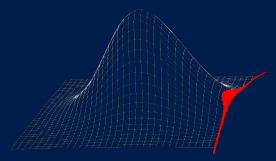
TECHNISCHE UNIVERSITÄT DRESDEN

Faculty of Mechanical Science and Engineering · Institute of Fluid Mechanics · Chair of Turbomachinery and Jet Propulsion



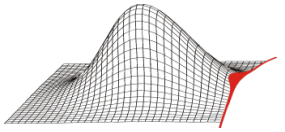
A Guideline to enable Probabilistic Profile Design based on Optical Measurement Data

Lars Högner, Thomas Backhaus, Oliver Baum, Sebastian Knebel, Paul Voigt, Robin Schmidt

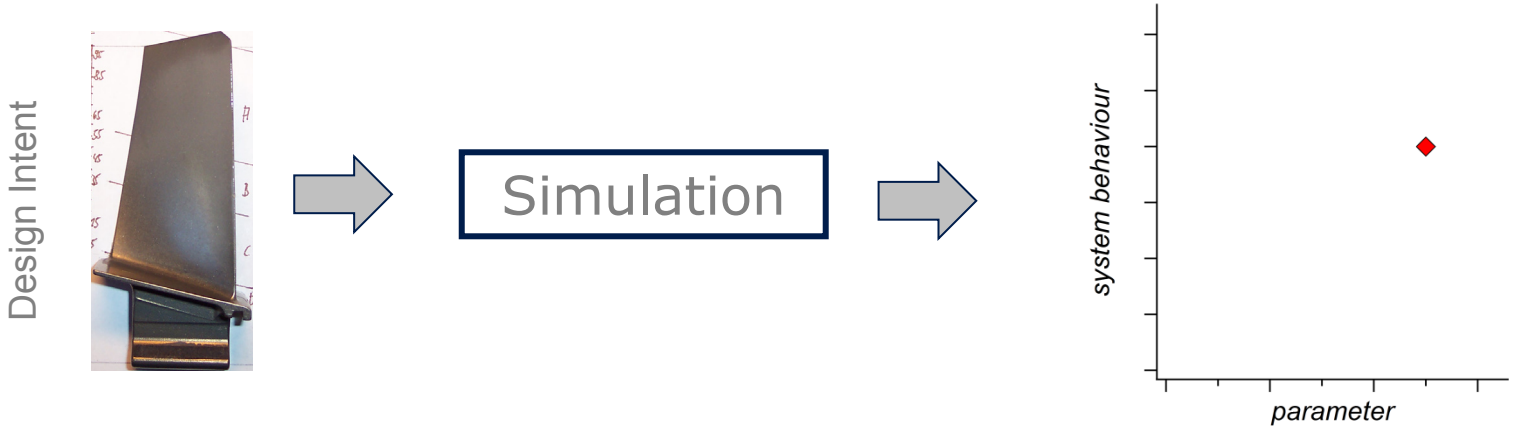
8. Dresdner Probabilistik-Workshop
8th – 9th October 2015

TECHNISCHE UNIVERSITÄT DRESDEN

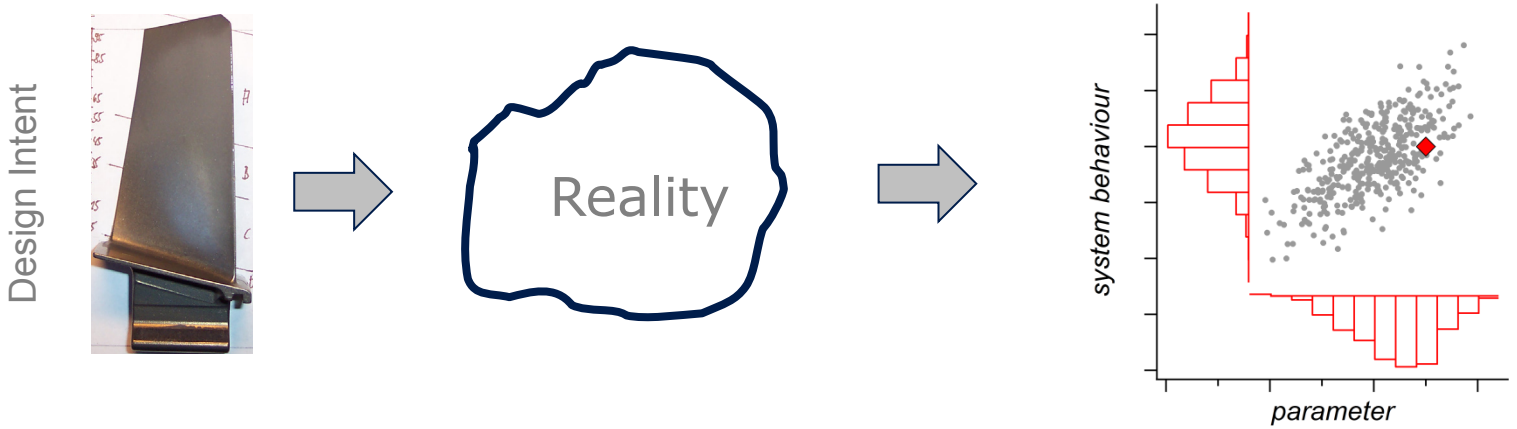
1.1 Motivation



- Classic simulation-based approach used in design

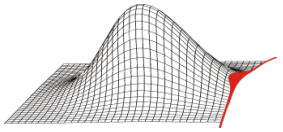


- Real behavior of physical system



TECHNISCHE UNIVERSITÄT DRESDEN

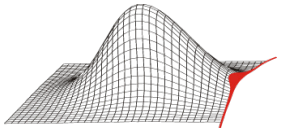
1.1 Motivation

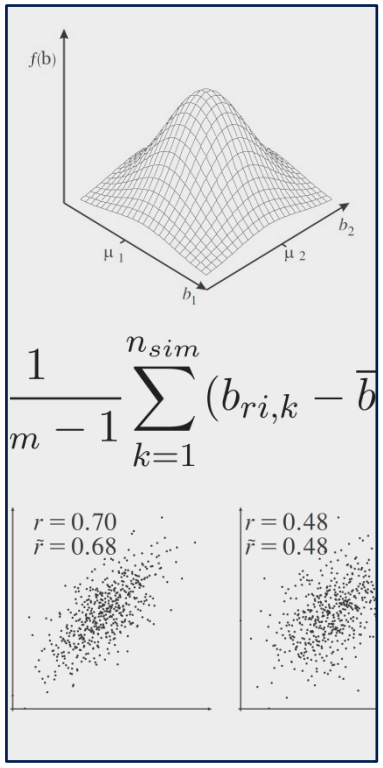


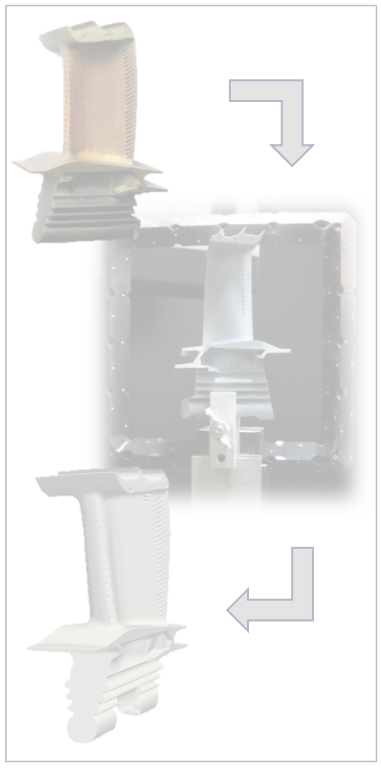
Two individual turbine blades from the same engine

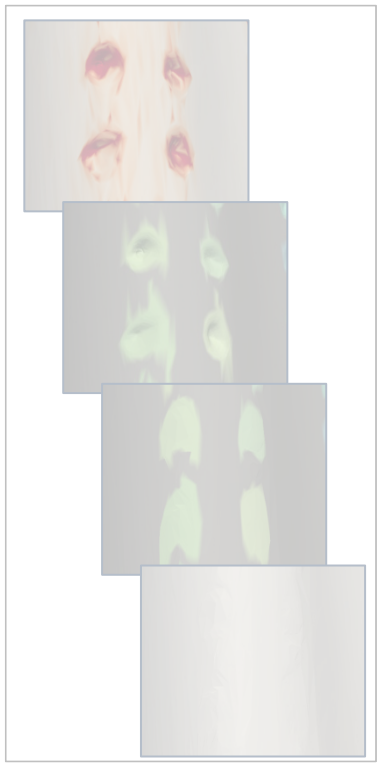
Massachusetts Institute of Technology, Prof. David L. Darmofal

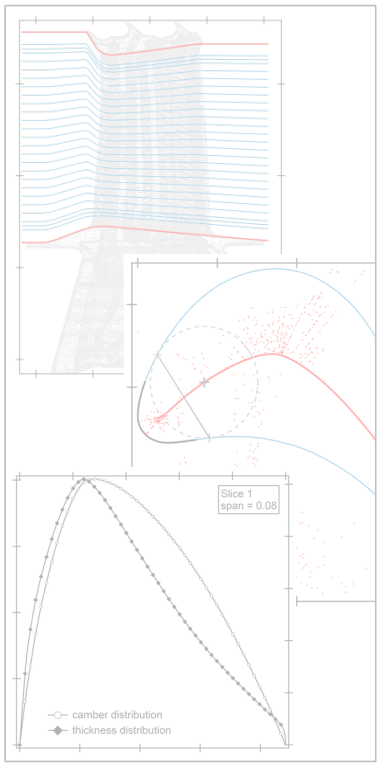
Outline

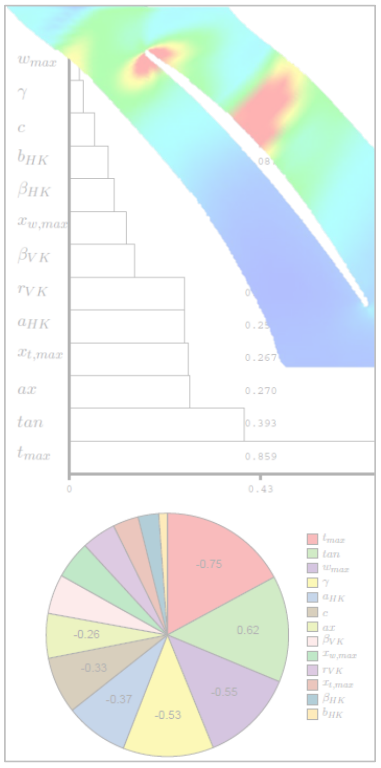






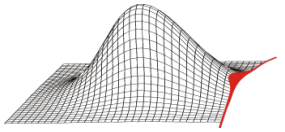


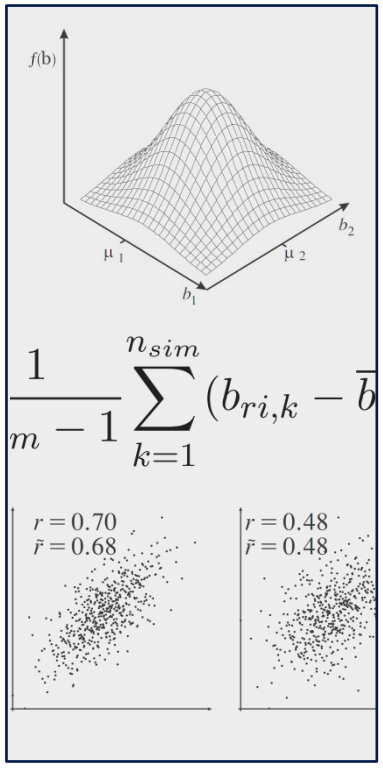




TECHNISCHE UNIVERSITÄT DRESDEN

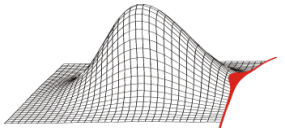
1 Introduction





TECHNISCHE UNIVERSITÄT DRESDEN

1.2.1 Random variables



random experiment

↓

discrete ← random variable → continuous

probability mass function **(pmf)**

probability **d**ensity **f**unction **(pdf)**

↓ ↓

$$F(b) = \sum_{b_{ri} \leq b} f(b_{ri})$$

cummulative density function **(cdf)**

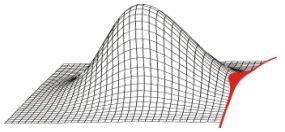
$$F(b) = \int_{-\infty}^{b} f(\tilde{b}) d\tilde{b}$$

↘ ↙

$$F(b) = P(\boldsymbol{b} \leq b)$$

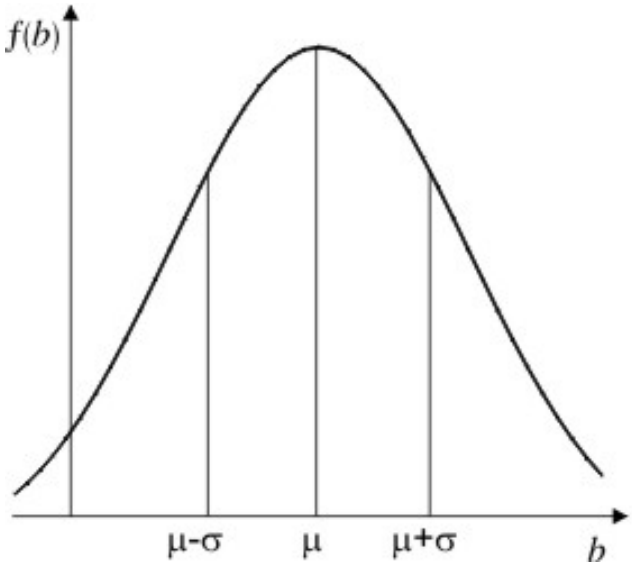
TECHNISCHE UNIVERSITÄT DRESDEN

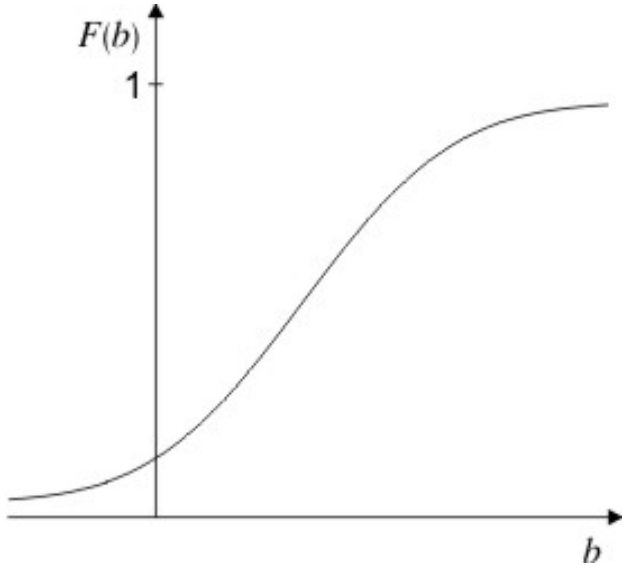
1.2.2 Distributions



Gaussian Distribution (Normal Distribution)

[1]





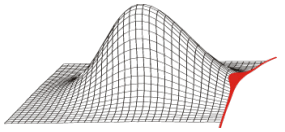
$$f(b) = \frac{1}{\sigma\sqrt{2\pi}} exp\left[-\frac{(b-\mu)^2}{2\sigma^2}\right]$$

$$F(b) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{b} exp\left[-\frac{(\tilde{b}-\mu)^2}{2\sigma^2}\right] d\tilde{b}$$

[1] Sachs, L., 2004, *Angewandte Statistik, Anwendung statistischer Methoden*

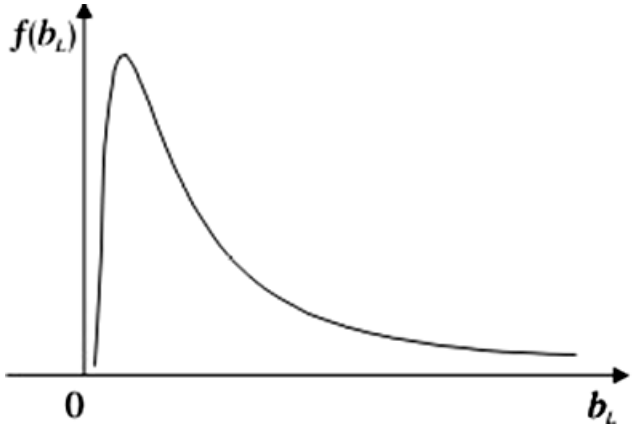
TECHNISCHE UNIVERSITÄT DRESDEN

1.2.2 Distributions

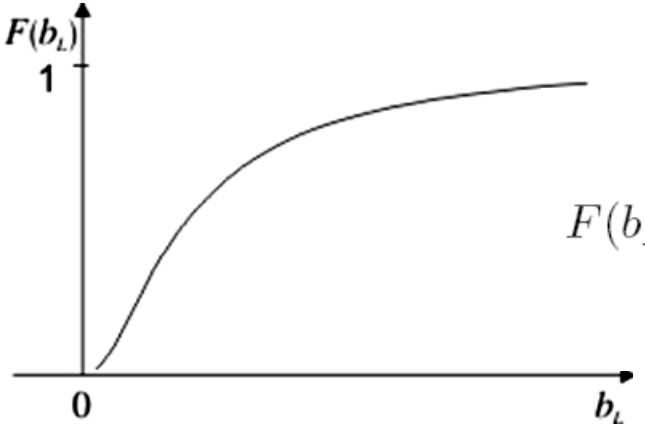


[1]

log-Normal Distribution



$$f(b_L) = \begin{cases} \dfrac{1}{\zeta\sqrt{2\pi}\, b_L} \exp\left\{-\dfrac{(\ln b_L - \lambda)^2}{2\,\zeta^2}\right\} & \text{für } b_L > 0 \\ 0 & \text{sonst} \end{cases}$$

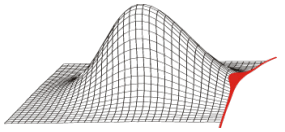


$$F(b_L) = \begin{cases} \dfrac{1}{\zeta\sqrt{2\,\pi}} \displaystyle\int_0^{b_L} \frac{1}{\widetilde{b}_L} \exp\left\{-\frac{(\ln \widetilde{b}_L - \lambda)^2}{2\,\zeta^2}\right\} d\widetilde{b}_L & \text{für } \widetilde{b}_L > 0 \\ 0 & \text{sonst} \end{cases}$$

[1] Sachs, L., 2004, *Angewandte Statistik, Anwendung statistischer Methoden*

TECHNISCHE UNIVERSITÄT DRESDEN

1.2.3 Statistical measures



- **arithmetic mean**

$$\bar{b}_{ri} = \frac{1}{n_{sim}} \sum_{k=1}^{n_{sim}} b_{ri,k}$$

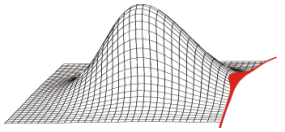
  - centroid of the area underneath the density function
  - sensitive towards outliers

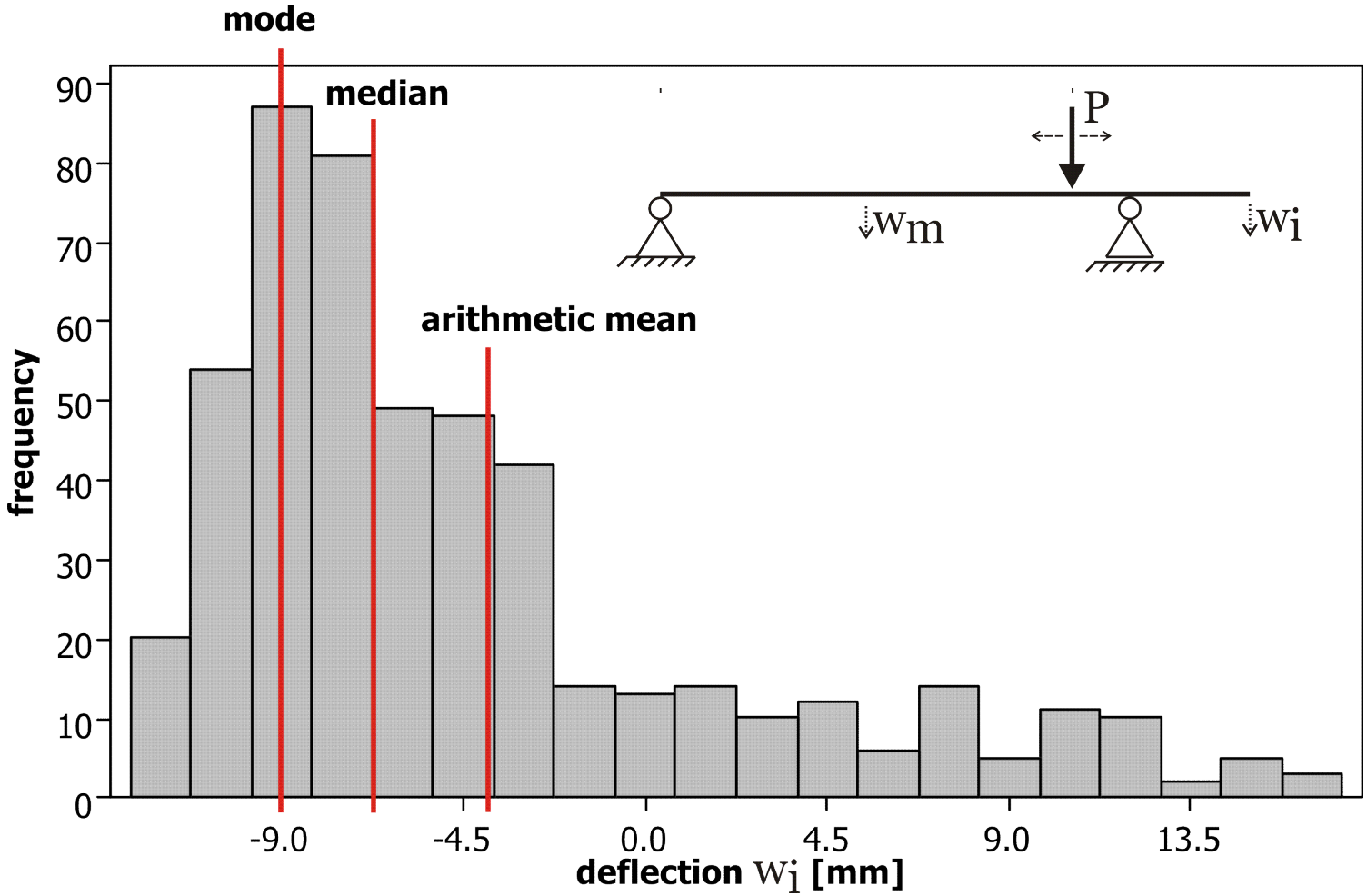
- **median**
  - divides the area below the probability density function into two pieces of equal size
  - robust towards outliers

- **modal value or mode**
  - value of the data set, that occurs with the greatest frequency
  - not necessarily unique

TECHNISCHE UNIVERSITÄT DRESDEN

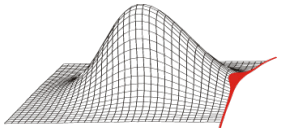
1.2.3 Statistical measures





TECHNISCHE UNIVERSITÄT DRESDEN

1.2.3 Statistical measures



- **standard deviation**

$$\sigma(b_{ri}) = \sqrt{Var(\mathbf{b}_{ri})} = \sqrt{\frac{1}{n_{sim}-1}\sum_{k=1}^{n_{sim}}(b_{ri,k} - \bar{b}_{ri})^2}$$

  - Variation towards the expected value $\bar{b}_{ri}$

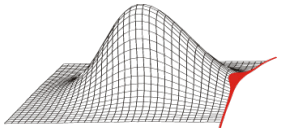
- **coefficient of variation**

$$\delta(\mathbf{b}_{ri}) = \frac{\sigma(\mathbf{b}_{ri})}{\bar{b}_{ri}}$$

  - Normalisation of standard deviation using expected value
  - Enables the comparison of different stochastic variables $\mathbf{b}$

TECHNISCHE UNIVERSITÄT DRESDEN

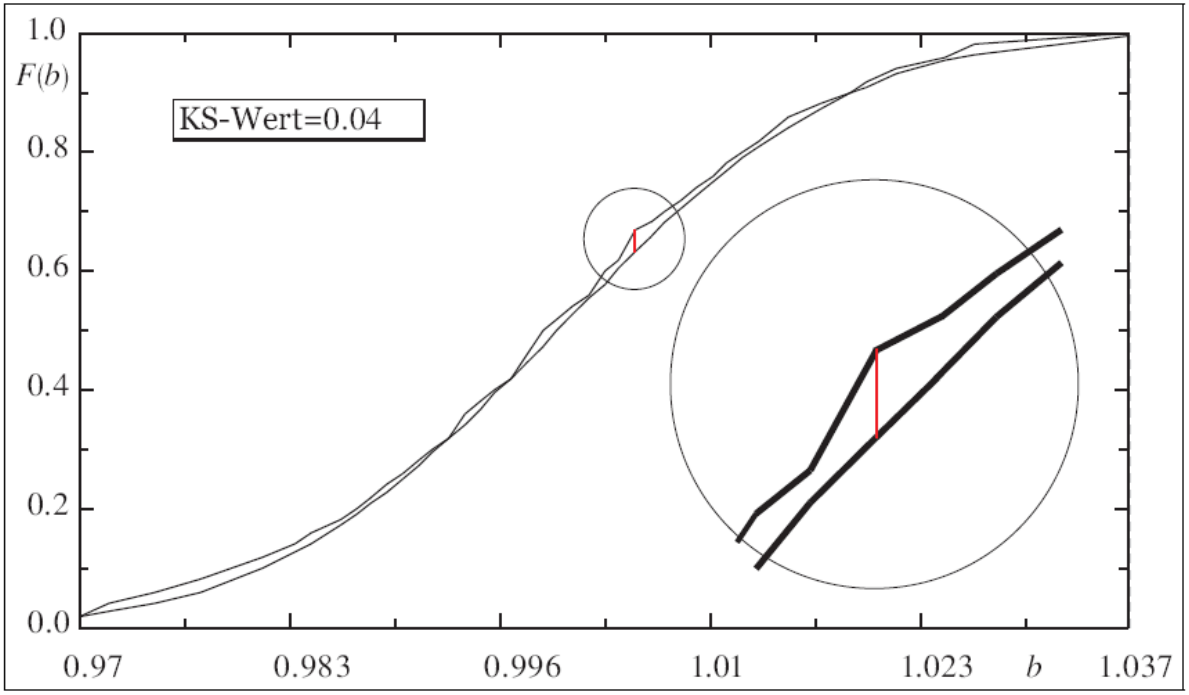
1.2.4 Goodness-of-fit test



Kolmogorow-Smirnow-Test

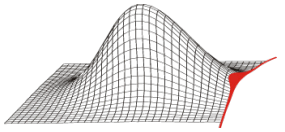
- Direct comparison of discrete density function F_d and continuous density function F_c

$$KS = \max_{-\infty<b<\infty} |F_d(b) - F_c(b)|$$



TECHNISCHE UNIVERSITÄT DRESDEN

1.2.4 Goodness-of-fit test



Kolmogorow-Smirnow-Test

- Direct comparison of discrete density function F_d and continuous density function F_c

$$KS = \max_{-\infty<b<\infty} |F_d(b) - F_c(b)|$$

Anderson-Darling-Test

- Modification of Kolmogorow-Smirnow-Test
- Stronger weighting of deviations F_d and F_c in the edge region

$$A^2 = -n_{sim} - \frac{1}{n_{sim}} \sum_k^{n_{sim}} (2k-1)\left(\ln F_s(b_k) + \ln\left[1 - F_s\left(b_{n_{sim}+1-k}\right)\right]\right.$$

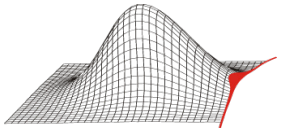
- Tables of critical values of A for different distributions are available in [3]

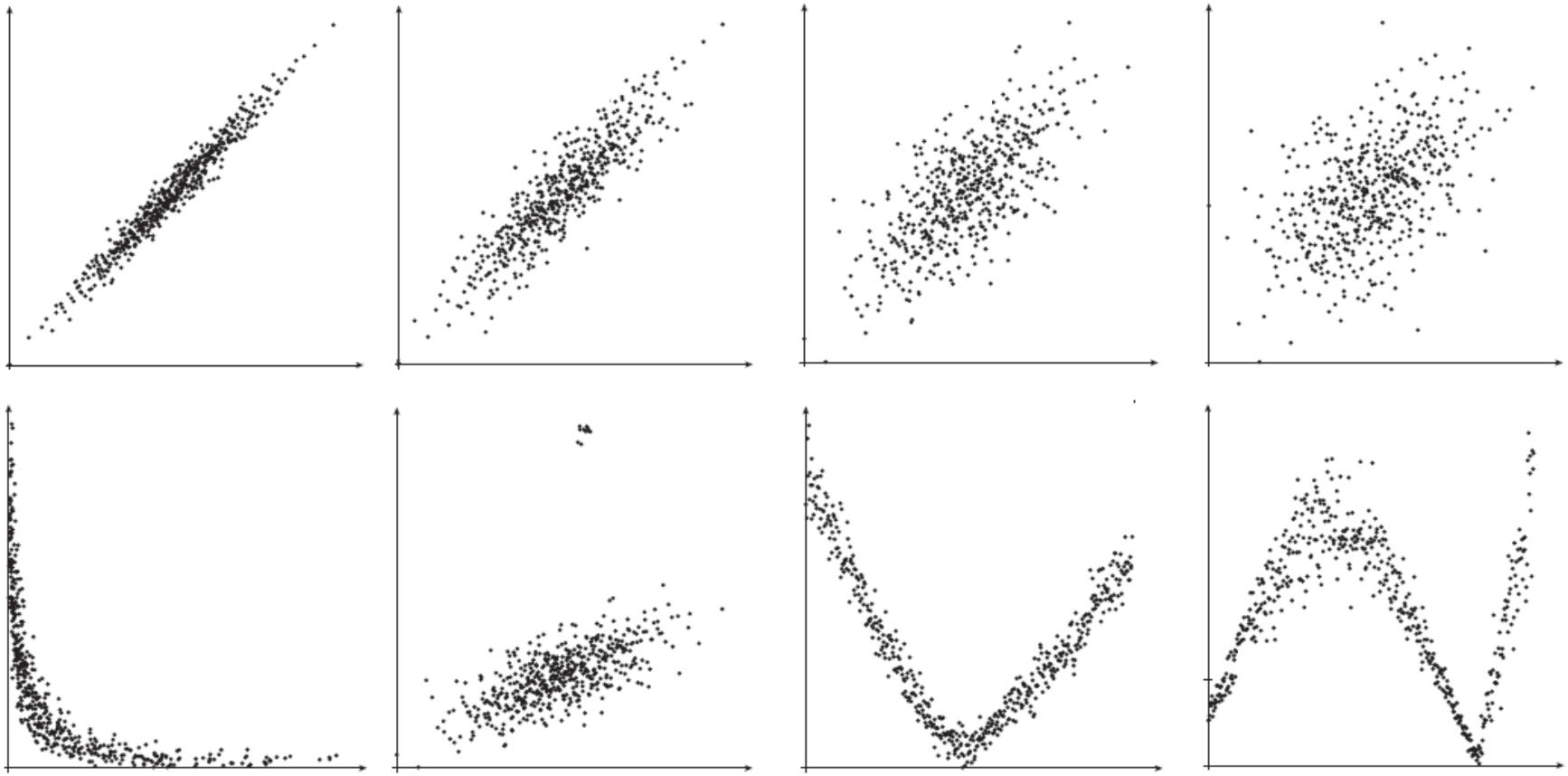
[2] Anderson, T. W., Darling, D.A., 1952, Asymptotic Theory of Certain “Goodness of Fit” Criteria Based on Stochastic Processes, Annals of Mathematical Statistics 23, Pages 193-212

[3] Stephens, M.A., 1974, EDF Statistics for Goodness of Fit and some Comparisons, Journal of the American Statistical Association, Vol. 69, Pages 730-737

TECHNISCHE UNIVERSITÄT DRESDEN

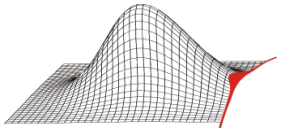
1.2.5 Correlation





TECHNISCHE UNIVERSITÄT DRESDEN

1.2.5 Correlation



Pearson's Correlation Coefficient

$$r_{b_{ri}b_{rj}} = \frac{Cov(\mathbf{b}_{ri},\mathbf{b}_{rj})}{\sqrt{Var(\mathbf{b}_{ri})}\sqrt{Var(\mathbf{b}_{rj})}}$$

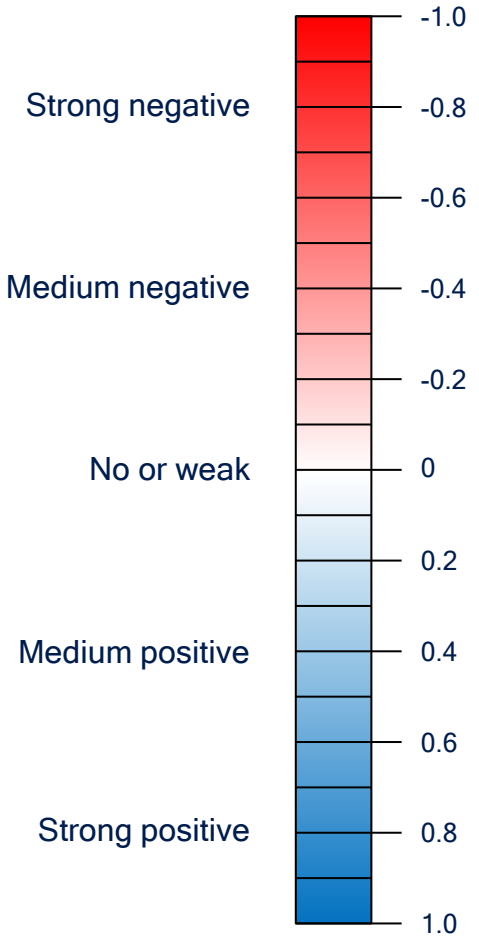
- Identification of linear relationships

Spearman's Rank Correlation Coefficient

$$\mathbf{b}_{ri} = \begin{bmatrix} b_{ri,1} \\ \vdots \\ b_{ri,n_{sim}} \end{bmatrix} \Longrightarrow \mathrm{Rank}(\mathbf{b}_{ri}) = \begin{bmatrix} R_{b_{ri,1}} = \text{Rank of } b_{ri,1} \text{ in } \mathbf{b}_{ri} \\ \vdots \\ R_{b_{ri,n_{sim}}} = \text{Rank of } b_{ri,n_{sim}} \text{ in } \mathbf{b}_{ri} \end{bmatrix}$$

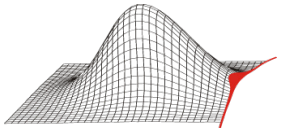
$$\tilde{r}_{b_{ri}b_{rj}} = \frac{\sum_{k=1}^{n_{sim}}(R_{b_{ri,k}} - \bar{R}_{b_{ri}})(R_{b_{rj,k}} - \bar{R}_{b_{rj}})}{\sqrt{\sum_{k=1}^{n_{sim}}(R_{b_{ri,k}} - \bar{R}_{b_{ri}})^2}\sqrt{\sum_{k=1}^{n_{sim}}(R_{b_{rj,k}} - \bar{R}_{b_{rj}})^2}}$$

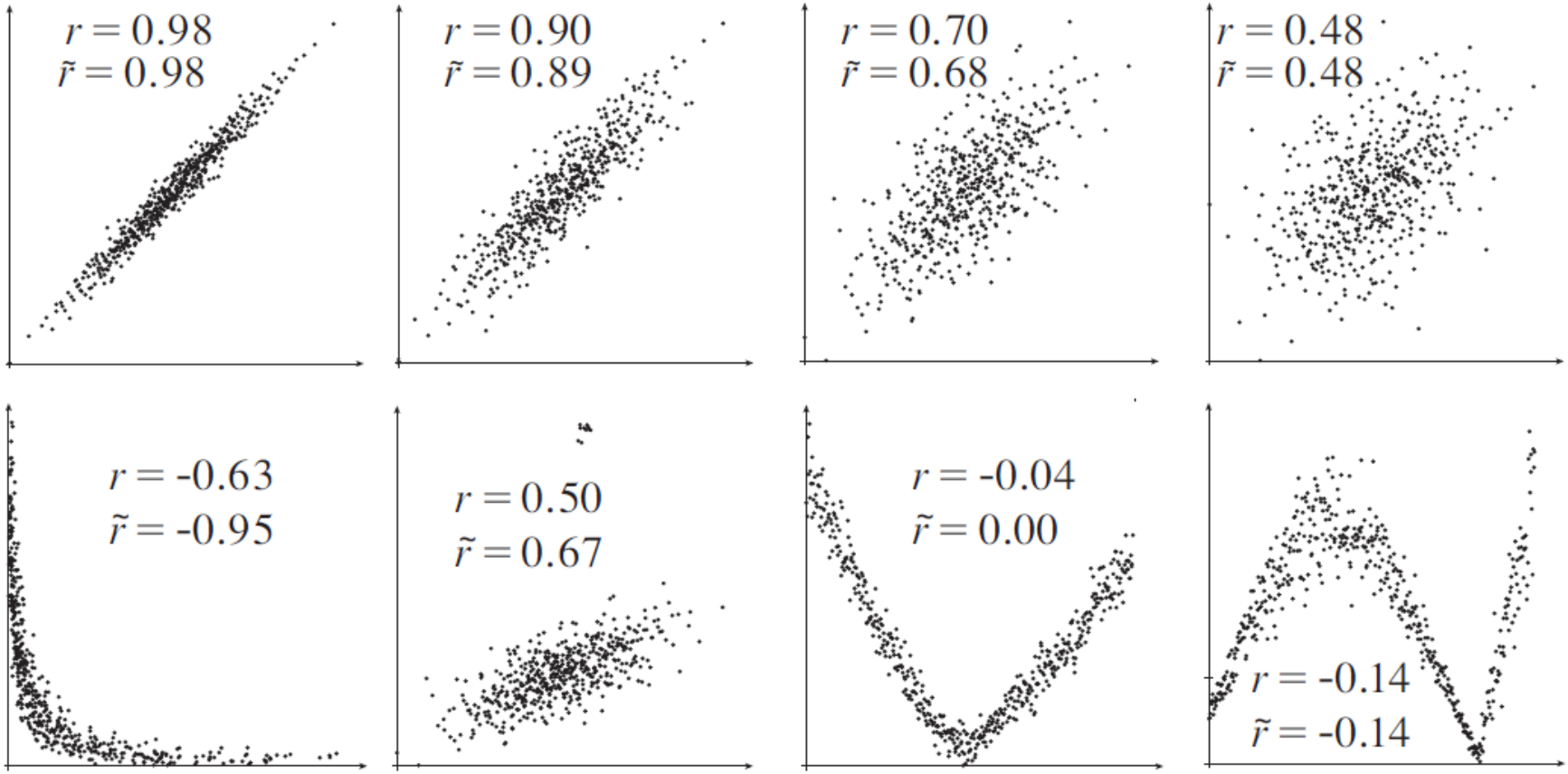
- Identification of linear or monotonic no-linear relationships



TECHNISCHE UNIVERSITÄT DRESDEN

1.2.5 Correlation



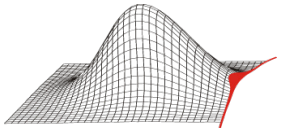


r ... Pearson's Correlation Coefficient

$\tilde{r}$ ... Spearman's Rank Correlation Coefficient

TECHNISCHE UNIVERSITÄT DRESDEN

1.2.6 Confidence interval



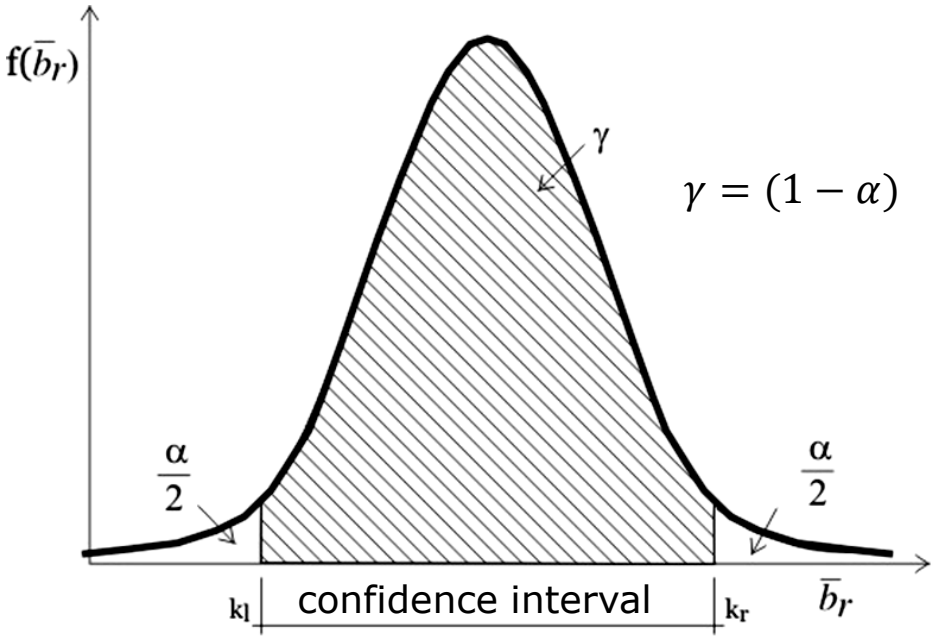
- Statistical measures (mean, standard deviation, …) are point estimations
- Confidence interval provides information about quality of estimation

γ … confidence level

α … statistical significance

$\gamma = 1 - \alpha$

$\hat{p}$ … relative frequency $\quad \hat{p} = \frac{n_f}{n_{sim}}$

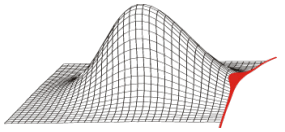


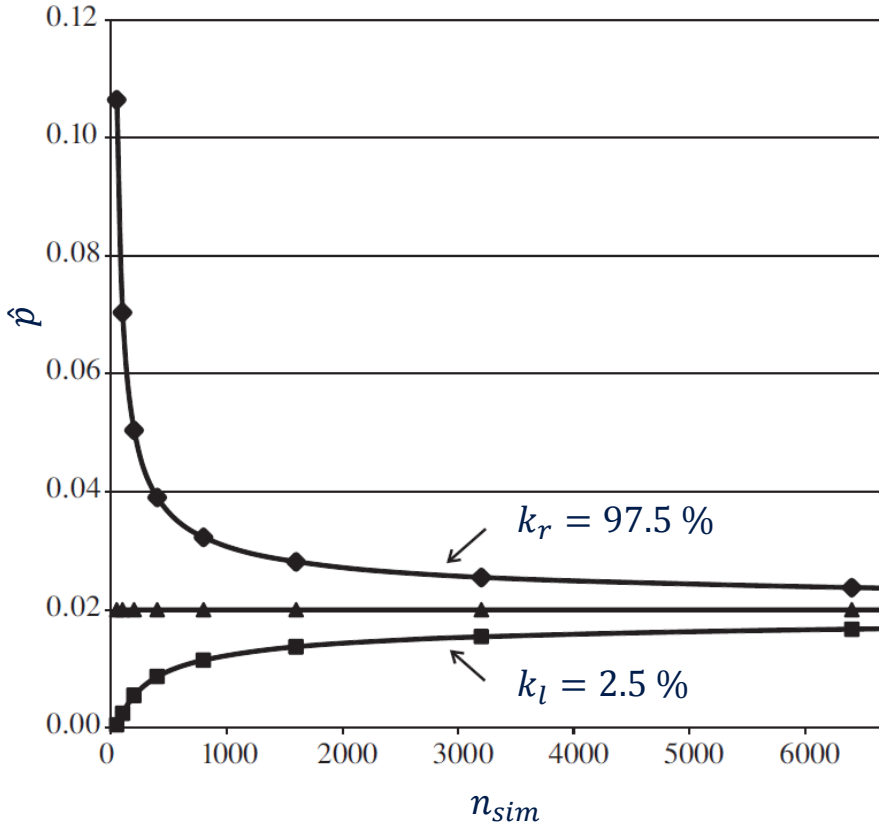
$$k_l = \frac{n_f}{n_f + (n_{sim} - n_f + 1) F_{\frac{\alpha}{2};2(n_{sim}-n_f+1);2n_f}}$$

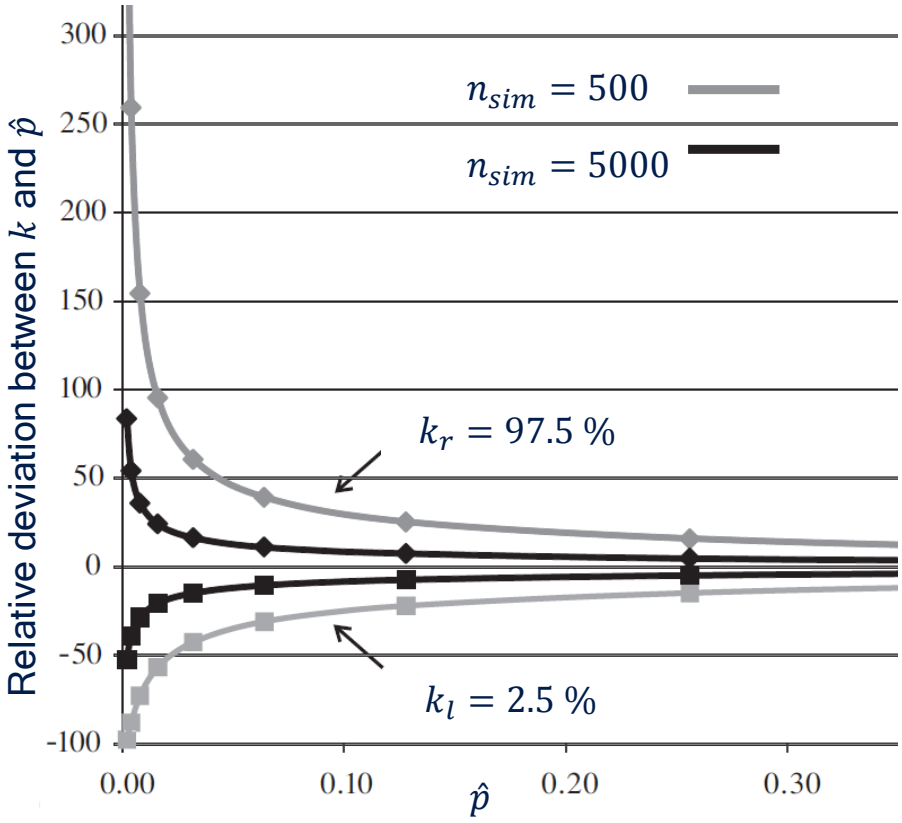
$$k_r = \frac{(n_f+1) F_{\frac{\alpha}{2};2(n_f+1);2(n_{sim}-n_f)}}{n_{sim} - n_f + (n_f+1) F_{\frac{\alpha}{2};2(n_f+1);2(n_{sim}-n_f)}}$$

TECHNISCHE UNIVERSITÄT DRESDEN

1.2.6 Confidence interval





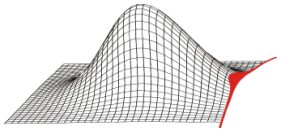


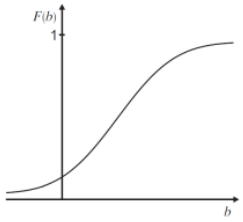
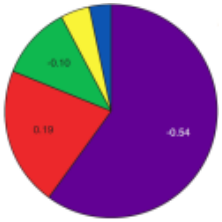
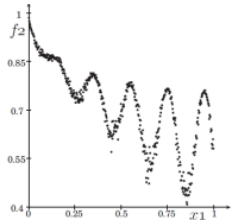
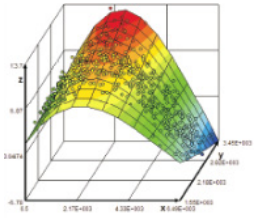
- Confidence interval depends on n_{sim}
- Increase of n_{sim} leads to improved statistical quality

- Confidence interval depends on $\hat{p}$
- Estimation of rare events are more challenging

TECHNISCHE UNIVERSITÄT DRESDEN

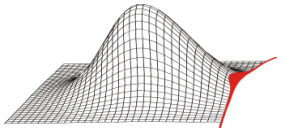
1.2.7 Exemplary results

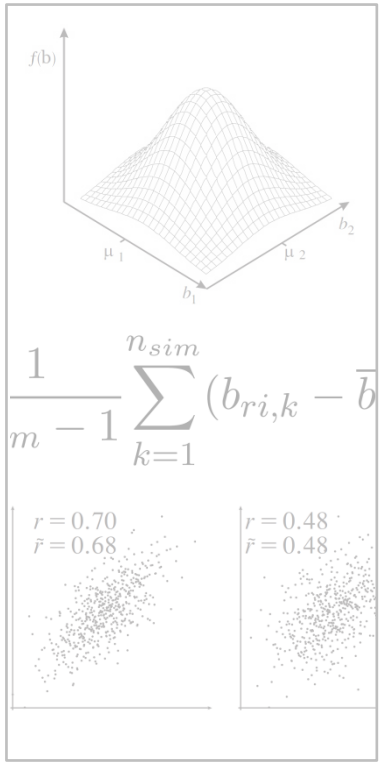


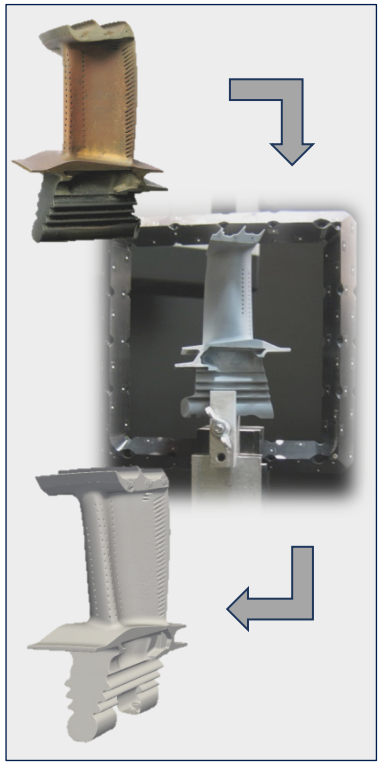
Result of probabilistic Simulation	Probability of failure	Sensitivities	Robustness	System improvement
pdf and correlation of input variables • roughly known (as in industry)				
• precisely known (rarely)				
Required number of deterministic runs	$n_{sim,LHS} \geq \frac{10}{\hat{P}_f}$ [3]	- Verification by confidence interval - Position of the mean values of the output quantities $n_{sim} \approx 50$; minimum: n_{sim} = no. inputs + 10…20		
Output • one single MC Simulation provides all result quantities				

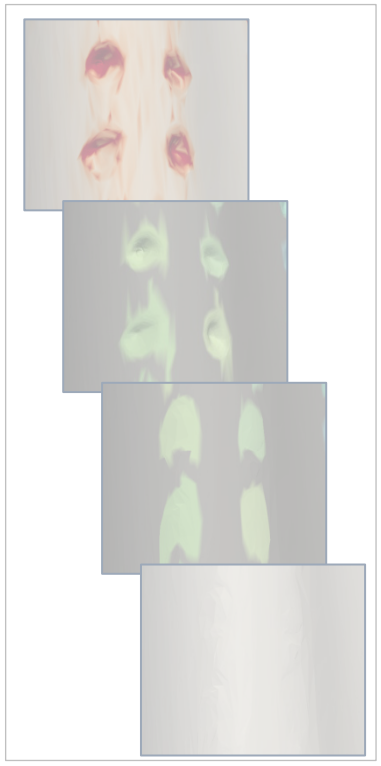
[3] Roos et al. Design Reliability Analysis. 24th CAD-FEM Users' Meeting. International Congress on FEM Technology. Stuttgart. 2006

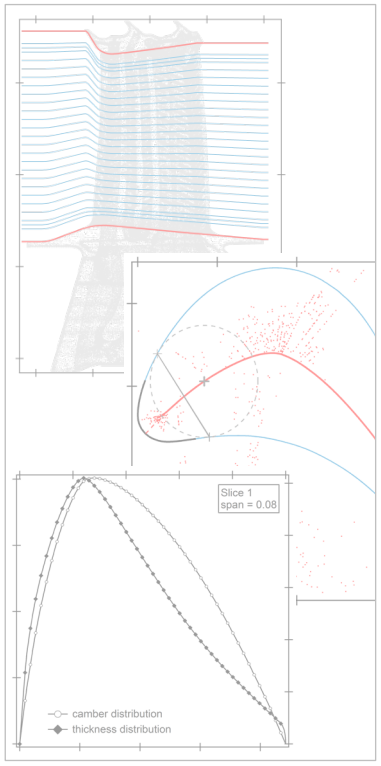
Outline

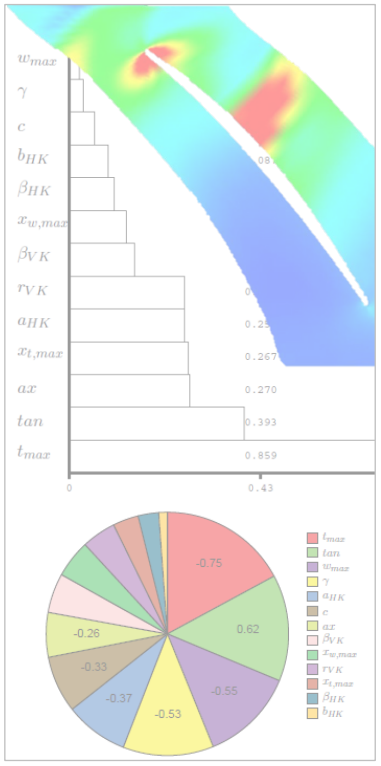






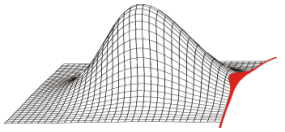






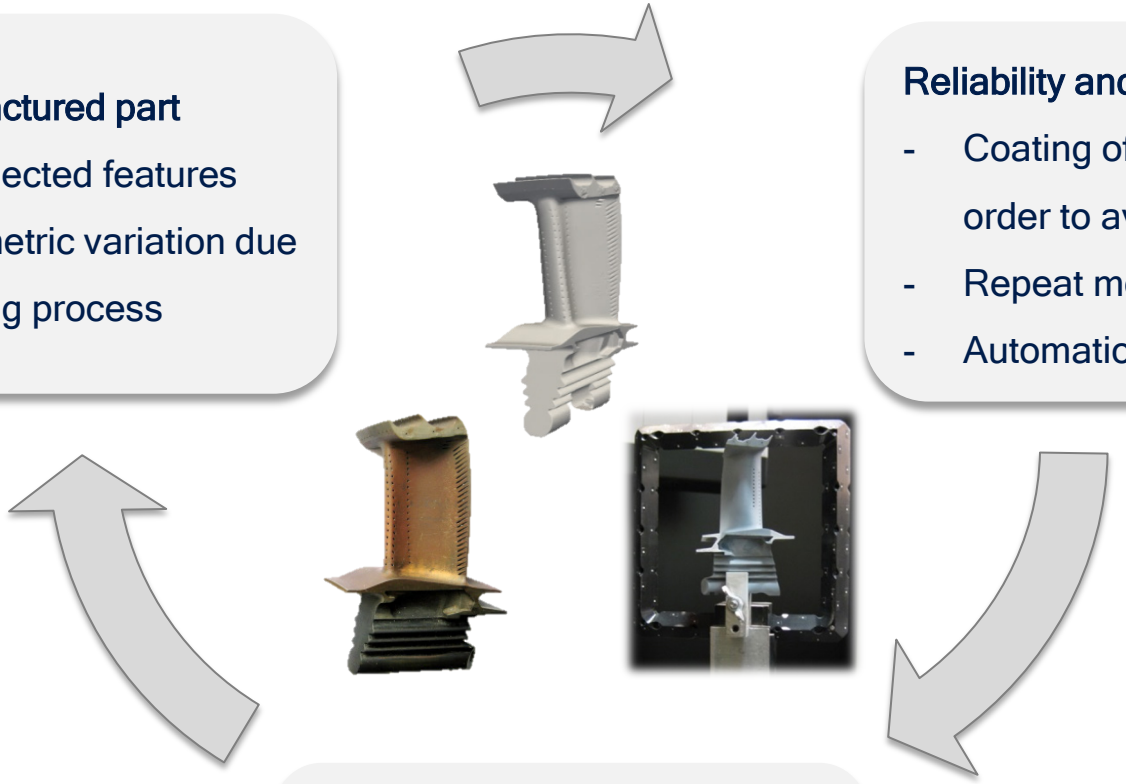
TECHNISCHE UNIVERSITÄT DRESDEN

2 Optical Measurement



Scatter of manufactured part

- Detection of selected features
- Expected geometric variation due to manufacturing process



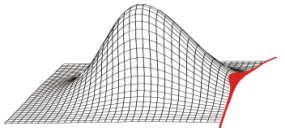
Reliability and Reproducibility

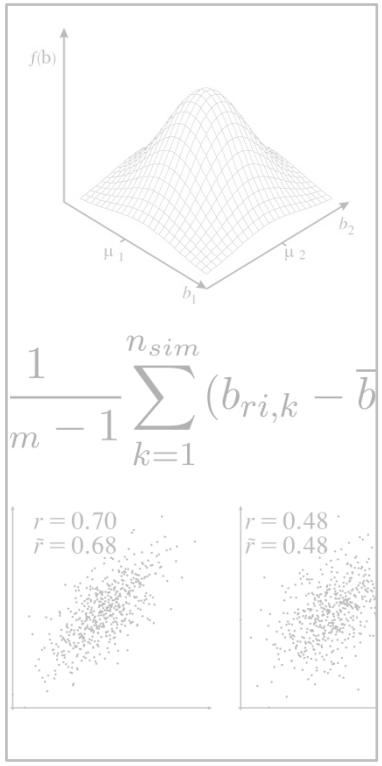
- Coating of components in order to avoid reflections
- Repeat measurements
- Automation

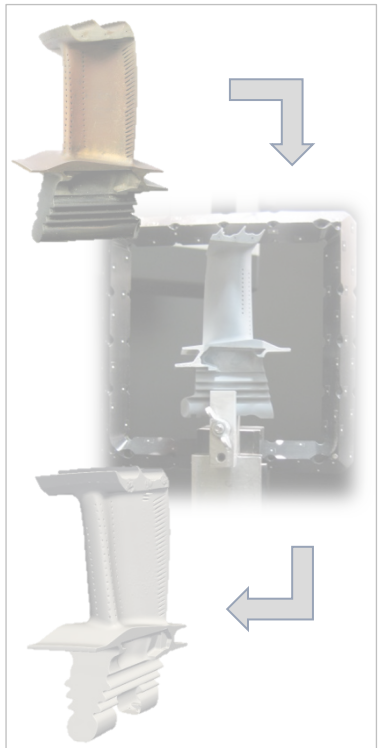
Accuracy

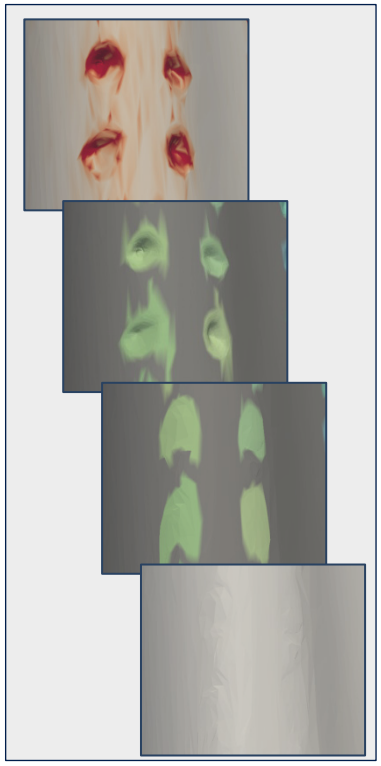
- Systematic errors (coating, geometry)
- Random error

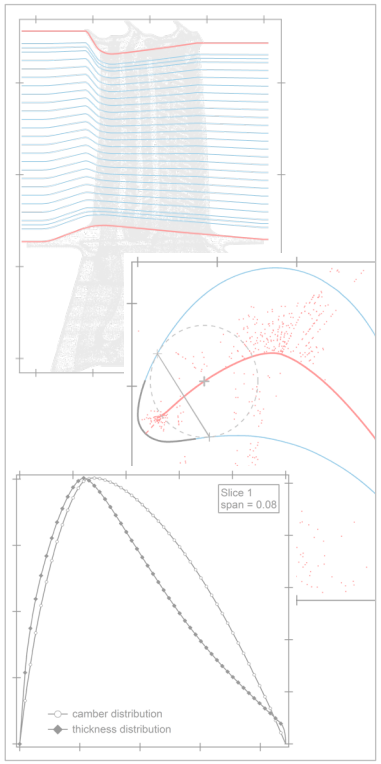
Outline

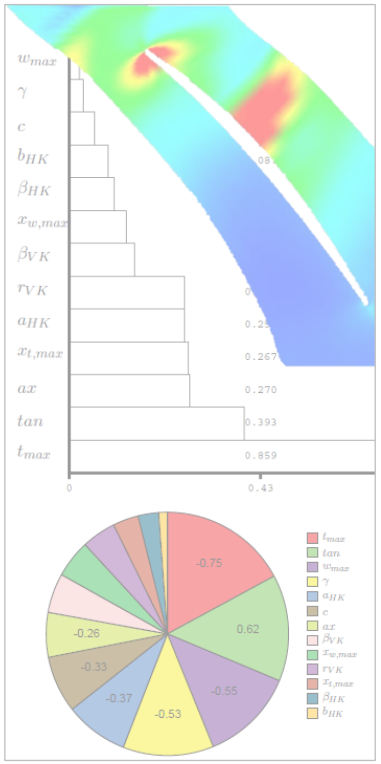






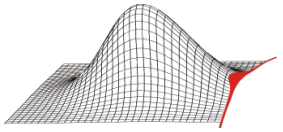


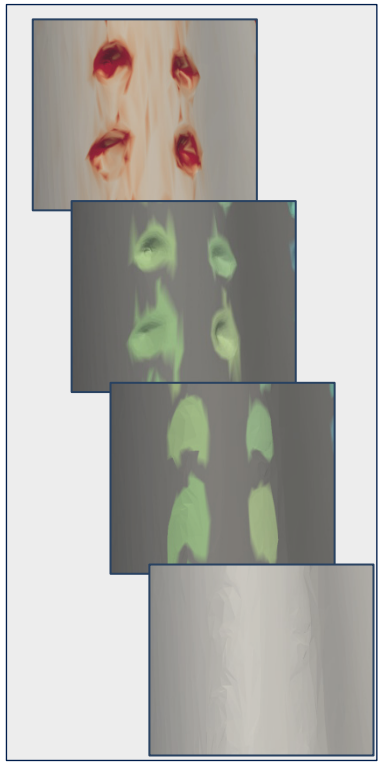




TECHNISCHE UNIVERSITÄT DRESDEN

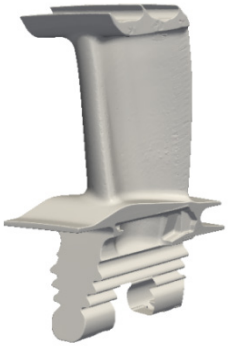
3 Mesh Pre-Processing

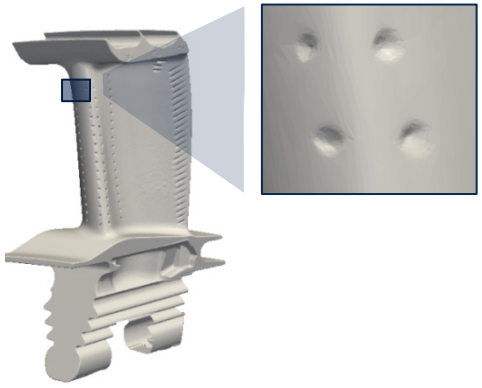




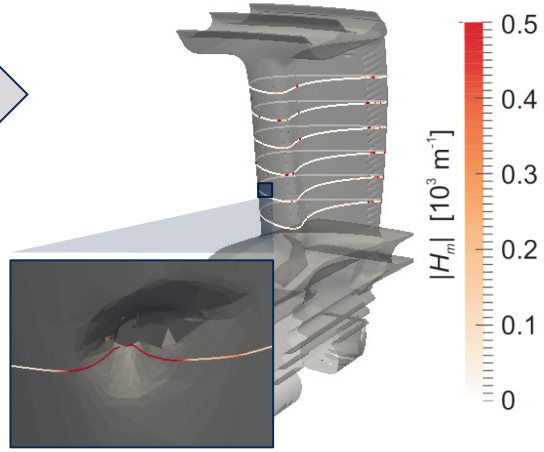
Profile parameterisation

Polygon mesh

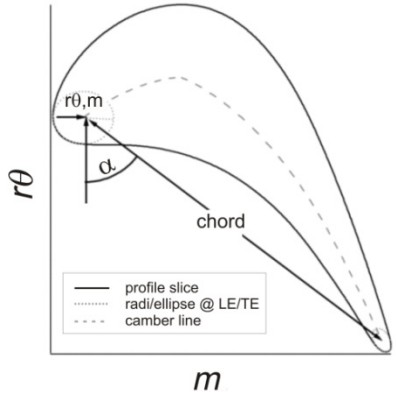


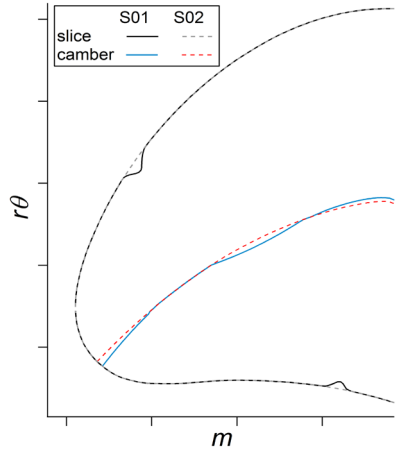


Slice extraction



Parameterisation

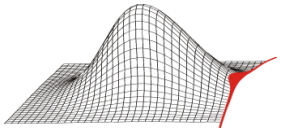


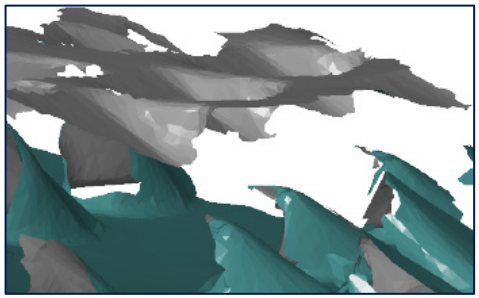


[1] Lange et al. 2009
[2] Scharfenstein et al. 2013

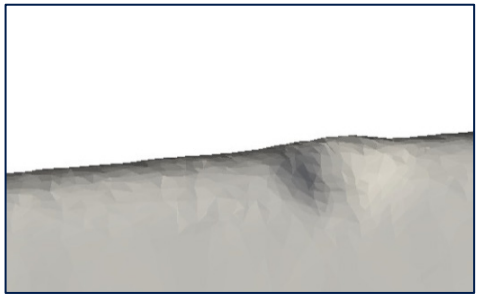
TECHNISCHE UNIVERSITÄT DRESDEN

3.1 Motivation & Aim

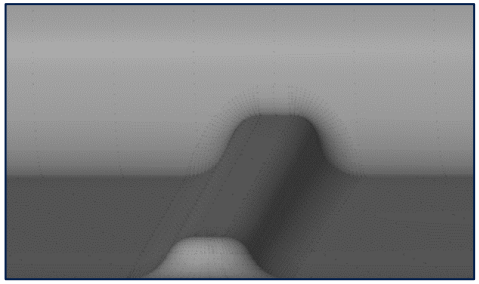




Measurement artefacts
(holes, detached mesh snippets, regions of bad resolution, etc.)



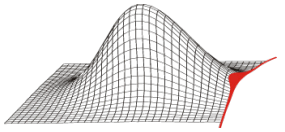
Physical blade modifications and damages
(dents, humps, cracks, etc.)

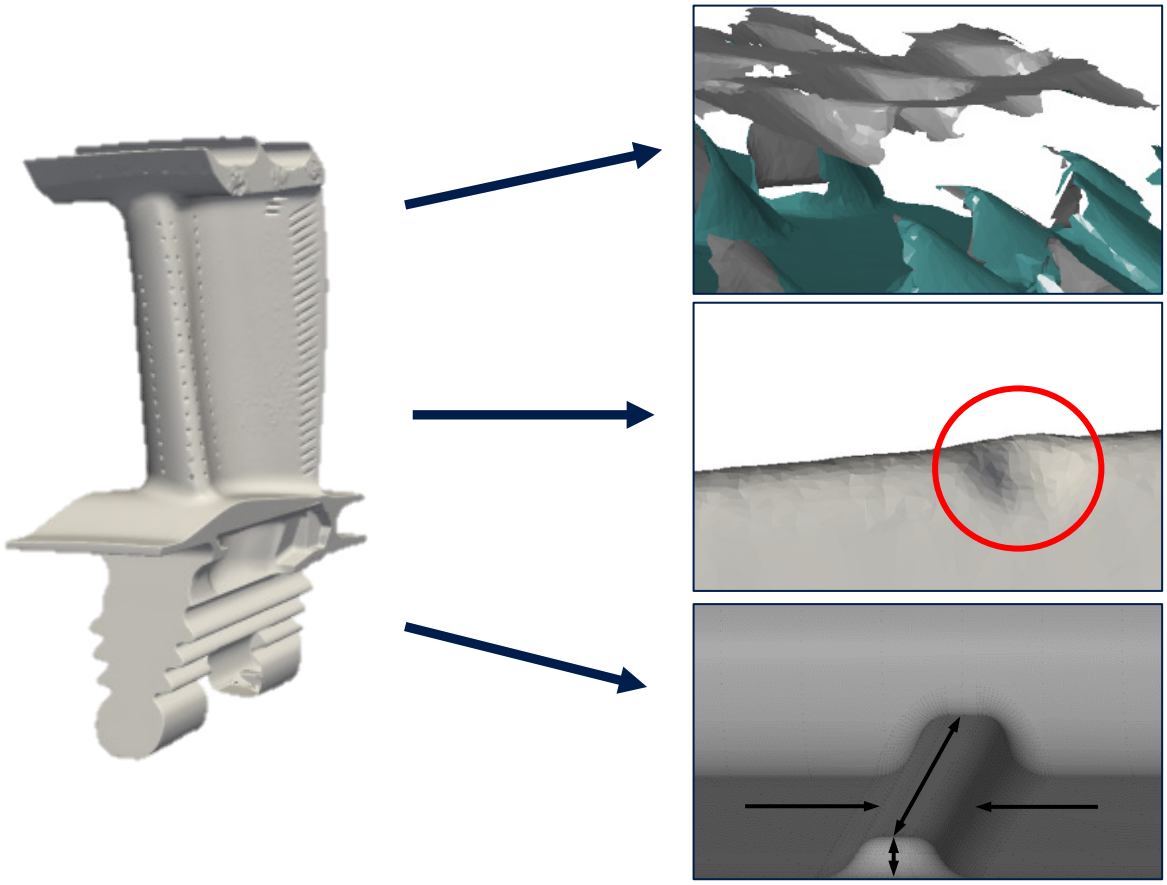


Small blade features
(turbulators, cooling holes, etc.)

TECHNISCHE UNIVERSITÄT DRESDEN

3.1 Motivation & Aim





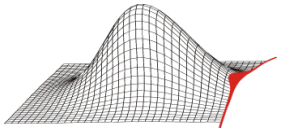
Clean the mesh from measurement artefacts

Capture information for maintenance & overhaul

Enable robust profile parameterisation

TECHNISCHE UNIVERSITÄT DRESDEN

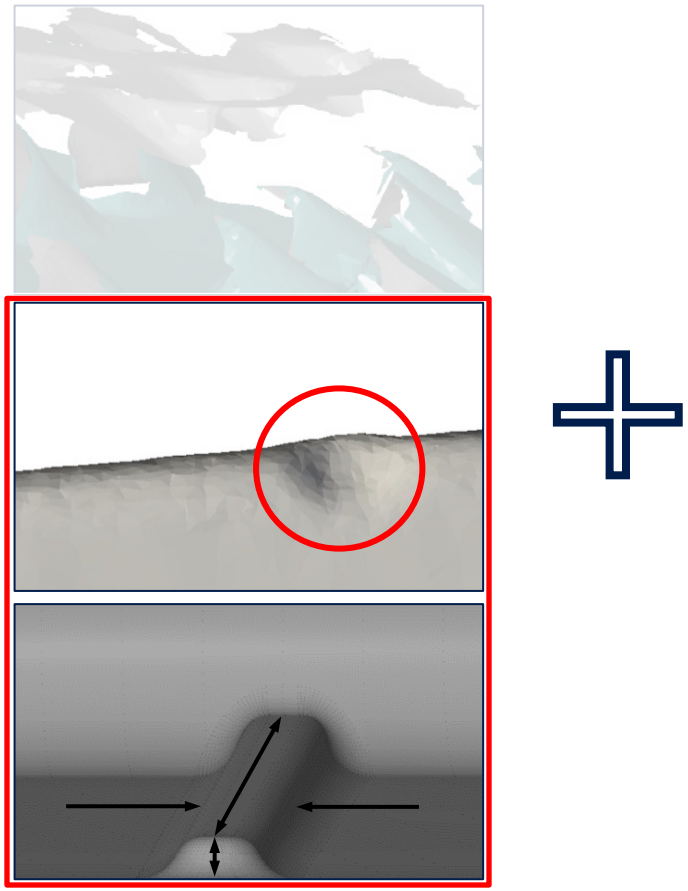
3.1 Motivation & Aim

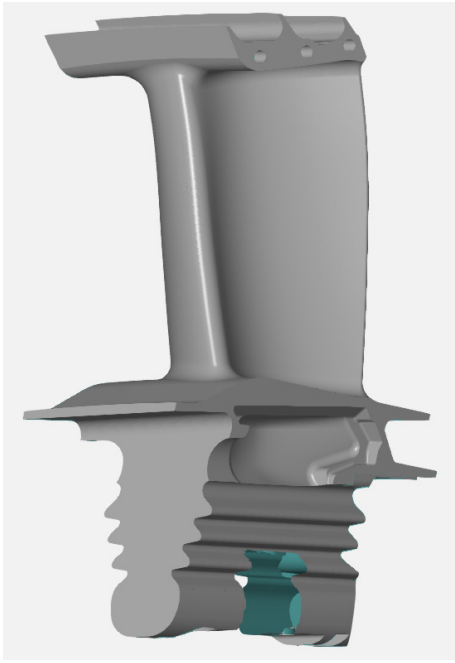


„Featured“ mesh

Information of features

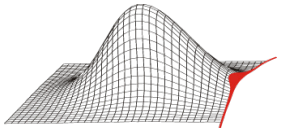
„Cleaned“ mesh

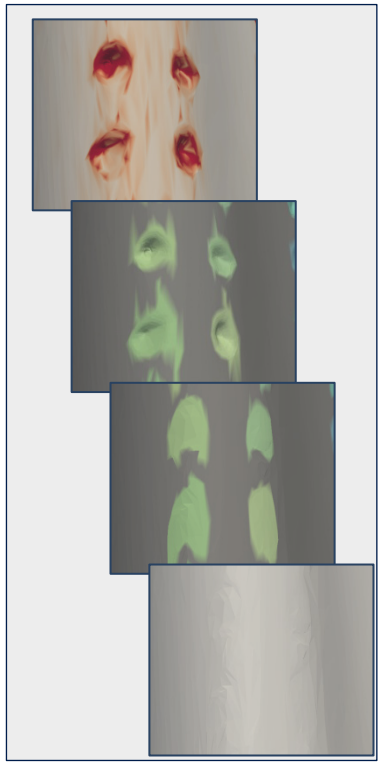




TECHNISCHE UNIVERSITÄT DRESDEN

3 Mesh Pre-Processing

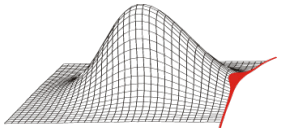




TECHNISCHE UNIVERSITÄT DRESDEN

3.2 Feature Detection

3.2.1 Underlying Method



Main principle: curvature investigation

Mean curvature

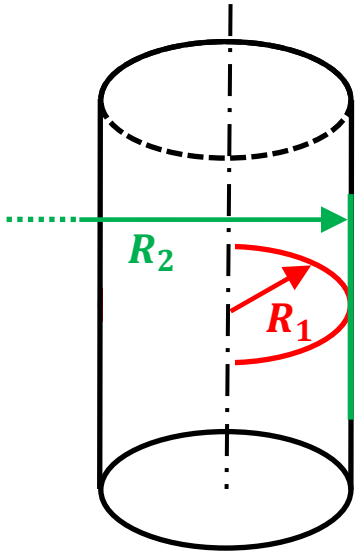
$$H = \frac{1}{2}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

≠ 0 for parabolic points (cylinder)

Gauß curvature

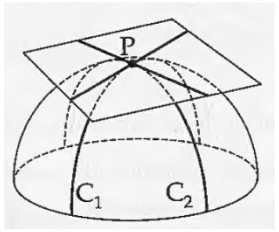
$$K = \frac{1}{R_1 R_2}$$

= 0 for cylinders etc.



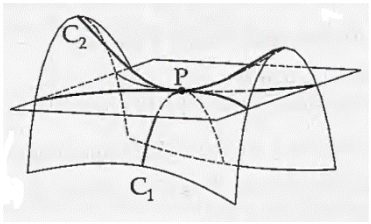
≈ *Leading edge*

Dents etc.



elliptic:

$K > 0$



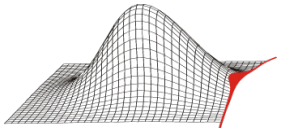
hyperbolic:

$K < 0$

TECHNISCHE UNIVERSITÄT DRESDEN

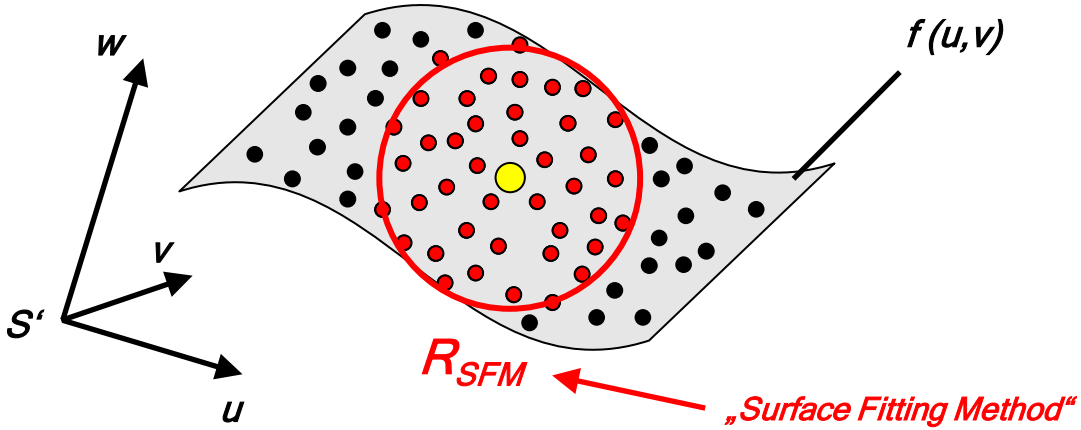
3.2 Feature Detection

3.2.2 Procedure of Detection



For each point ● of the mesh:

regression surface → analytical surface function *f (u,v)* in system *S'*



Connection between surface function & curvature:

$$K[f(u,v)] = \frac{\frac{\partial^2 f}{\partial u^2}\frac{\partial^2 f}{\partial v^2} - \left[\frac{\partial^2 f}{\partial u \partial v}\right]^2}{\left(1+\left[\frac{\partial f}{\partial u}\right]^2+\left[\frac{\partial f}{\partial v}\right]^2\right)^2}$$

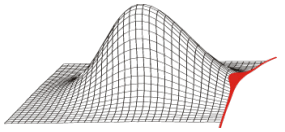
$$H[f(u,v)] = \frac{\frac{\partial^2 f}{\partial u^2}\left(1+\left[\frac{\partial f}{\partial v}\right]^2\right) - 2\frac{\partial f}{\partial u}\frac{\partial f}{\partial v}\frac{\partial^2 f}{\partial u \partial v} + \frac{\partial^2 f}{\partial v^2}\left(1+\left[\frac{\partial f}{\partial u}\right]^2\right)}{2\left(1+\left[\frac{\partial f}{\partial u}\right]^2+\left[\frac{\partial f}{\partial v}\right]^2\right)^{3/2}}$$

Entire mesh gets curvature distribution

TECHNISCHE UNIVERSITÄT DRESDEN

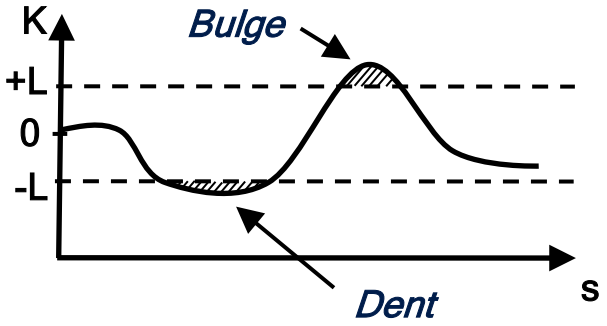
3.2 Feature Detection

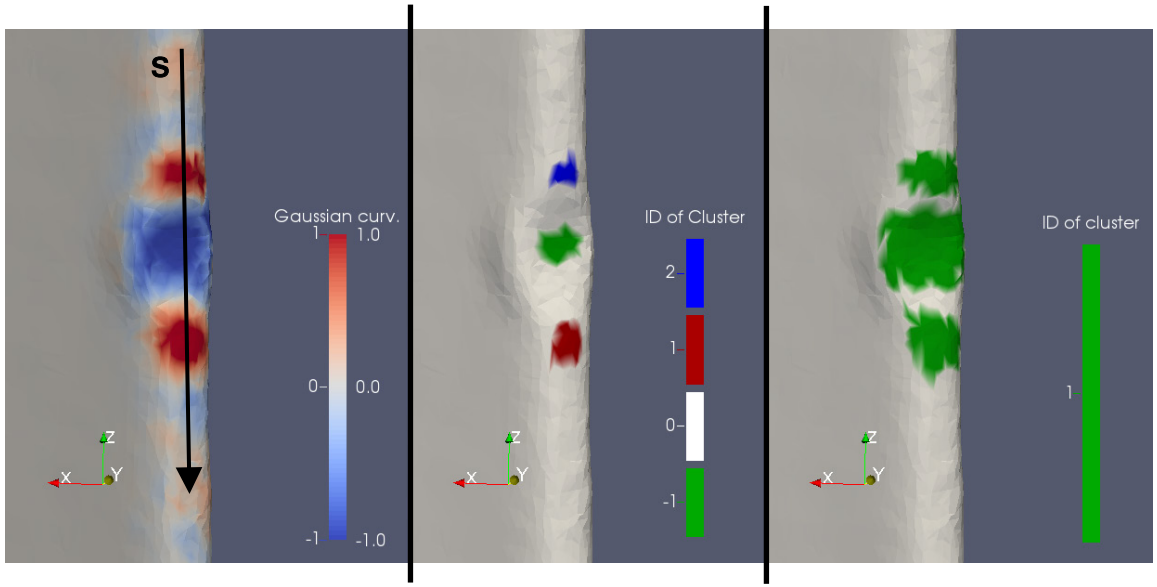
3.2.2 Procedure of Detection



- Discretise analytical (smooth) distribution
- Seperate actual feature from adjacent regions

→ ‚clustering‘



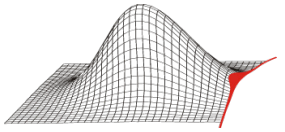


Analytical distribution ⇨ **Clustered** ⇨ **Extented**

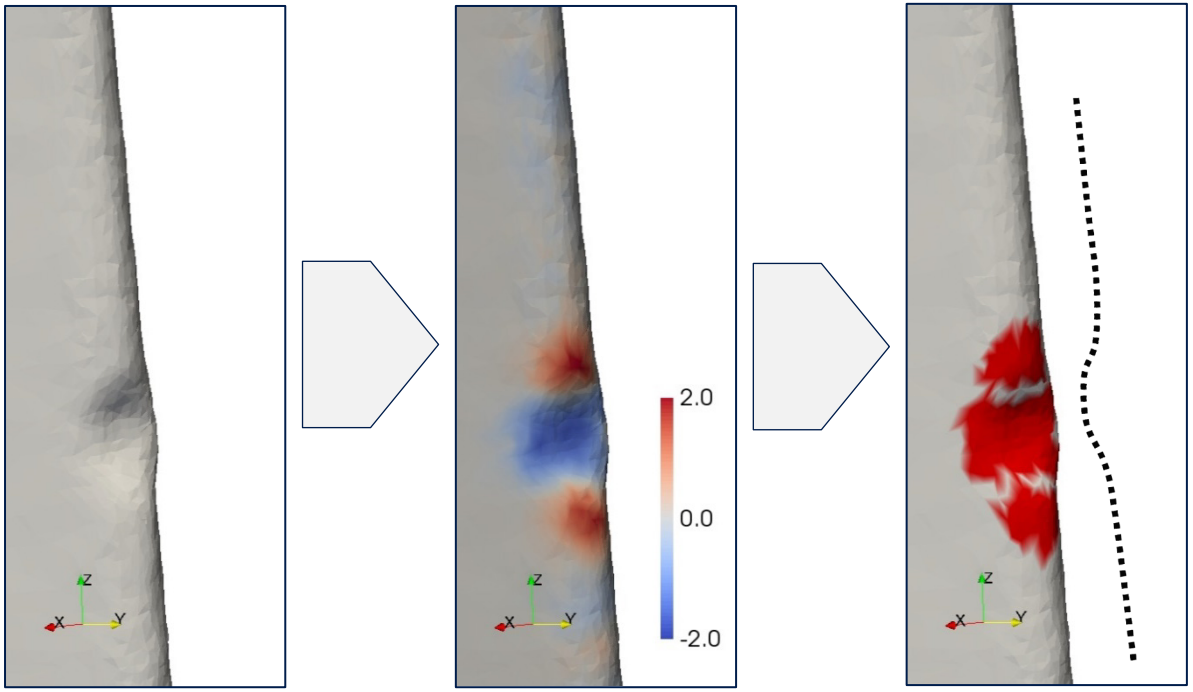
TECHNISCHE UNIVERSITÄT DRESDEN

3.2 Feature Detection

3.2.3 Capability of Algorithm



Different possible features detectable by curvature distribution: dents, cooling holes, etc.



Leading edge fan blade | Gaussian curvature distribution | Identification of impact

Sensitivity of algorithm adjustable:

- limit value of curvature for clustering
- radius for surface regression

Application example:

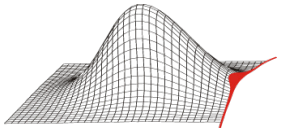
in combination with a dent depth computation algorithm

→ automatic assessment of blades regarding FODs

TECHNISCHE UNIVERSITÄT DRESDEN

3.2 Feature Detection

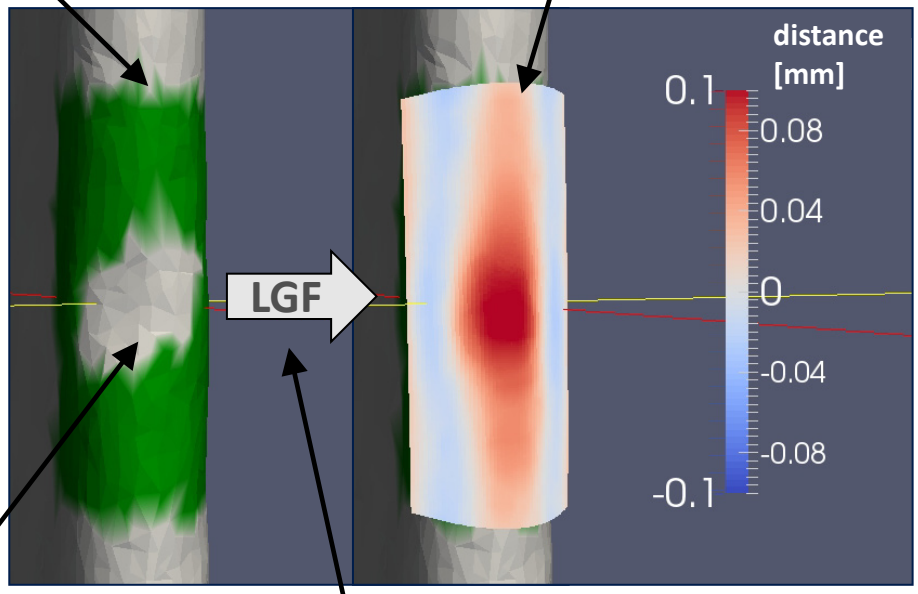
3.2.4 Idea of Application



- Application for maintenance purposes
- Here: measuring the impact depth of a leading edge dent

Area „around“ dent

„Second“ skin: surface, that is as close to the undamaged geometry as possible

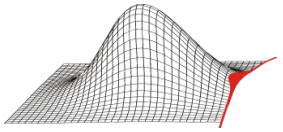


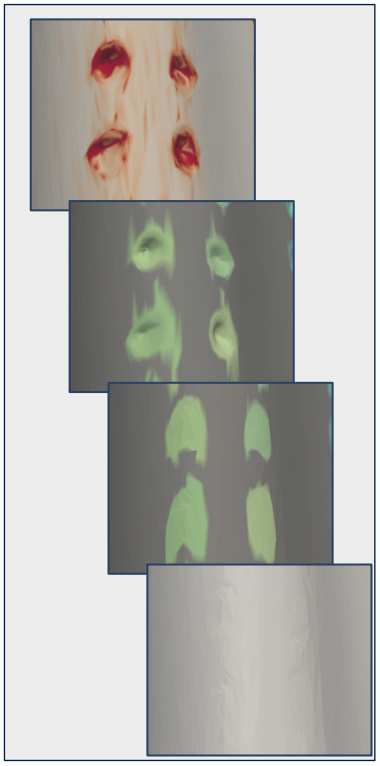
Region of „high“ curvature

LGF: „local geometry fit“

TECHNISCHE UNIVERSITÄT DRESDEN

3 Mesh Pre-Processing

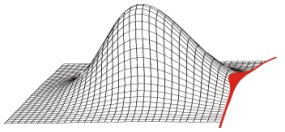




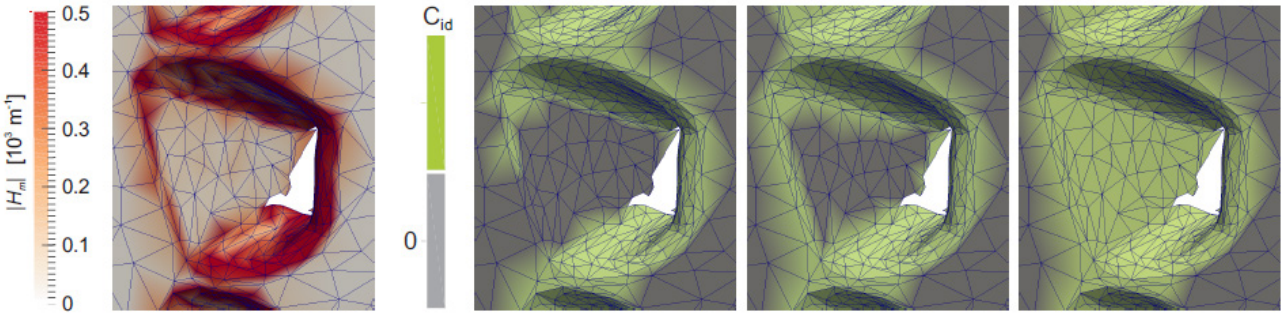
TECHNISCHE UNIVERSITÄT DRESDEN

3.4 Cleaning of the Mesh

3.4.1 Removal of Detected Features

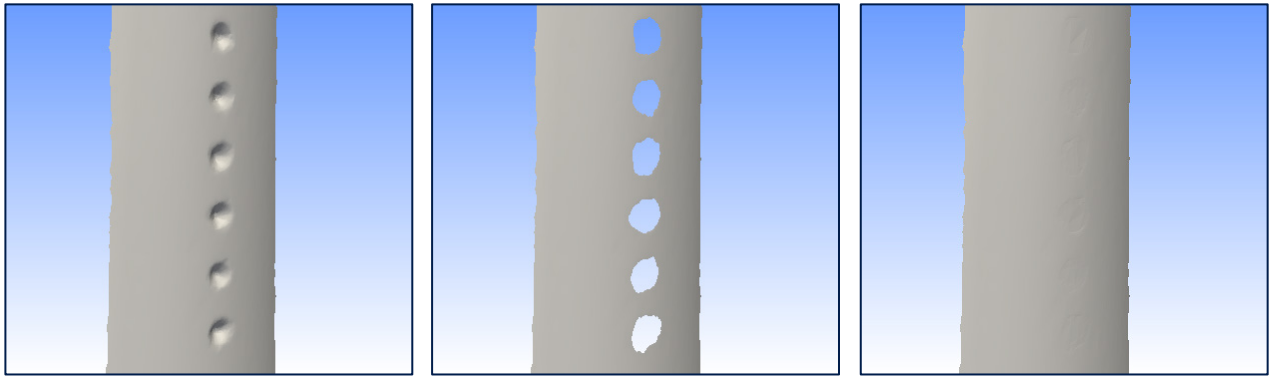


Preparation



Curvature distribution | *Initial cluster* | *Extented cluster* | *Filled cluster*

Removal & closing

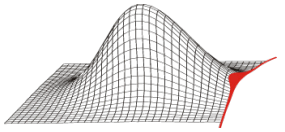


Original data | *Removed clusters* | *Closed holes*

TECHNISCHE UNIVERSITÄT DRESDEN

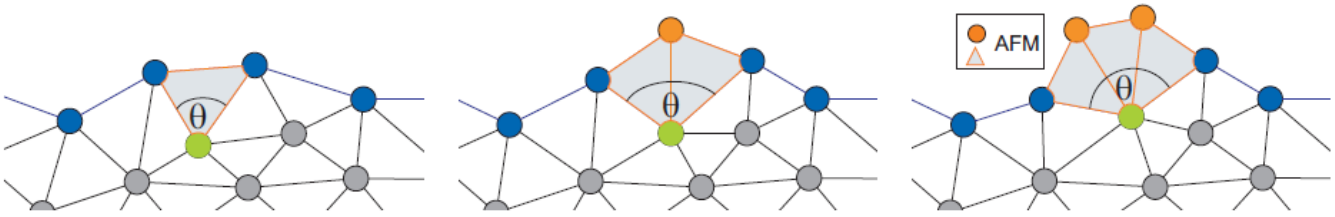
3.4 Removal of Detected Features

3.4.1 Closing of the Mesh Holes



- When detected, deletion of features/ artefacts relatively simple
- Closing of holes is significant step
- 2 algorithms implemented:
  - Advancing Front Meshing (AFM):
    - Pros: simple, quick, robust
    - Cons: does not consider curved surfaces

→ further smoothing step necessary

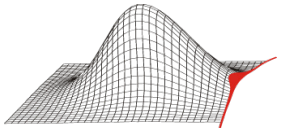


(a) $\theta \leq 75°$ (b) $75° < \theta \leq 135°$ (c) $\theta > 135°$

TECHNISCHE UNIVERSITÄT DRESDEN

3.4 Removal of Detected Features

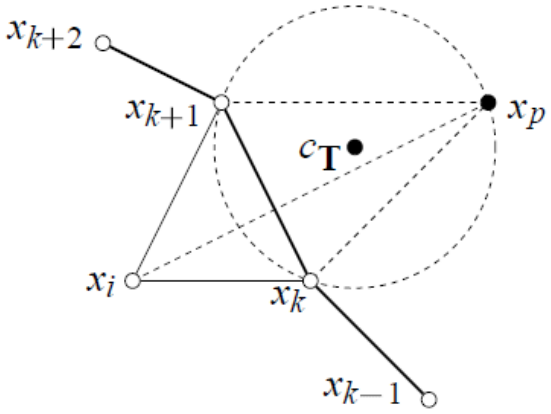
3.4.1 Closing of the Mesh Holes

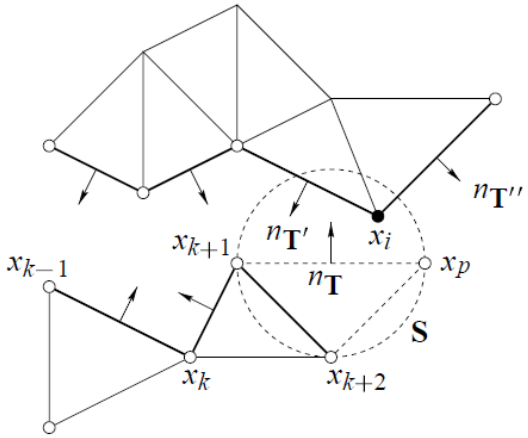


- Marching Triangles (MT):
  - high sophisticated algorithm for many advanced geometry applications
  - Pros: follows the curved nominal geometry; resulting triangle sizes can be adapted automatically; equally distributed nodes
  - Cons: quite complex implementations; slower than simple algorithms like AFM

Base principle:

check of Delaunay constraint for new triangle



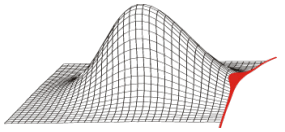


S. Akkouche et al.: Adaptive Implicit Polygonization using Marching Triangles. Comput. Graph. Forum 20(2) (2001)

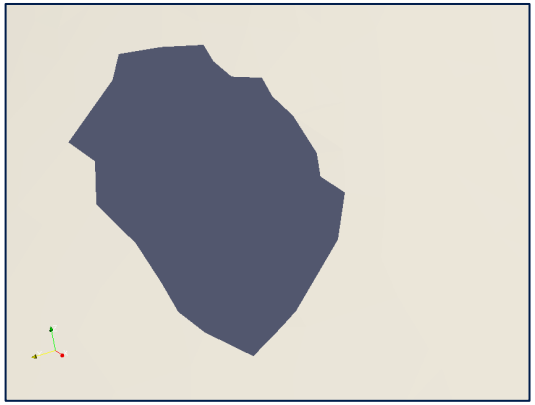
TECHNISCHE UNIVERSITÄT DRESDEN

3.4 Removal of Detected Features

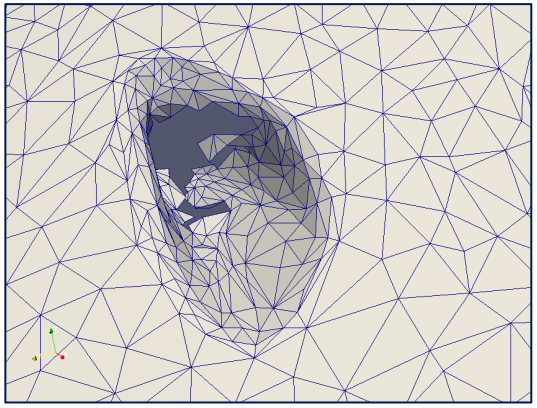
3.4.1 Closing of the Mesh Holes

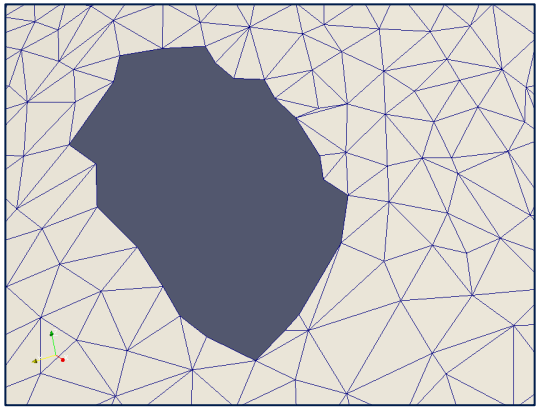


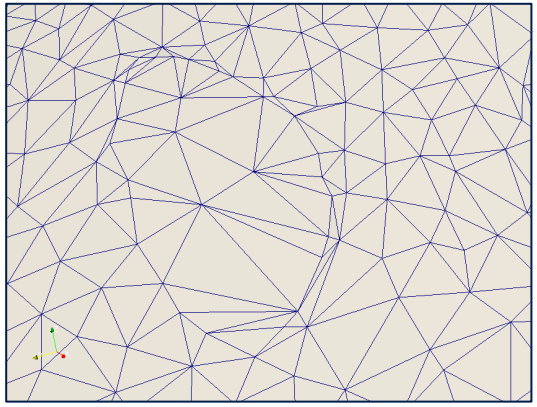
Mesh surface



Mesh grid



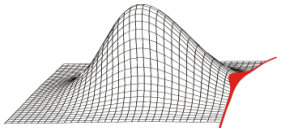


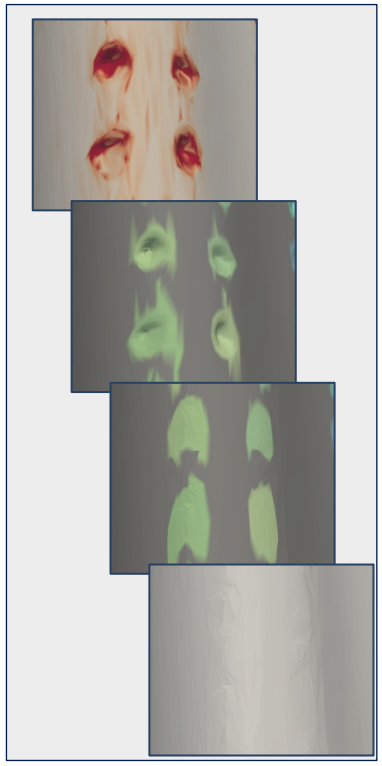


Feature (cooling hole) | Deleteded feature | Closed mesh hole

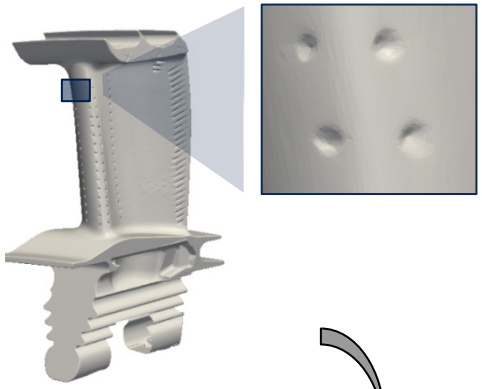
TECHNISCHE UNIVERSITÄT DRESDEN

3 Mesh Pre-Processing

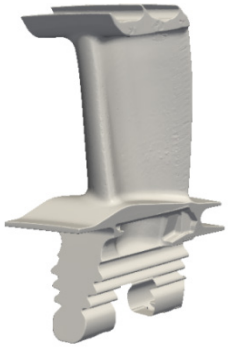




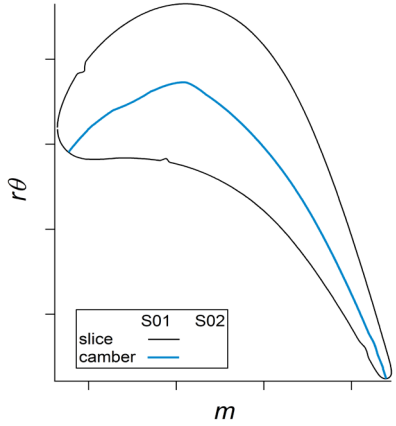
Mesh with artefacts

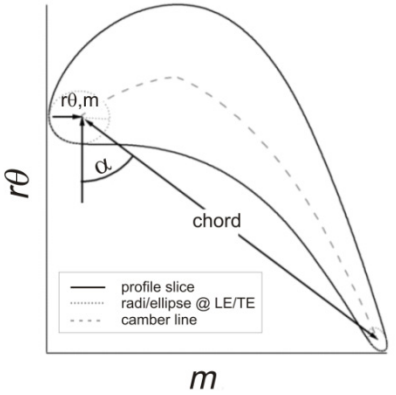


Cleaned mesh



Parameterisation errorneous

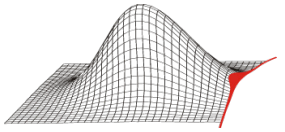


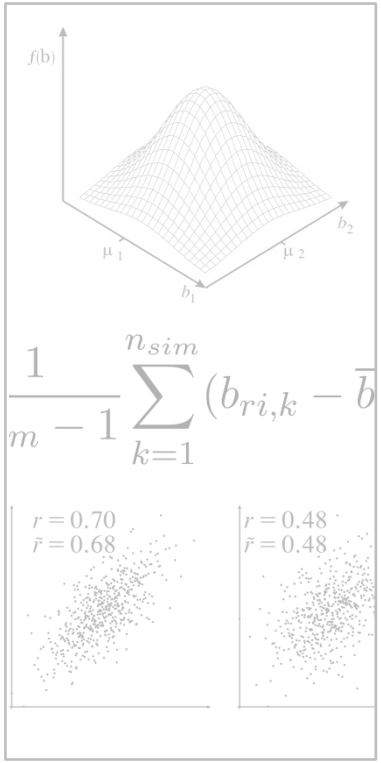


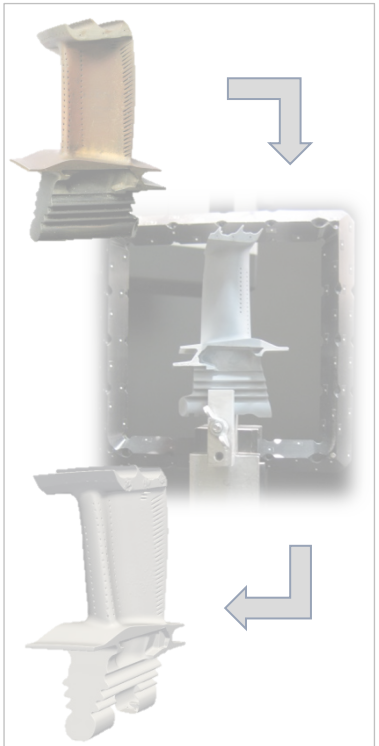
[1] Lange et al. 2009
[2] Scharfenstein et al. 2013

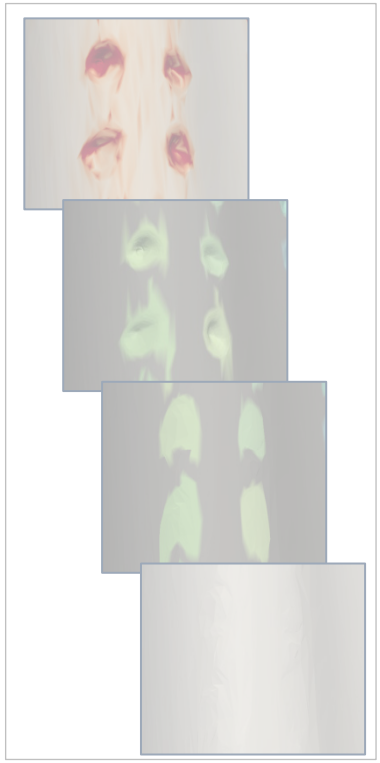
Correct parameterisation possible

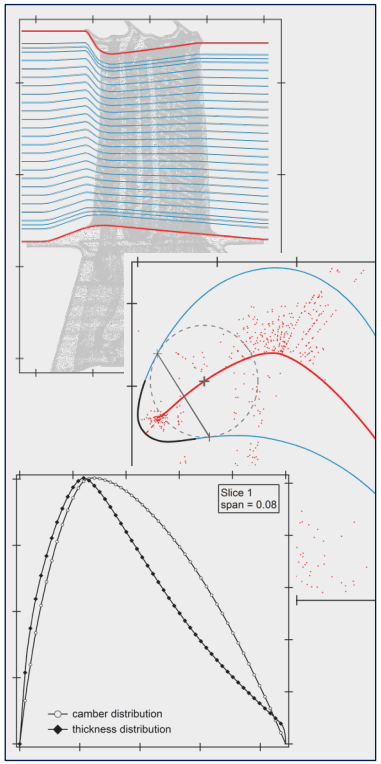
Outline

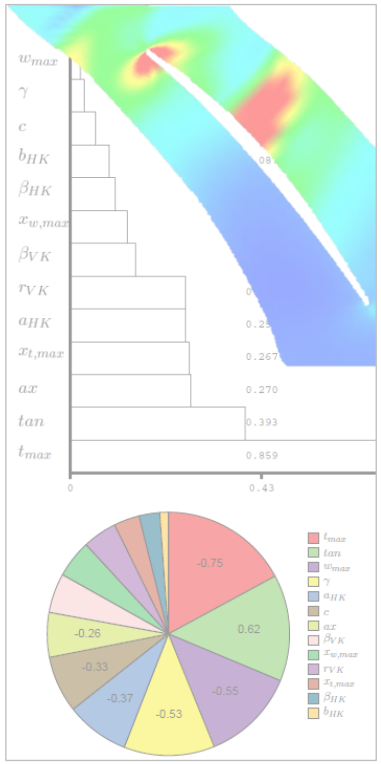






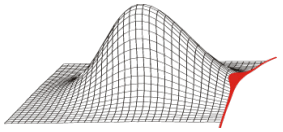


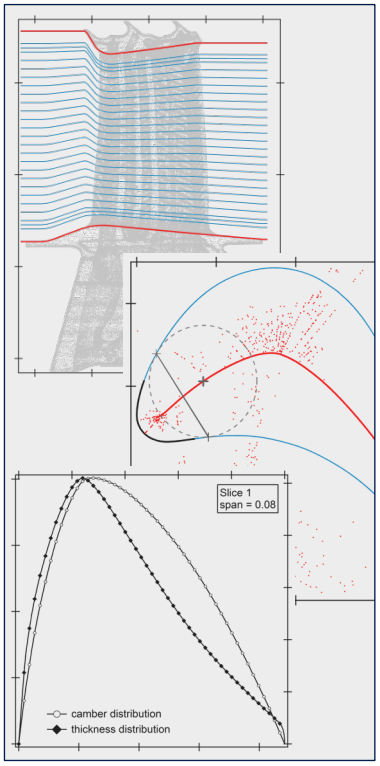




TECHNISCHE UNIVERSITÄT DRESDEN

4 Parameterisation and Rebuild





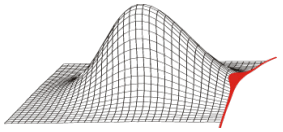
4.1 Parameterisation

4.2 Parameter based Rebuild

4.3 One to One Rebuild

TECHNISCHE UNIVERSITÄT DRESDEN

4 Parameterisation and Rebuild



Cleaned Aerofoil Mesh

Parameterisation of the aerofoil

Statistical survey of the varying aerofoil parameter

Probabilistic simulation through the probability distributions and the corresponding correlations of the varying aerofoil parameter

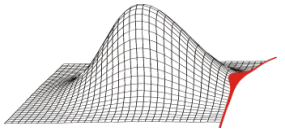
Rebuild of a probabilistic generated aerofoil geometry within a parameter based 3D blade model

Rebuild of the aerofoil mesh geometry within a 3D blade model

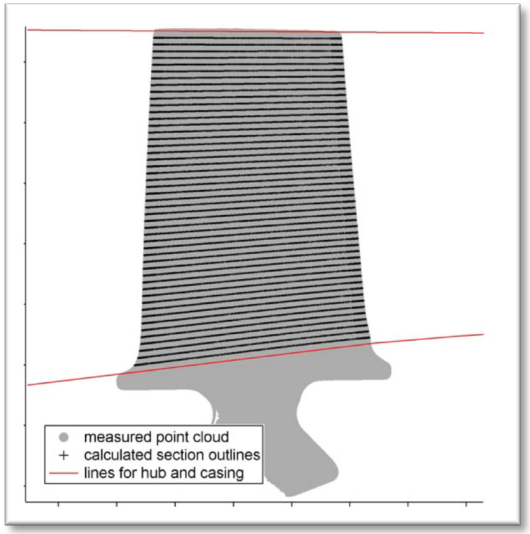
Application (FEM,CFD,...)

TECHNISCHE UNIVERSITÄT DRESDEN

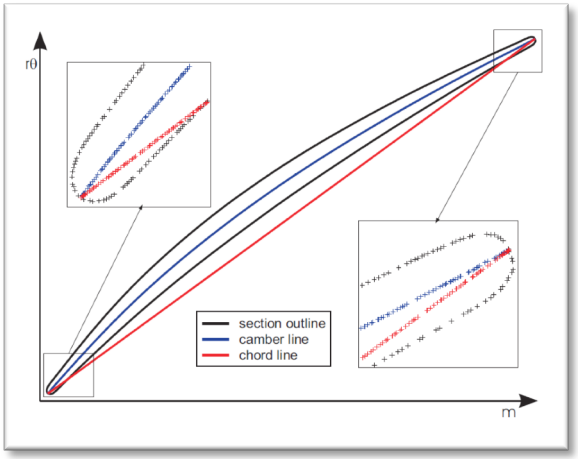
4.1 Parameterisation

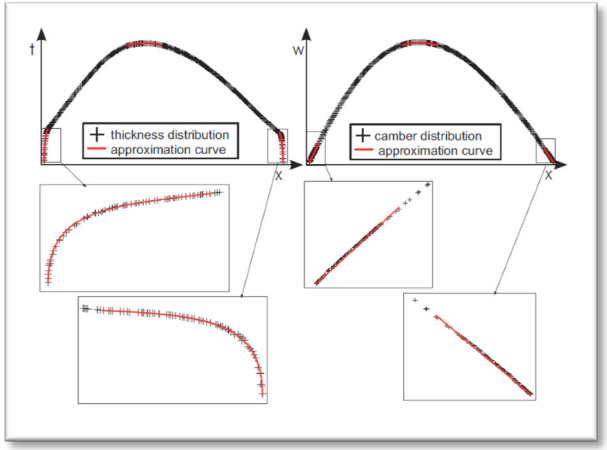


A) cut aerofoil into sections



B) extraction of the profile geometry and skeleton line calculation



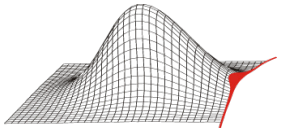


C) evaluation of all aerofoil parameter

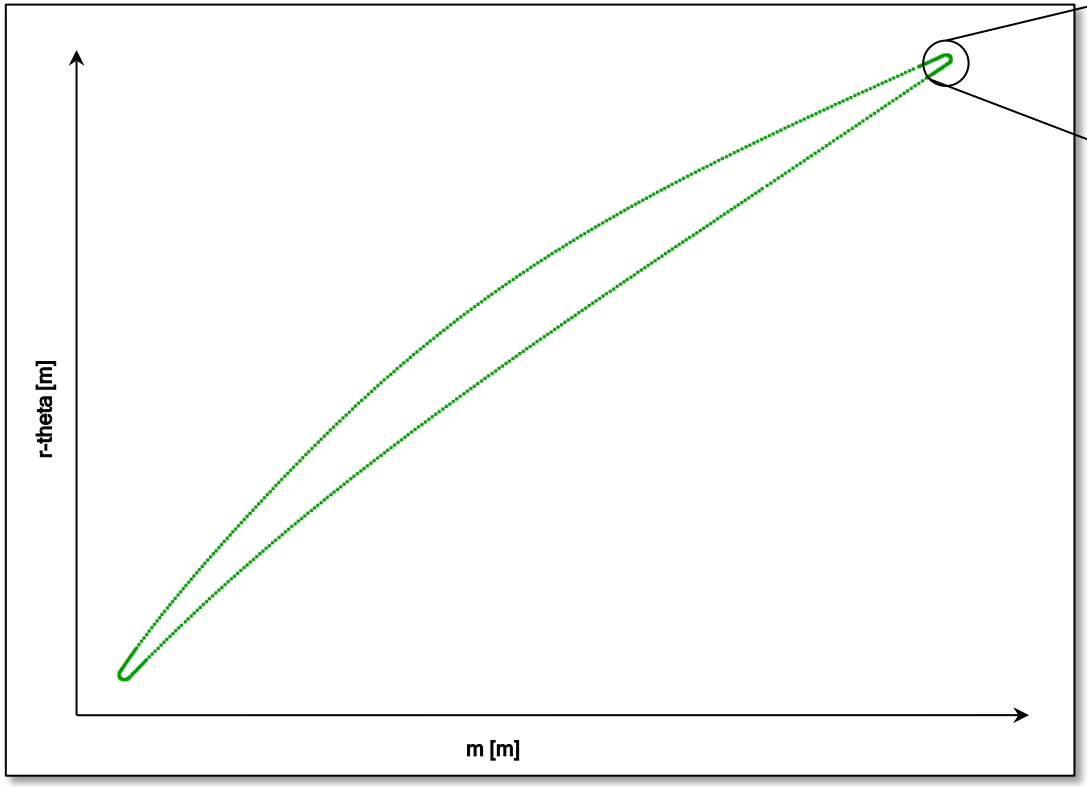
[1] A. Lange: Introduction of a parameter based compressor blade model for considering measured geometry uncertainties in numerical simulation, ASME Turbo Expo, GT2009-59937, Orlando, 2009

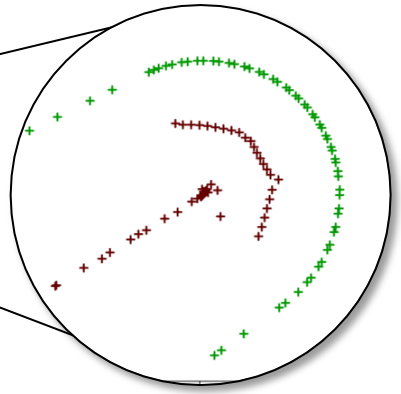
TECHNISCHE UNIVERSITÄT DRESDEN

4.1 Parameterisation

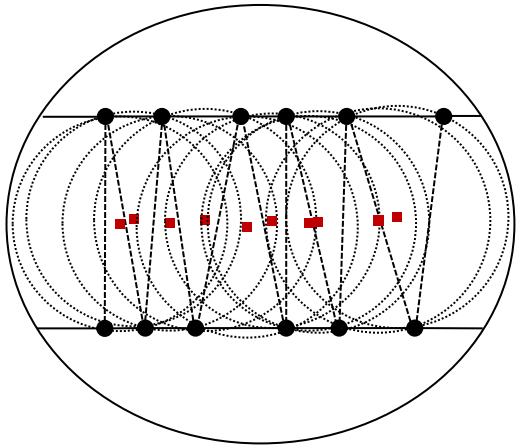


B.1) generation of the skeleton line with Delaunay-Voronoi-triangulation



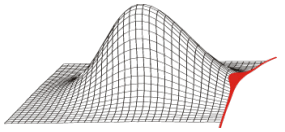


generation of the Delaunay triangles
with the corresponding Voronoi points

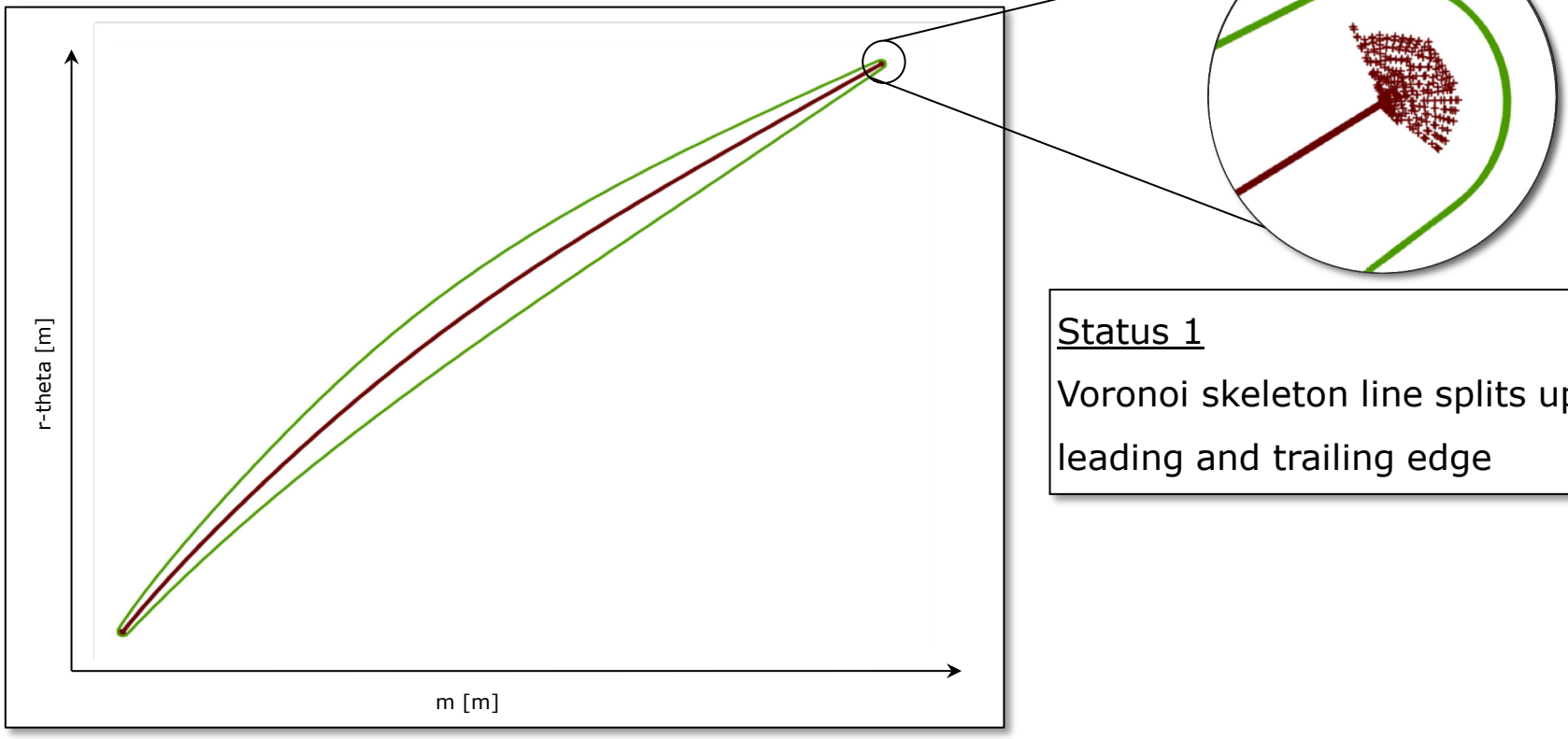


TECHNISCHE UNIVERSITÄT DRESDEN

4.1 Parameterisation



B.2) higher details on skeleton line with more points on profile outline

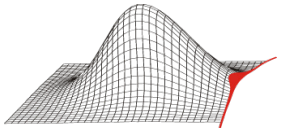


Status 1

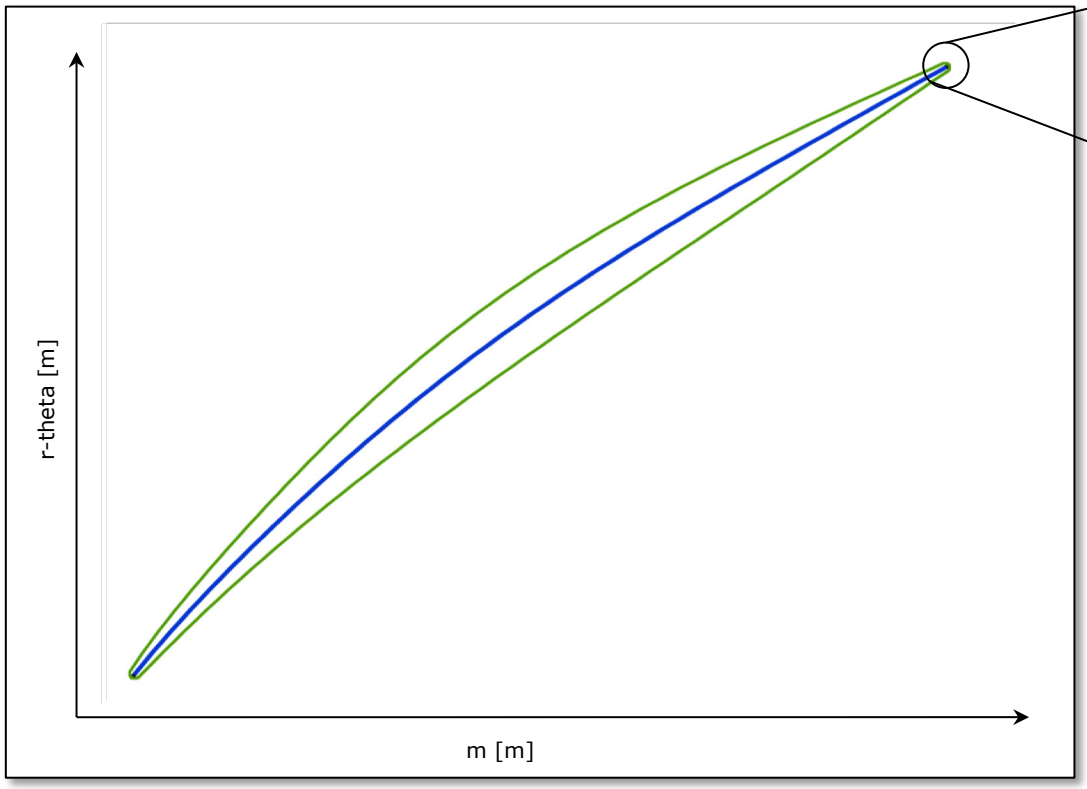
Voronoi skeleton line splits up at leading and trailing edge

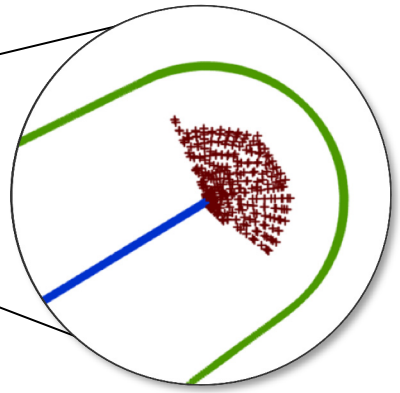
TECHNISCHE UNIVERSITÄT DRESDEN

4.1 Parameterisation



B.3) extrapolation of the skeleton line



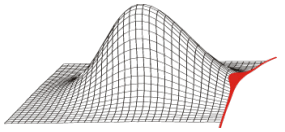


Status 2

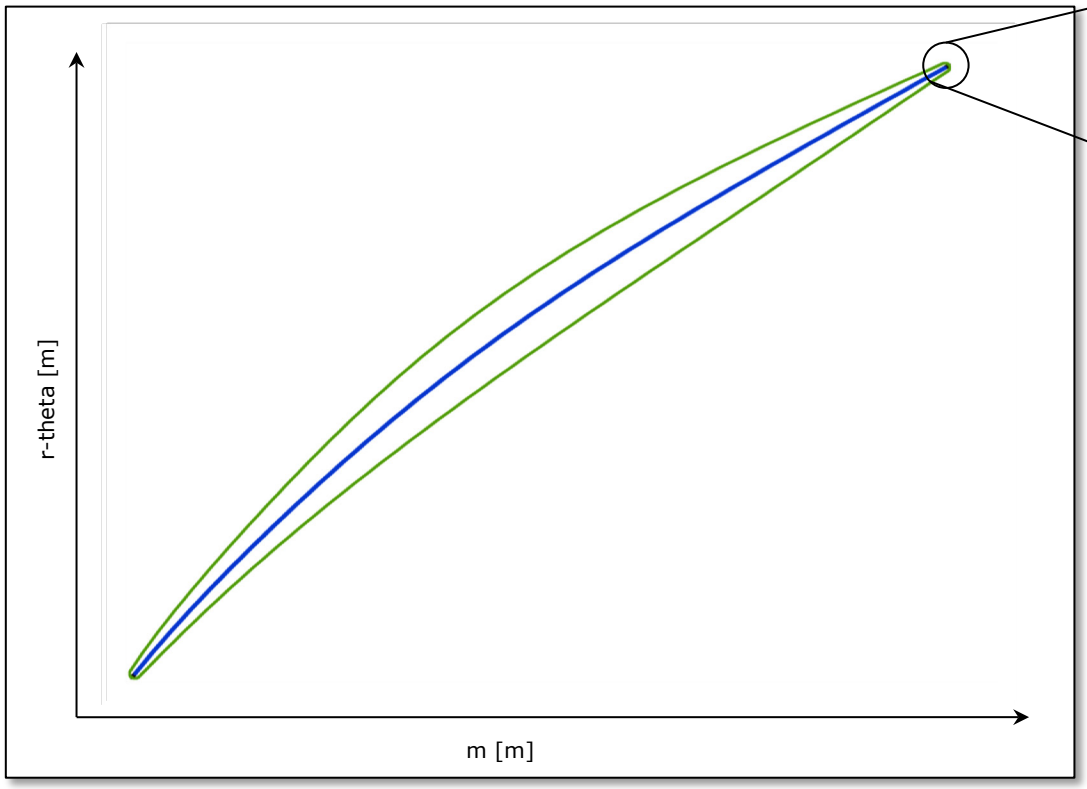
the skeleton line will be cut of after the splitting points at leading and trailing edge

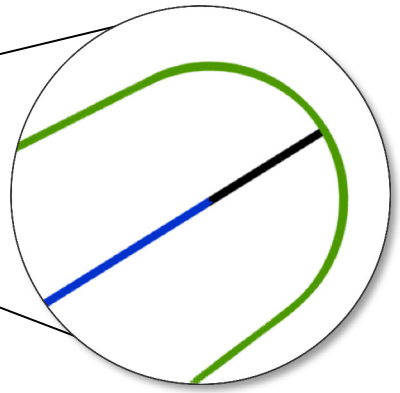
TECHNISCHE UNIVERSITÄT DRESDEN

4.1 Parameterisation



B.3) extrapolation of the skeleton line



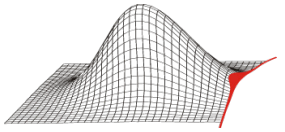


Status 3

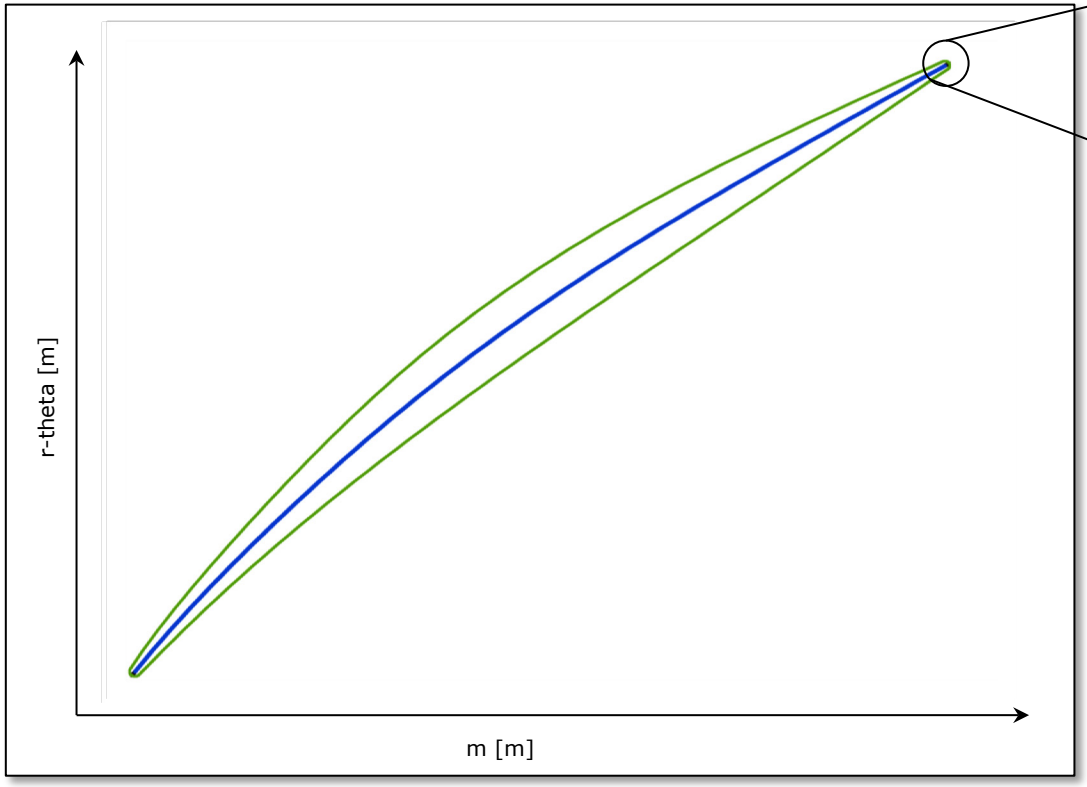
the skeleton line will be extrapolated at leading and trailing edge and the cross points towards the profile outline will be calculated

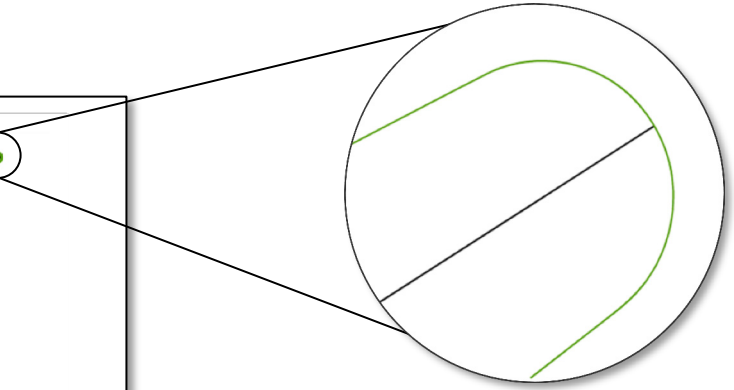
TECHNISCHE UNIVERSITÄT DRESDEN

4.1 Parameterisation



B.3) extrapolation of the skeleton line



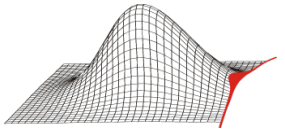


Status 4

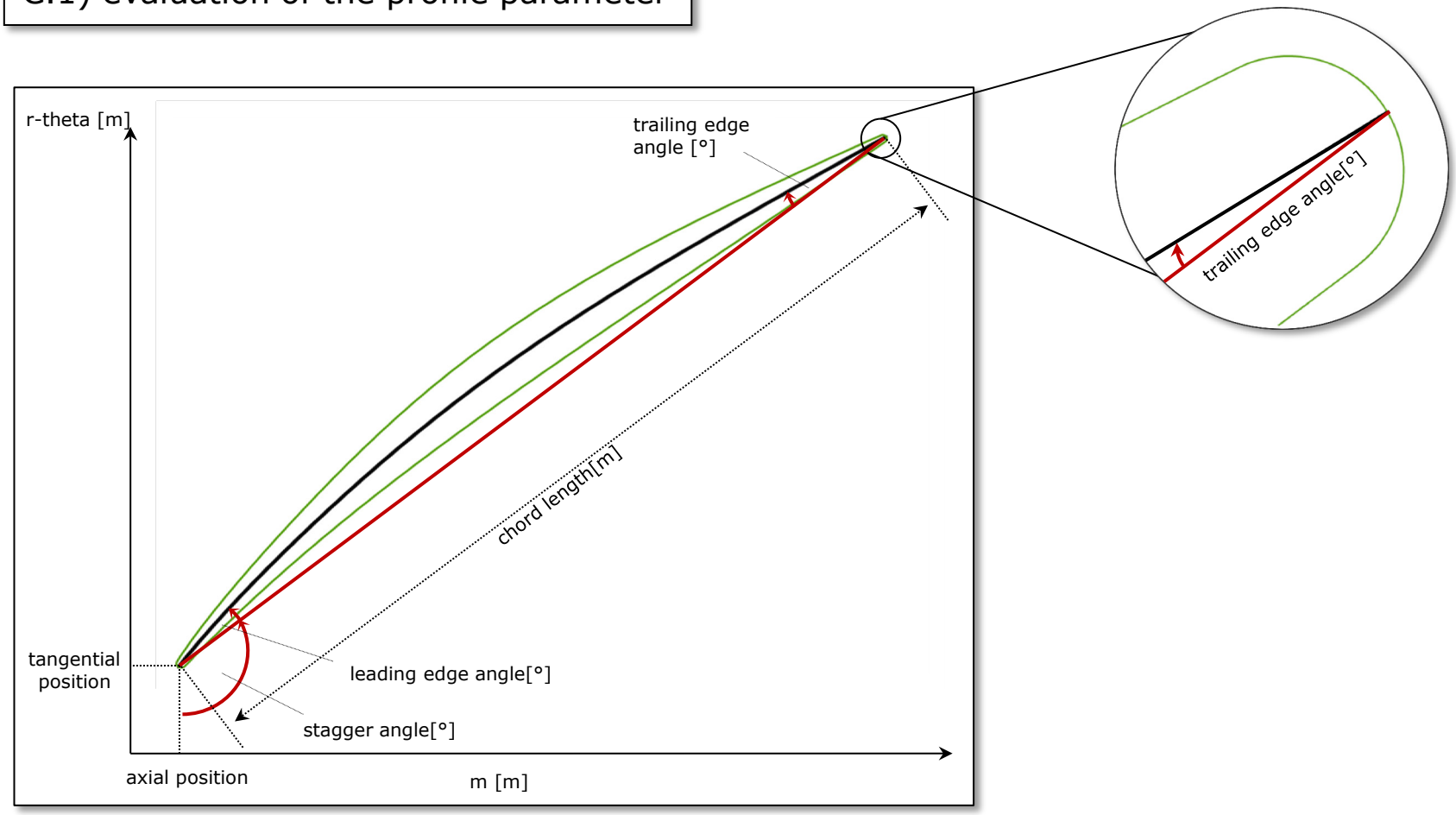
the final skeleton line will be generated and discretised

TECHNISCHE UNIVERSITÄT DRESDEN

4.1 Parameterisation

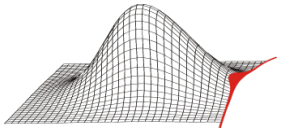


C.1) evaluation of the profile parameter

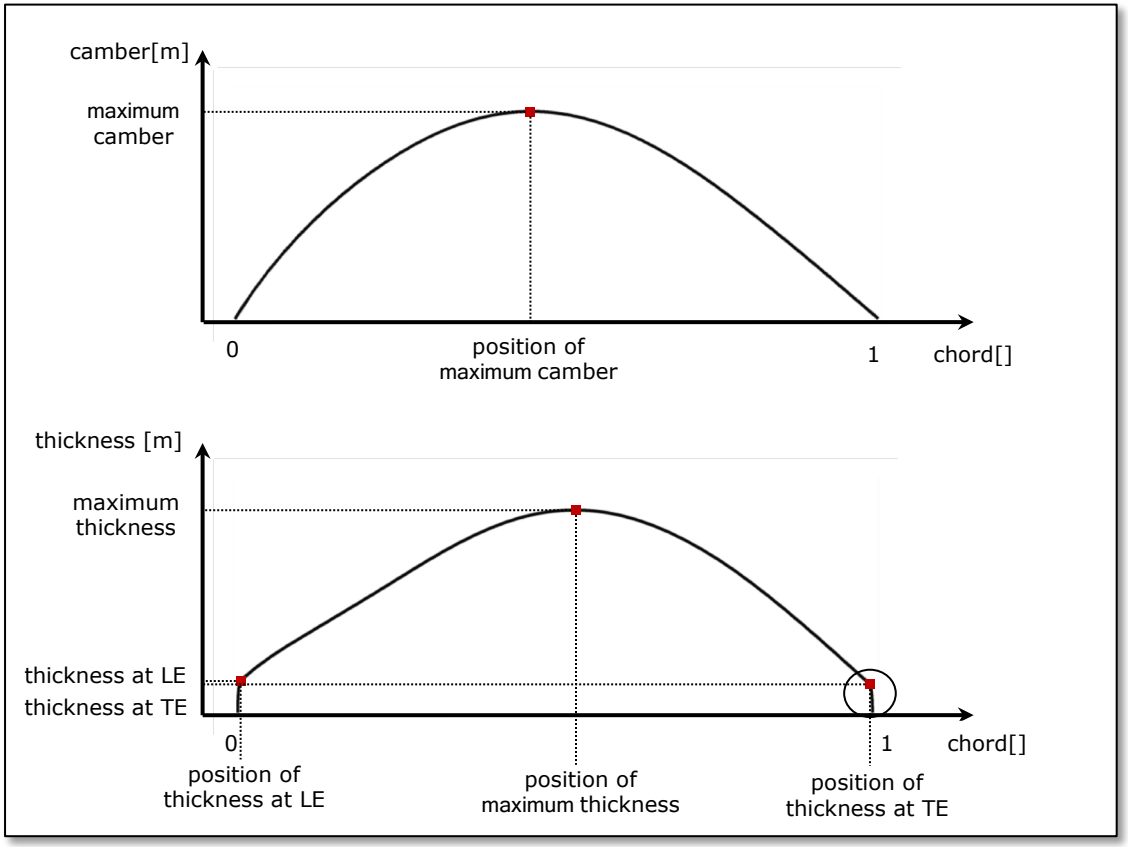


TECHNISCHE UNIVERSITÄT DRESDEN

4.1 Parameterisation

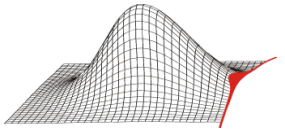


C.2) evaluation of the profile parameter



TECHNISCHE UNIVERSITÄT DRESDEN

4.2 Parameter based Rebuild



nominal aerofoil geometry

scanned aerofoil geometry

statistic with specific aerofoil parameter

nominal set of aerofoil parameter

thickness distribution

camber distribution

+

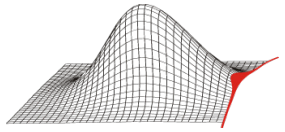
set of generated aerofoil parameter based on probabilistic methods

=

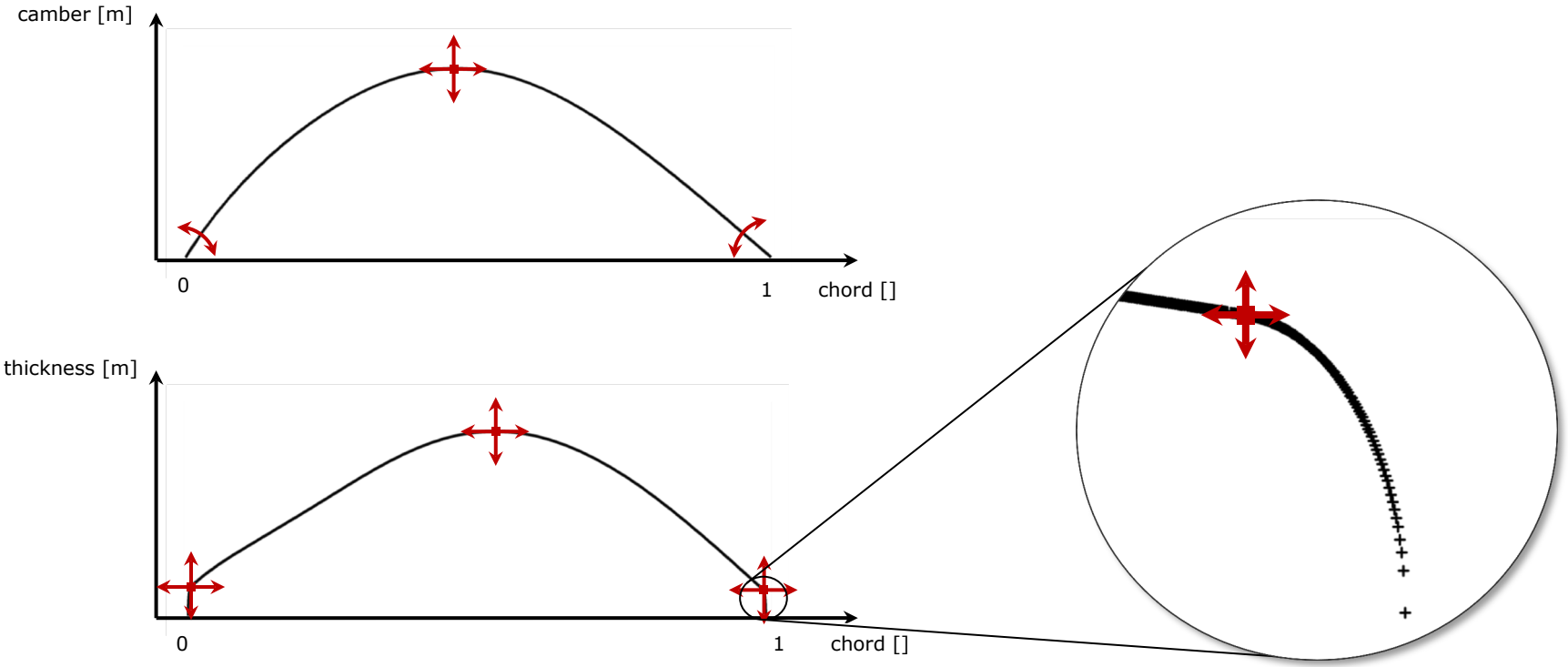
CAD model of the reconstructed aerofoil geometry

TECHNISCHE UNIVERSITÄT DRESDEN

4.2 Parameter based Rebuild

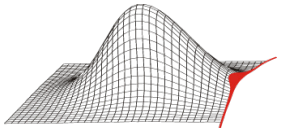


morphing of thickness and camber

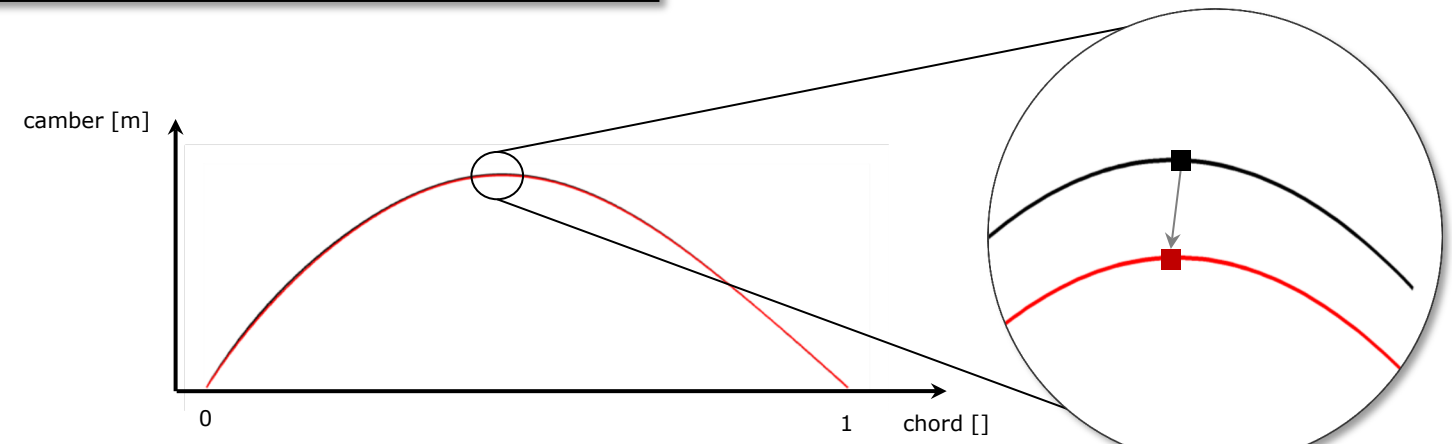


TECHNISCHE UNIVERSITÄT DRESDEN

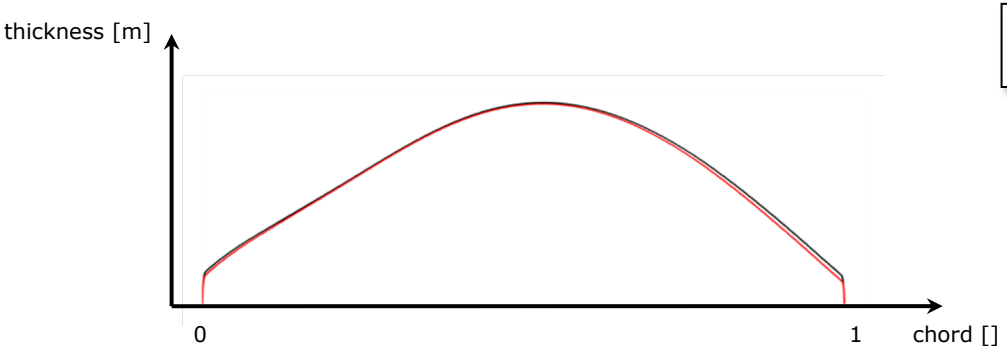
4.2 Parameter based Rebuild



morphing of thickness and camber

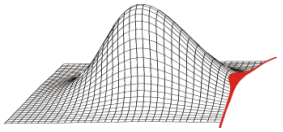


maximum camber

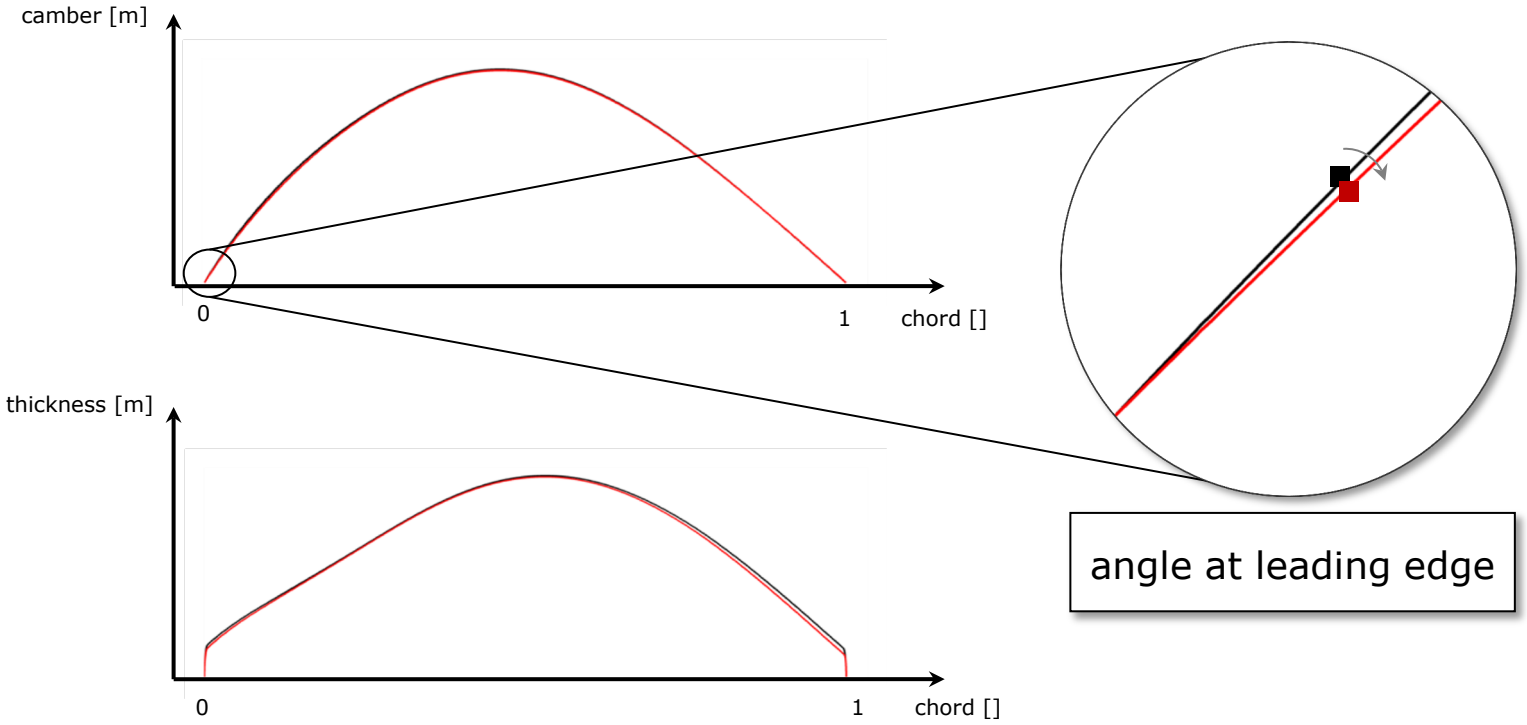


TECHNISCHE UNIVERSITÄT DRESDEN

4.2 Parameter based Rebuild



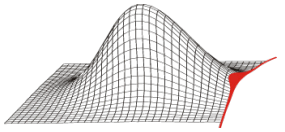
morphing of thickness and camber



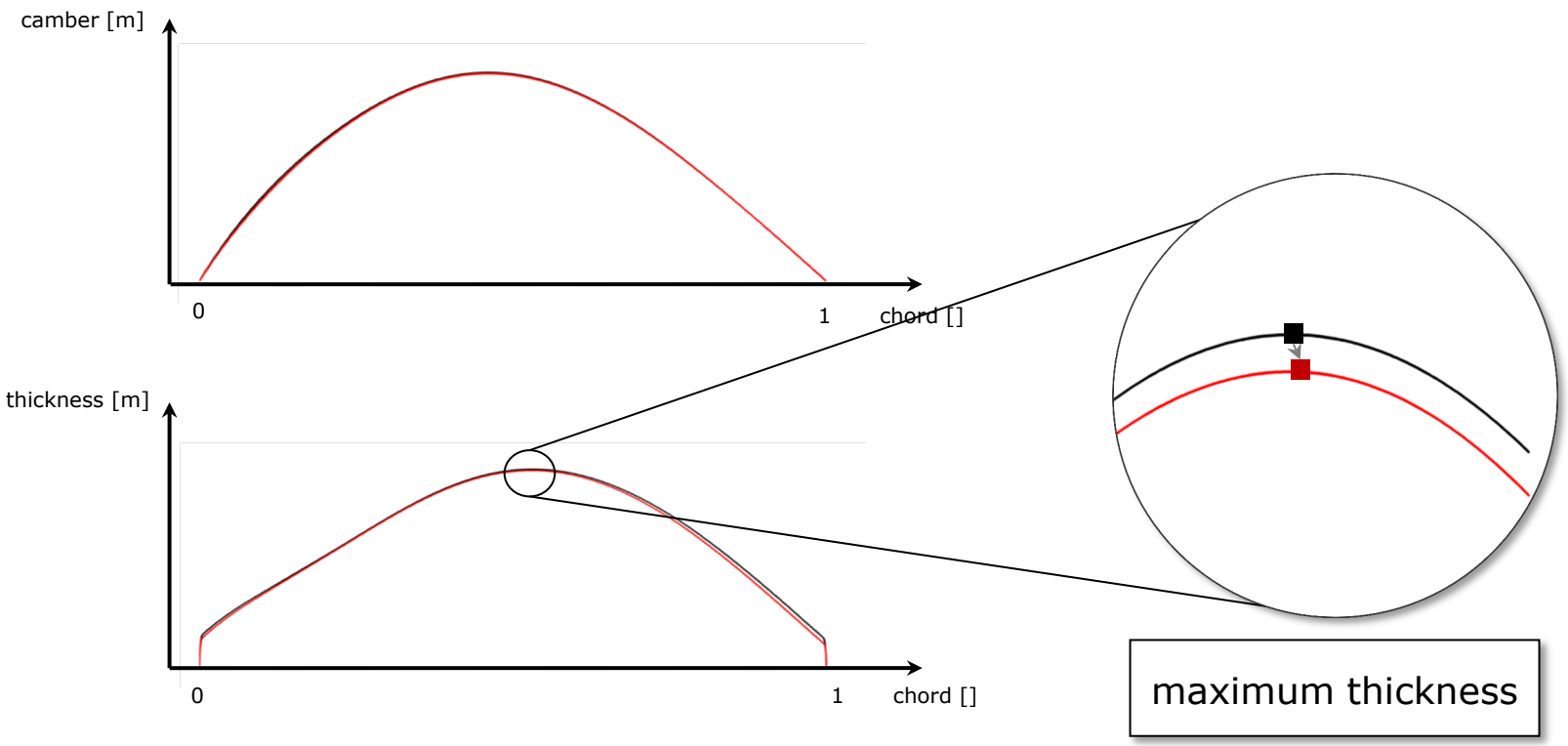
angle at leading edge

TECHNISCHE UNIVERSITÄT DRESDEN

4.2 Parameter based Rebuild

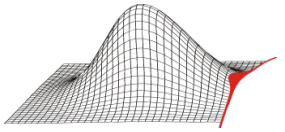


morphing of thickness and camber

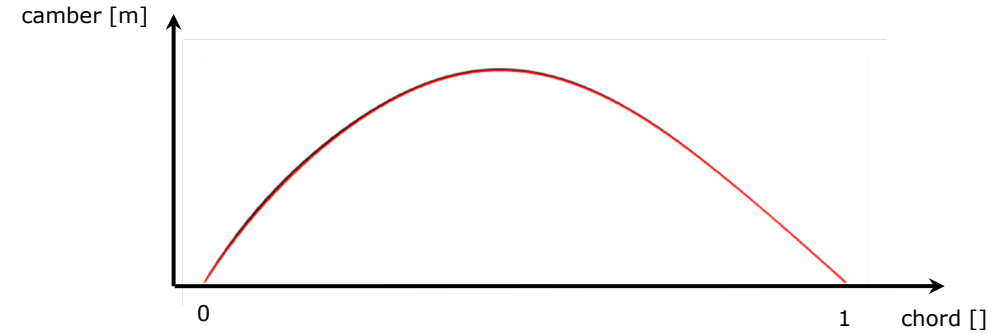


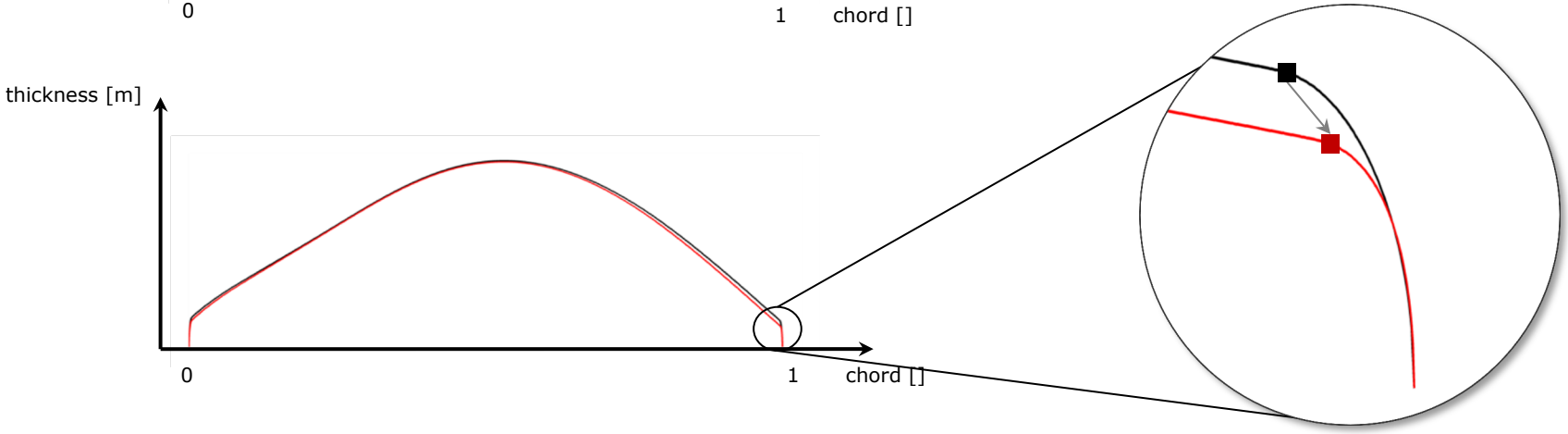
TECHNISCHE UNIVERSITÄT DRESDEN

4.2 Parameter based Rebuild



morphing of thickness and camber

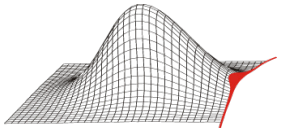




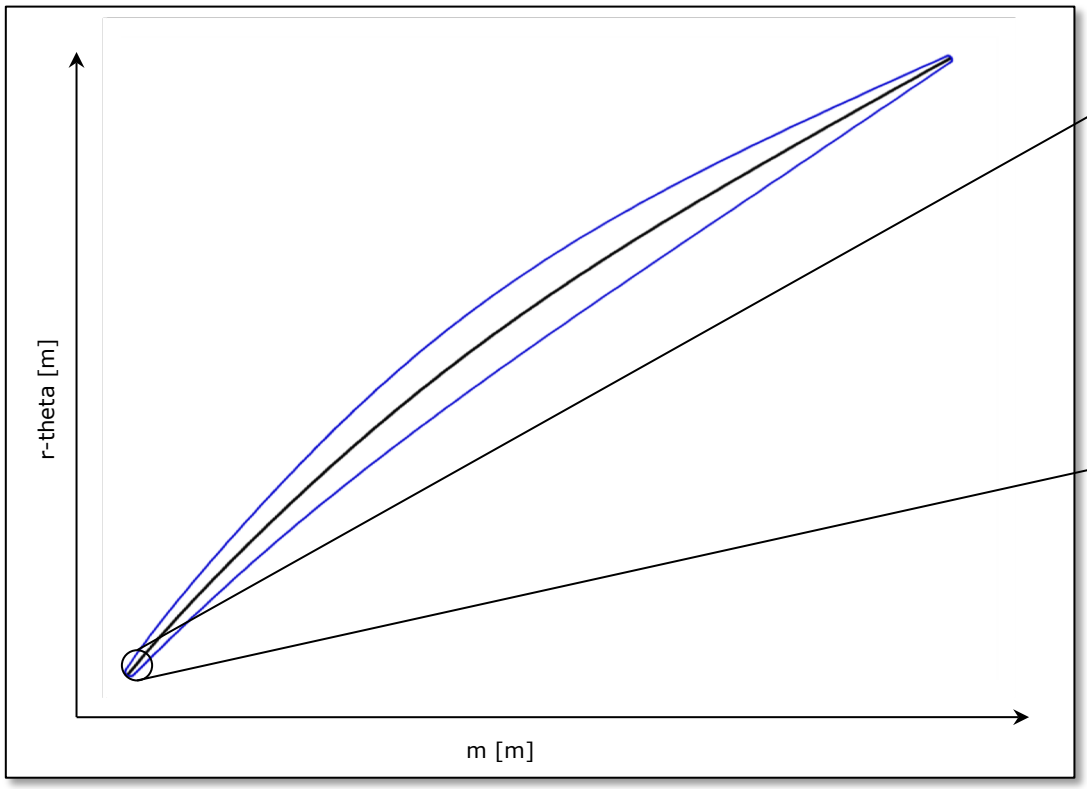
thickness at trailing edge

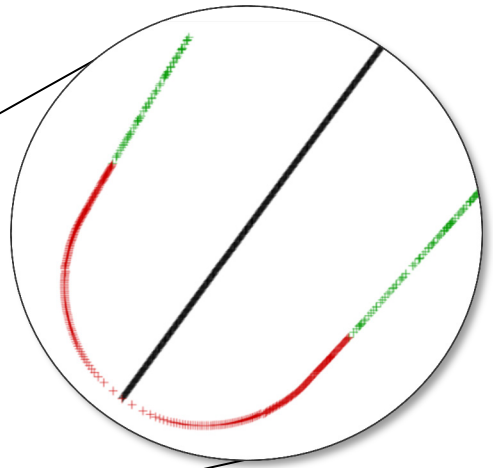
TECHNISCHE UNIVERSITÄT DRESDEN

4.2 Parameter based Rebuild



reconstruction of the blade aerofoil

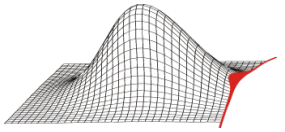




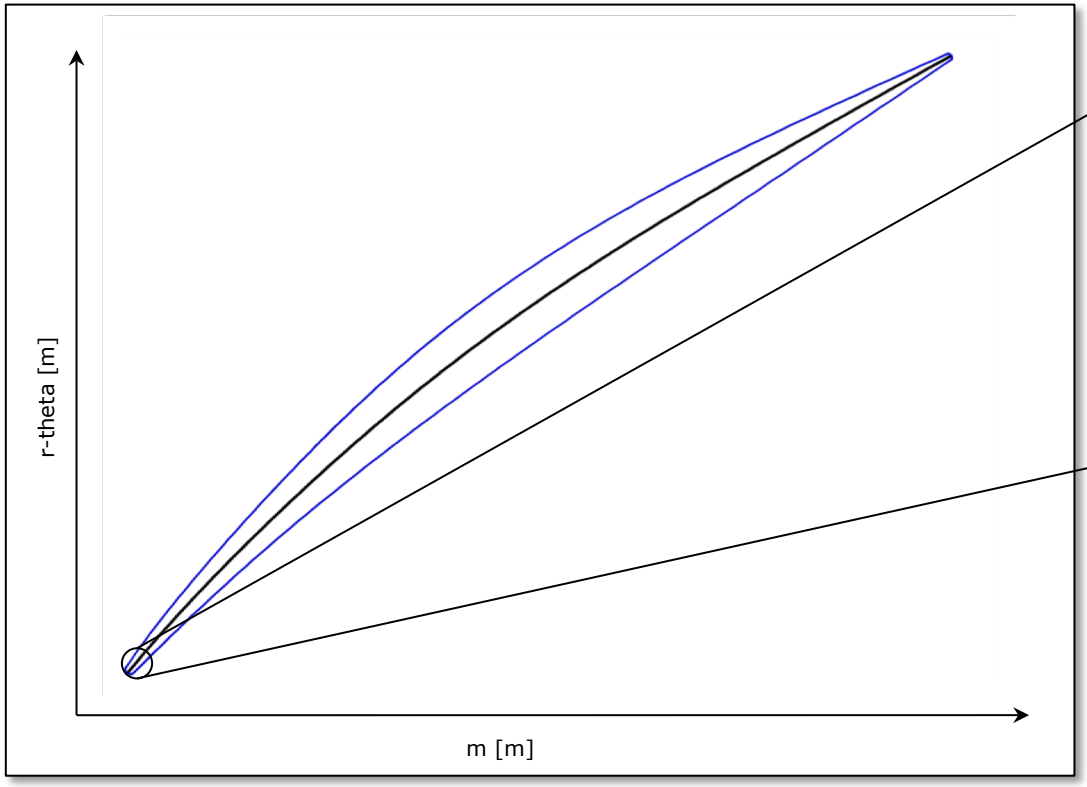
rebuild of the profile outline with 4 patches (LE,TE,PS,SS)

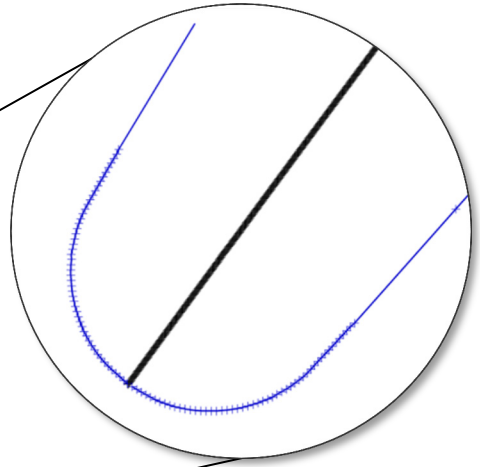
TECHNISCHE UNIVERSITÄT DRESDEN

4.2 Parameter based Rebuild



reconstruction of the blade aerofoil

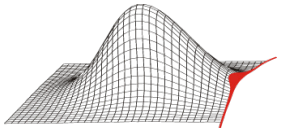




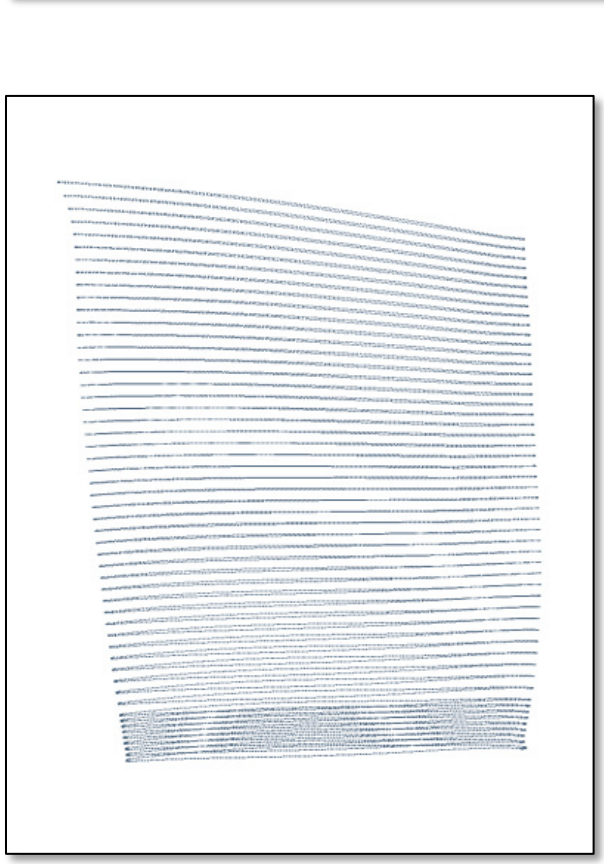
generate a smooth discretization of the profile outline

TECHNISCHE UNIVERSITÄT DRESDEN

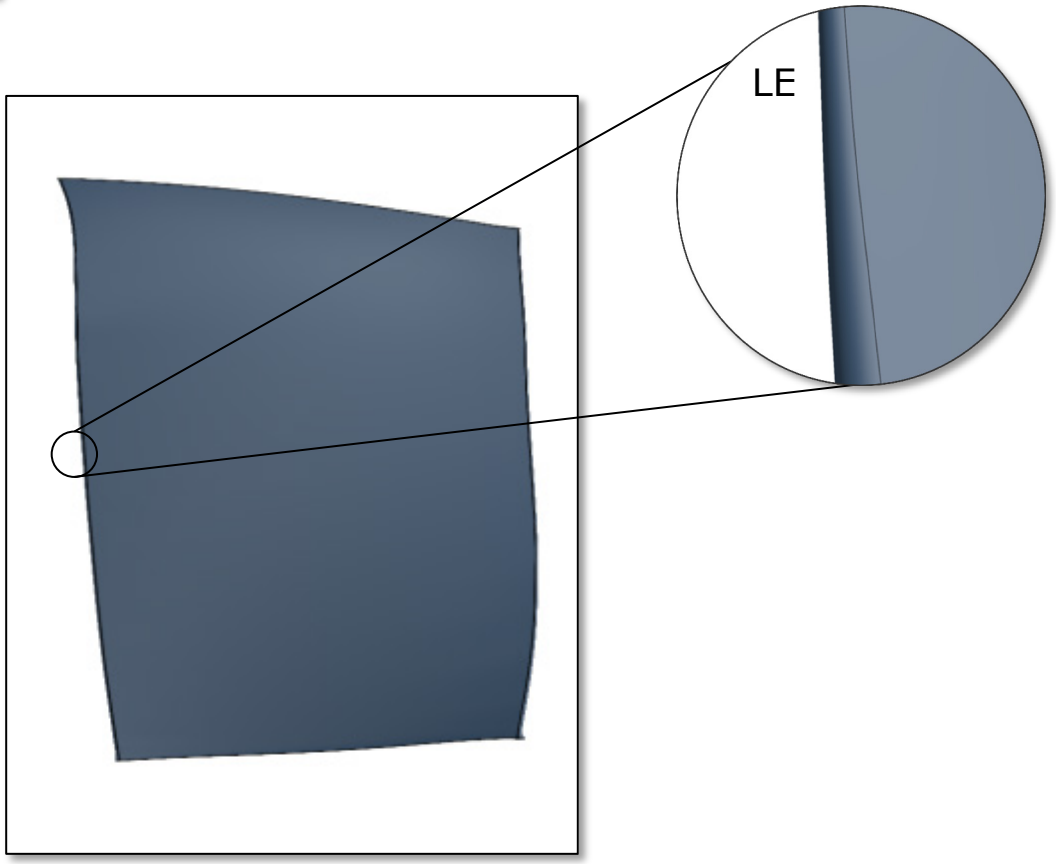
4.2 Parameter based Rebuild



reconstruction of the blade aerofoil



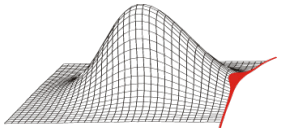
reconstructed profile sections

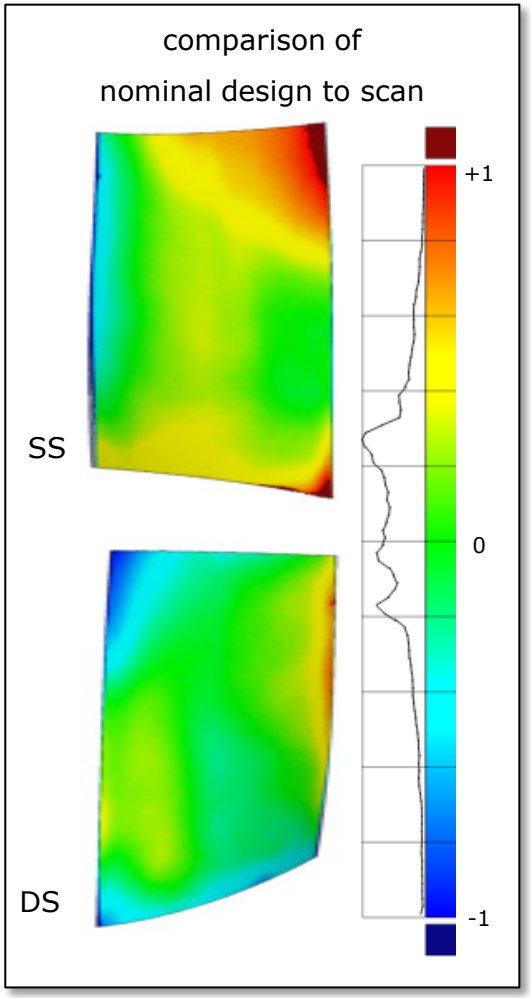


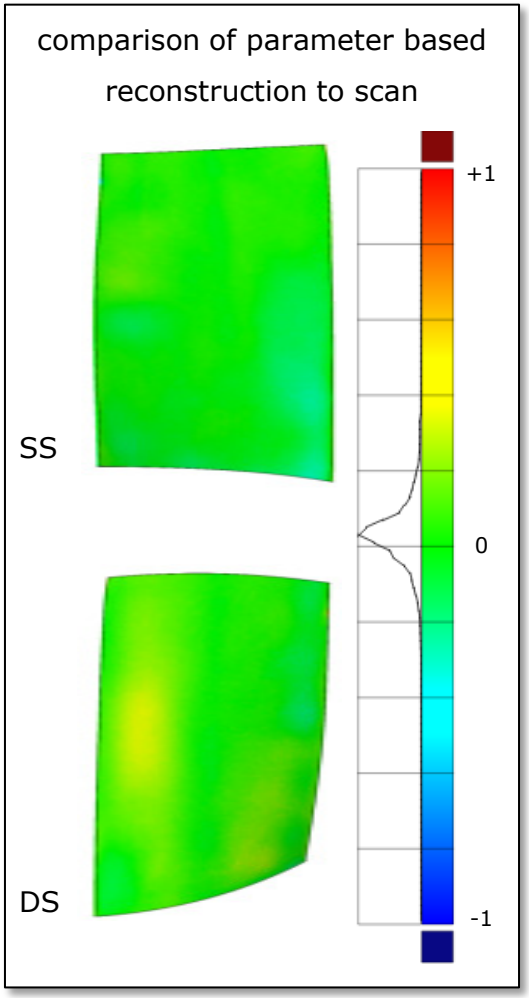
reconstructed 3d model

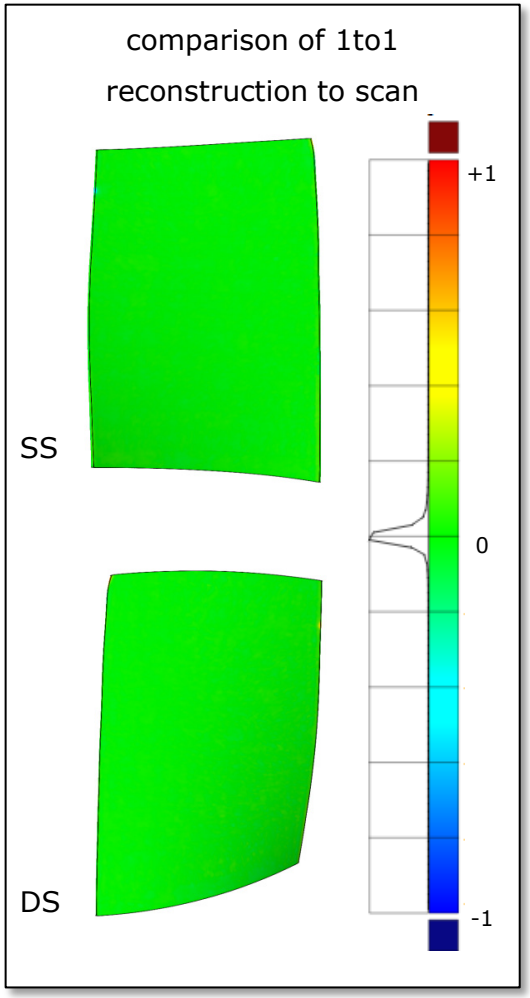
TECHNISCHE UNIVERSITÄT DRESDEN

4.2 Parameter based Rebuild



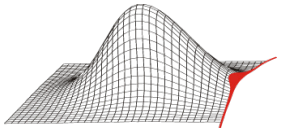


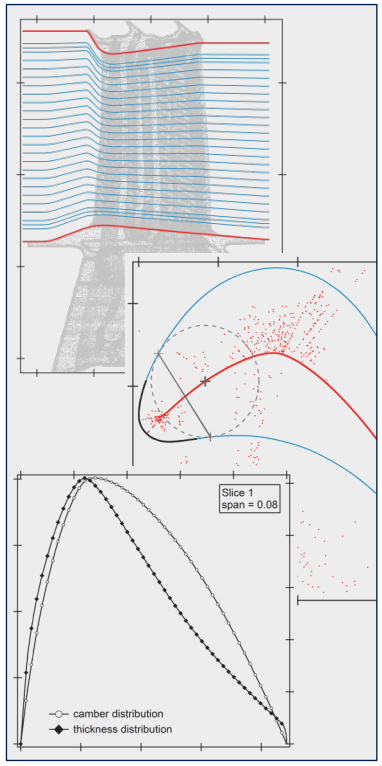




TECHNISCHE UNIVERSITÄT DRESDEN

4 Parameterisation and Rebuild





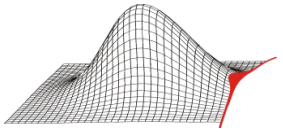
4.1 Parameterisation

4.2 Parameter based Rebuild

4.3 One to One Rebuild

TECHNISCHE UNIVERSITÄT DRESDEN

4.3 One to One Rebuild



Cleaned Aerofoil Mesh

Parameterisation of the aerofoil

Statistical survey of the varying aerofoil parameter

Probabilistic simulation through the probability distributions and the corresponding correlations of the varying aerofoil parameter

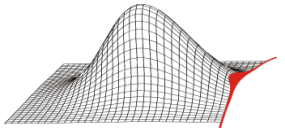
Rebuild of a probabilistic generated aerofoil geometry within a parameter based 3D blade model

Rebuild of the aerofoil mesh geometry within a 3D blade model

Application (FEM,CFD,...)

TECHNISCHE UNIVERSITÄT DRESDEN

4.3.1 Motivation

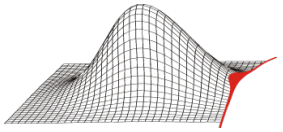


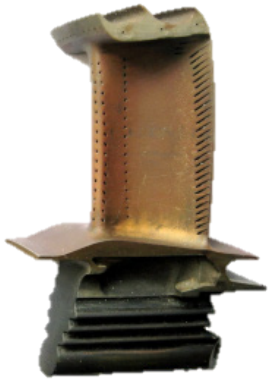
- reverse-engineering: One to One implementation of the manufactured component back into the development process for further design-processing and validation (CFD, FEM)

- advantages over common surface reconstruction software:
  - customised especially for turbo machinery components
  - robust
  - fast and automatic process
  - output of selected parameters for a subsequent analysis of component-characteristics

TECHNISCHE UNIVERSITÄT DRESDEN

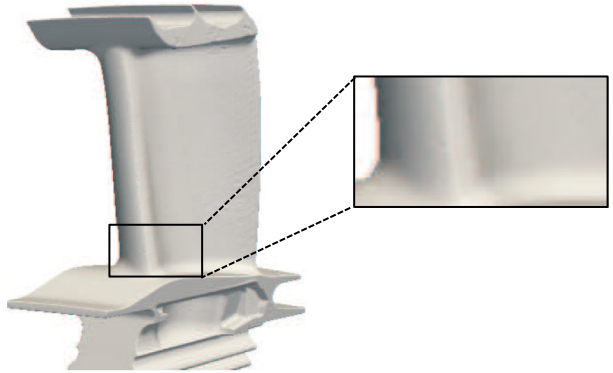
4.3.2 Process Operation



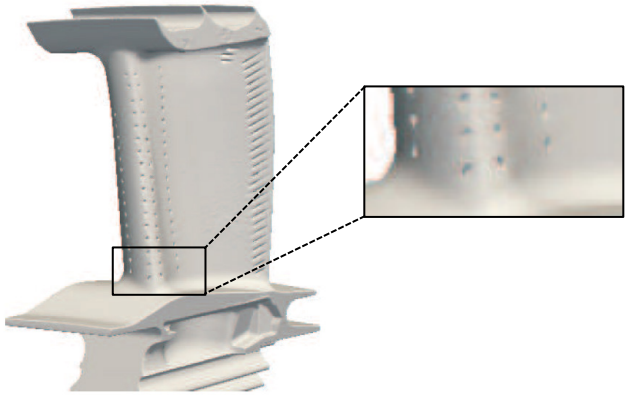


optical 3D measurement

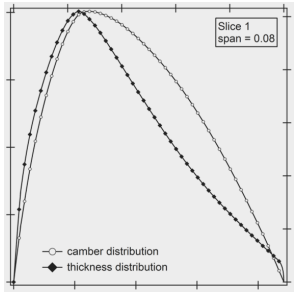
pre-processed STL-mesh
(closed cooling holes)



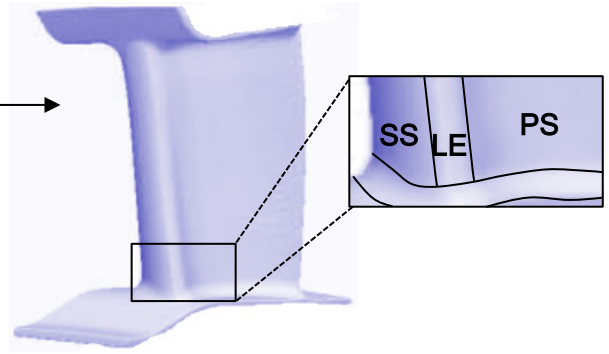
STL-mesh



parameter extraction &
parameter based rebuild

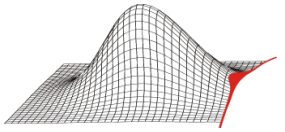


one to one rebuild

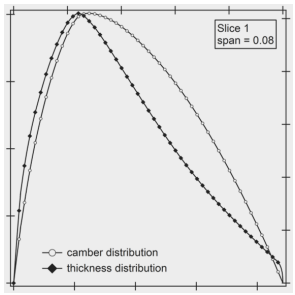


TECHNISCHE UNIVERSITÄT DRESDEN

4.3.2 Process Operation

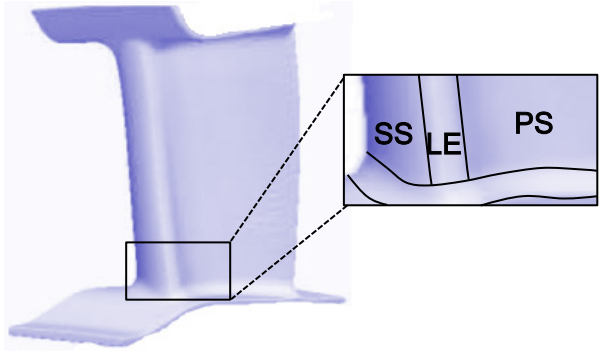


parameter extraction & parameter based rebuild



- rebuild the component as accurate as possible with the least possible amount of parameters (with acceptable deviations):
  - probabilistic simulations
  - optimisation
  - estimate manufacturing scatter

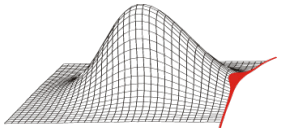
one to one rebuild



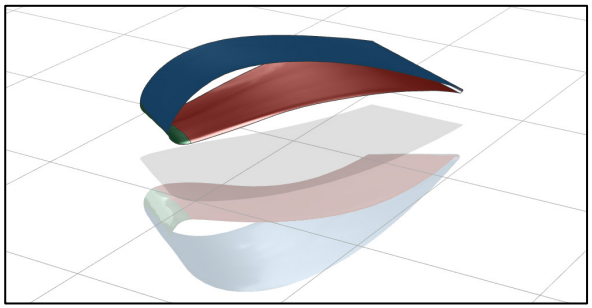
- rebuild the component as close to reality as possible:
  - validation purposes (comparison to measurements)
  - analysis of component characteristics

TECHNISCHE UNIVERSITÄT DRESDEN

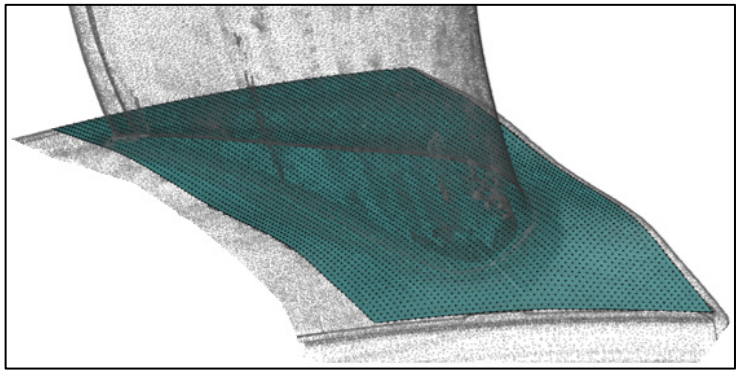
4.3.3 Extraction Methods



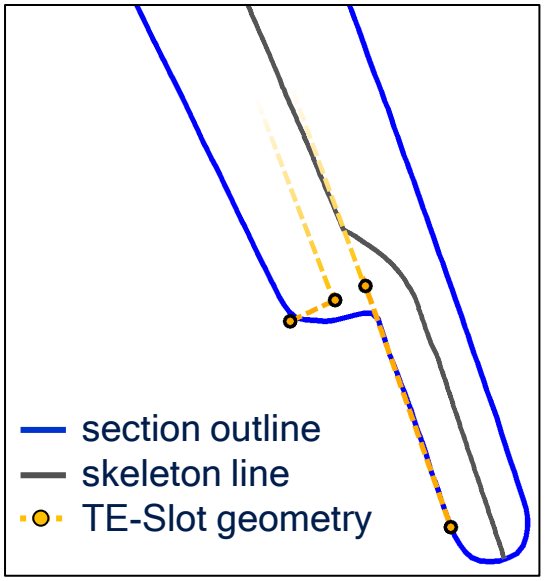
Aerofoil



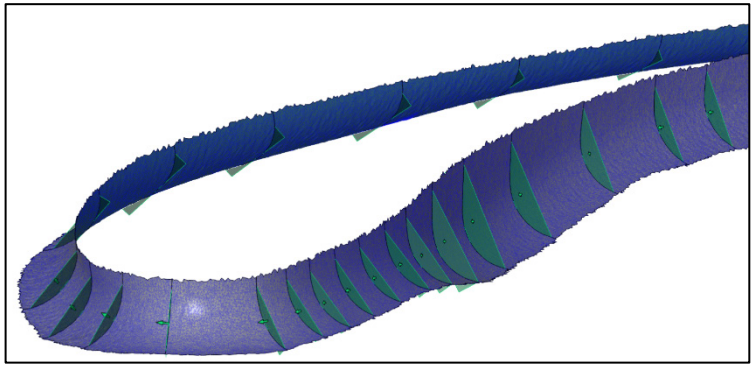
Profiled Endwall (PEW)



Trailing Edge Slot

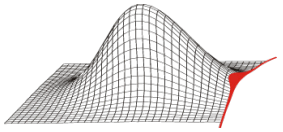


Fillet

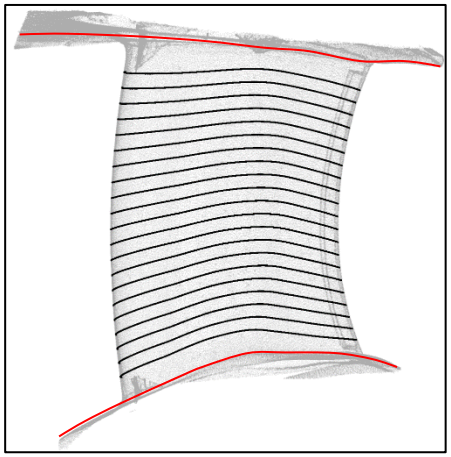


TECHNISCHE UNIVERSITÄT DRESDEN

4.3.3 Extraction Methods - Aerofoil



1) profile partition into n slices



- measured point cloud
- generated section outlines
- lines for hub and casing

2) 3D to 2D coordinate transformation (X,Y,Z to rθ,m)

$$dm^2 = dr^2 + dz^2$$

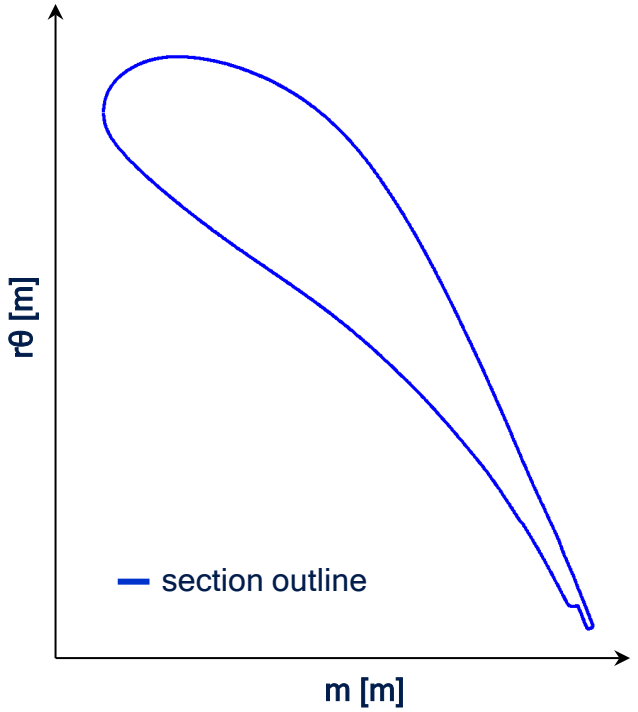
$$m_k = \begin{cases} m_{k-1} + \sqrt{(r_k - r_{k-1})^2 + (z_k - z_{k-1})^2} \; for \; \Delta z_k \geq 0 \\ m_{k-1} - \sqrt{(r_k - r_{k-1})^2 + (z_k - z_{k-1})^2} \; for \; \Delta z_k < 0 \end{cases}$$

$$r\theta_k = r_k \theta_k$$

$$\theta_k = arctan \frac{y_k}{x_k}$$

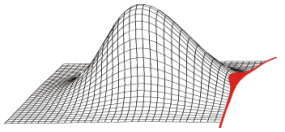
$$r_k = \sqrt{{y_k}^2 + {x_k}^2}$$

3) extracted profile contour

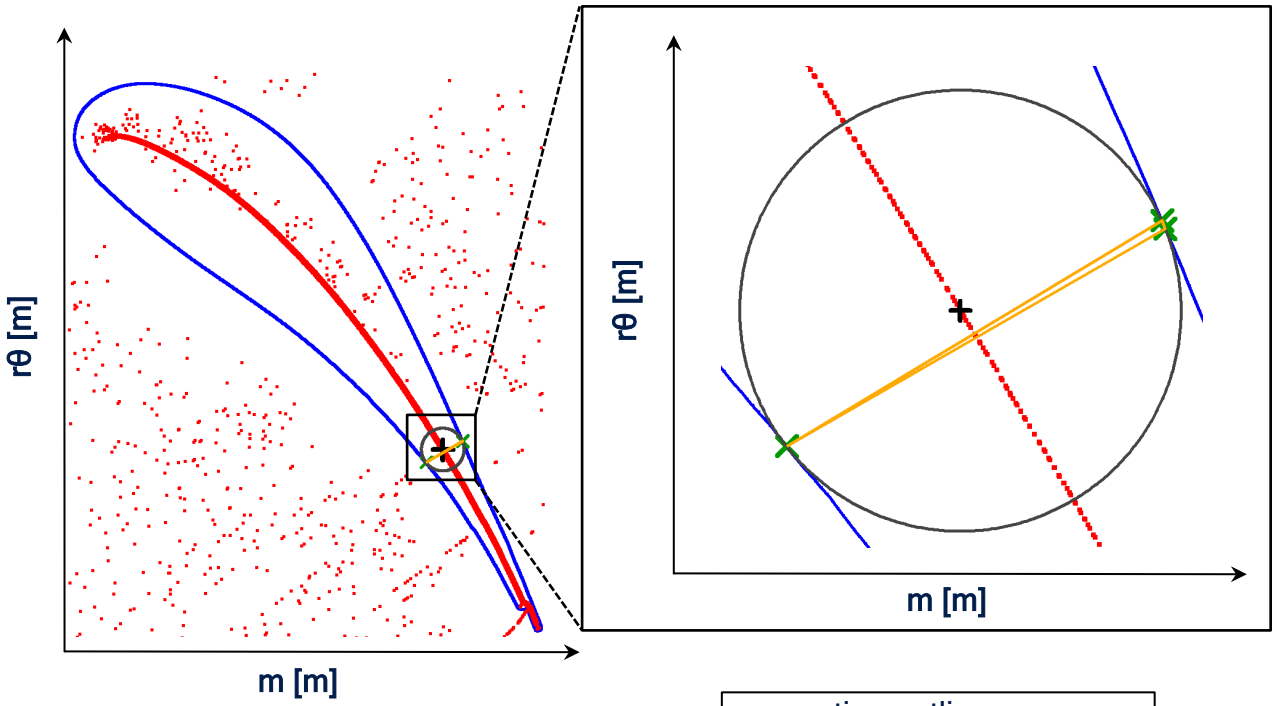


TECHNISCHE UNIVERSITÄT DRESDEN

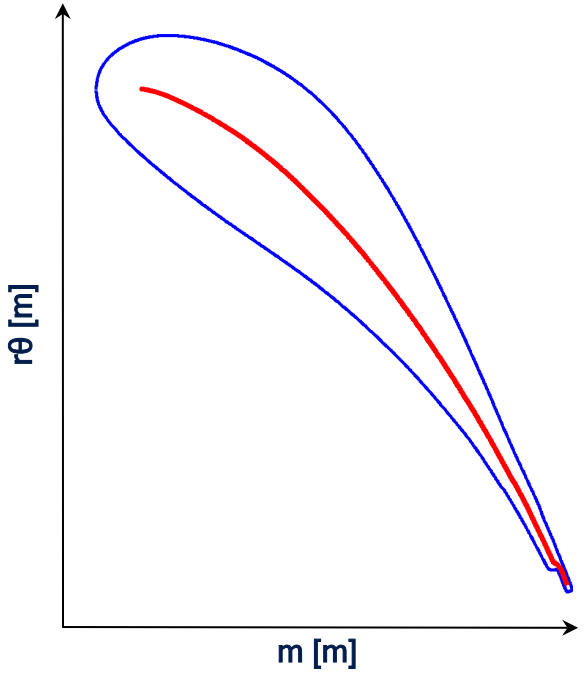
4.3.3 Extraction Methods - Aerofoil



4) Delaunay - Voronoi - Triangulation



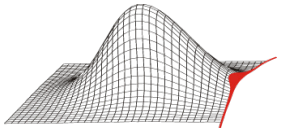
5) filter created points



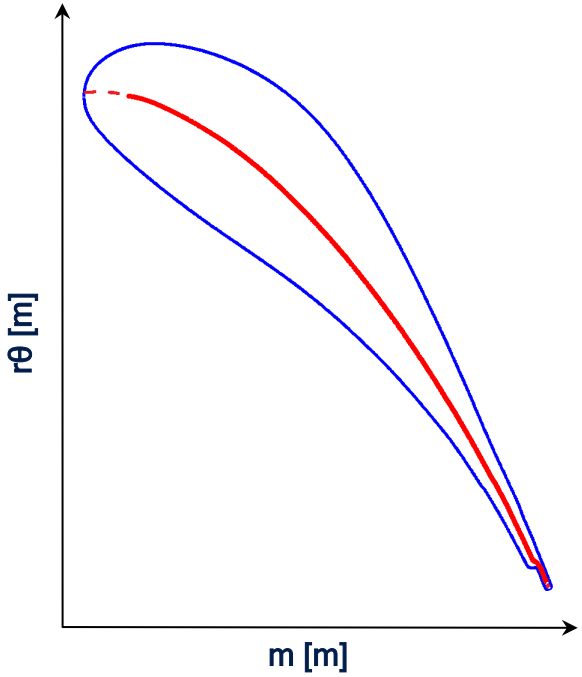
- section outline
- Voronoi points
- current triangle
- related circle
- related Voronoi point

TECHNISCHE UNIVERSITÄT DRESDEN

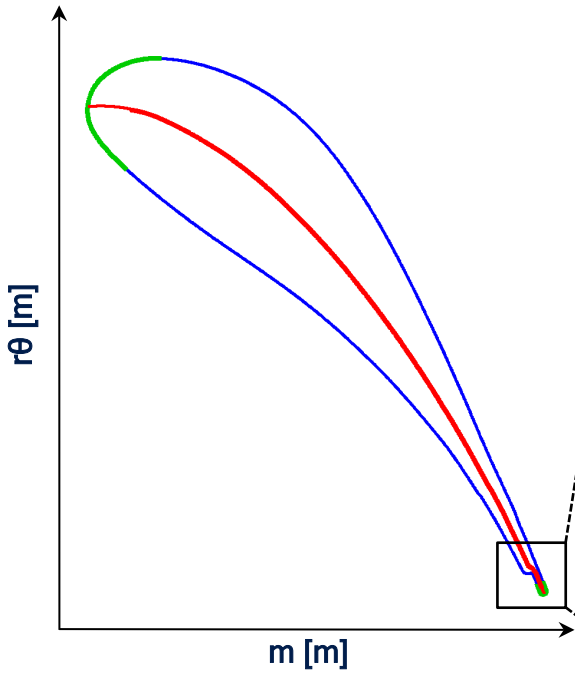
4.3.3 Extraction Methods - Aerofoil



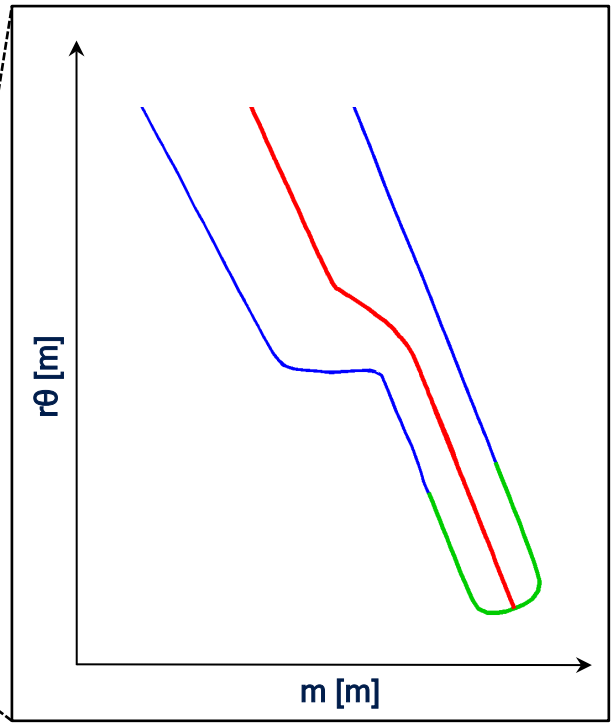
6) skeleton line extrapolation

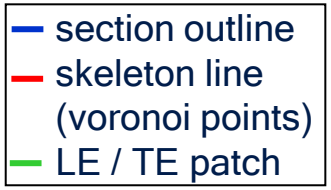


7) LE & TE patch detection



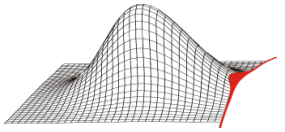
Trailing Edge Slot



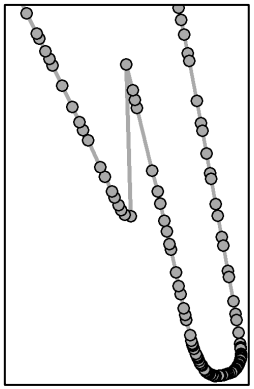


TECHNISCHE UNIVERSITÄT DRESDEN

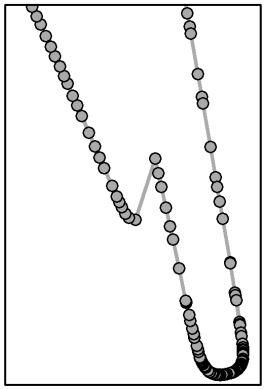
4.3.3 Extraction Methods - Aerofoil



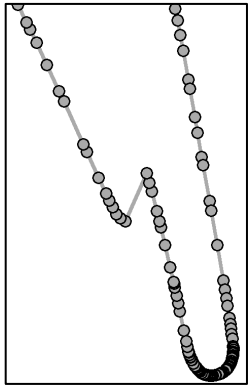
intersection points between streamwise slices and mesh



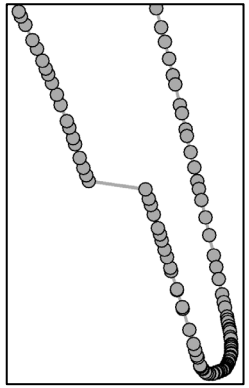
20 % span



40% span

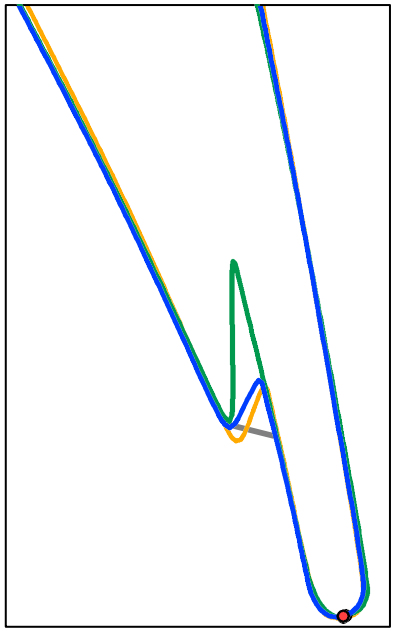


60 % span



80 % span

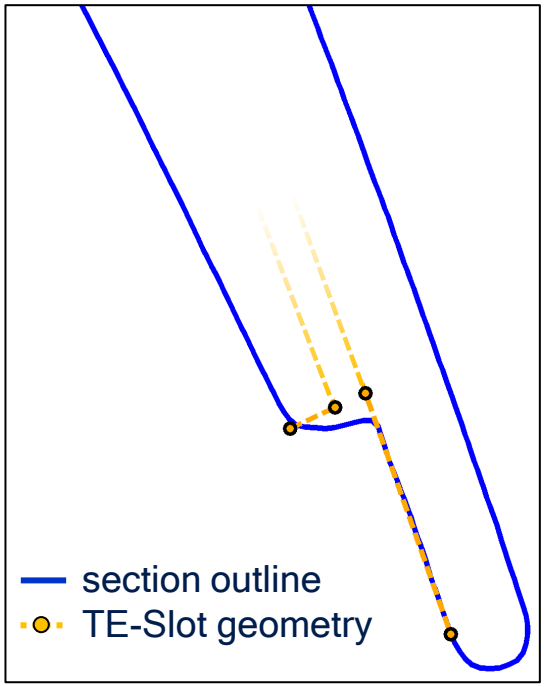
superimposed



TE Position

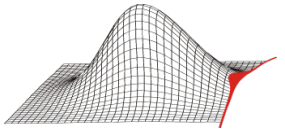
different section outlines

TE-Slot geometry

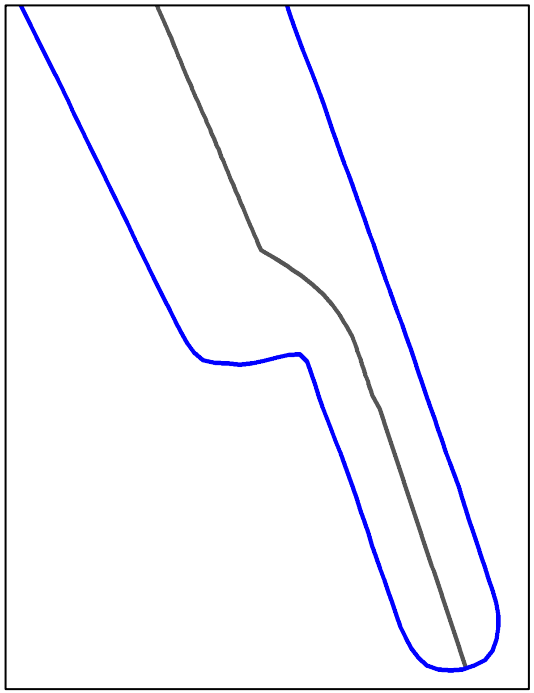


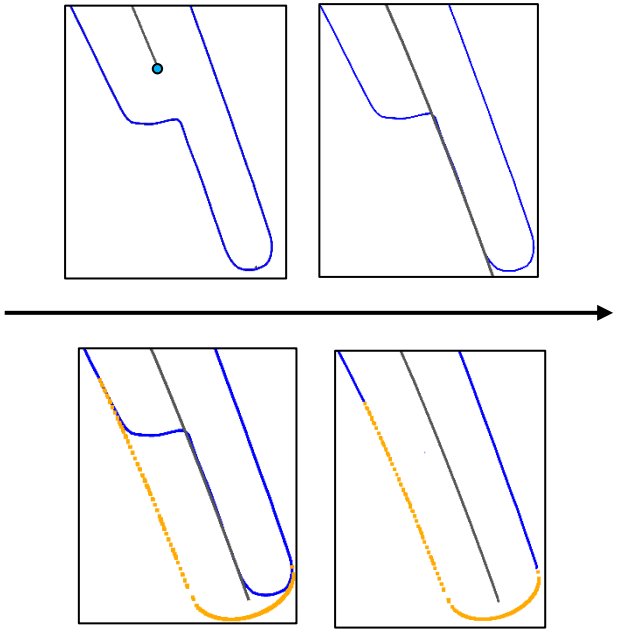
TECHNISCHE UNIVERSITÄT DRESDEN

4.3.3 Extraction Methods - Aerofoil

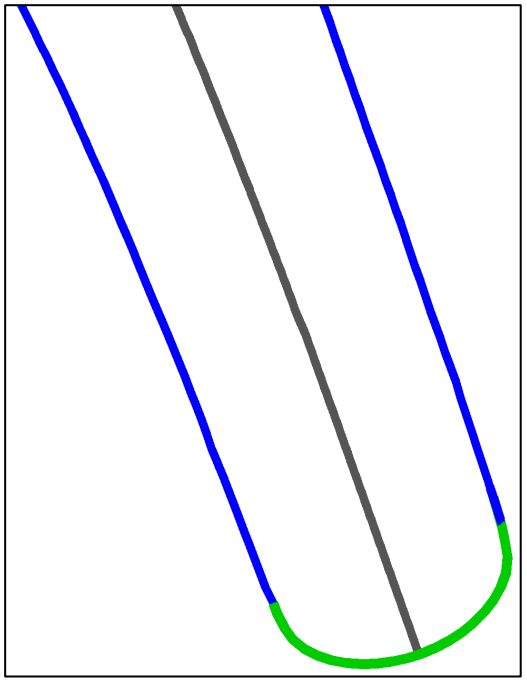


measured component





closed component

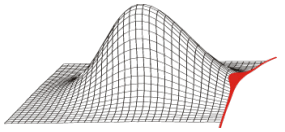


section outline
skeleton line

section outline
skeleton line
TE patch

TECHNISCHE UNIVERSITÄT DRESDEN

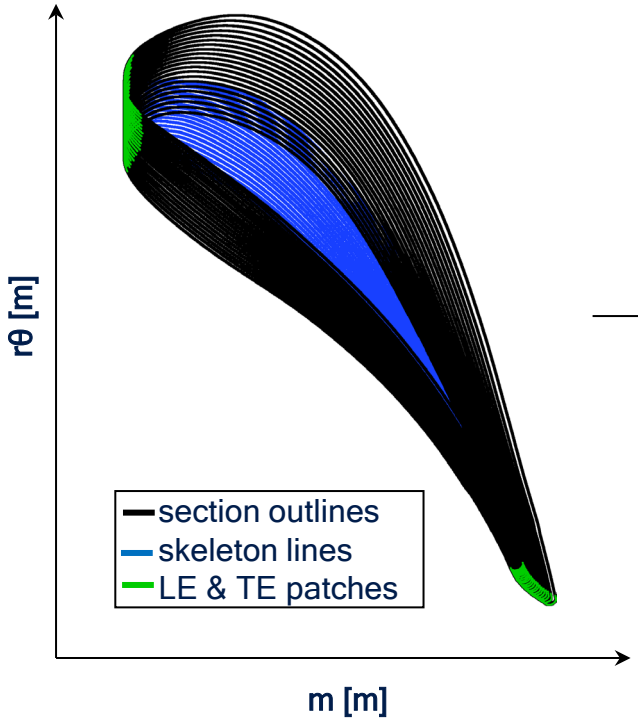
4.3.3 Extraction Methods - Aerofoil

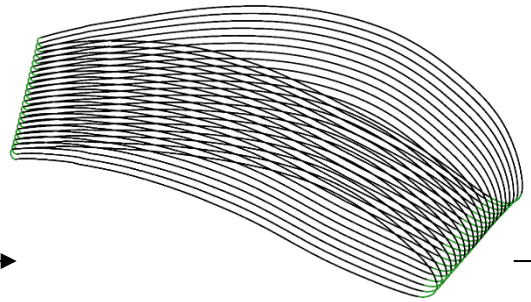


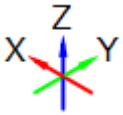
1) extracted profile contours and calculated skeleton lines

2) 2D to 3D coordinate transformation (rθ,m to X,Y,Z)

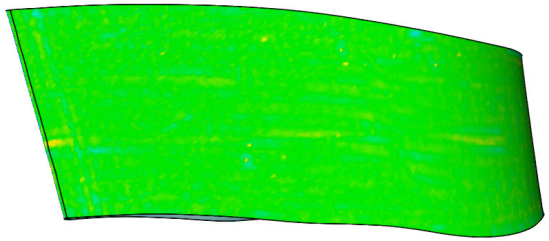
3) recreation of the aerofoil with common CAD-software



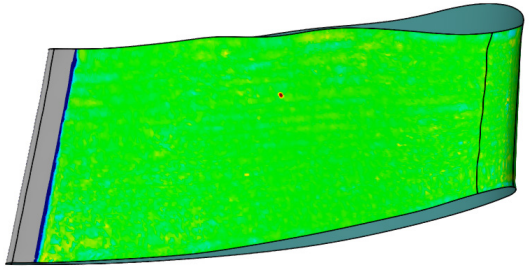


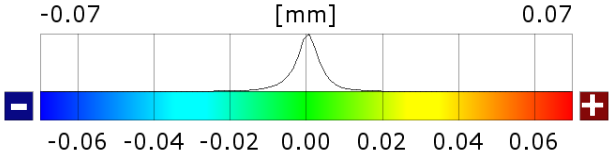


suction side



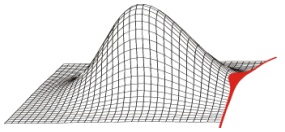
pressure side





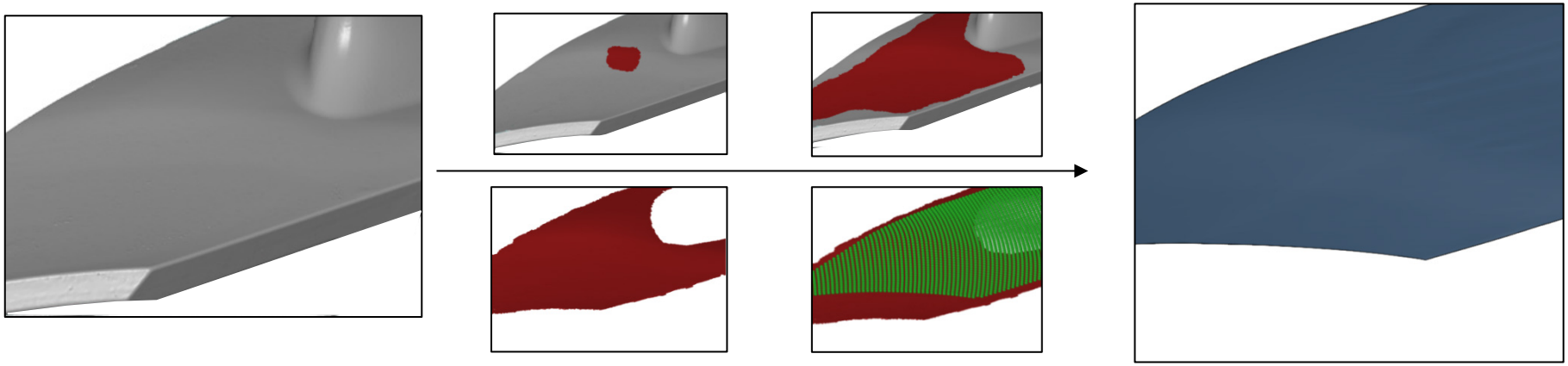
TECHNISCHE UNIVERSITÄT DRESDEN

4.3.3 Extraction Methods – PEW & Fillet

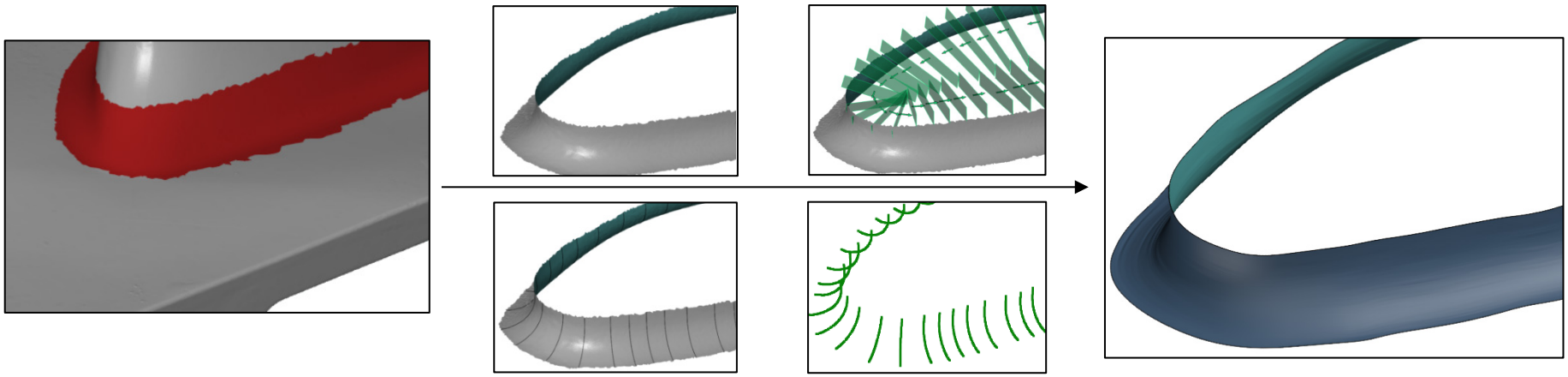


STL - mesh → CAD - geometry

Profiled Endwalls

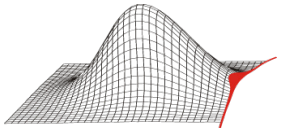


Fillet

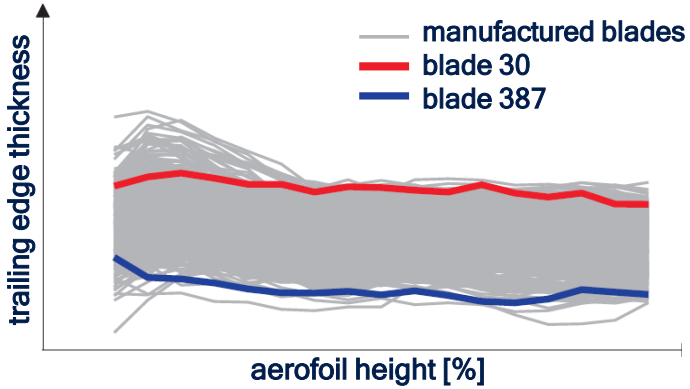


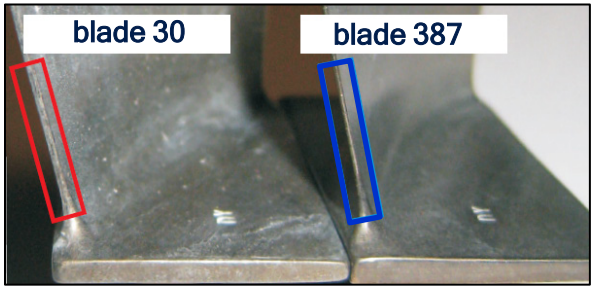
TECHNISCHE UNIVERSITÄT DRESDEN

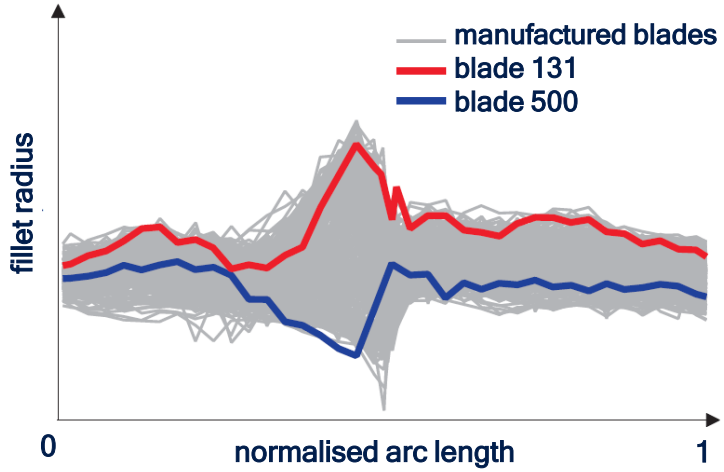
4.3.4 Analyses of blade-characteristics

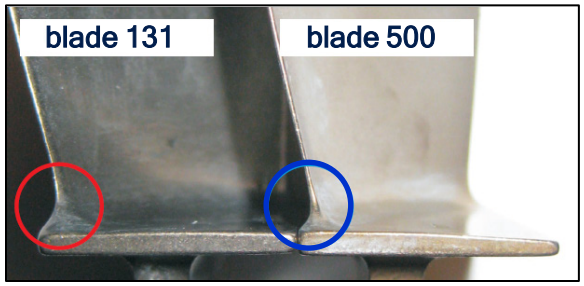


examples for obtained blade-characteristics[2]:



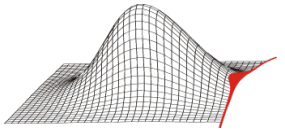


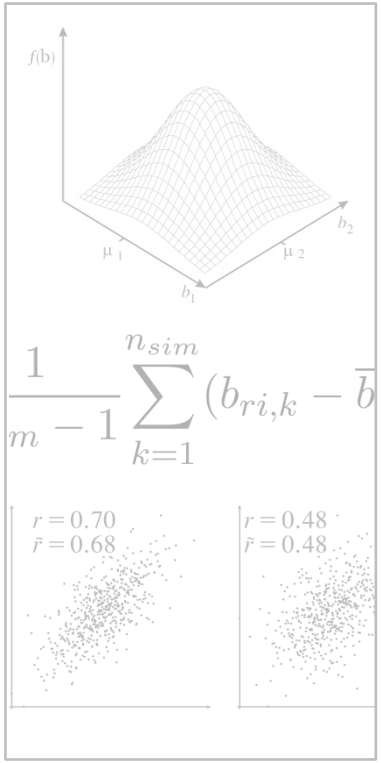


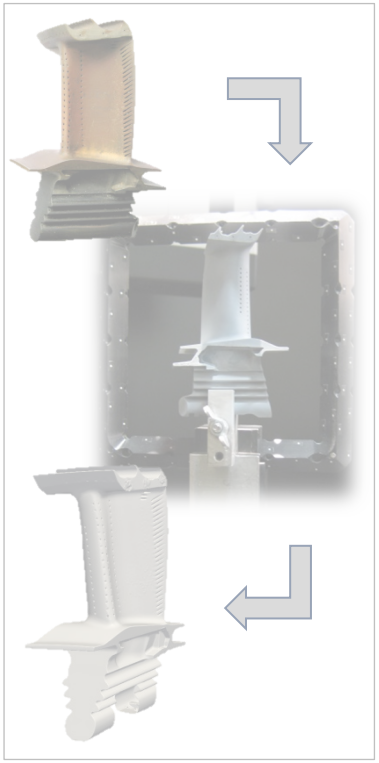


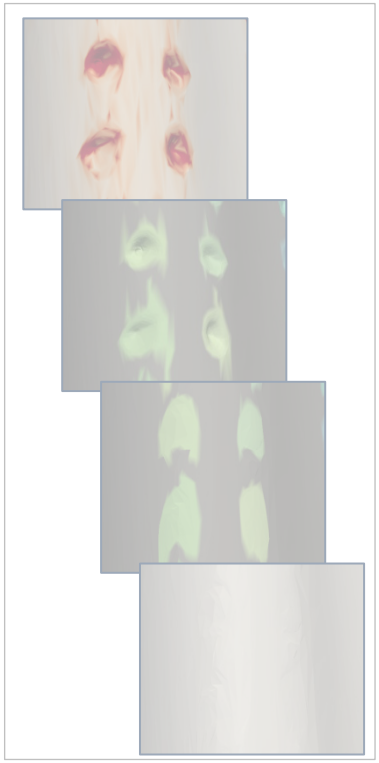
[2] Heinze, K.: *Eine Methode für probabilistische Untersuchungen zum Einfluss von Fertigungsstreuungen auf die hochzyklische Ermüdung von Verdichterschaufeln*, Dissertation

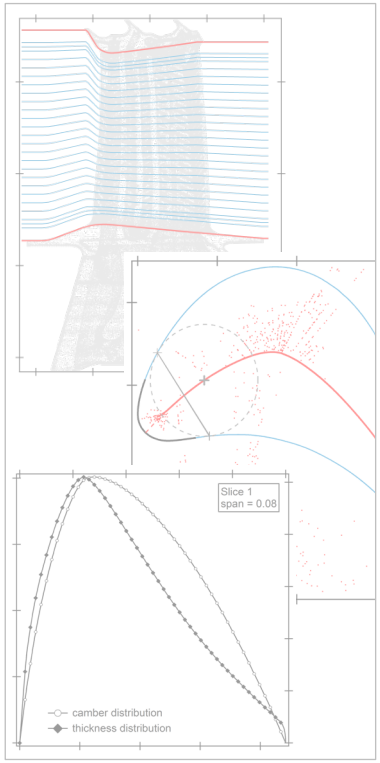
Outline

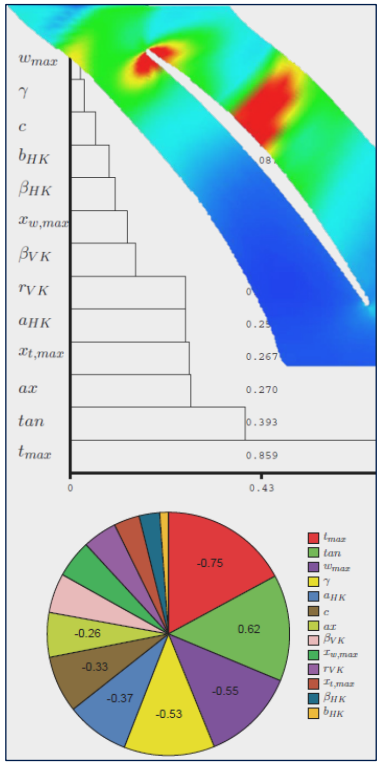






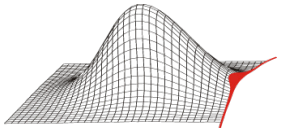


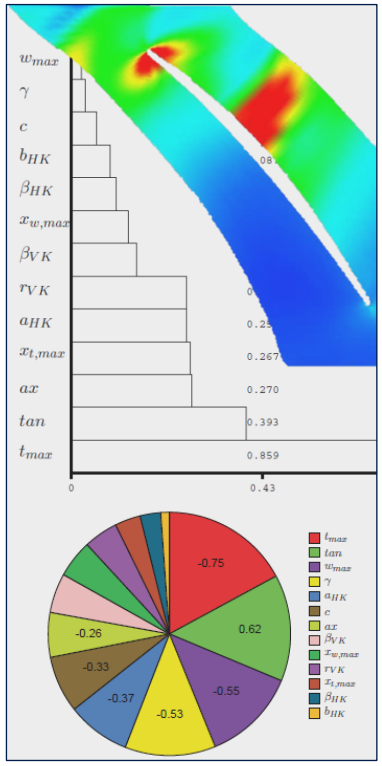




TECHNISCHE UNIVERSITÄT DRESDEN

5 Applications





5.1 Non-deterministic CFD simulation

5.1.1 UQ method - Monte Carlo Simulation

5.1.2 Deterministic model

5.1.3 Incorporate the geometry into CFD mesh

5.1.4 Influence of simulation parameters

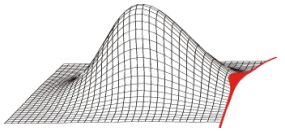
5.1.5 Sensitivity analysis

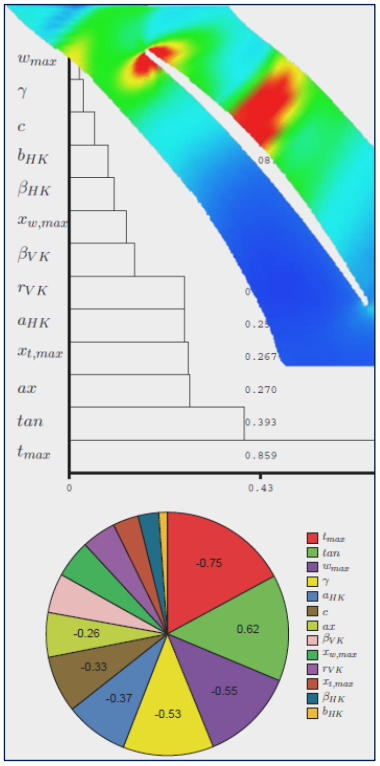
5.1.6 Statistics on passage

5.2 UQ applications

TECHNISCHE UNIVERSITÄT DRESDEN

5 Applications





5.1 Non-deterministic CFD simulation

5.1.1 UQ method - Monte Carlo Simulation

5.1.2 Deterministic model

5.1.3 Incorporate the geometry into CFD mesh

5.1.4 Influence of simulation parameters

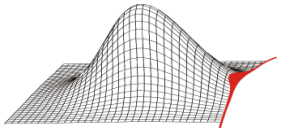
5.1.5 Sensitivity analysis

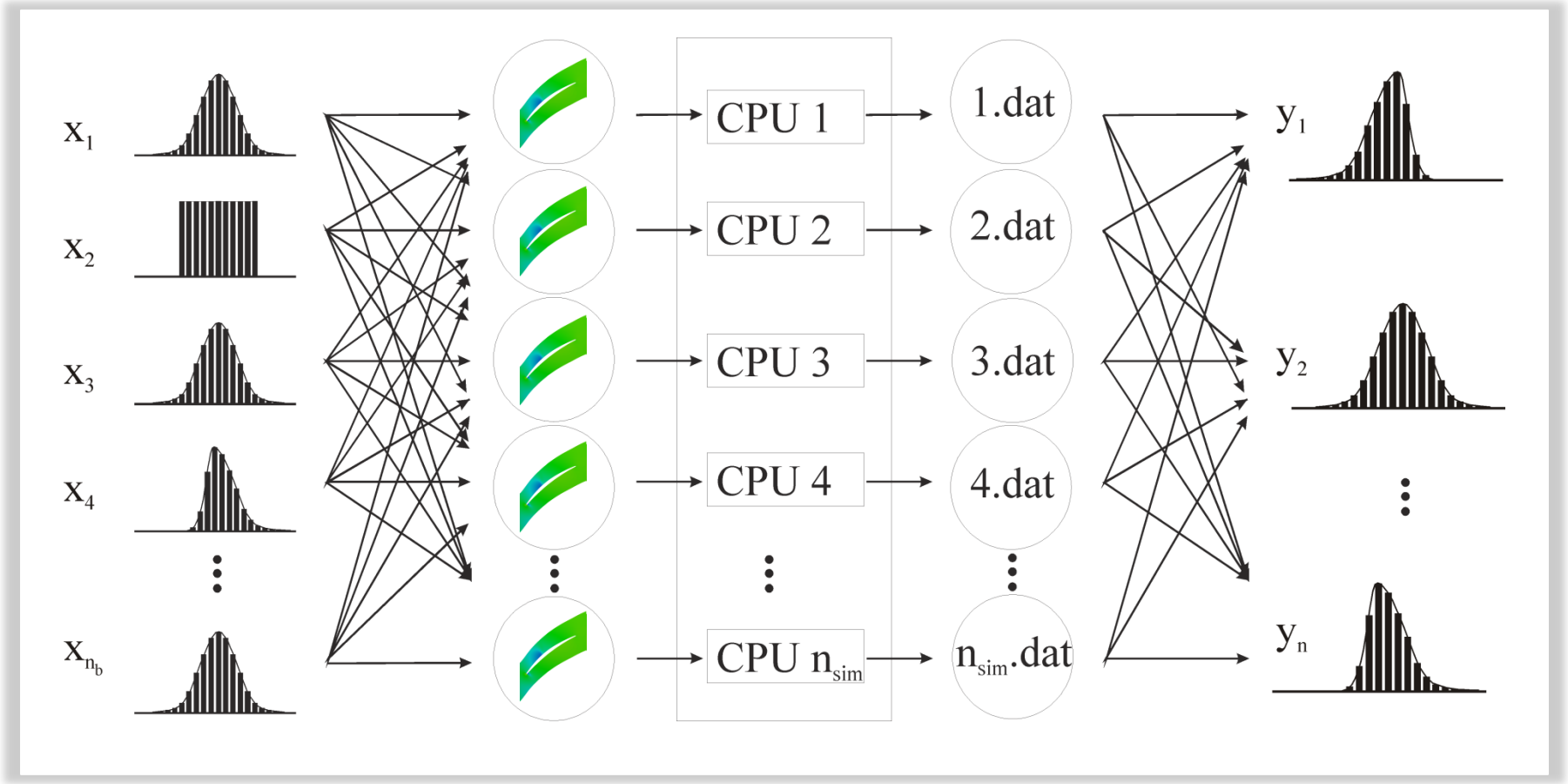
5.1.6 Statistics on passage

5.2 UQ applications

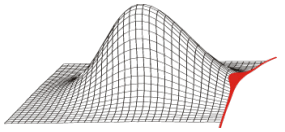
TECHNISCHE UNIVERSITÄT DRESDEN

5.1.1 UQ method – Monte Carlo Simulation



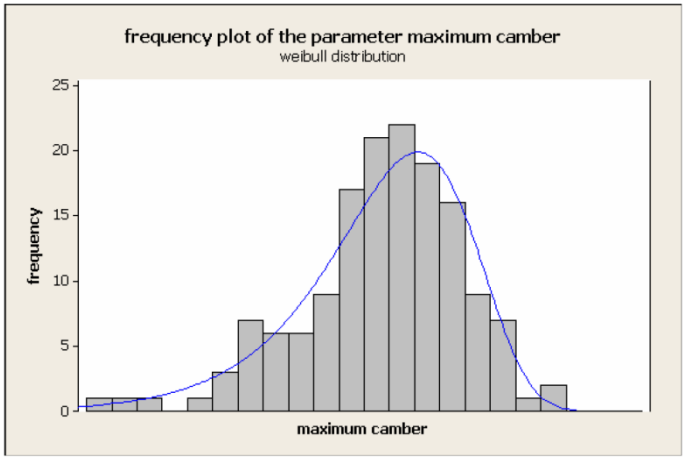


5.1.1 UQ method – Monte Carlo Simulation



Identification of statistical parameters from measured blades

- PDF of marginal distribution with e.g. Anderson-Darling test

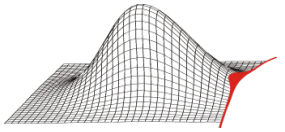


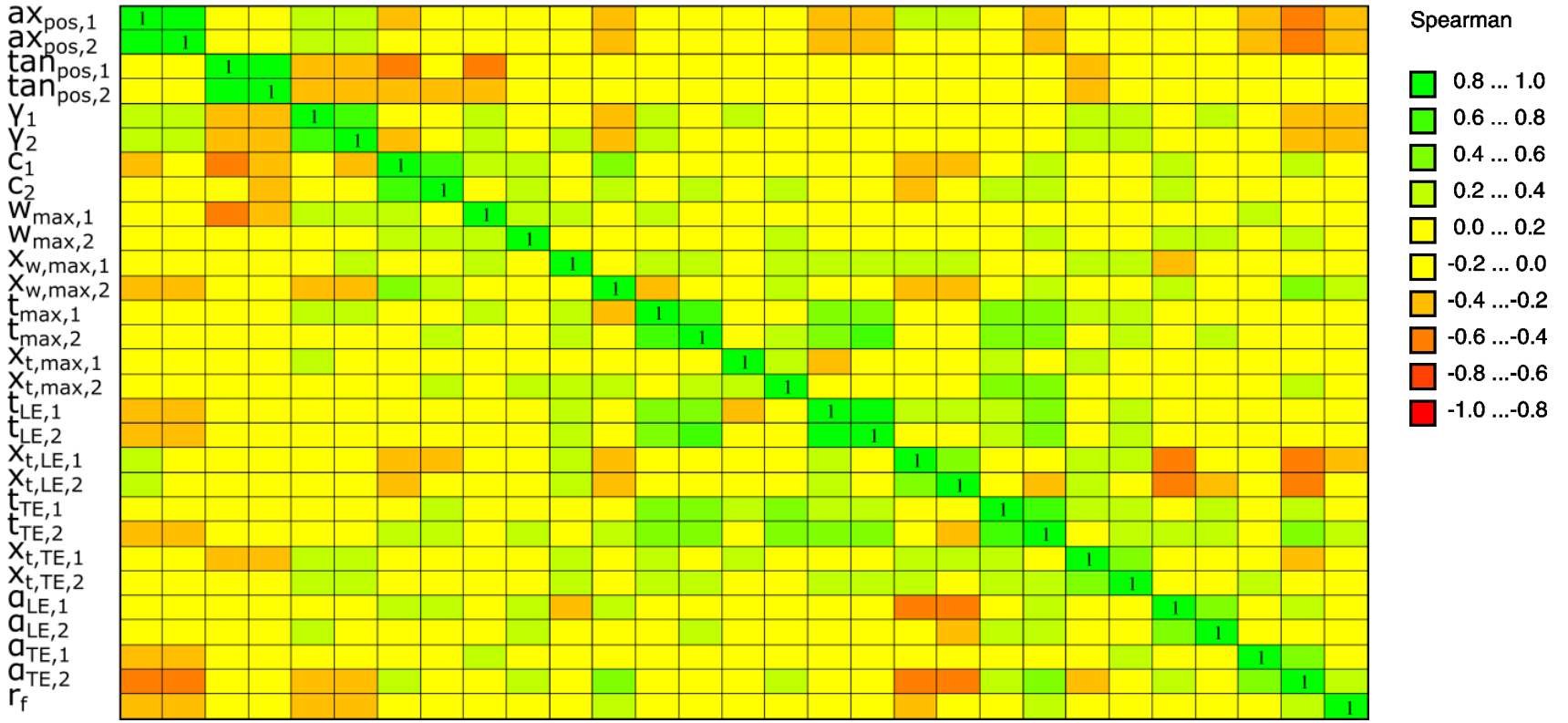
[Lange et al., 2010]

- Linking of the individual marginal distributions in terms of a multivariate distribution (rank correlation, copula)

TECHNISCHE UNIVERSITÄT DRESDEN

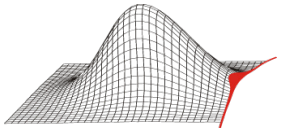
5.1.1 UQ method – Monte Carlo Simulation

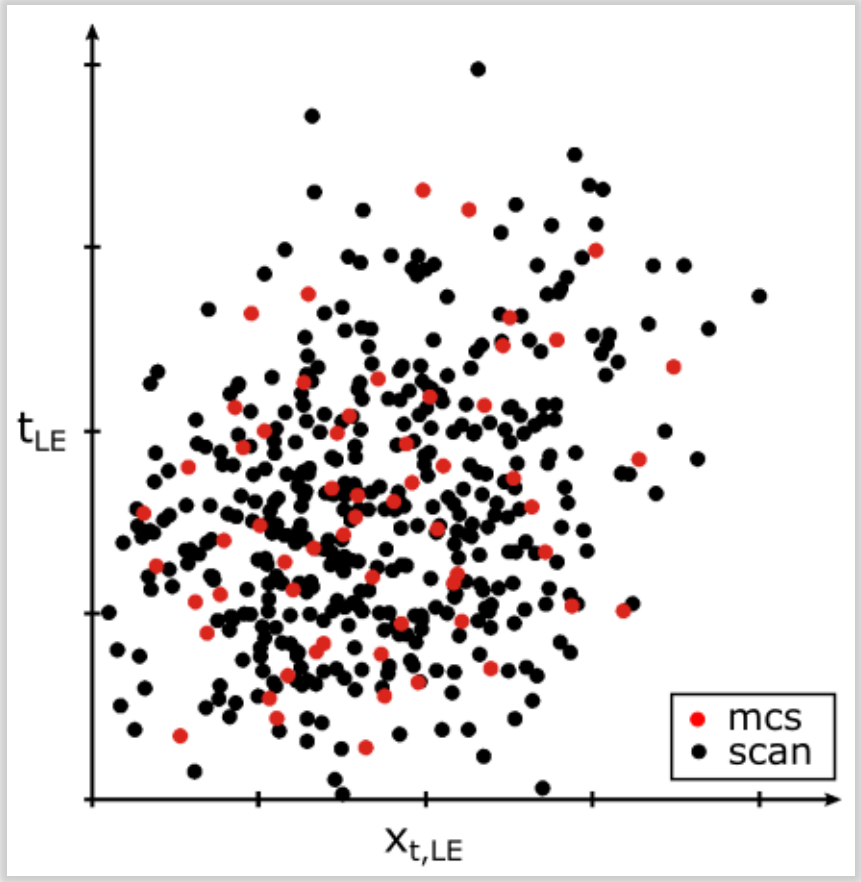




TECHNISCHE UNIVERSITÄT DRESDEN

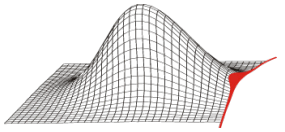
5.1.1 UQ method – Monte Carlo Simulation

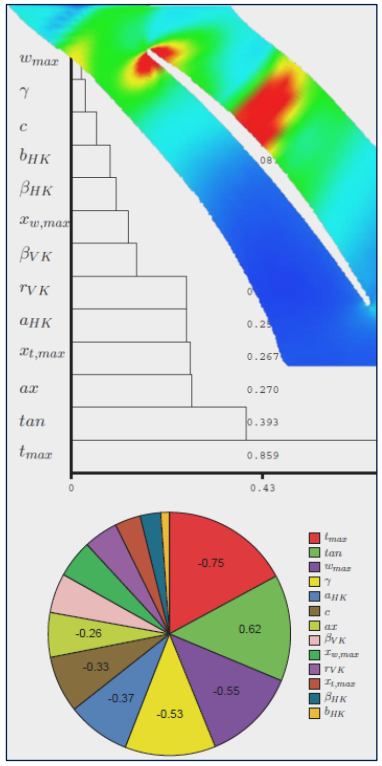




TECHNISCHE UNIVERSITÄT DRESDEN

5 Applications





5.1 Non-deterministic CFD simulation

5.1.1 UQ method - Monte Carlo Simulation

5.1.2 Deterministic model

5.1.3 Incorporate the geometry into CFD mesh

5.1.4 Influence of simulation parameters

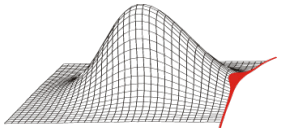
5.1.5 Sensitivity analysis

5.1.6 Statistics on passage

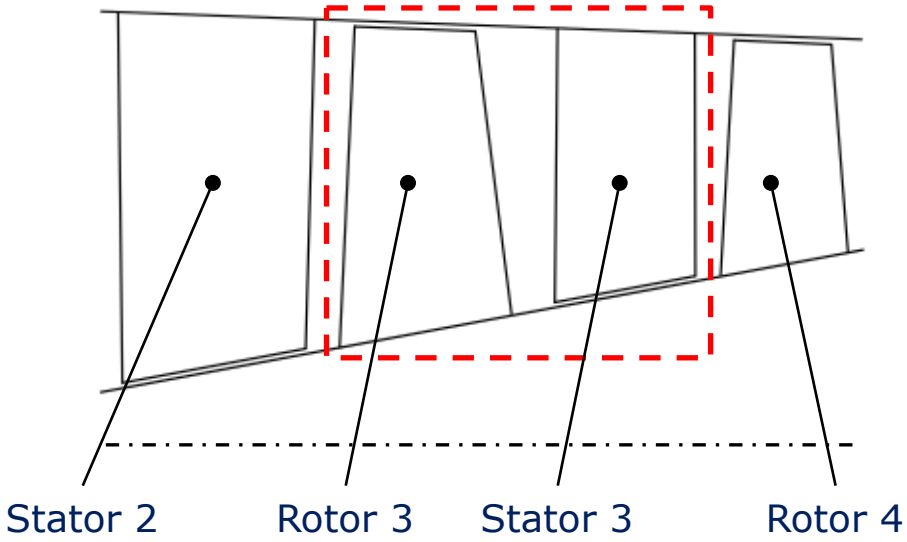
5.2 UQ applications

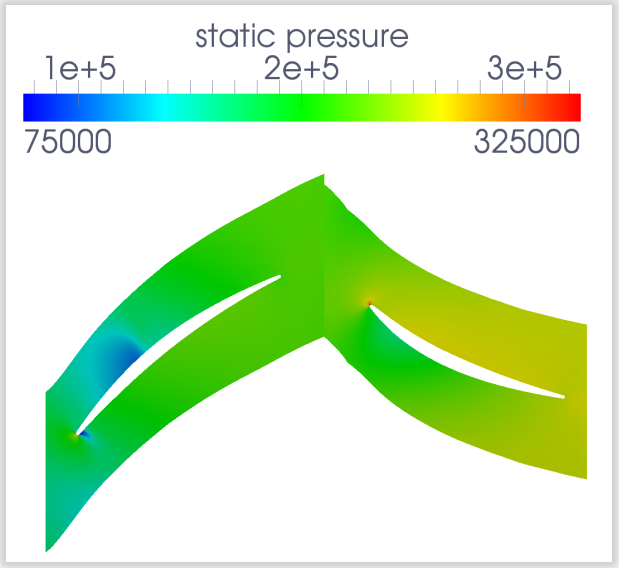
TECHNISCHE UNIVERSITÄT DRESDEN

5.1.2 Deterministic model



- Two-stage high pressure compressor (hpc)

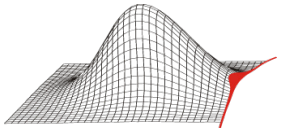


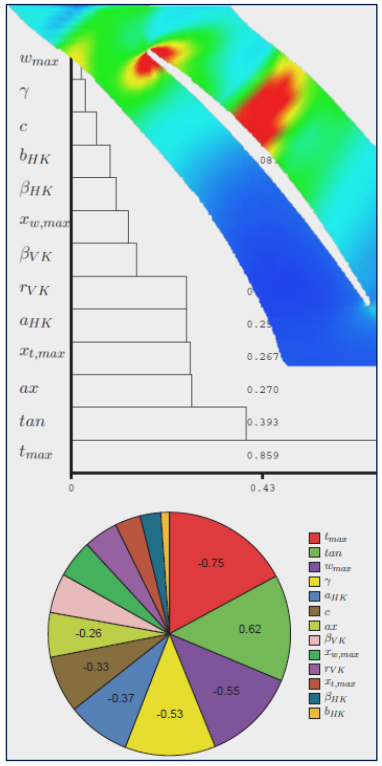


- Deterministic CFD model
  - steady RANS calculation
  - boundary and initial conditions are given by radial profiles at inlet, fixed mass flow at the outlet
  - data transfer between the blocks is solved by mixing planes
  - constant grid setup

TECHNISCHE UNIVERSITÄT DRESDEN

5 Applications





5.1 Non-deterministic CFD simulation

5.1.1 UQ method - Monte Carlo Simulation

5.1.2 Deterministic model

5.1.3 Incorporate the geometry into CFD mesh

5.1.4 Influence of simulation parameters

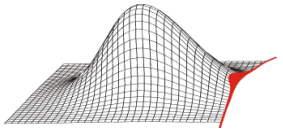
5.1.5 Sensitivity analysis

5.1.6 Statistics on passage

5.2 UQ applications

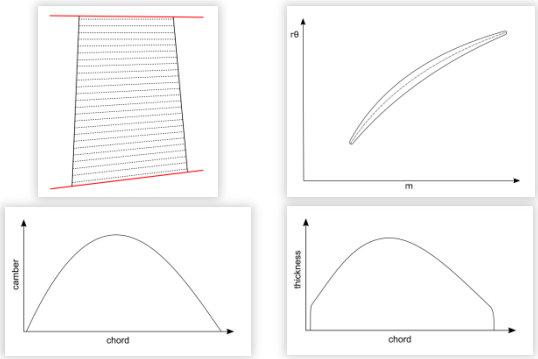
TECHNISCHE UNIVERSITÄT DRESDEN

5.1.3 Incorporate the geometry into CFD mesh



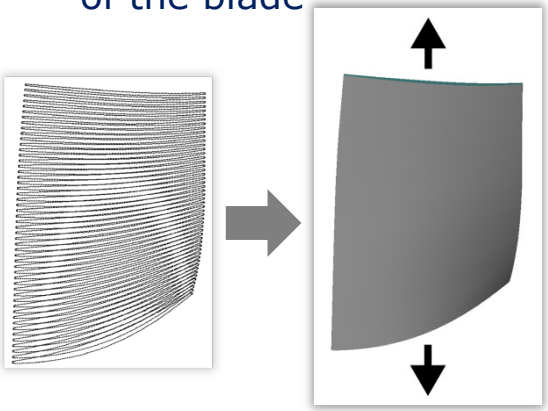
Blade2Parameter → **CAD aerofoil generator** → **CFD input generator**

- parametrisation of the mean model (basis)

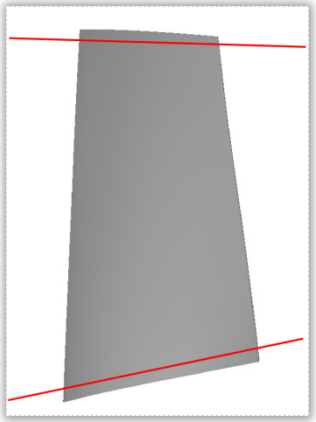


- Δ-parameter which resemble typical scatter of investigated compressor blades
- output of discrete profile sections

- generation of 3D surfaces and extension of the blade

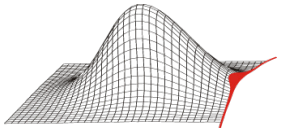


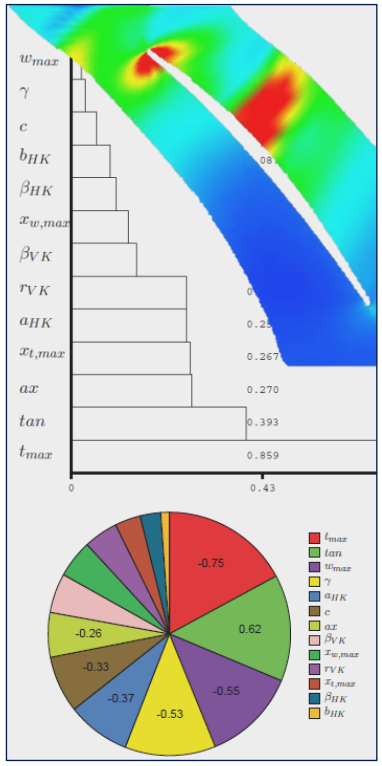
- cut the blade according to the passage contour
- output of geometry file for mesh generation



TECHNISCHE UNIVERSITÄT DRESDEN

5 Applications





5.1 Non-deterministic CFD simulation

5.1.1 UQ method - Monte Carlo Simulation

5.1.2 Deterministic model

5.1.3 Incorporate the geometry into CFD mesh

5.1.4 Influence of simulation parameters

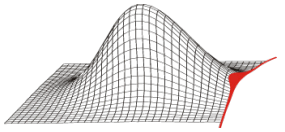
5.1.5 Sensitivity analysis

5.1.6 Statistics on passage

5.2 UQ applications

TECHNISCHE UNIVERSITÄT DRESDEN

5.1.4 Influence of simulation parameters



Parameters:

- Grid Resolution
  - Deterministic Grid Study

no. of grid nodes [$\cdot 10^6$]	0.45	0.9	1.8	3.6 (ref)
calculation time [h]*	0.5	1	2.5	6
η/η_{ref}	0.9847	0.9928	0.9977	1
M/M_{ref}	1.0074	1.0041	1.0040	1
$\Delta p_t/\Delta p_{t\,ref}$	0.9983	0.9998	1.0002	1

*parallel calculation on 4 Intel Itanium CPU

[Lange et al., 2010]

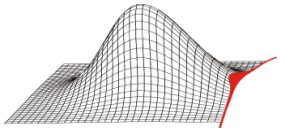
  - Probabilistic Grid Study

no. of grid nodes [$\cdot 10^6$]	0.9	1.8 (ref)	$\tilde{r}(0.9, 1.8)$
$\sigma(\eta)/\sigma(\eta_{ref})$	1.0782	1	0.99
$\sigma(M)/\sigma(M_{ref})$	1.0493	1	1.00
$\sigma(\Delta p_t)/\sigma(\Delta p_{t\,ref})$	1.0534	1	1.00

[Lange et al., 2010]

TECHNISCHE UNIVERSITÄT DRESDEN

5.1.4 Influence of simulation parameters



Parameters:

- Grid Resolution
- Number of Iterations

no. of iterations	150	300	600 (ref)
$\sigma(\eta)/\sigma(\eta_{ref})$	1.0565	1.0055	1
$\sigma(M)/\sigma(M_{ref})$	0.9983	1.0002	1
$\sigma(\Delta p_t)/\sigma(\Delta p_{t\,ref})$	0.9958	0.9988	1

[Lange et al., 2010]

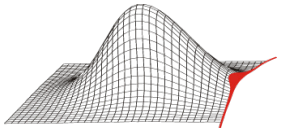
- Spanwise Averaging Sections

no. of averaging sections	1	2	4	7 (ref)
no. of parameters	18	34	66	114
$\sigma(\eta)/\sigma(\eta_{ref})$	0.9369	0.9722	0.9976	1
$\sigma(M)/\sigma(M_{ref})$	1.0064	1.0010	0.9981	1
$\sigma(\Delta p_t)/\sigma(\Delta p_{t\,ref})$	0.9801	0.9855	0.9966	1

[Lange et al., 2010]

TECHNISCHE UNIVERSITÄT DRESDEN

5.1.4 Influence of simulation parameters



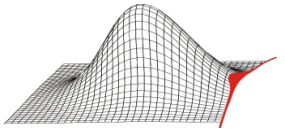
Parameters:

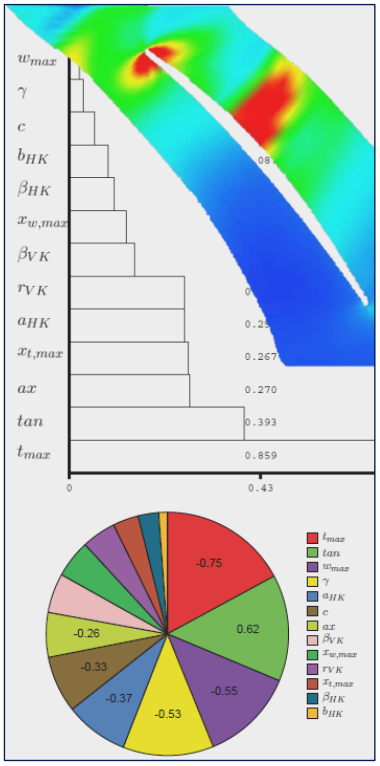
- Grid Resolution
- Number of Iterations
- Spanwise Averaging Sections
- Number of MC realization

  Usage of an adaptive sampling scheme – extended Latin Hypercube Sampling [Schmidt et al., 2014]

TECHNISCHE UNIVERSITÄT DRESDEN

5 Applications





5.1 Non-deterministic CFD simulation

5.1.1 UQ method - Monte Carlo Simulation

5.1.2 Deterministic model

5.1.3 Incorporate the geometry into CFD mesh

5.1.4 Influence of simulation parameters

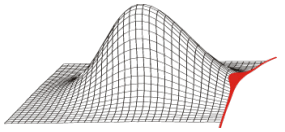
5.1.5 Sensitivity analysis

5.1.6 Statistics on passage

5.2 UQ applications

TECHNISCHE UNIVERSITÄT DRESDEN

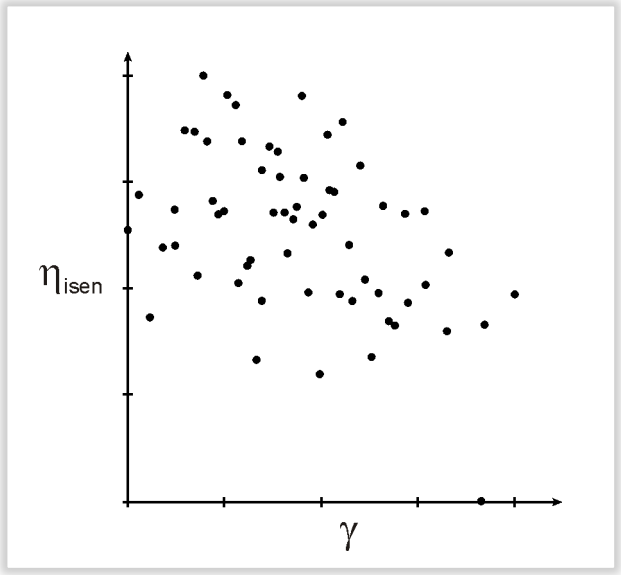
5.1.5 Sensitivity analysis



Result quantity: Isentropic efficiency of stage 3

$$\eta_{isen} = \frac{\text{specific compressor work isentropic}}{\text{specific compressor work polytropic}}$$

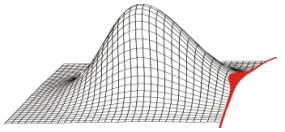
Use of rank correlation coefficient:



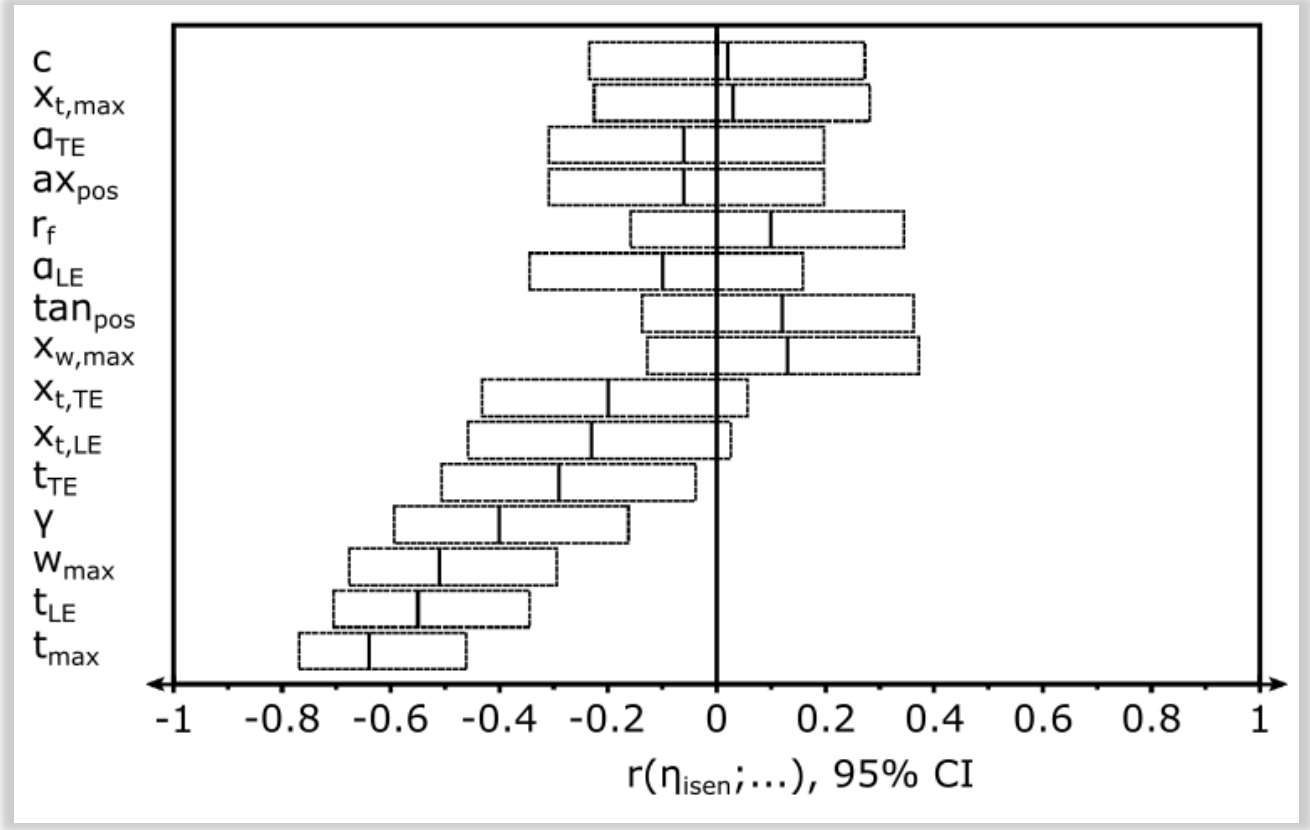
$$\tilde{r} = -0.40$$

TECHNISCHE UNIVERSITÄT DRESDEN

5.1.5 Sensitivity analysis

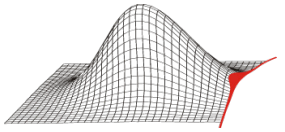


Rank correlation coefficient for result quantity: Isentropic efficiency of stage 3



TECHNISCHE UNIVERSITÄT DRESDEN

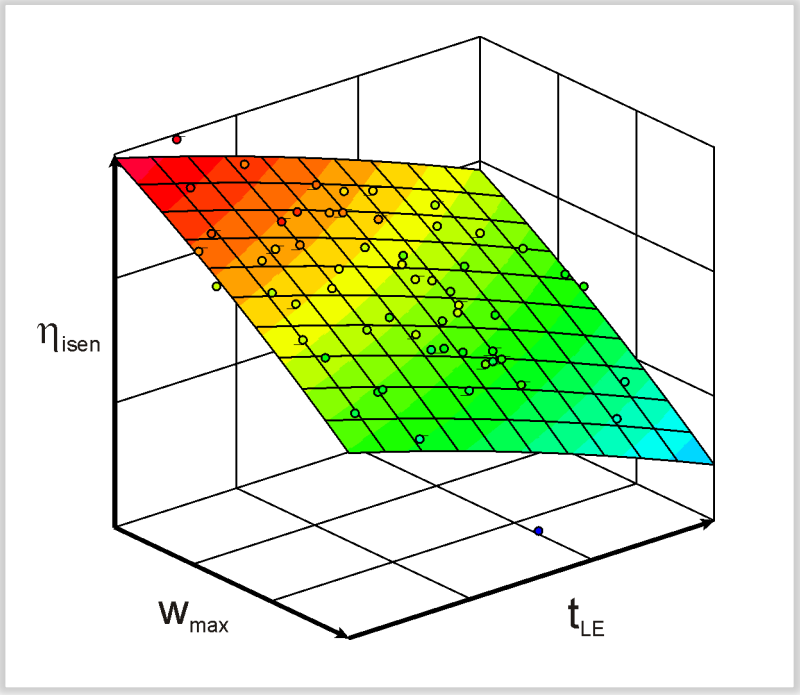
5.1.5 Sensitivity analysis



Result quantity: Isentropic efficiency of stage 3

Use of response surface methods:

$$\tilde{y}_i = c_0 + c_1 b_{1,i} + c_2 b_{2,i} + c_3 {b_{1,i}}^2 + c_4 {b_{2,i}}^2$$



Calculation of the Coefficient of Importance:

$$CoI_{i,j} = {R_i}^2 - {R_{i,j}}^2$$

Evaluation of response surface with Monte Carlo cross-validation.

[Beschorner et al., 2014]

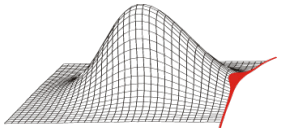
Polynomial of second order without mixed terms delivers:

$$R_{mccv,\eta_{isen}} = 0.962$$

$$R_{\eta_{isen}} = 0.994$$

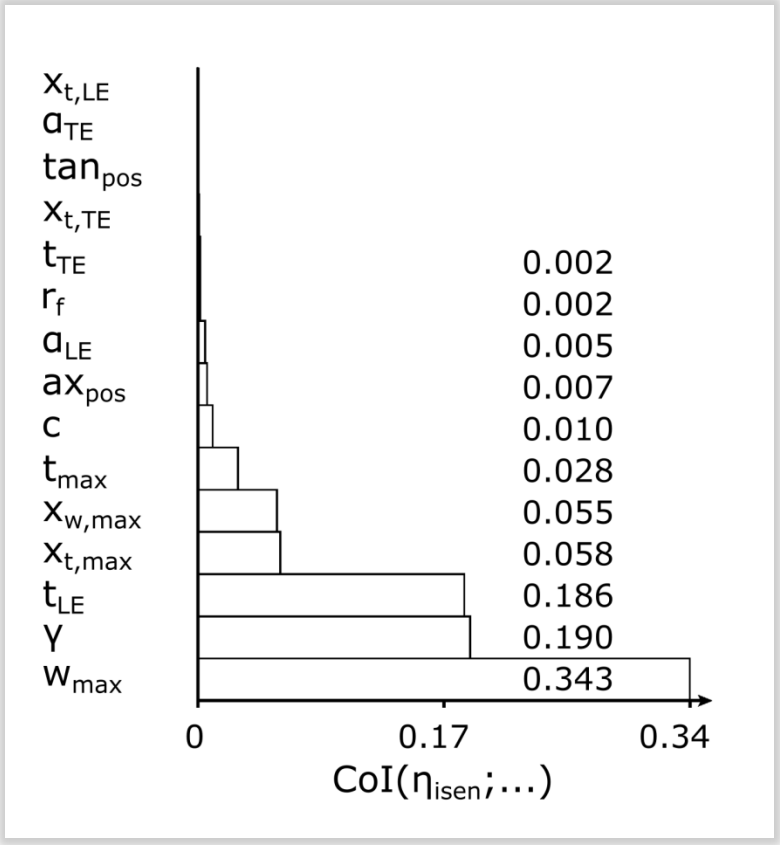
TECHNISCHE UNIVERSITÄT DRESDEN

5.1.5 Sensitivity analysis



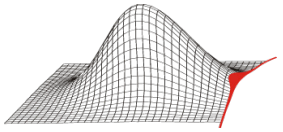
Result quantity: Isentropic efficiency of stage 3

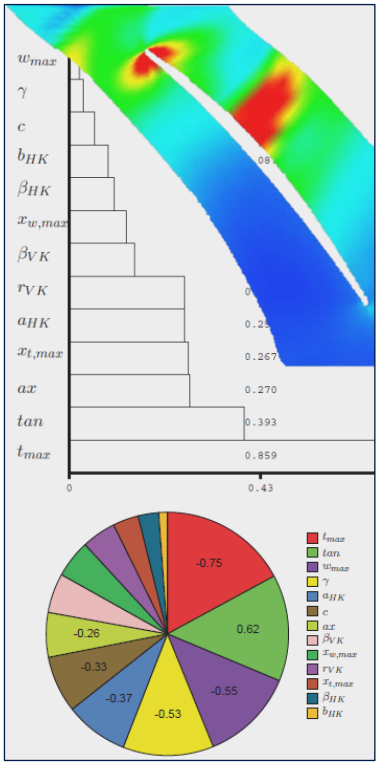
Use of response surface methods:



TECHNISCHE UNIVERSITÄT DRESDEN

5 Applications





5.1 Non-deterministic CFD simulation

5.1.1 UQ method - Monte Carlo Simulation

5.1.2 Deterministic model

5.1.3 Incorporate the geometry into CFD mesh

5.1.4 Influence of simulation parameters

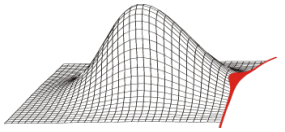
5.1.5 Sensitivity analysis

5.1.6 Statistics on passage

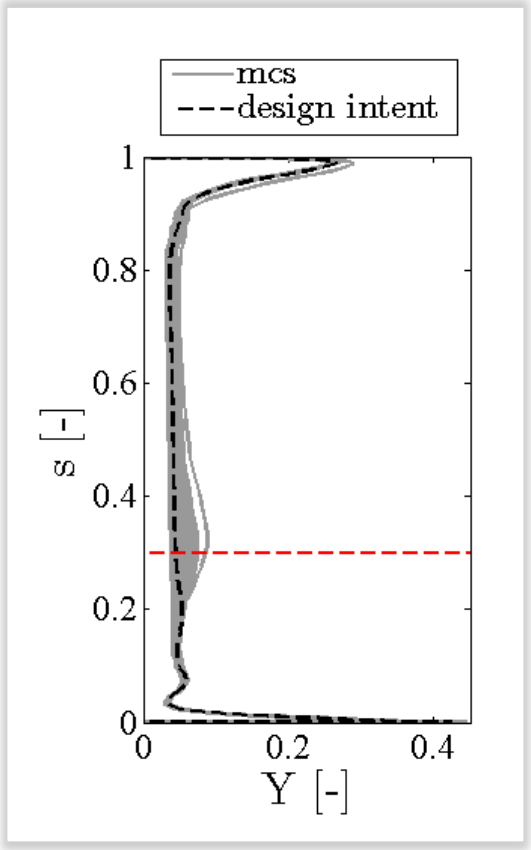
5.2 UQ applications

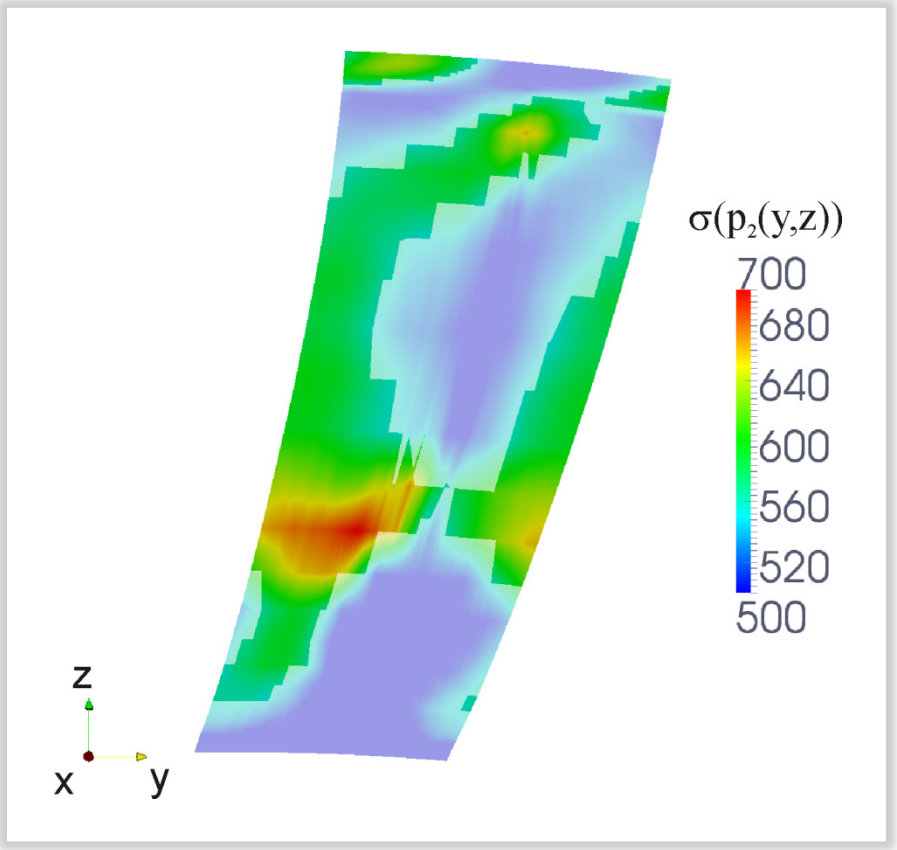
TECHNISCHE UNIVERSITÄT DRESDEN

5.1.6 Statistics on passage



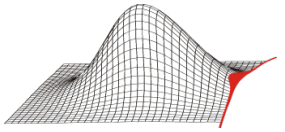
Result quantity: Loss of rotor 3 $$Y = \frac{p_{2,isen} - p_2}{p_{t,1} - p_1}$$





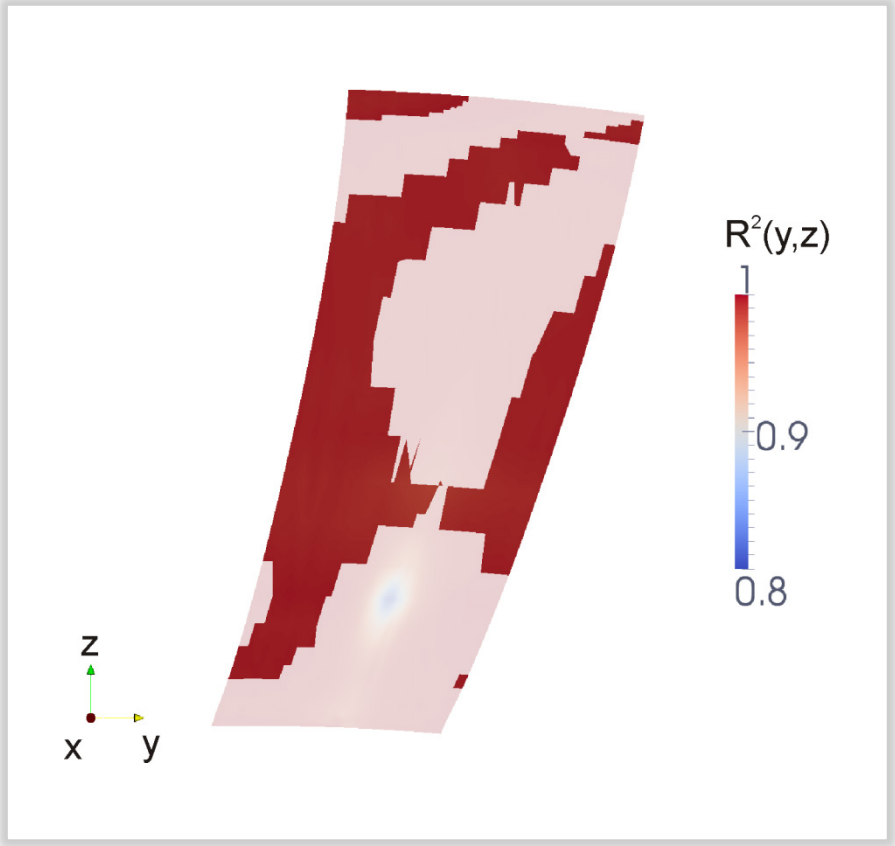
TECHNISCHE UNIVERSITÄT DRESDEN

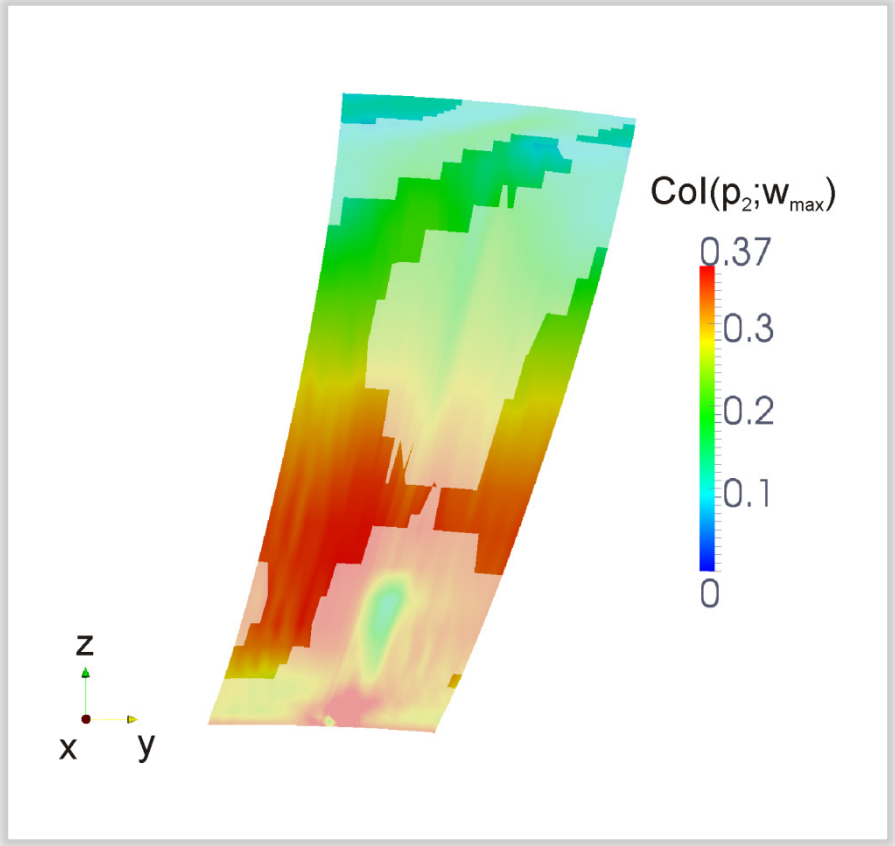
5.1.6 Statistics on passage



Result quantity: Loss of rotor 3

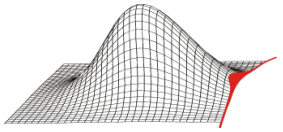
Use of response surface methods: polynomial of 2nd order without mixed terms

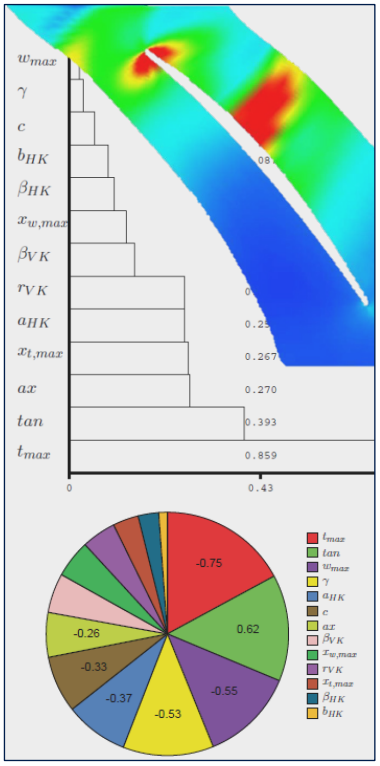




TECHNISCHE UNIVERSITÄT DRESDEN

5 Applications





5.1 Non-deterministic CFD simulation

5.1.1 UQ method - Monte Carlo Simulation

5.1.2 Deterministic model

5.1.3 Incorporate the geometry into CFD mesh

5.1.4 Influence of simulation parameters

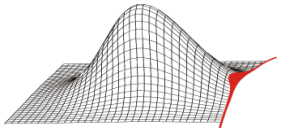
5.1.5 Sensitivity analysis

5.1.6 Statistics on passage

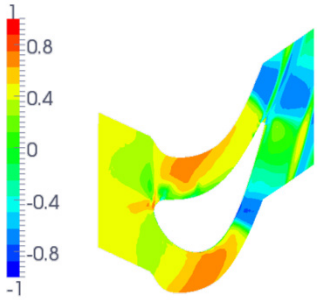
5.2 UQ applications

TECHNISCHE UNIVERSITÄT DRESDEN

5.2 UQ applications

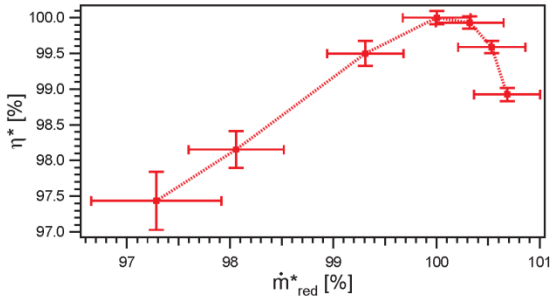


- Probabilistic CFD Analysis of High Pressure Turbine Blades considering real geometric Effects and non-axisymmetric assembling [Scharfenstein et al., 06/2013, Scharfenstein et al., 10/2013]



correlation of relative Mach number and stagger angle
[Scharfenstein et al., 10/2013]

- Probabilistic HCF-investigation of compressor blades considering manufacturing tolerances [Heinze et al., 2009, Heinze, 2015]
- Probabilistic CFD simulation of a high-pressure compressor considering manufacturing tolerances [Lange et al., 2010, Lange et al., 01/2012, Lange et al., 11/2012]



Normalized isentropic efficiency vs. normalized reduced mass flow
[Lange et al., 11/2012]