmatrix} \boldsymbol{g} \\ 0 \end{pmatrix} \qquad M_{ij} = \varphi\left(\boldsymbol{x}_{k_i} - \boldsymbol{x}_{k_j}\right) \qquad 1 \le i, j \le N \qquad \mathbf{P} = \begin{bmatrix} 1 & x_{k_1} & y_{k_1} & z_{k_1} \\ 1 & x_{k_2} & y_{k_2} & z_{k_2} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_{k_N} & y_{k_N} & z_{k_N} \end{bmatrix}$$

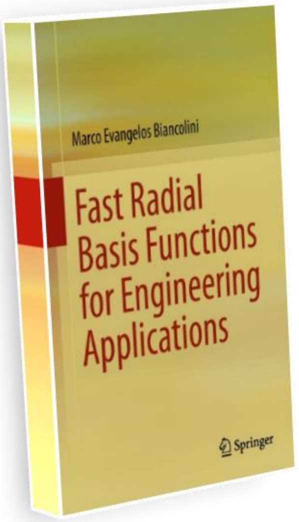
# RBF Background

- Once solved the RBF problem each displacement component is interpolated:

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

- Several different radial function (kernel) can be employed:

| RBF | φ(r) | RBF | φ(r) |
|---|---|---|---|
| Spline type (Rn) | $r^n$, *n odd* | Inverse multiquadratic (IMQ) | $\frac{1}{\sqrt{1+r^2}}$ |
| Thin plate spline | $r^n \log(r)$ *n even* | Inverse quadratic (IQ) | $\frac{1}{1+r^2}$ |
| Multiquadratic (MQ) | $\sqrt{1+r^2}$ | Gaussian (GS) | $e^{-r^2}$ |



## RBF implicit surface

- Let's consider the RBF of a scalar field (cubic radial function)

$$s(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i \left( \sqrt{(x - x_{s_i})^2 + (y - y_{s_i})^2 + (z - z_{s_i})^2} \right)^3 + h(\mathbf{x})$$

- It can be differentiated in closed form

$$\frac{\partial s(\mathbf{x})}{\partial x} = 3 \sum_{i=1}^{N} \gamma_i \, (x - x_{s_i}) \sqrt{(x - x_{s_i})^2 + (y - y_{s_i})^2 + (z - z_{s_i})^2} + \beta_1$$

$$\frac{\partial s(\mathbf{x})}{\partial y} = 3 \sum_{i=1}^{N} \gamma_i \, (y - y_{s_i}) \sqrt{(x - x_{s_i})^2 + (y - y_{s_i})^2 + (z - z_{s_i})^2} + \beta_2$$

$$\frac{\partial s(\mathbf{x})}{\partial z} = 3 \sum_{i=1}^{N} \gamma_i \, (z - z_{s_i}) \sqrt{(x - x_{s_i})^2 + (y - y_{s_i})^2 + (z - z_{s_i})^2} + \beta_3$$

# RBF implicit surface

- The analytic gradient

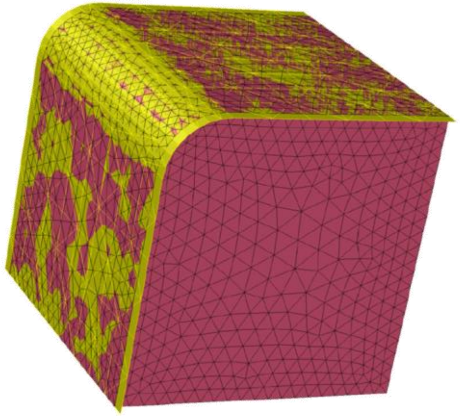
$$\nabla s(\mathbf{x}) = \left\{ \frac{\partial s(\mathbf{x})}{\partial x} \quad \frac{\partial s(\mathbf{x})}{\partial y} \quad \frac{\partial s(\mathbf{x})}{\partial z} \right\}^T$$

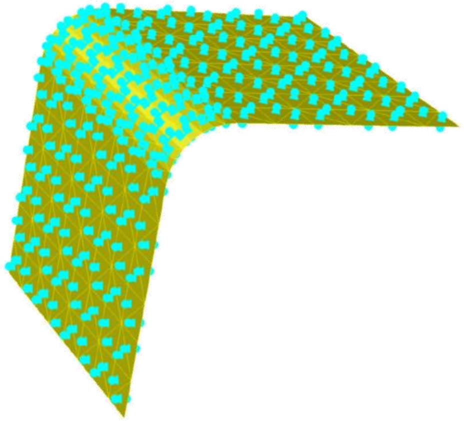
- can be used to project a point on iso-surfaces of the scalar field

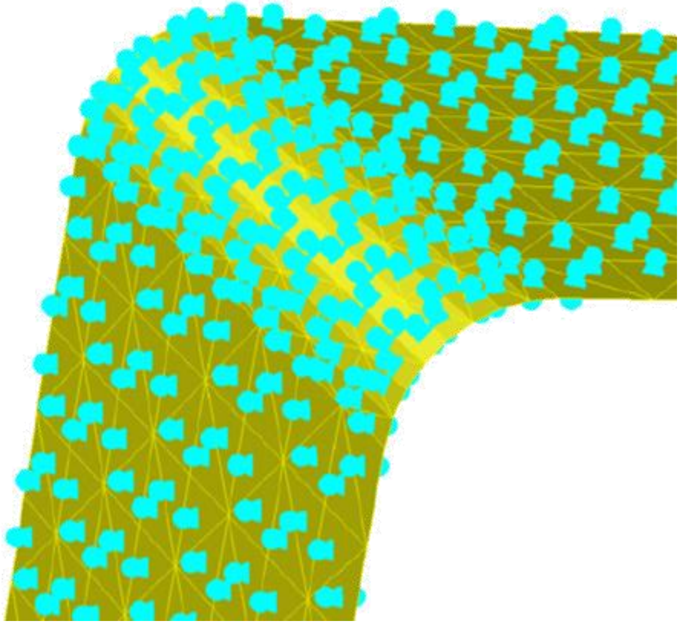
$$\mathbf{x}_{k+1} = \mathbf{x}_k + \frac{s(\mathbf{x}_k)}{||\nabla s(\mathbf{x}_k)||^2} \nabla s(\mathbf{x}_k)$$

# RBF implicit surface

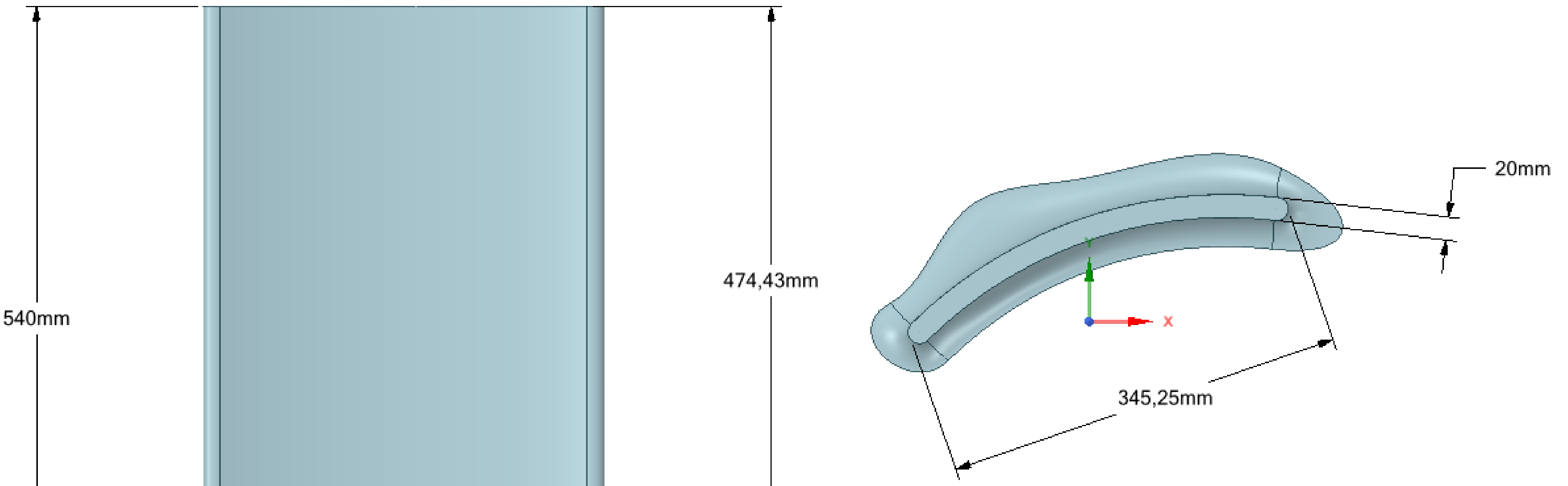
- **Source** points of the RBF are defined:
  - On centroids (f = 0)
  - On inner offset points (f = -1)
  - On outer offset points (f = 1)
- The gradient projects onto the 0 iso-surface
- Offset **distance** (uniform along the normal direction) should be tuned to **avoid clash** of offset points



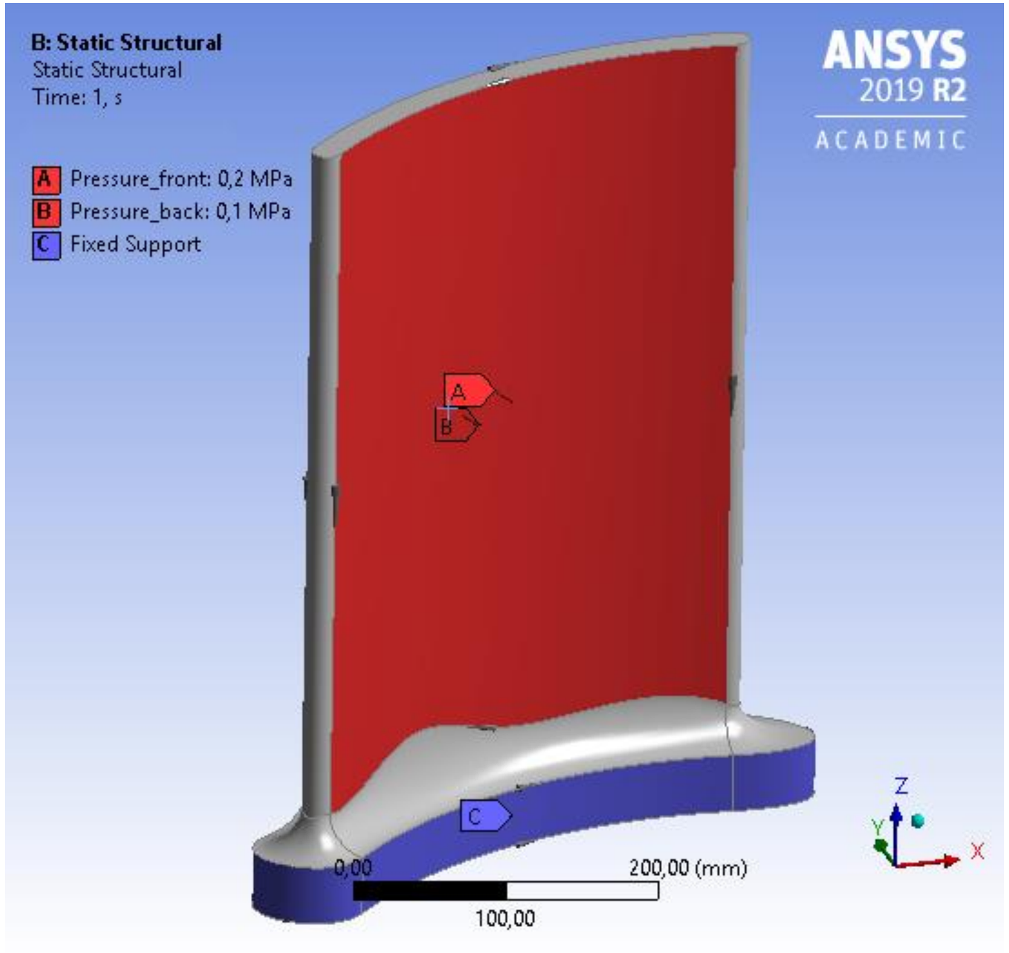


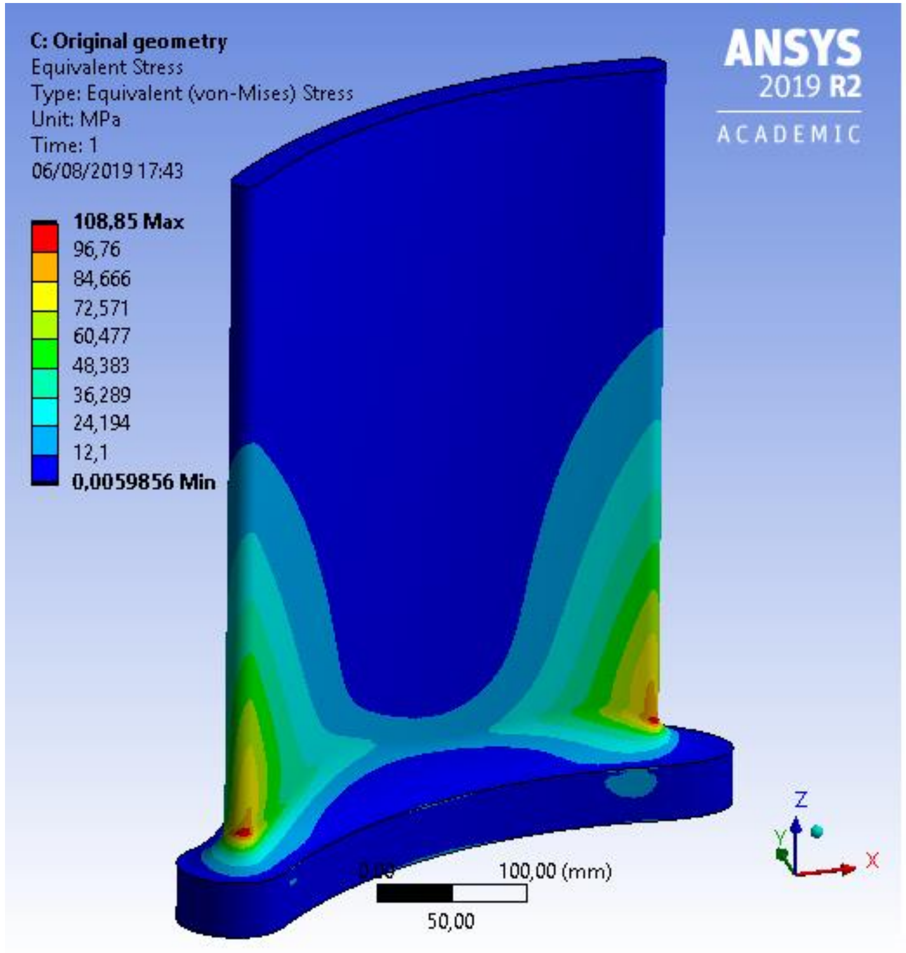


# Test case – mock up of a turbine blade



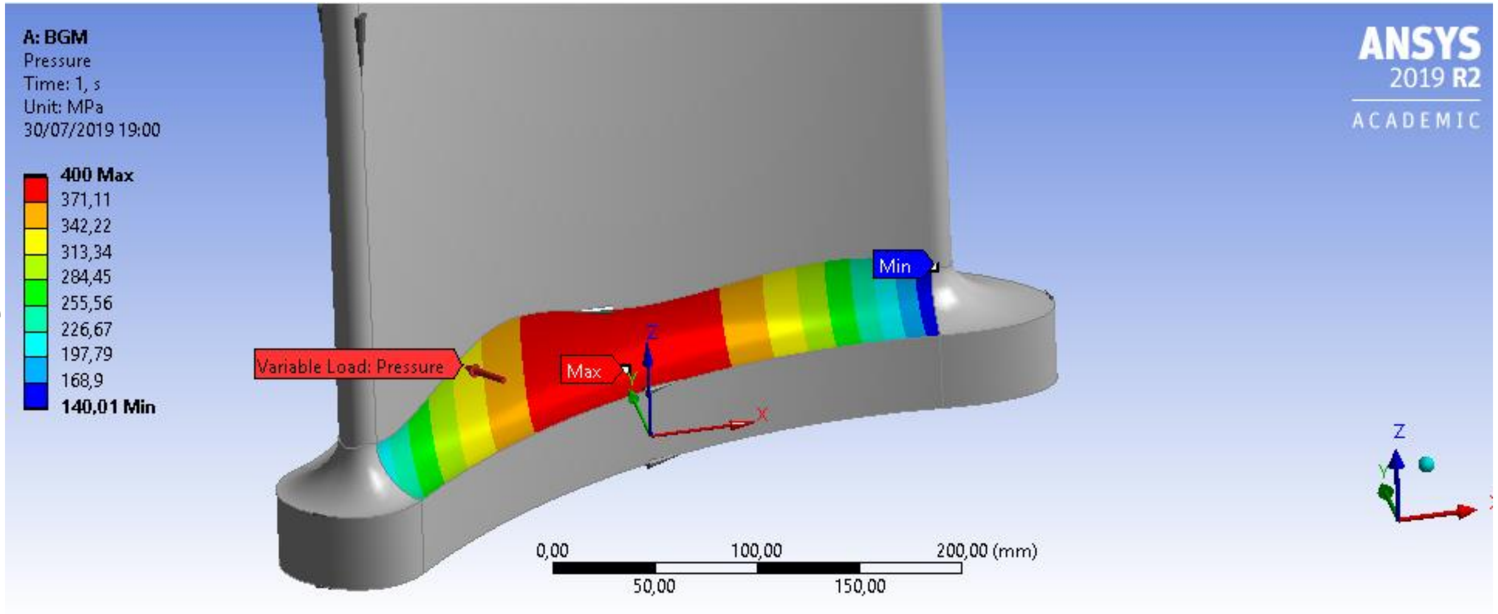
# Test case – baseline stress



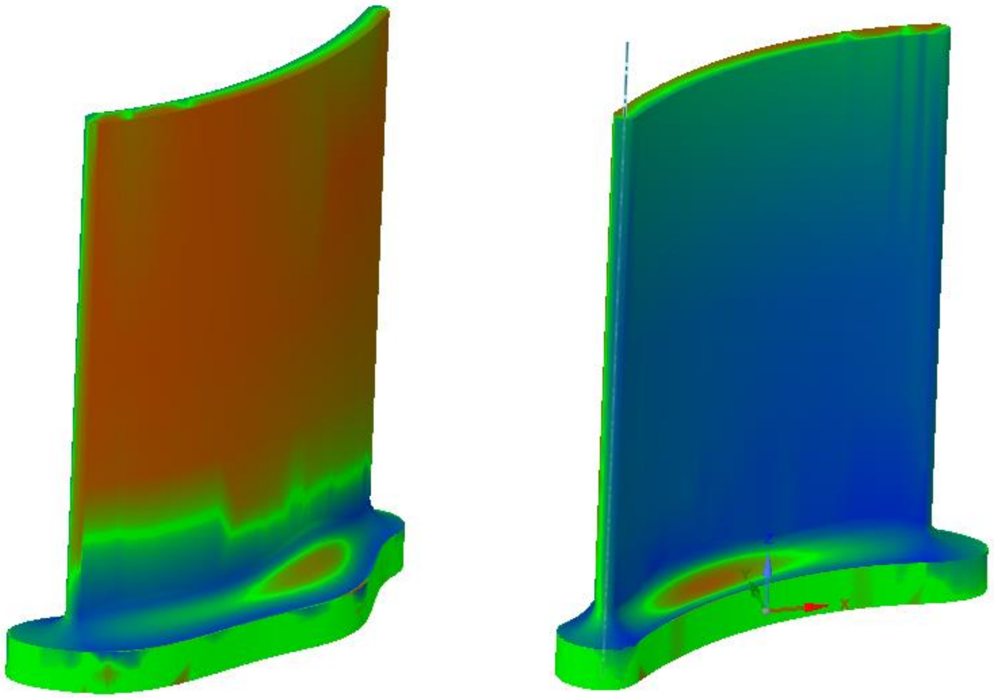
# Test case – shape deviation

- The example examines the effects of manufacturing errors on a simplified **turbine blade** model
- A scan of the manufactured shape was not available and so a synthetic 3d scanned shape was generated by the application of a variable pressure field on the pressure side fillet and then by updating the shape according to local stress (BGM). A **maximum deviation of 0.4 mm** was applied.
- The shape perturbation was created adopting a **fictitious loading condition** (root clamped + constant pressure on the airfoil surface)



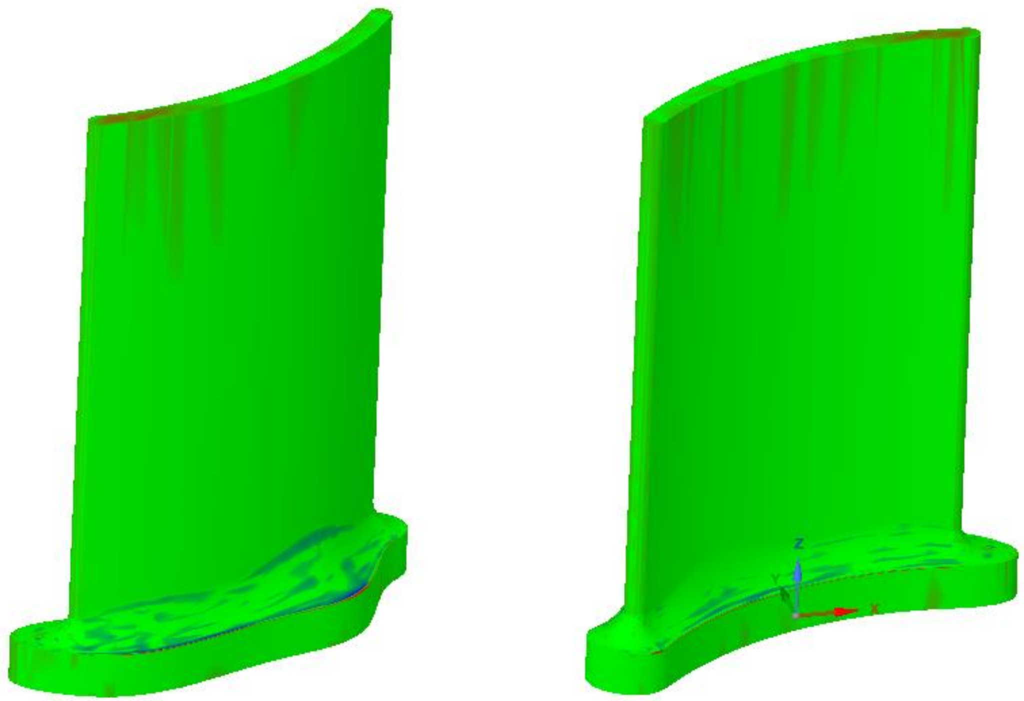
# Test case - shape deviation

- A colour map is used to show the **deviation** between the two geometries
- The largest differences are in the fillet area, and the **maximum deviation** values are 0.38 mm for the inside area and 0.28 mm for the outside area



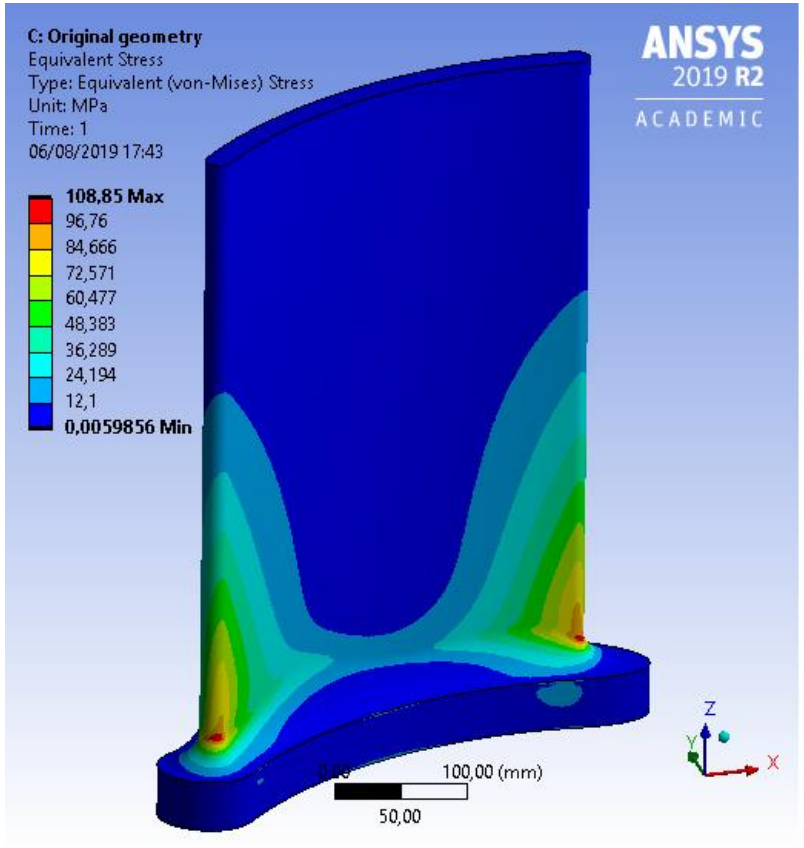
# Results

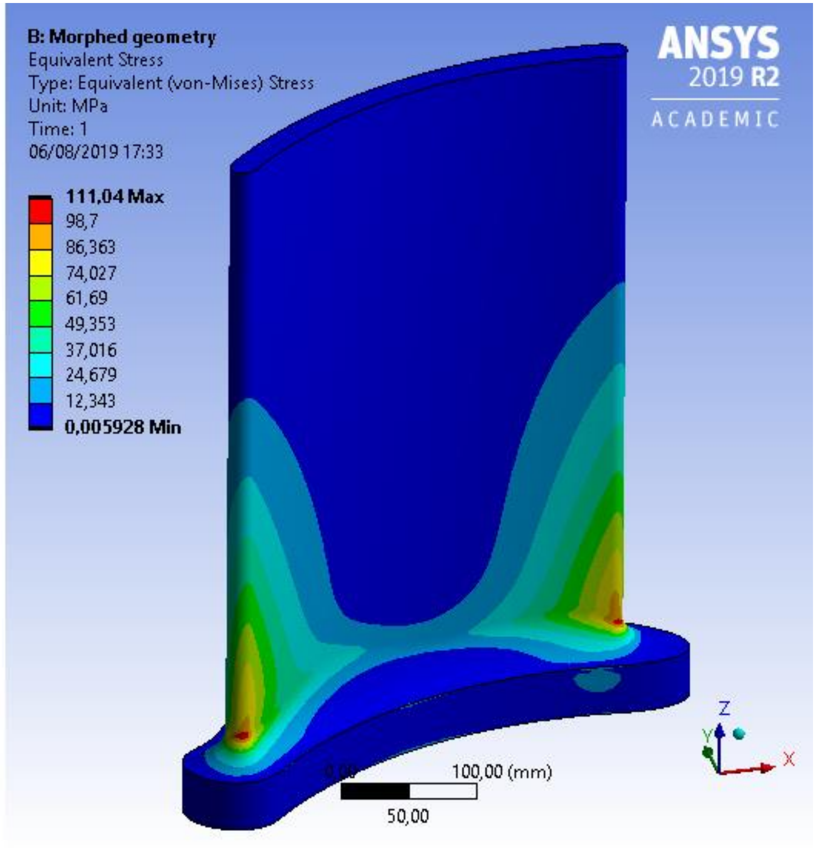
- The **morphed mesh** matches almost perfectly the target model
- The distance of almost all the sample points of the morphed body from the target one is **less than 0.01mm**
- The **measured difference** between the two geometries is contained within an interval of 0.03mm, that means less than 8% of the manufacturing tolerance



# Results

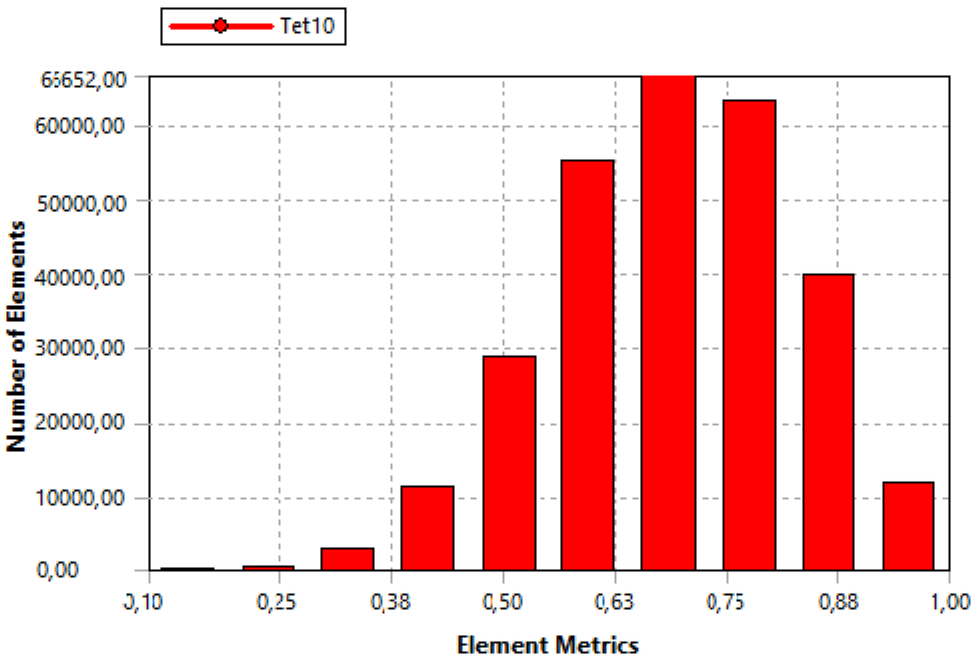
- The numerical solution shows a little increase of the maximum equivalent stress that changes from 109 MPa to 111 MPa approximately, namely below 2% in absolute terms

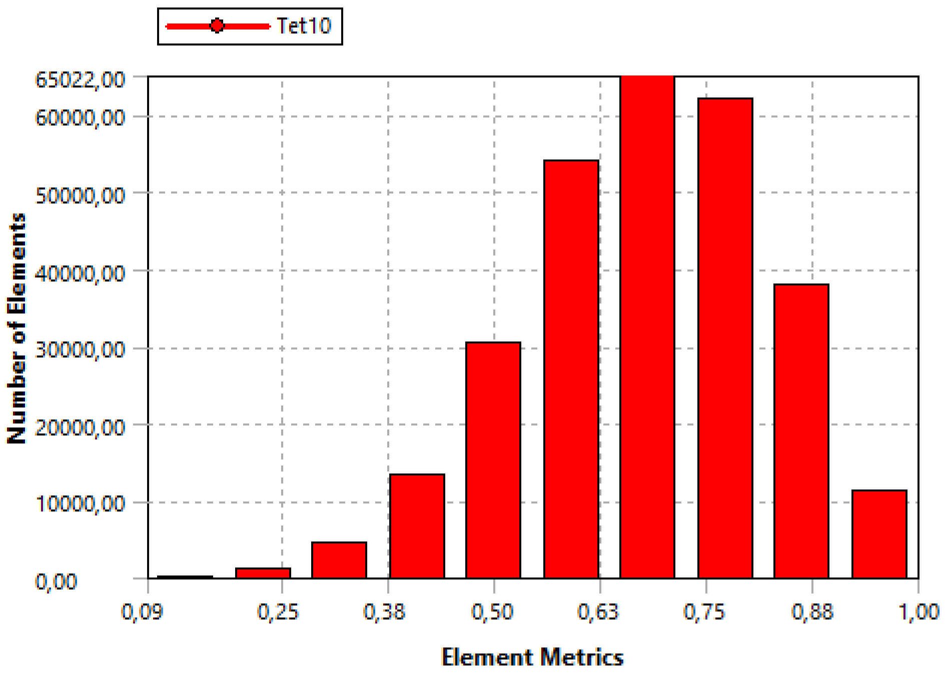


# Results

- To test the goodness of the mesh morphing process, it was also made a comparison between element quality of the original mesh and the morphed mesh



# Conclusions

- The adoption of the described procedure, based on the use of **RBF mesh morphing**, was showcased using a test case of a simplified blade
- Surface **projecting** technique based on the use of **RBF implicit surface** confirmed to guarantee high accuracy and flexibility in tackling **geometrical reconstruction** problems providing the capability to significantly reduce the effort if compared to a model reconstruction procedure adopting CAD systems.
- The workflow today demonstrated for **structural (FEA)** example is adopted for **multi-physics simulation** (including CFD) and the service of CAE Up is designed to accept different mesh format to accomadate multiple physics

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# Thank you!

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