TECHNISCHE UNIVERSITÄT DRESDEN

Faculty of Mechanical Science and Engineering | Institute of Fluid Mechanics | Chair of Turbomachines and jet Propulsion

Probabilistic LCF Investigation of a Steam Turbine Rotor under Transient Thermal Loads

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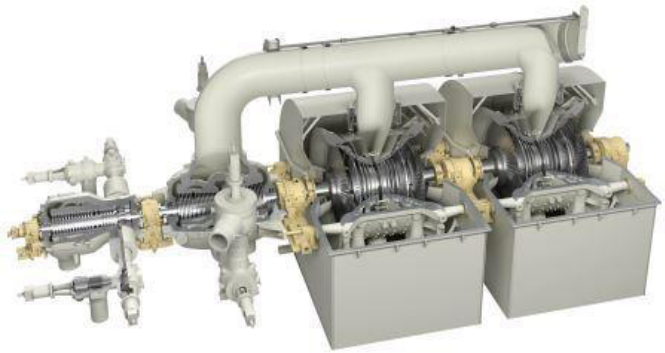
Siemens AG
Mülheim an der Ruhr

DRESDEN concept
Exzellenz aus Wissenschaft und Kultur

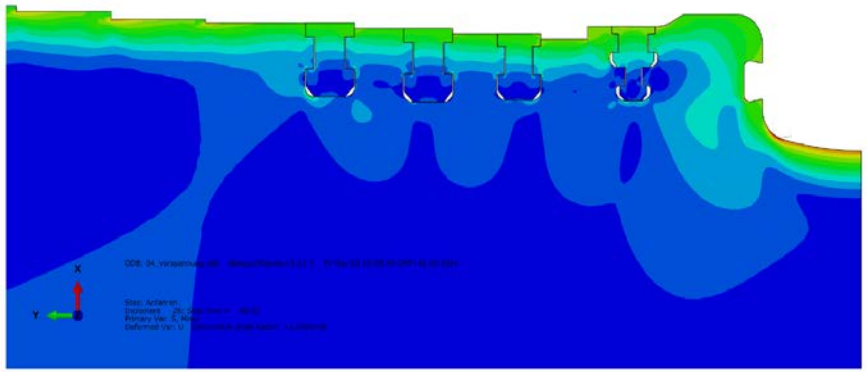
Dresden, 09.10.2015

Motivation



- thermo – mechanic low cycle fatigue in steam turbine rotors during transient operation

Simulation of LCF damage for lifetime prediction



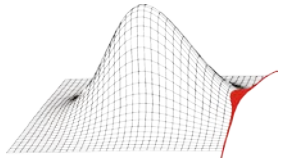
- Measurement data required to define material properties and boundary conditions

www.tu-dresden.de

- Young‘s Modulus
- Poisson‘s Ratio
- Heat Capacity
- Conductivity
- Yield Strength
- Heat Transfer Coefficient
- …

→ Measurement uncertainties affect the accuracy of lifetime prediction

Structure



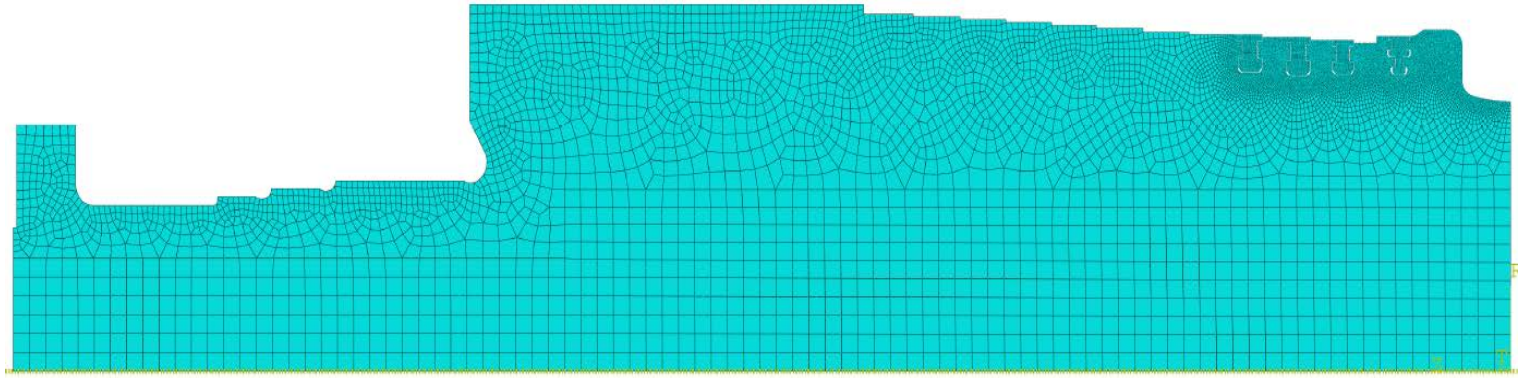
Motivation

LCF Prediction Model

Investigation of Model Uncertainties

Results

The FE Model



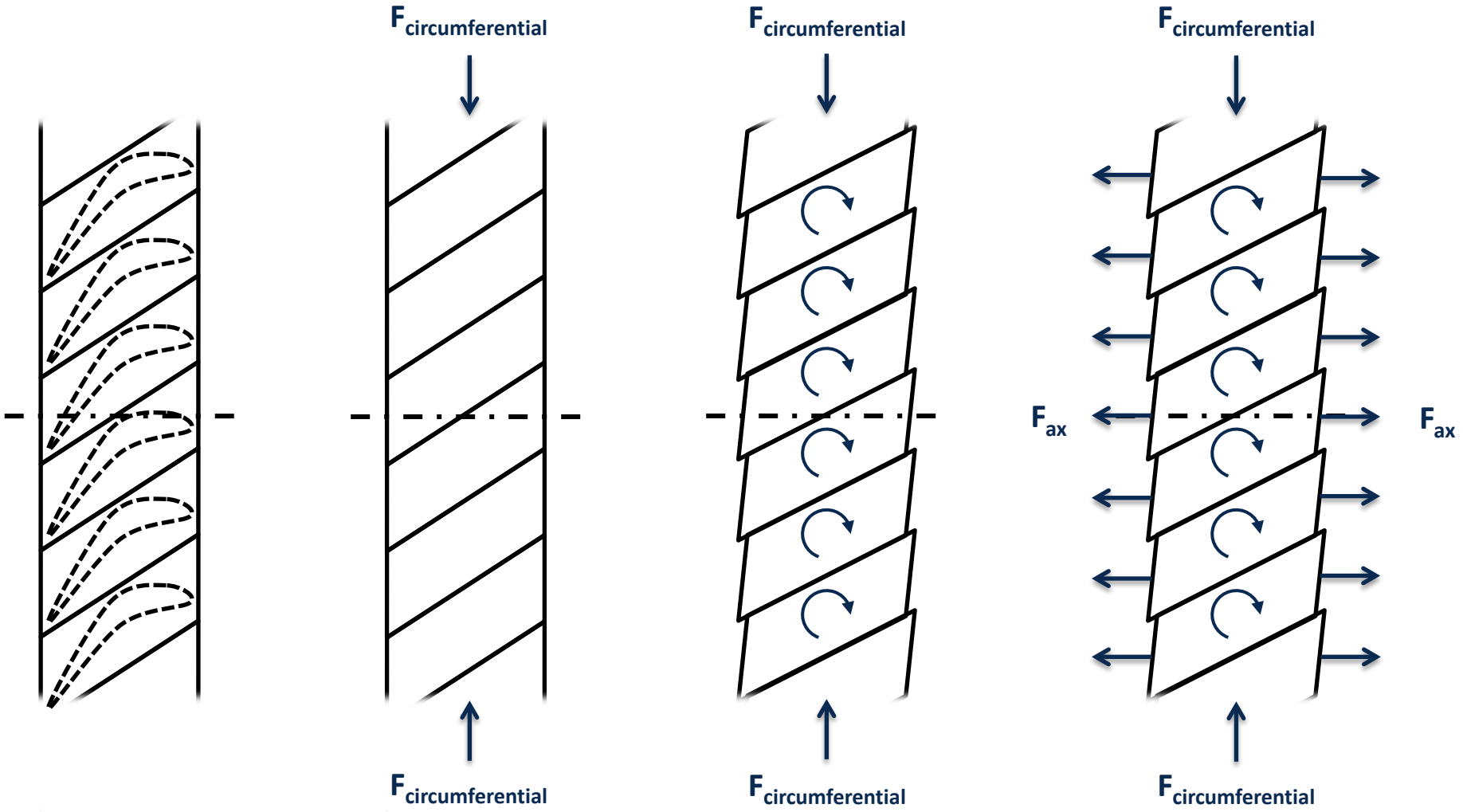
- axisymmetric model of a IP steam turbine shaft
- thermal boundary conditions are calculated based on real operation data
- linear - elastic material

- transformation into elastic-plastic behavior using *Neuber's* rule
- number of cycles to failure from *Wöhler* curve

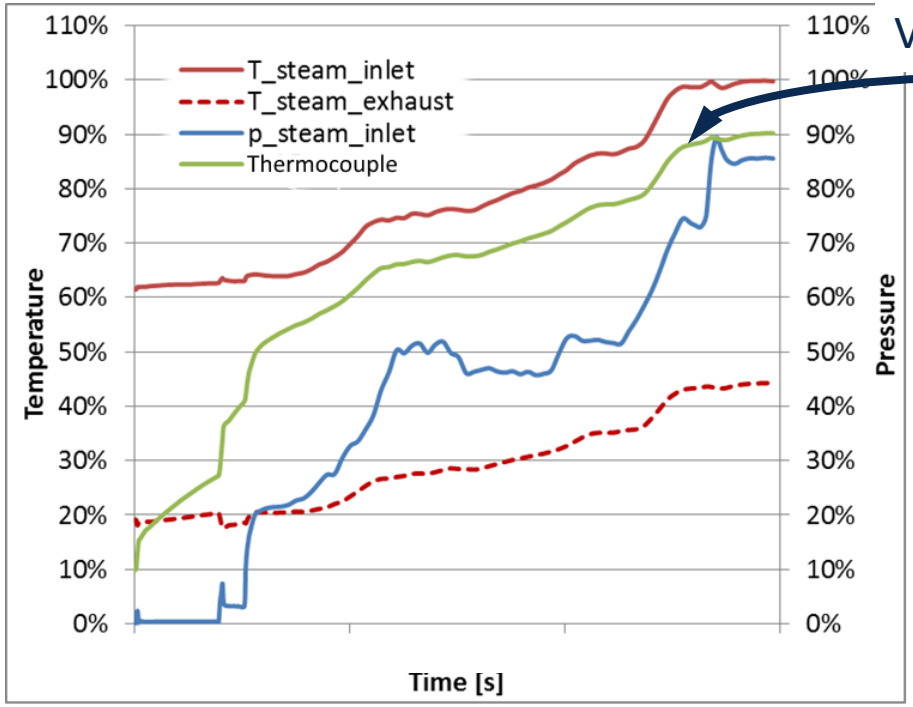
Boundary Conditions:

1. thermal:
   - heat transfer at all wetted surfaces
   - contact conductance between blade root and shaft

2. mechanic:
   - rotation
   - compressive forces
   - axial pretension of blade roots (initial overclosure)


F circumferential
F circumferential
F circumferential
F circumferential
F circumferential
F circumferential
F ax
F ax

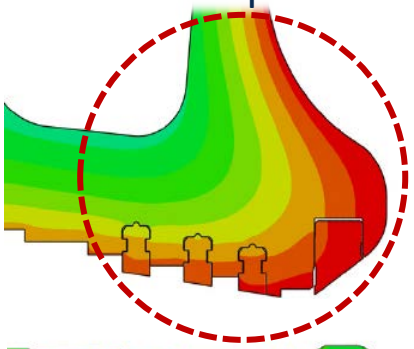
Operating Data

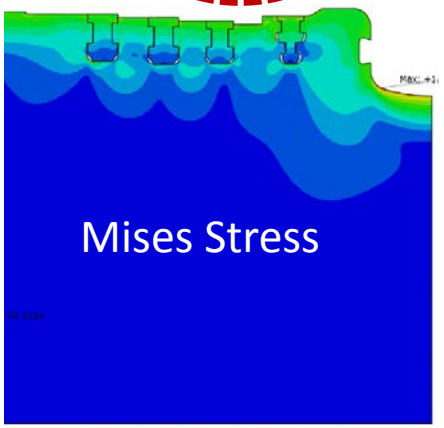


Validation

Temperature

Thermocouple

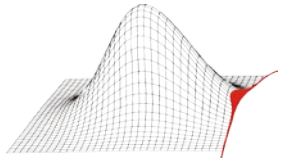


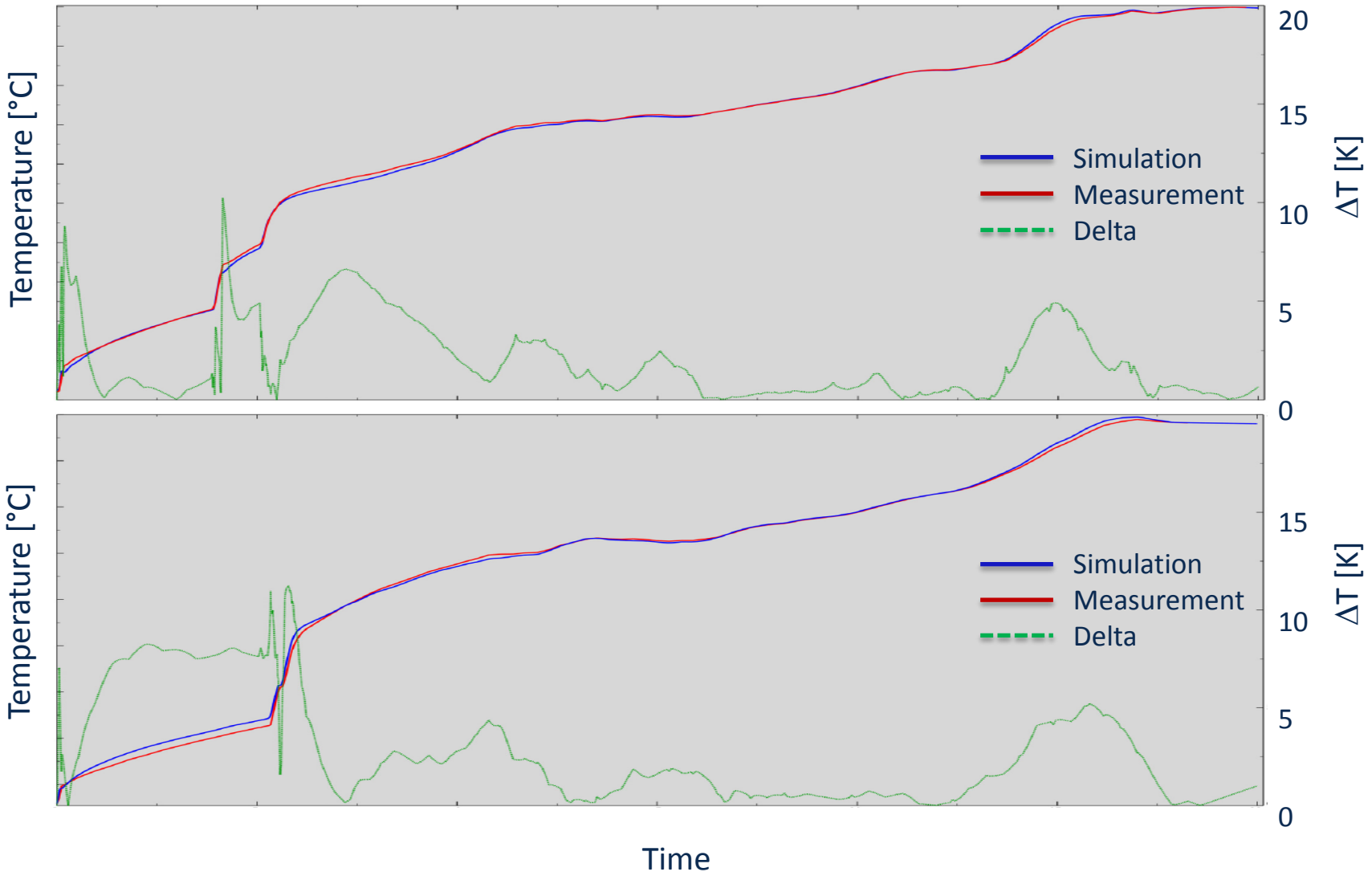


HTC (x,t)

T_{steam} (x,t)

Validation Result





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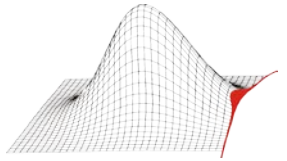
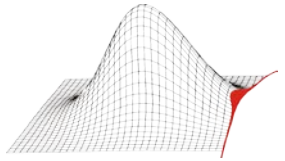
Input Parameters



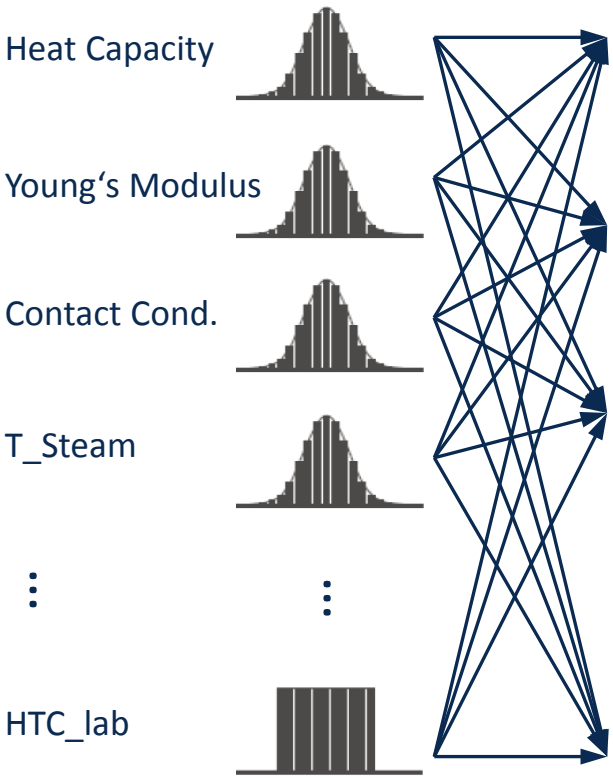
Nr.	Parameter	Distribution	Range	μ, resp. lower bound	σ, resp. upper bound	Bemerkung
1	Density	Gaussian	+- 0.1%	nominal	0.03%	measuring inaccuracy acc. to *Richter*
2	Heat Capacity	Gaussian	+- 3%	nominal	1.0%	measuring inaccuracy acc. to *Richter*
3	Thermal Conductivity	Gaussian	+- 7%	nominal	2.33%	measuring inaccuracy acc. to *Richter*
4	Young‘s Modulus	Gaussian	+- 3%	nominal	1.0%	measuring inaccuracy acc. to *Richter*
5	Poisson‘s Ratio	Gaussian	+- 3%	nominal	1.0%	measuring inaccuracy acc. to *Richter*
6	Lin. Therm. Expans. Coeff.	Gaussian	+- 2%	nominal	0.667%	measuring inaccuracy acc. to *Richter*
7	Yield Strength	Gaussian	+- 3%	nominal	1.0%	based on Young‘s Modulus
8	n (Ramberg-Osgood)	Gaussian	+- 3%	nominal	1.0%	based on Young‘s Modulus
9	p_Steam	Gaussian	+- 0.5%	nominal	0.1667%	measuring inaccuracy acc. to datasheet
10	T_Steam	Gaussian	+- 0.75%	nominal	0.25%	measuring inaccuracy acc. to datasheet
11	Contact conductance	Uniform		1500 W/m²K	4500 W/m²K	estimation
12	HTC_Blade	Uniform	+- 20%	0.8 · nominal	1.2 · nominal	estimation (nusselt correlations)
13	HTC_Labyrinth	Uniform	+- 20%	0.8 · nominal	1.2 · nominal	estimation (nusselt correlations)
14	HTC_vortexcooling	Uniform	+-10%	0.9 · nominal	1.1 · nominal	estimation (nusselt correlations)
15	HTC_miscelleanous	Uniform	+- 20%	0.8 · nominal	1.2 · nominal	estimation (nusselt correlations)
16 - 19	Initial overclosure	Uniform		0 mm	0.05 mm	estimation

F. Richter, *Die physikalischen Eigenschaften der Stähle “Das 100-Stähle-Programm” Teil I: Tafeln und Bilder*. Mülheim an der Ruhr.

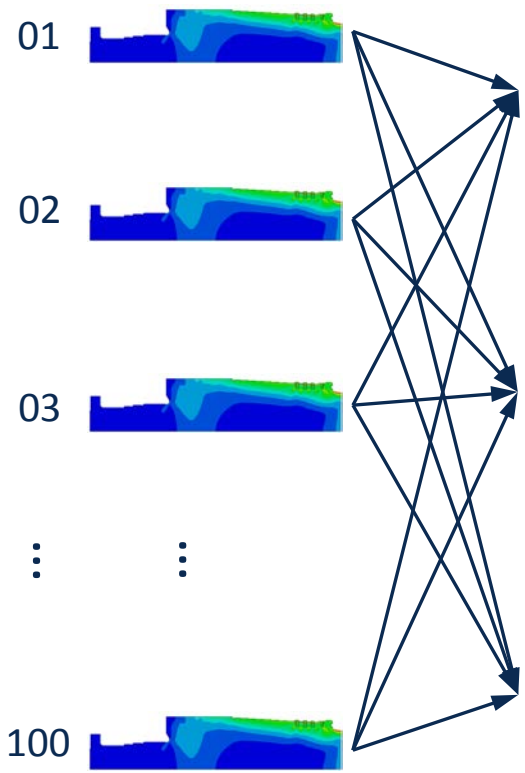
Monte-Carlo-Simulation



Sampling of Input Parameters



Independent deterministic Calculations



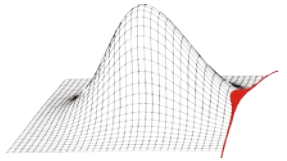
Statistical Evaluation of Target Values

(temperature, stress, …)
e.g.:

- Mean
- Standarddeviation
- Correlations
- Metamodells
- COI
- …

ProSi Pre | ProSi Exe | ProSi Post

Structure



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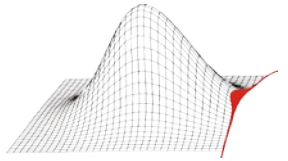
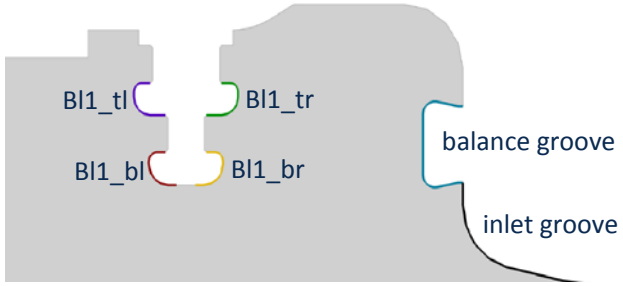
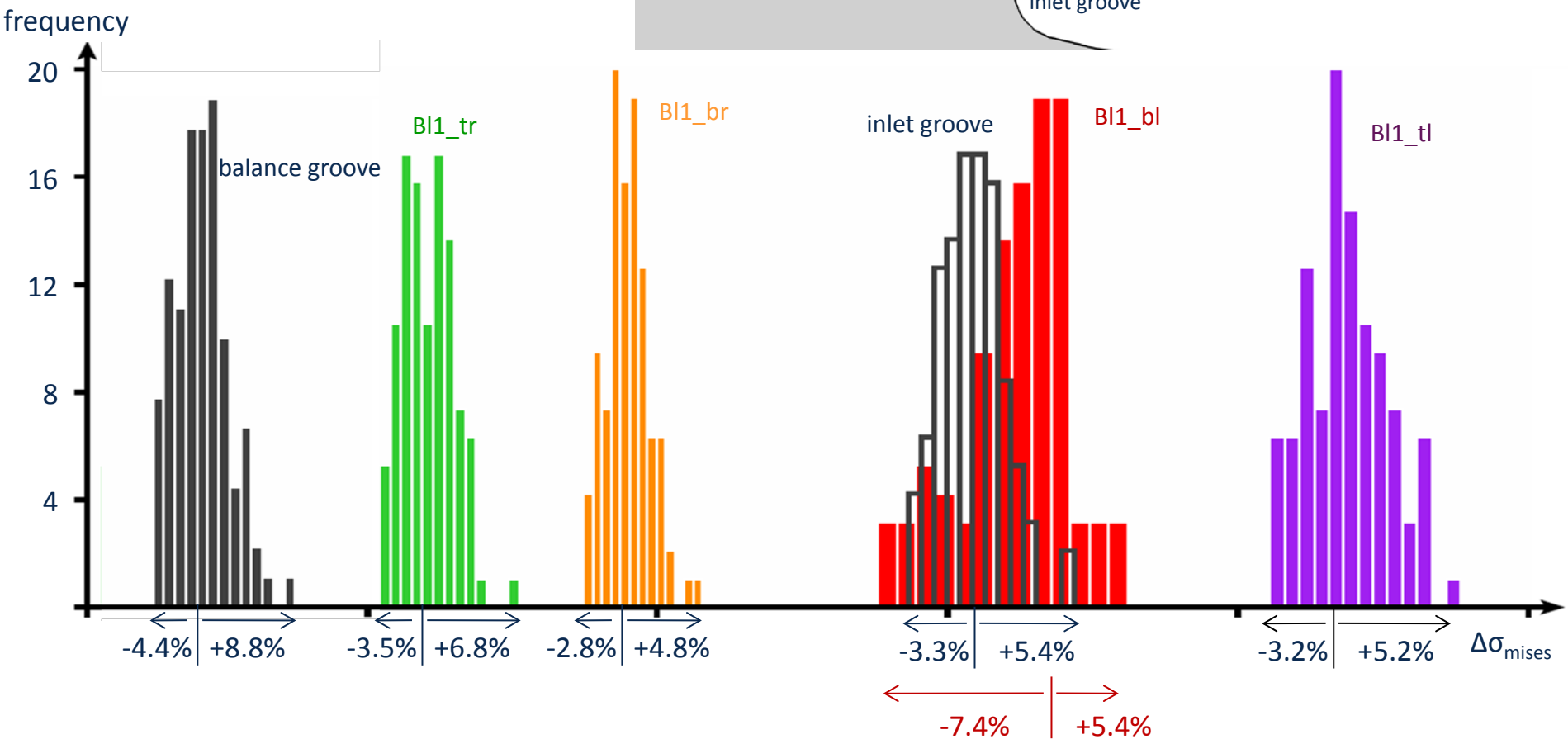
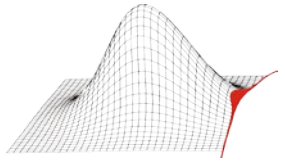
PDF of Stress Amplitude







Correlation Matrix – Stress Amplitude



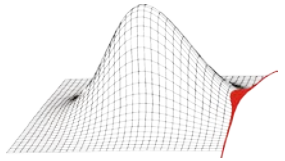
	Density	Heat Capacity	Thermal Conductivity	Young's Modulus	Poisson's Ratio	Lin. Therm. Exp. Coefficient	Yield Strength	N (Ramberg-Osgood)	p_{Steam}	T_{Steam}	Contact Conductance	α_{Blade}	α_{Labyr}	α_{Vortex}	α_{misc}	initial Overclosure Bl. 1	initial Overclosure Bl. 2	initial Overclosure Bl. 3	initial Overclosure Bl. 4
inl. groove	-0.04	0.19	-0.46	0.59	0.32	0.39	-0.06	-0.01	-0.00	0.18	0.10	0.05	0.19	-0.01	-0.00	-0.06	-0.00	-0.09	-0.00
bal. groove	-0.03	0.21	-0.43	0.44	0.29	0.30	-0.05	-0.01	-0.02	0.16	-0.07	-0.15	0.07	-0.09	-0.02	-0.51	-0.17	-0.15	-0.05
Bl1_tl	-0.02	0.19	-0.32	0.52	0.07	0.35	-0.03	-0.00	-0.03	0.17	-0.33	-0.17	-0.09	-0.06	-0.02	-0.52	0.01	-0.07	-0.00
Bl1_bl	-0.06	0.11	-0.23	0.36	0.30	0.26	-0.05	-0.01	0.05	0.16	0.10	-0.17	0.09	-0.00	-0.08	-0.45	0.37	0.18	0.04
Bl1_tr	-0.03	0.16	-0.28	0.46	0.03	0.31	-0.02	-0.01	-0.02	0.18	-0.38	-0.04	-0.02	-0.16	0.01	-0.51	-0.26	-0.15	-0.04
Bl1_br	-0.05	0.19	-0.42	0.63	0.10	0.42	-0.07	-0.01	0.00	0.21	0.09	-0.16	0.05	0.03	0.00	-0.05	-0.22	-0.16	-0.05

Spearman

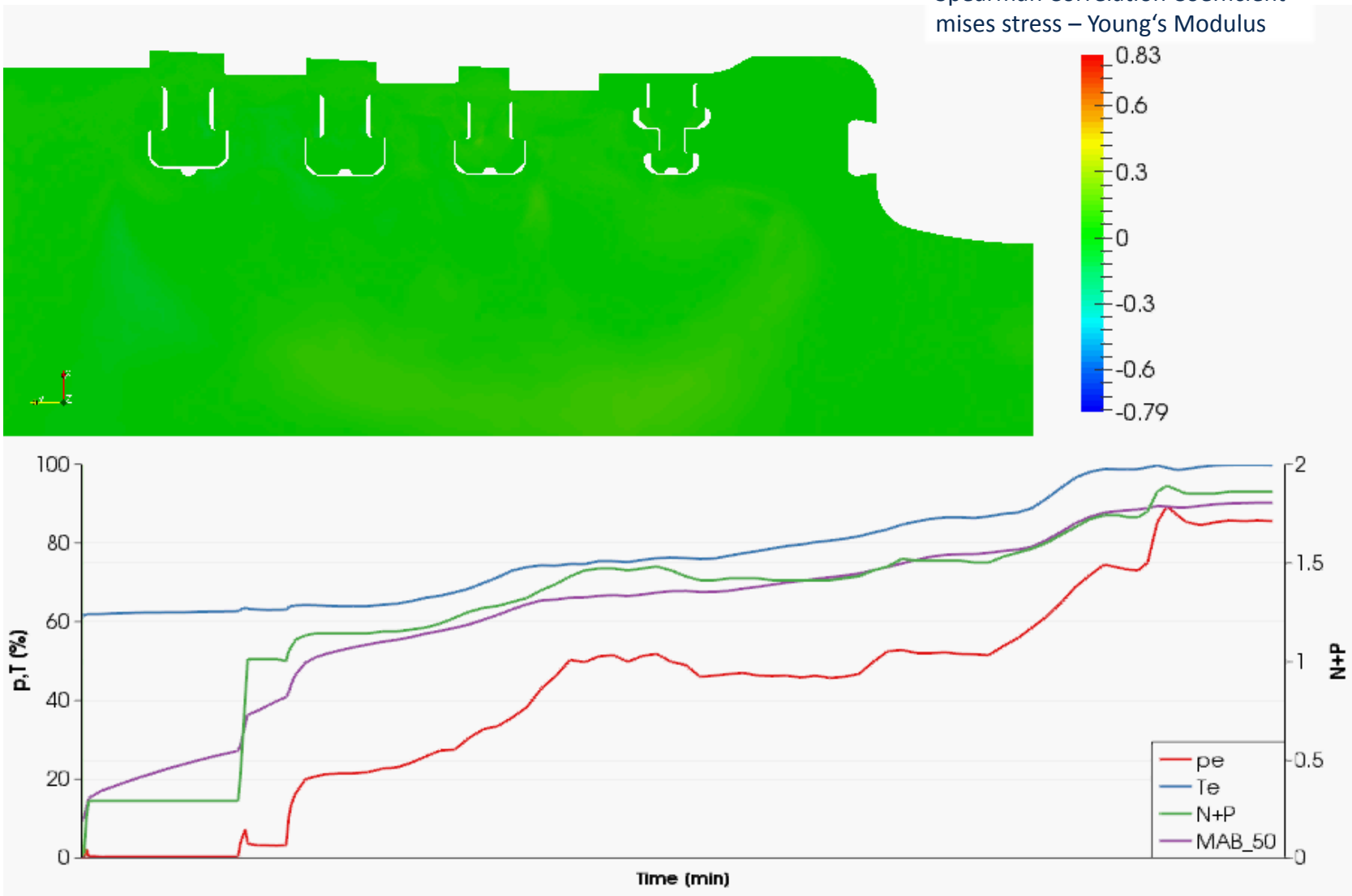
- 0.8 ... 1.0 (0.72 / 1.00)
- 0.6 ... 0.8 (0.46 / 0.86)
- 0.4 ... 0.6 (0.22 / 0.71)
- 0.2 ... 0.4 (0.00 / 0.55)
- 0.0 ... 0.2 (-0.20 / 0.38)
- -0.2 ... 0.0 (-0.38 / 0.20)
- -0.4 ...-0.2 (-0.55 / -0.00)
- -0.6 ...-0.4 (-0.71 / -0.22)
- -0.8 ...-0.6 (-0.86 / -0.46)
- -1.0 ...-0.8 (-1.00 / -0.72)

level of confidence: 95%

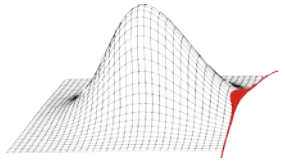
Mises Stress – Young‘s Modulus

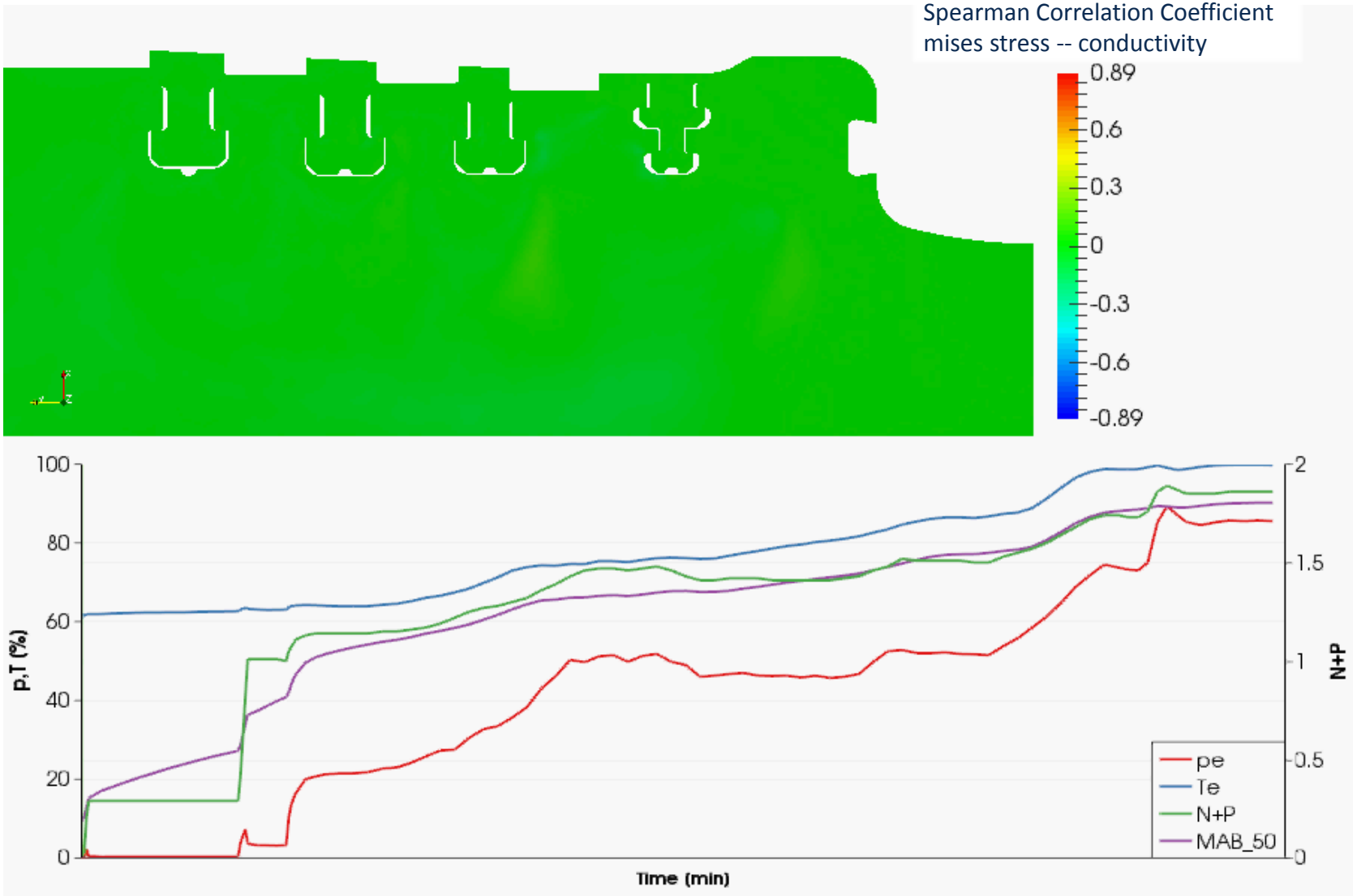


Spearman Correlation Coefficient
mises stress – Young‘s Modulus

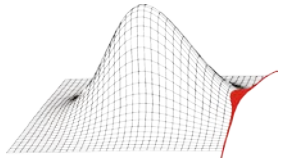


Mises Stress – Conductivity

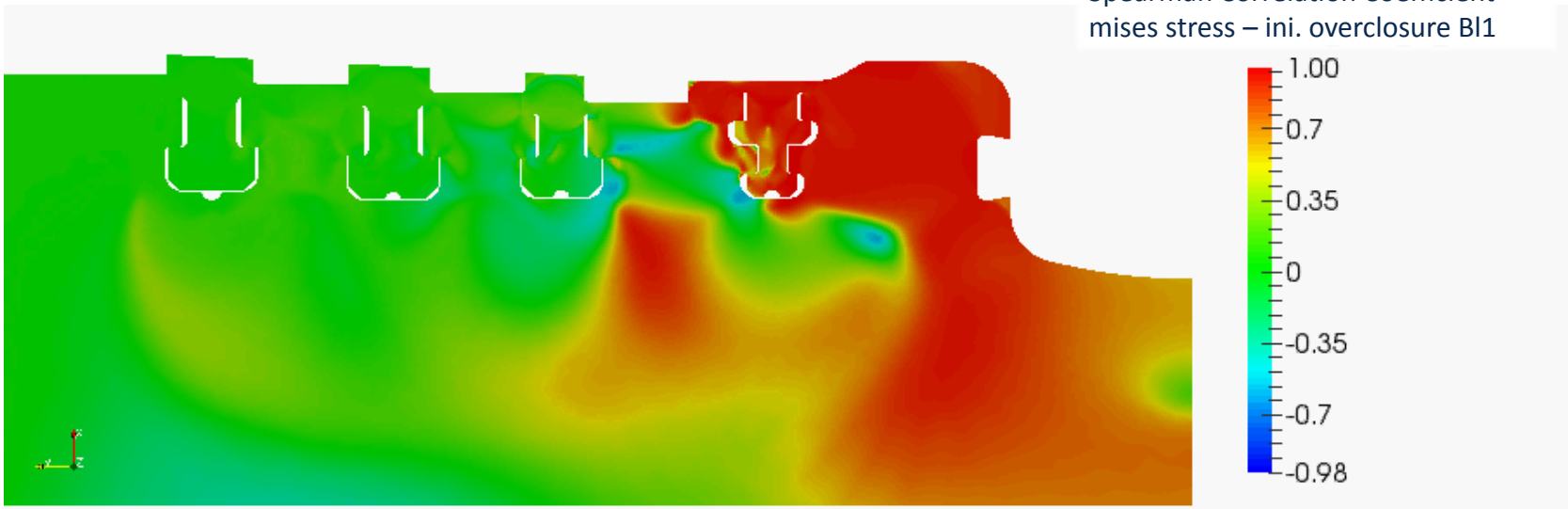


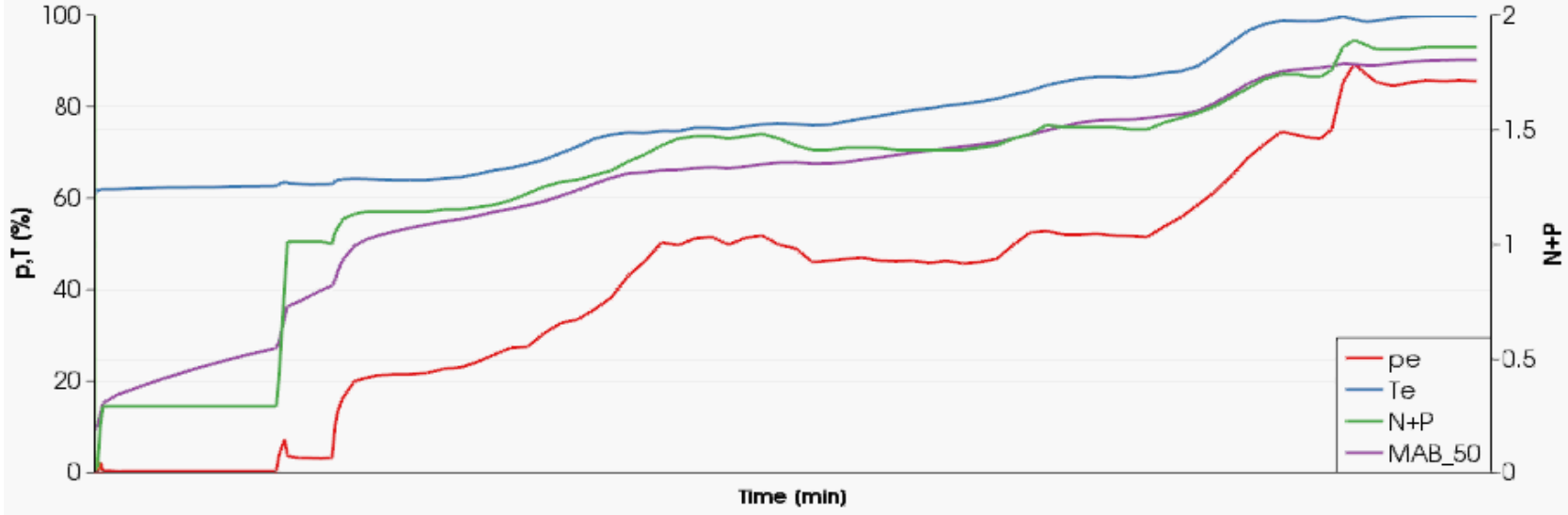


Miese Stress – Initial Overclosure Bl1

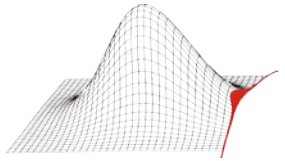


Spearman Correlation Coefficient
mises stress – ini. overclosure Bl1



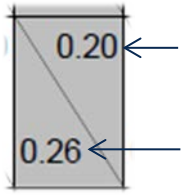


COI Matrix – Stress Amplitude



	R^2	Density	Heat Capacity	Thermal Conductivity	Young's Modulus	Poisson's Ratio	Lin. Therm. Exp. Coefficient	Yield Strength	N (Ramberg-Osgood)	p_{Steam}	T_{Steam}	Contact Conductance	α_{Blade}	α_{Labyr}	α_{Vortex}	α_{misc}	initial Overclosure Bl. 1	initial Overclosure Bl. 2	initial Overclosure Bl. 3	initial Overclosure Bl. 4
inl. groove	1.00	0.00	0.03	0.23	0.35	0.10	0.16	0.00	0.00	0.00	0.03	0.01	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00
	1.00	0.00	0.03	0.23	0.35	0.10	0.16	0.00	0.00	0.00	0.03	0.01	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00
bal. groove	1.00	0.00	0.04	0.20	0.20	0.08	0.10	0.00	0.00	0.00	0.02	0.00	0.02	0.01	0.00	0.00	0.23	0.03	0.01	0.00
	1.00	0.00	0.04	0.20	0.19	0.08	0.09	0.00	0.00	0.00	0.02	0.00	0.02	0.01	0.00	0.00	0.23	0.04	0.01	0.00
Bl1_tl	0.99	0.00	0.04	0.11	0.27	0.01	0.12	0.00	0.00	0.00	0.03	0.10	0.04	0.01	0.00	0.00	0.25	0.00	0.00	0.00
	1.00	0.00	0.04	0.12	0.26	0.01	0.12	0.00	0.00	0.00	0.02	0.11	0.04	0.01	0.00	0.00	0.26	0.00	0.00	0.00
Bl1_bl	0.81	0.00	0.01	0.06	0.11	0.09	0.06	0.00	0.00	0.00	0.02	0.01	0.04	0.01	0.00	0.00	0.20	0.13	0.06	0.01
	0.89	0.01	0.02	0.04	0.11	0.08	0.05	0.00	0.00	0.00	0.04	0.01	0.04	0.01	0.00	0.02	0.26	0.14	0.06	0.01
Bl1_tr	0.99	0.00	0.02	0.07	0.22	0.00	0.10	0.00	0.00	0.00	0.02	0.13	0.00	0.00	0.02	0.00	0.25	0.08	0.01	0.00
	1.00	0.00	0.03	0.08	0.22	0.00	0.10	0.00	0.00	0.00	0.02	0.14	0.00	0.00	0.02	0.00	0.24	0.07	0.02	0.00
Bl1_br	0.99	0.00	0.03	0.19	0.40	0.01	0.18	0.00	0.00	0.00	0.03	0.01	0.03	0.00	0.00	0.00	0.00	0.05	0.01	0.00
	1.00	0.00	0.04	0.18	0.40	0.01	0.18	0.00	0.00	0.00	0.04	0.01	0.03	0.01	0.00	0.00	0.00	0.06	0.01	0.00

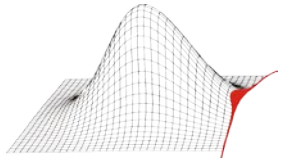
Coefficient
- 0.8 ... 1.0
- 0.6 ... 0.8
- 0.4 ... 0.6
- 0.2 ... 0.4
- 0.0 ... 0.2

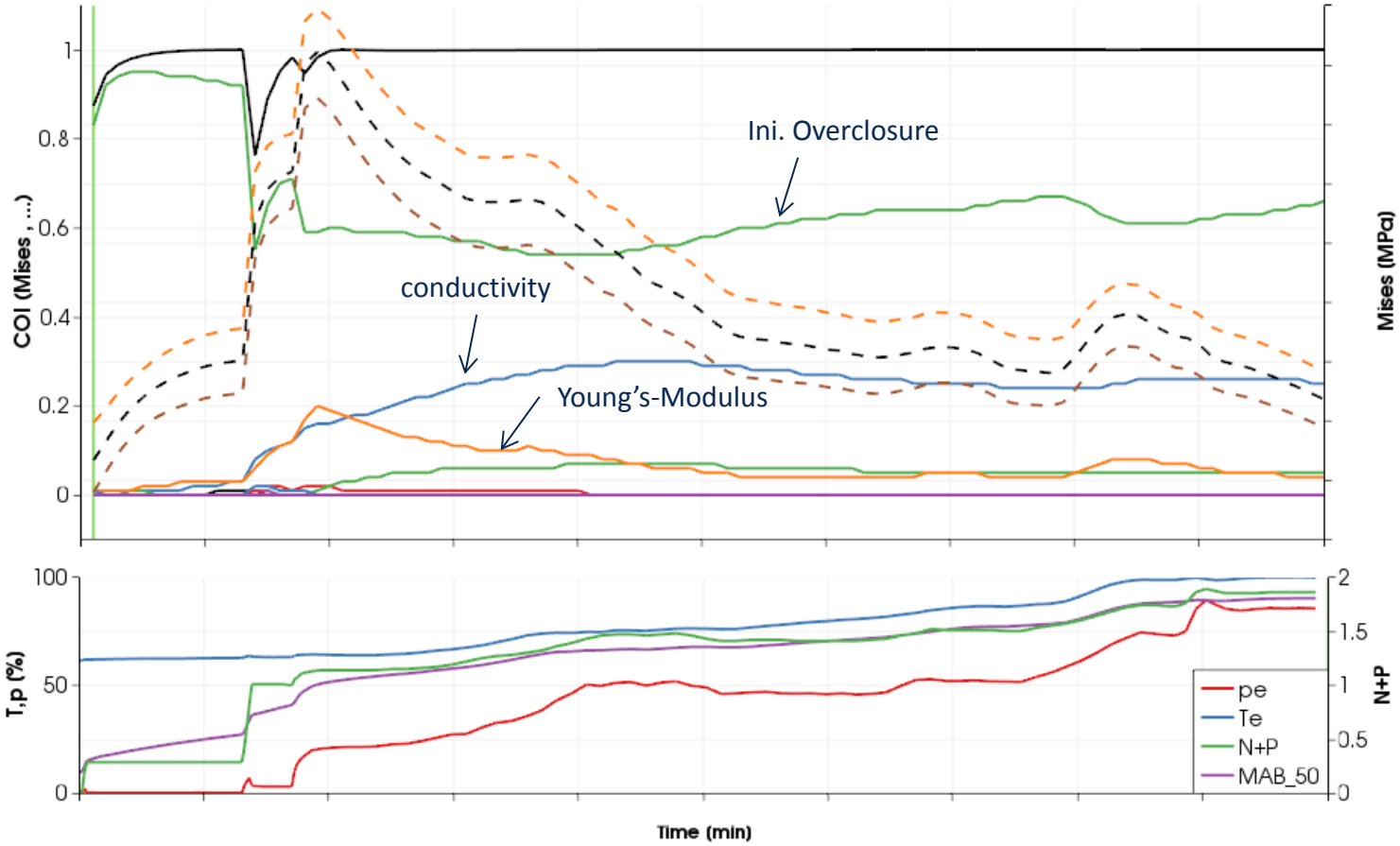


1st order

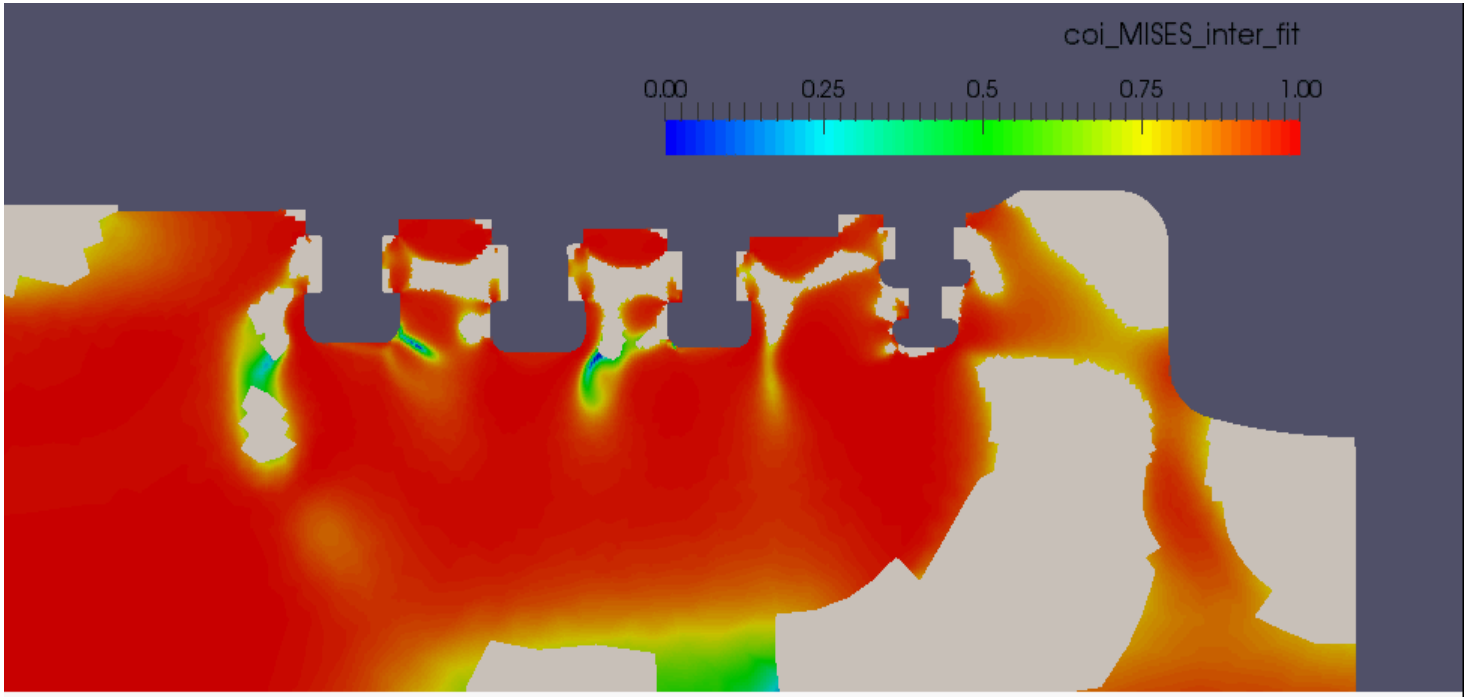
2nd order

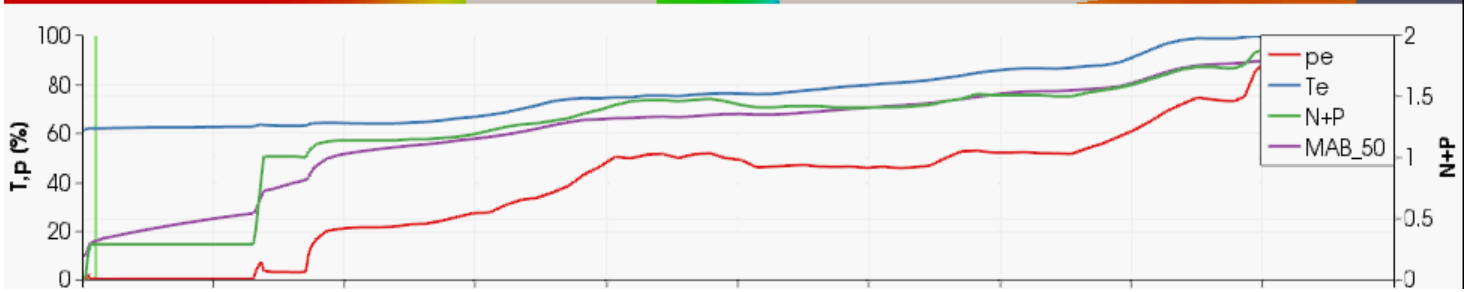
COI over Time





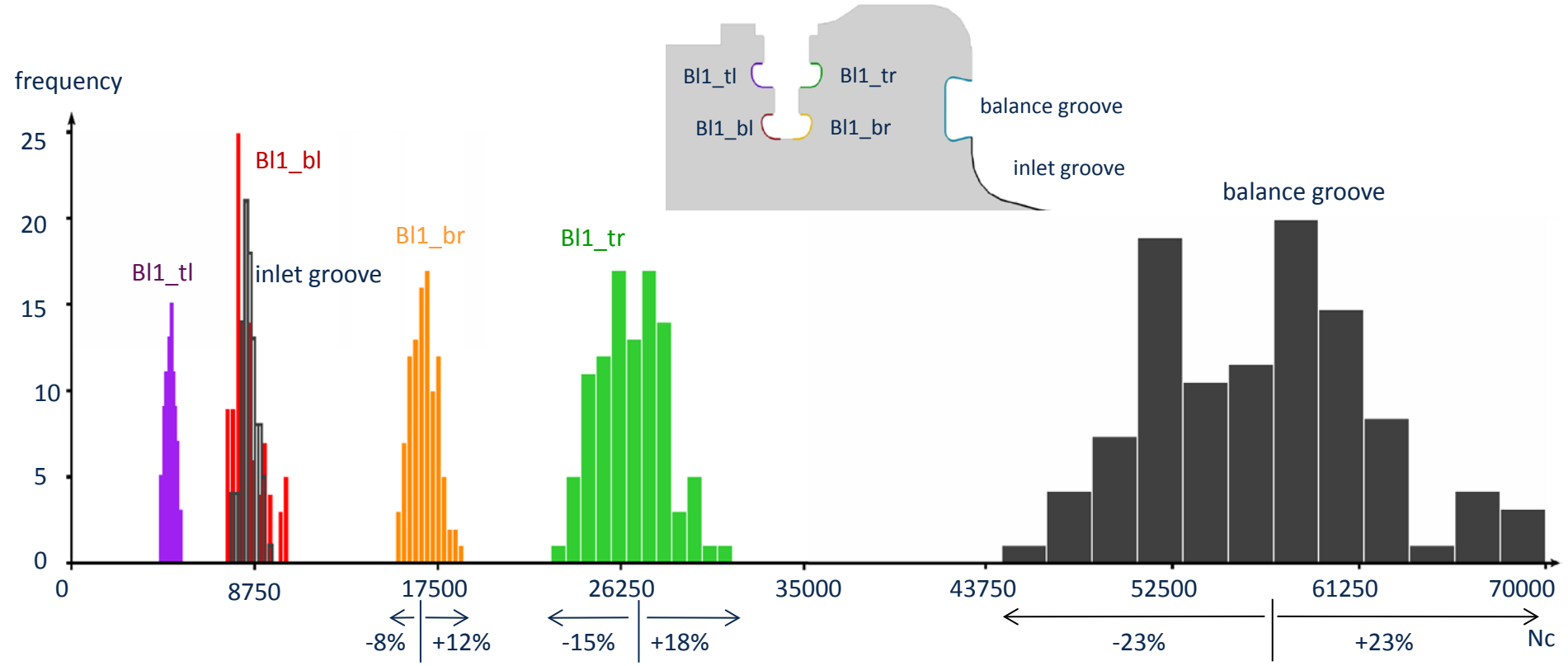
Transient COI on FE-Mesh





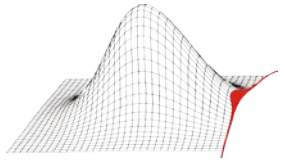
Areas with
$R^2 < 0.8$ are masked
light grey

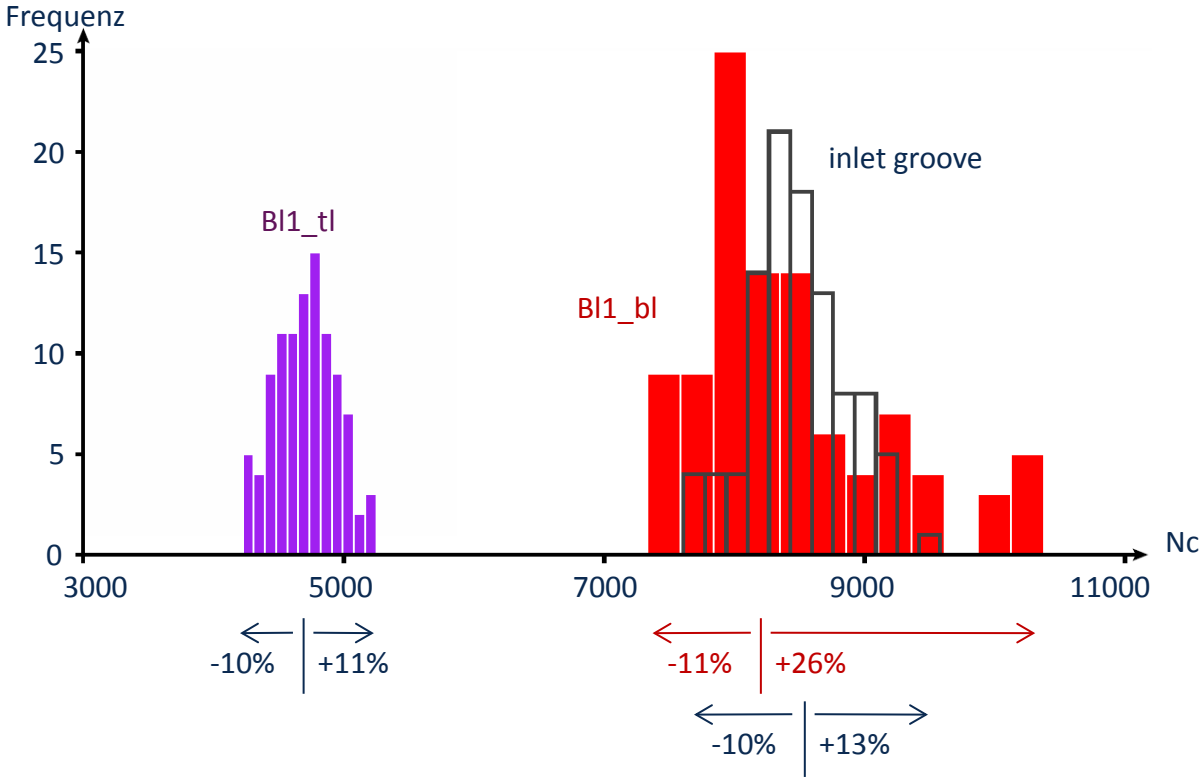
PDF of Lifetime

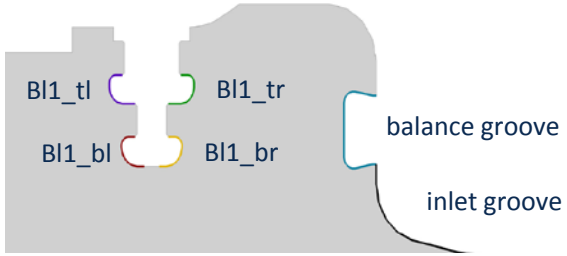


	Bl1_tl	Bl1_bl	inlet groove	Bl1_br	Bl1_tr	balance groove
Median	4715	8237	8472	16814	26795	58345
Min	4224	7334	7610	15481	22891	44974
Max	5249	10376	9580	18757	31576	71840

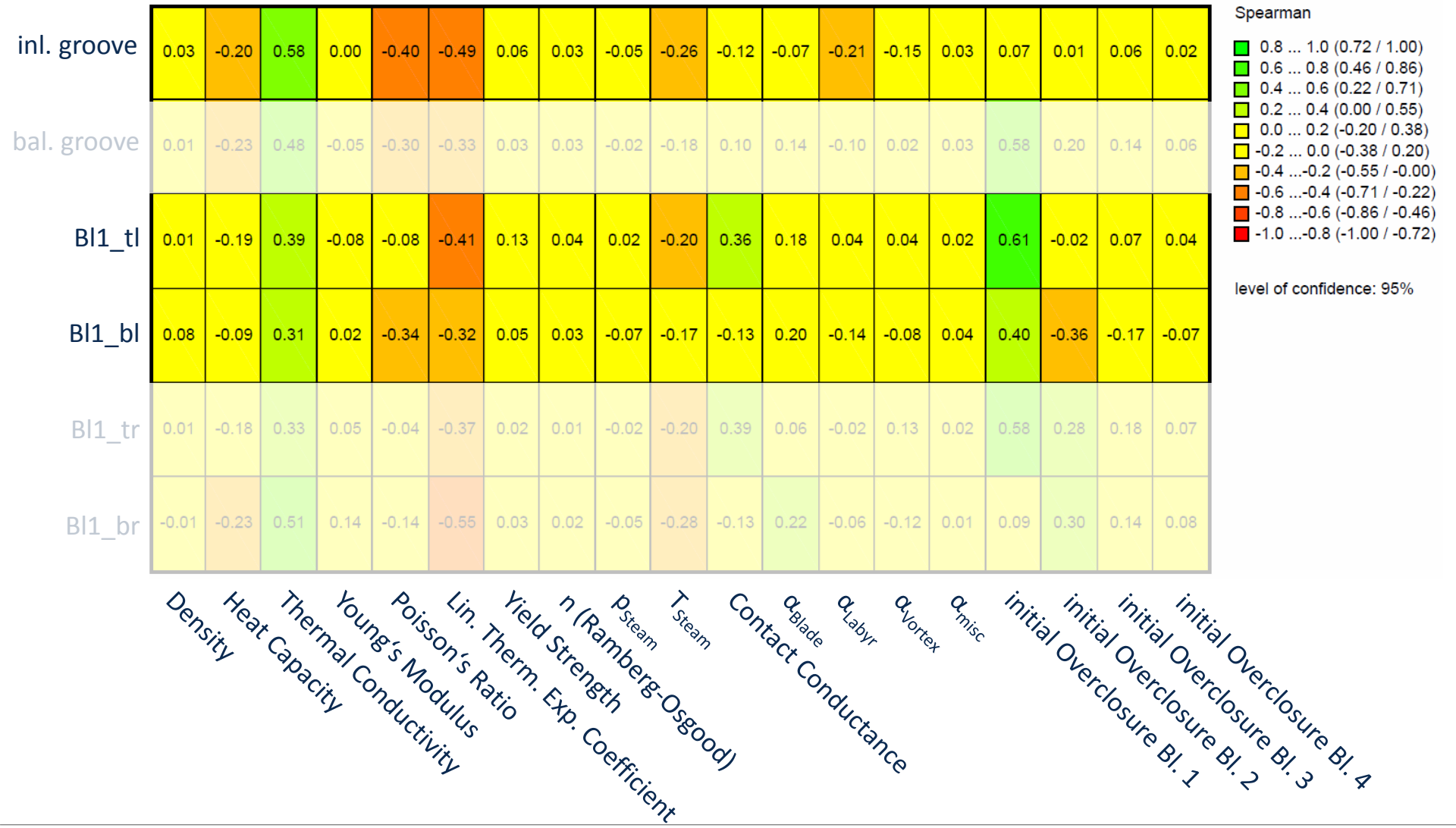
PDF of Lifetime



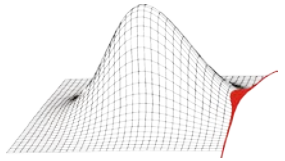




	Bl1_tl	Bl1_bl	inlet groove
Median	4715	8237	8472
Min	4224	7334	7610
Max	5249	10376	9580


inl. groove
0.03 -0.20 0.58 0.00 -0.40 -0.49 0.06 0.03 -0.05 -0.26 -0.12 -0.07 -0.21 -0.15 0.03 0.07 0.01 0.06 0.02
bal. groove
0.01 -0.23 0.48 -0.05 -0.30 -0.33 0.03 0.03 -0.02 -0.18 0.10 0.14 -0.10 0.02 0.03 0.58 0.20 0.14 0.06
Bl1_tl
0.01 -0.19 0.39 -0.08 -0.08 -0.41 0.13 0.04 0.02 -0.20 0.36 0.18 0.04 0.04 0.02 0.61 -0.02 0.07 0.04
Bl1_bl
0.08 -0.09 0.31 0.02 -0.34 -0.32 0.05 0.03 -0.07 -0.17 -0.13 0.20 -0.14 -0.08 0.04 0.40 -0.36 -0.17 -0.07
Bl1_tr
0.01 -0.18 0.33 0.05 -0.04 -0.37 0.02 0.01 -0.02 -0.20 0.39 0.06 -0.02 0.13 0.02 0.58 0.28 0.18 0.07
Bl1_br
-0.01 -0.23 0.51 0.14 -0.14 -0.55 0.03 0.02 -0.05 -0.28 -0.13 0.22 -0.06 -0.12 0.01 0.09 0.30 0.14 0.08
Density
Heat Capacity
Thermal Conductivity
Young's Modulus
Poisson's Ratio
Lin. Therm. Exp. Coefficient
Yield Strength
n (Ramberg-Osgood)
p_Steam
T_Steam
Contact Conductance
α_Blade
α_Labyr
α_Vortex
α_misc
initial Overclosure Bl. 1
initial Overclosure Bl. 2
initial Overclosure Bl. 3
initial Overclosure Bl. 4
Spearman
0.8 ... 1.0 (0.72 / 1.00)
0.6 ... 0.8 (0.46 / 0.86)
0.4 ... 0.6 (0.22 / 0.71)
0.2 ... 0.4 (0.00 / 0.55)
0.0 ... 0.2 (-0.20 / 0.38)
-0.2 ... 0.0 (-0.38 / 0.20)
-0.4 ...-0.2 (-0.55 / -0.00)
-0.6 ...-0.4 (-0.71 / -0.22)
-0.8 ...-0.6 (-0.86 / -0.46)
-1.0 ...-0.8 (-1.00 / -0.72)
level of confidence: 95%

Conclusions



- Input data of simulations (material parameters, boundary conditions, …) are often measured values → include measurement uncertainty
- some input data can not be measured and needs to be estimated
- the uncertainties in input data affect the accuracy of the simulation results

- Example of steam turbine shaft during cold start:
  - Uncertainty of mises stress in highly loaded areas up to -7.4% / +5.4%
  - Mainly caused by uncertainties of:
    - Thermal Conductivity
    - Young‘s Modulus
    - Linear Thermal Expansion Coefficient
    - Initial Overclosure Blade 1
  - Uncertainty of number of cycles to failure -10% / +11%
  - Mainly caused by uncertainties of:
    - Thermal Conductivity
    - Linear Thermal Expansion Coefficient
    - Initial Overclosure Blade 1

Thank you for your attention!

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