Bernhard Poethke

10/09/2015

Multi-Fidelity Surrogate Models for Predicting the Aerodynamic Performance of Gas Turbine Airfoils

Answers for energy.

SIEMENS

Content

Motivation and goal
- current situation (single-fidelity optimization)
- benefits of multi-fidelity optimization
- differences 2D- / 3D-CFD

Method 1: domain correction
- based on decomposition of computational domain into principal components

Method 2: output correction
- based on correction of low-fidelity objective values

Results
- comparison of methods
- Which method gives better prediction with less effort?

Motivation

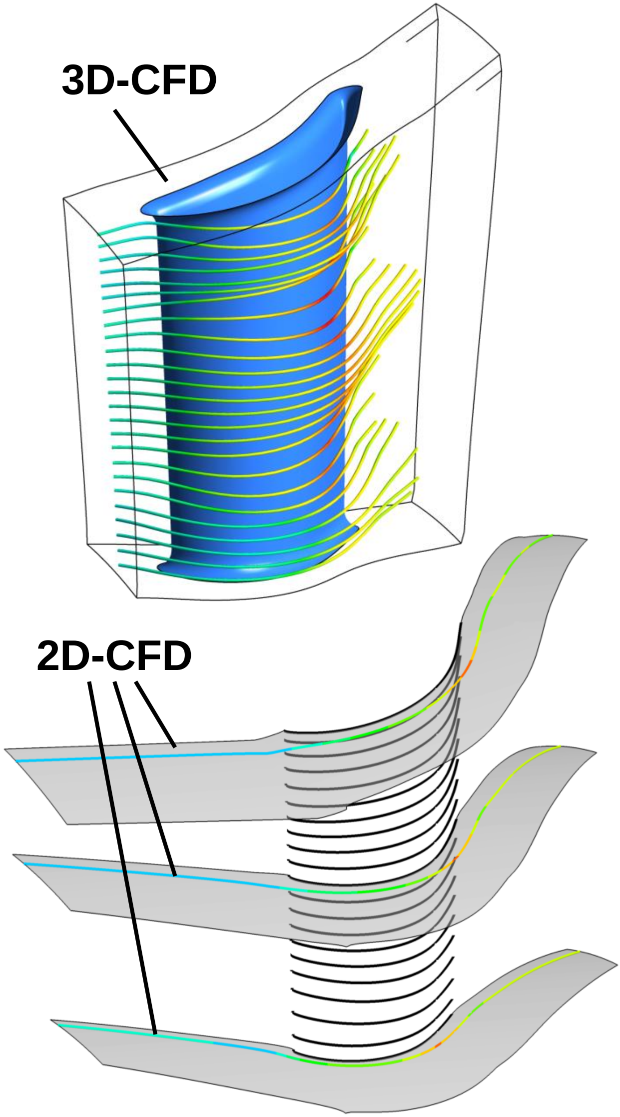
Current situation

- aerodynamic airfoil optimization by accurate and time-consuming 3D-CFD (HiFi)

Goal

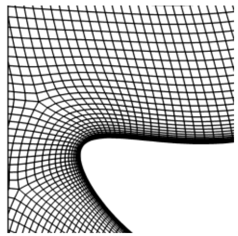
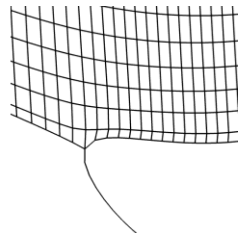
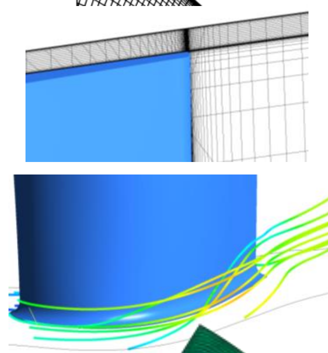
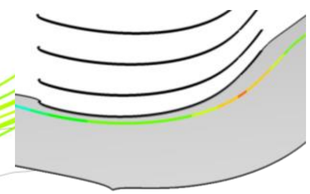
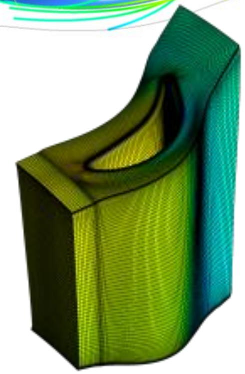
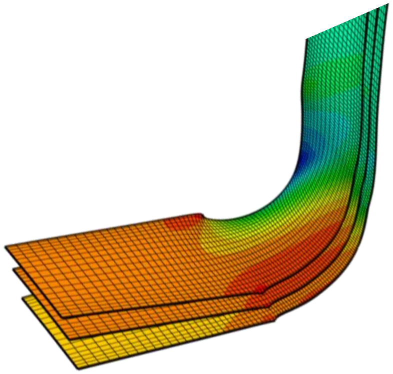
- time-reduced airfoil optimization by coupled 2D/3D-CFD (LoFi, HiFi)

	3D-CFD (CFX)	2D-CFD (Mises)
domain	1 x 3D domain	e.g. 21 x 2D sections (radial stacked)
number of mesh cells	1.0 …1.5 million	~ 3 500 per section ~ 0.07 million total
time consumption (whole domain)		
• meshing • solving • post-processing	~ 10 min ~ 20 min ~ 1 min	~ 5 s ~ 45 s ~ 2 s

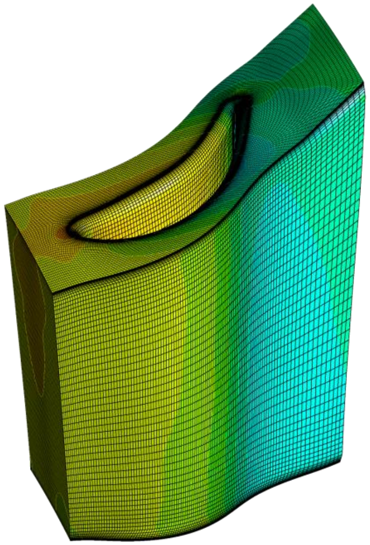


Differences between HiFi and LoFi

High Fidelity (HiFi, 3D-CFD) accurate, but time-consuming	**Low Fidelity (LoFi, 2D-CFD)** less accurate, but much faster
fine mesh	coarse mesh
incorporate geometry details	simplified geometry
continuous domain (3D)	separated, radial stacked airfoil sections (2D)

Objective value (efficiency)



HiFi | **LoFi**

$$\eta = \frac{\overline{h}_1^{\mathrm{M}} - \overline{h}_2^{\mathrm{M}}}{\overline{h}_1^{\mathrm{M}} - h_{2\mathrm{s}}}$$

HiFi:

$$\overline{h}^{\mathrm{M}} = \underbrace{\frac{1}{\dot{m}} \int h \, \mathrm{d}\dot{m}}_{\texttt{CFX massFlowAve}}$$

LoFi:

$$\overline{h}^{\mathrm{M}} = \frac{1}{\dot{m}} \sum_i h^{(i)} \dot{m}^{(i)}$$

$$h_{2\mathrm{s}} = h(\overline{s}_1^{\mathrm{M}}, \overline{p}_2^{\mathrm{A}},)$$

HiFi:

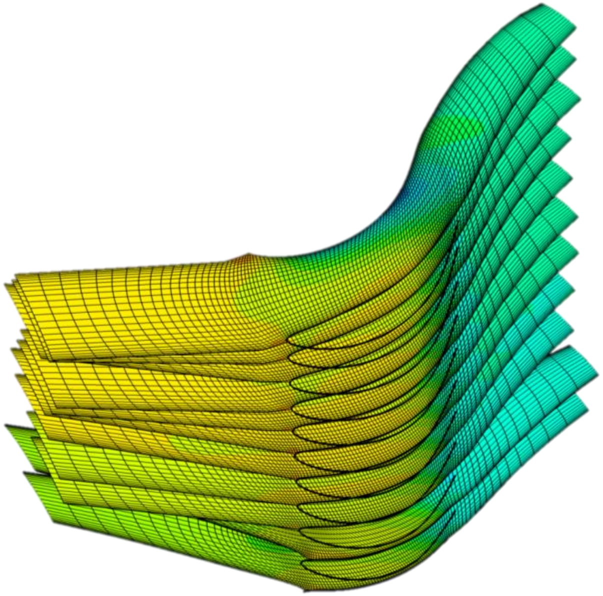
$$\overline{s}_1^{\mathrm{M}} = \frac{1}{\dot{m}} \int s_1 \, \mathrm{d}\dot{m}$$

$$\overline{p}_2^{\mathrm{A}} = \underbrace{\frac{1}{A_2} \int p_2 \, \mathrm{d}A}_{\texttt{CFX areaAve(Pressure)}}$$

LoFi:

$$\overline{s}_1^{\mathrm{M}} = \frac{1}{\dot{m}} \sum_i s_1^{(i)} \dot{m}^{(i)}$$

$$\overline{p}_2^{\mathrm{A}} = \frac{1}{A_2} \sum_i p_2^{(i)} A_2^{(i)}$$

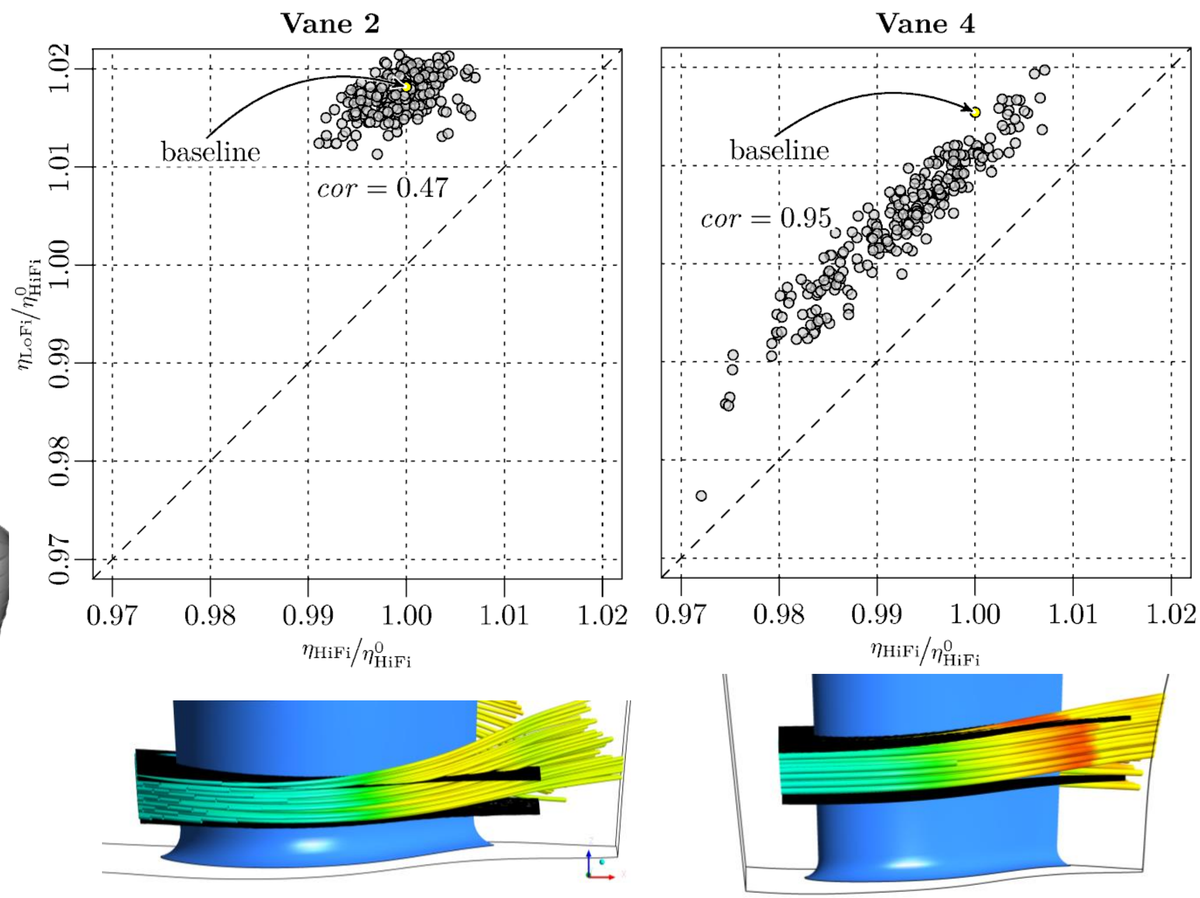


Equivalent objective value (efficiency) for both methods available

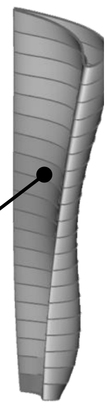
Correlation study

Procedure

- 250 different geometries for Vane 2 and Vane 4, respectively
- determine design space visually
- evaluate every sample with LoFi and HiFi
- at best, points fall on diagonal line
- Pearson correlation coefficient



extreme example
for variation in geometry



Correlation between objective values of LoFi and HiFi exists, but it depends on type of airfoil (flow regime)

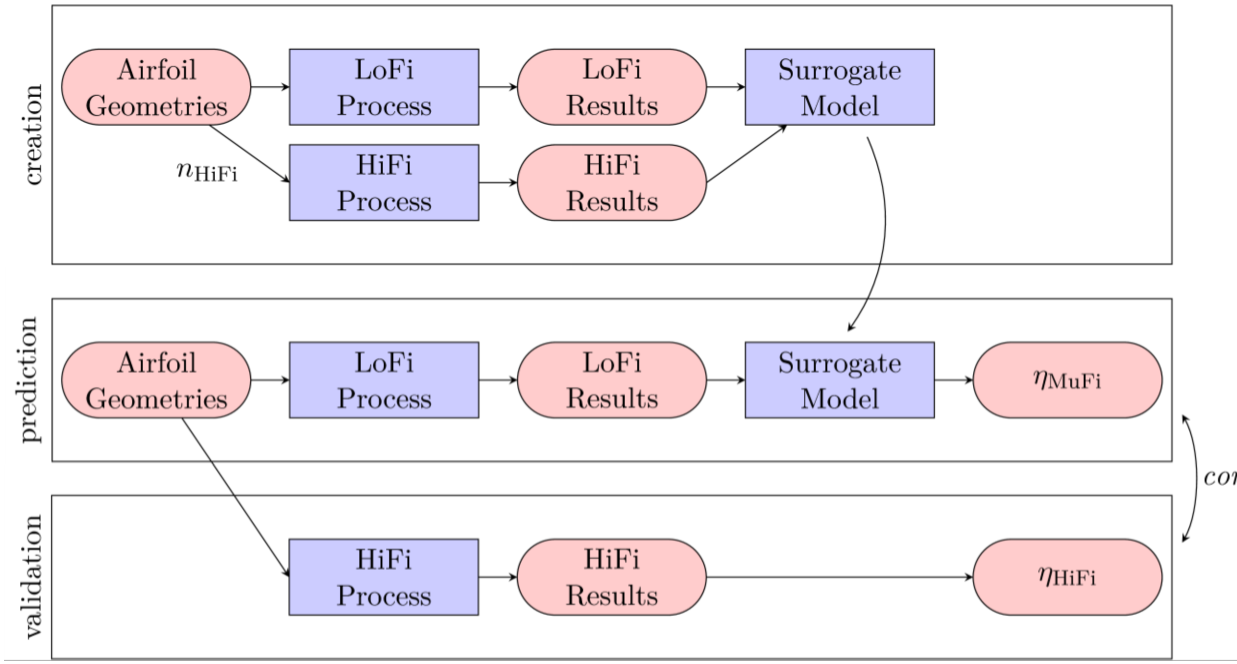
SIEMENS

Multi-Fidelity Surrogate Model

Creation
- evaluate set of samples by LoFi and HiFi process (n_{HiFi})
- build surrogate model

Prediction
- evaluate *different* set of samples by LoFi process
- prediction by using LoFi results and surrogate model

Validation
- evaluate second set by HiFi process
- compare to prediction (*cor*)

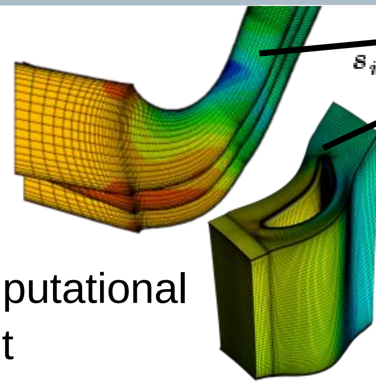


The ideal surrogate model would provide a high correlation (*cor*) while requiring only few HiFi evaluations (n_{HiFi})

Method 1: domain correction (gappy POD)

Procedure

- predict nodal values of a HiFi simulation by nodal values of a LoFi simulation
- based on decomposition of computational domain into principal component
- developed for image reconstruction (Sirovich et al. 1986, Turk et al. 1991)
- post-processing of HiFi domain to get (scalar) objective value



$$s_i = \begin{pmatrix} s_{\mathrm{lo},i} \\ s_{\mathrm{hi},i} \end{pmatrix}$$

snapshot from HiFi-/LoFi-Domain
↳ snapshot: nodevalues of domain

Proper Orthogonal Decomposition

- Where are the regions with great amount of information?
- Where is the variability high in the flow field?

$$s_i \approx \bar{s} + \sum_{j=1}^{l} \alpha_{i_j} \phi_j$$

approximate reconstruction

Advantage

- whole HiFi domain available

Disadvantages

- high memory requirements; lots of CFD-result files need to be stored and processed
- in the past only few applications in the field of aero

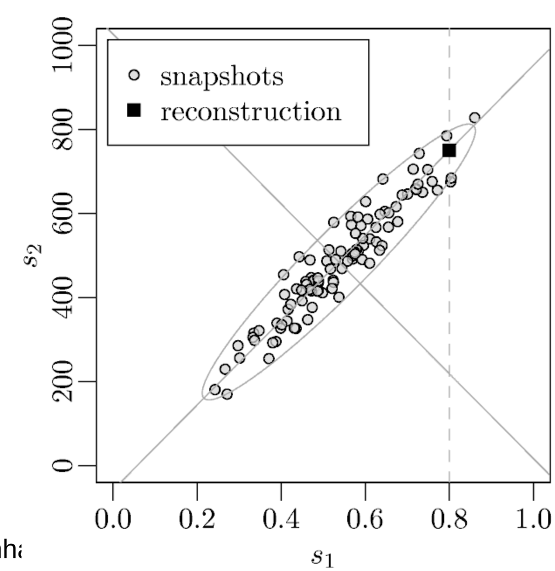
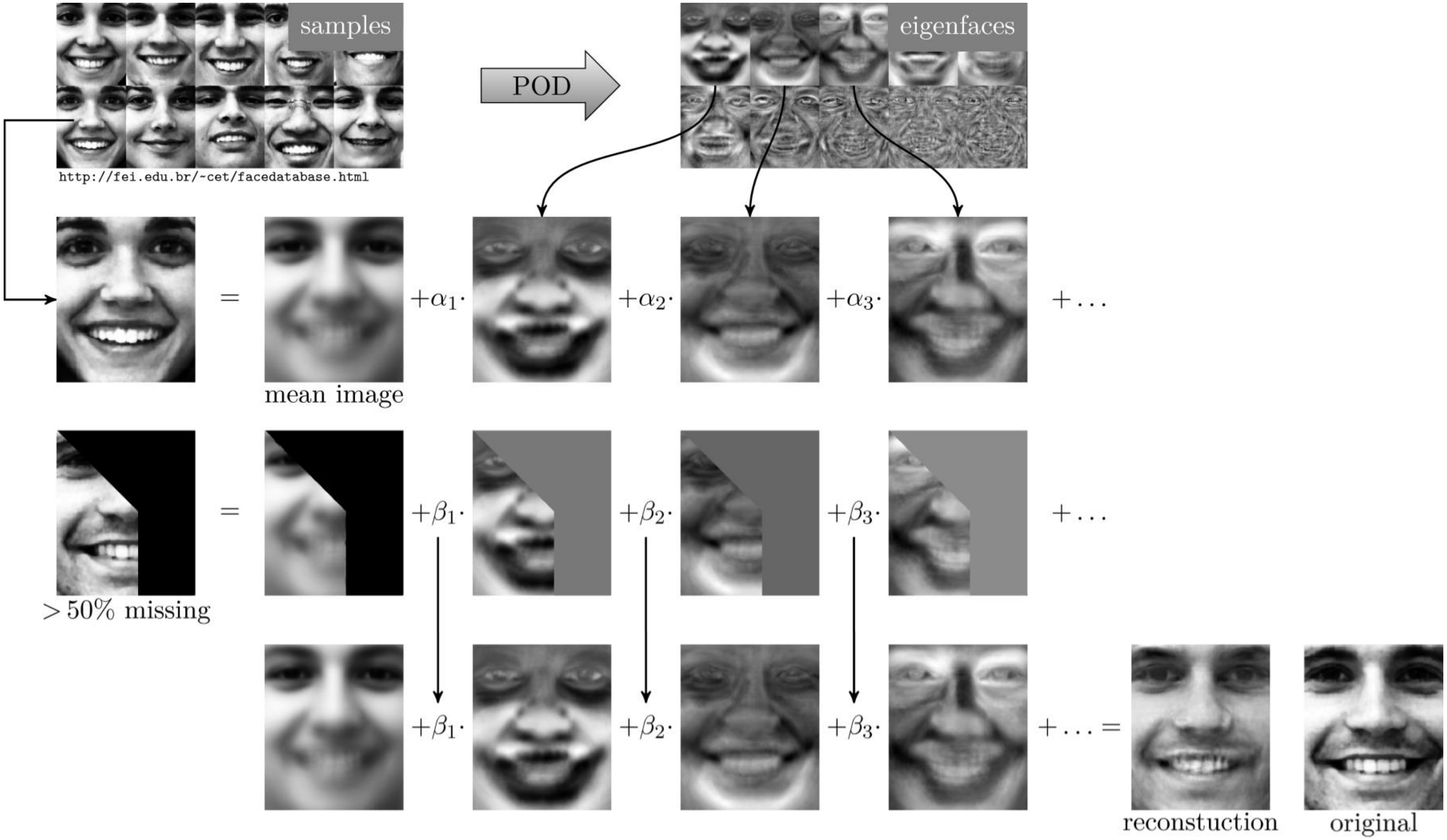
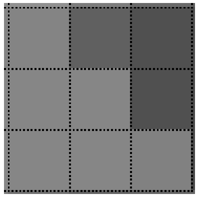


Image reconstruction



Analogy image / domain reconstruction



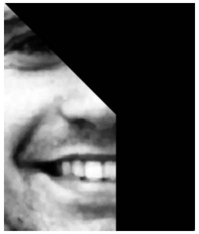
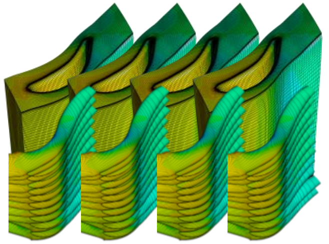
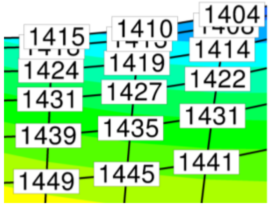
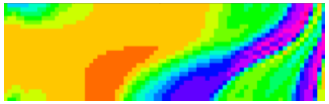
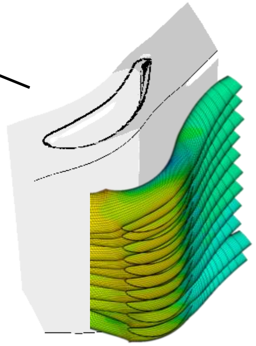


image reconstruction	domain reconstruction
set of similar images	set of similar HiFi and LoFi domains
pixel (gray value)	node (flow value)
variation by different faces	variation by different geometries
eigenfaces	eigensamples
missing parts of image	missing HiFi nodal values



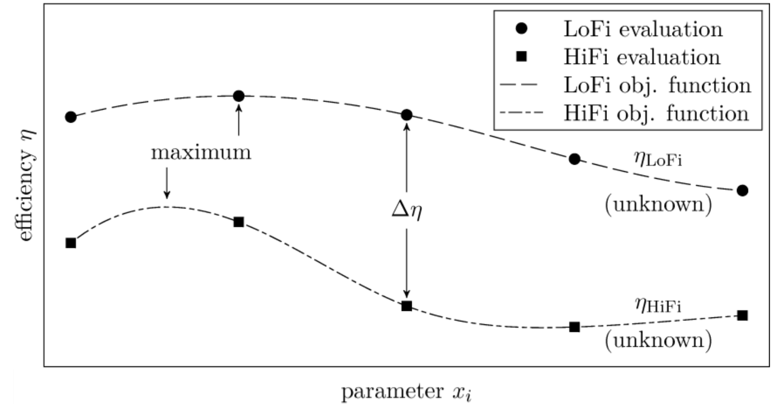






Method 2: output correction

Procedure
- alignment of objective value (efficiency) between LoFi and HiFi
- multi-fidelity model consists of a LoFi model and a correction model
- classification of correction models
  - additive and/or multiplicative



Advantages
- successful application in the field of aero (mostly for small design spaces < 20 dimensions)
- kriging based correction models give estimate for local error in prediction → selective sampling for refinement (instead of global sampling)

Disadvantage
- whole flow domain is not available

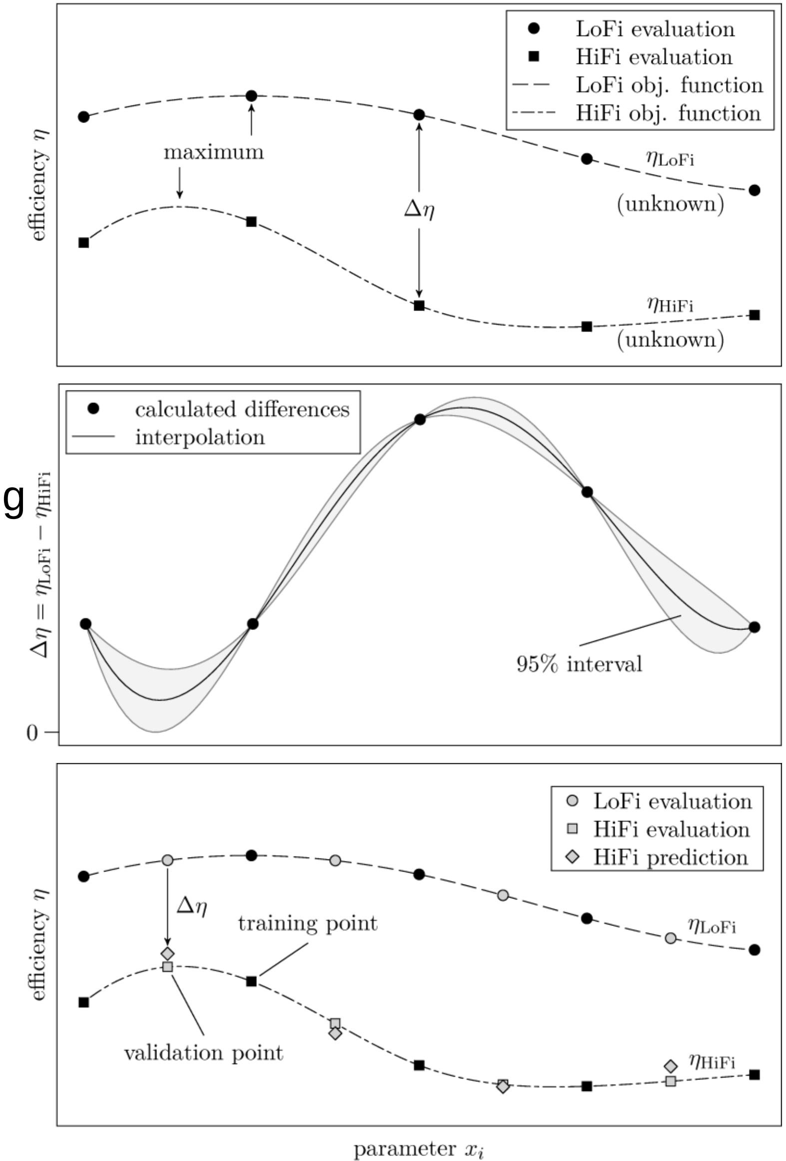
Application
- Alignment
  - Alexandrov et al. '97,'99, '00, '01,…
  - Hafka 1991
- Kriging
  - Forrester et al. '07, '08, '09
  - Han et al. '08, '09, '10, '12, '13

Method 2: output correction

Sampling
- uniform sampling over parameter space (training samples set, LHS)
- evaluation by LoFi and HiFi
- in general: maximal efficiency at different locations

Interpolation
- calculate differences at sampling locations
- correction function: interpolate values, e.g. by kriging
- advantage kriging: confidence interval for subsequent optimization

Prediction and Validation
- uniform sampling over parameter space at different locations (validation samples set, LHS)
- HiFi prediction: LoFi evaluation + correction
- HiFi evaluation for validation → correlation



Results

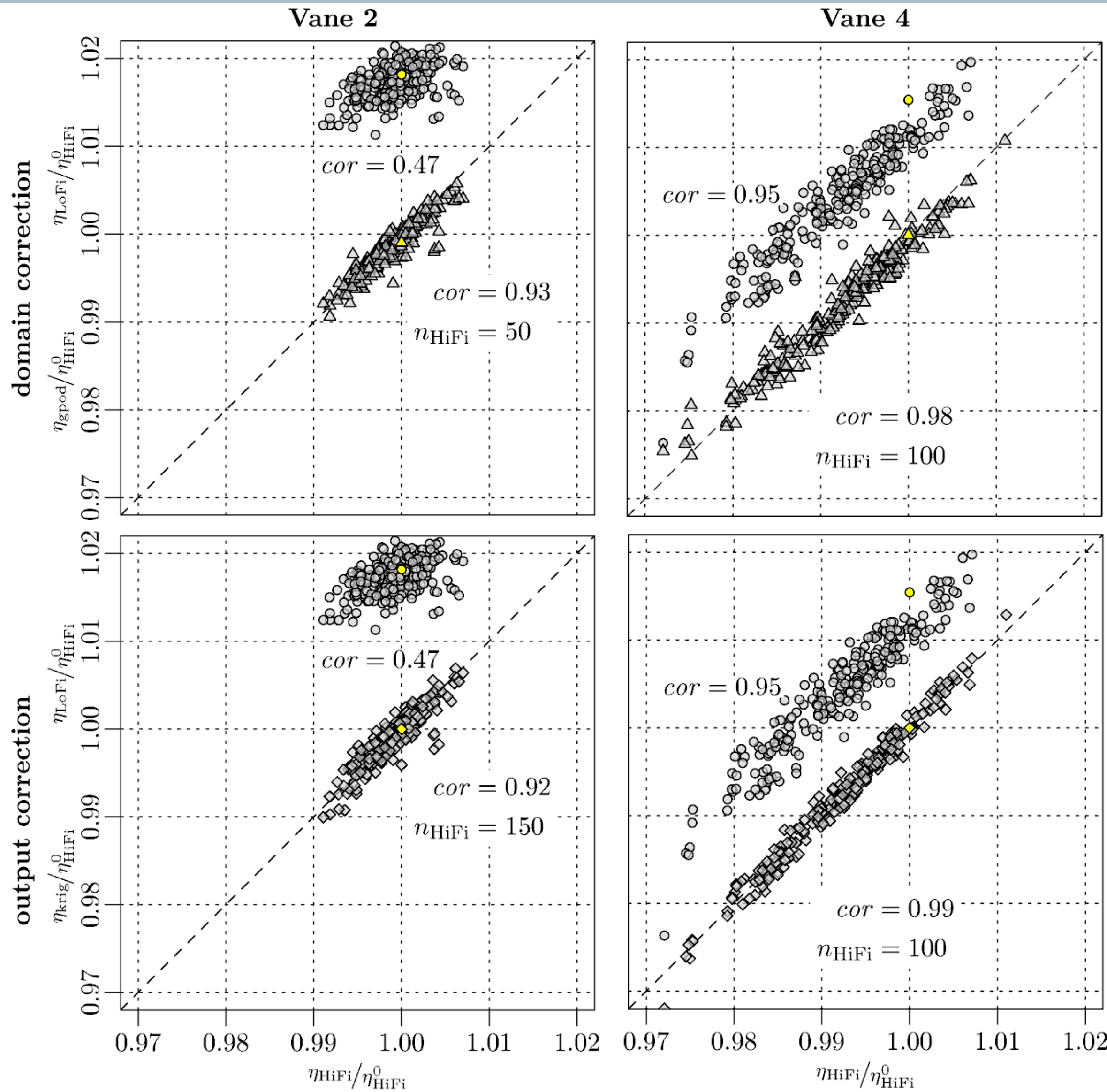
SIEMENS

Procedure

- one set of samples for *creation* of surrogate model
- one more set of samples for *validation* of surrogate model

Correlations

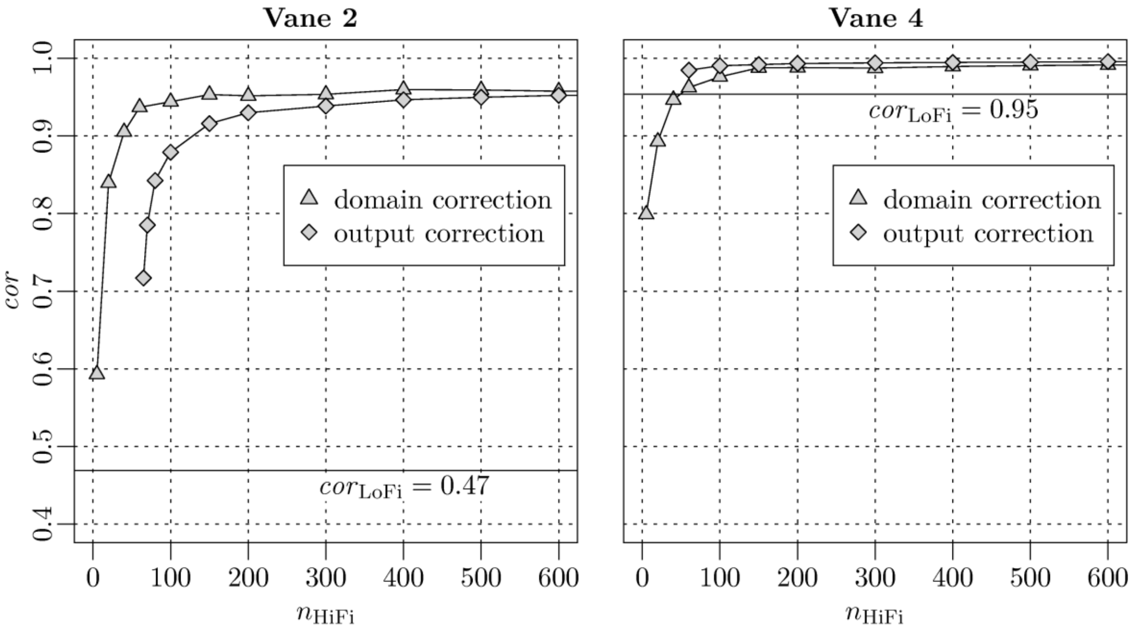
- correlation coefficient between HiFi and MuFi is higher than between HiFi and LoFi
- only little differences in the accuracy of prediction between the two methods
- differences in required HiFi evaluations



Results

Dependency on number of HiFi evaluations

- correlation coefficient is dependent on number of HiFi evaluations
- Vane 2: approx. 50 HiFi evaluations for *cor* > 0.90
- Vane 4: approx. 100 HiFi evaluations for *cor* > 0.98

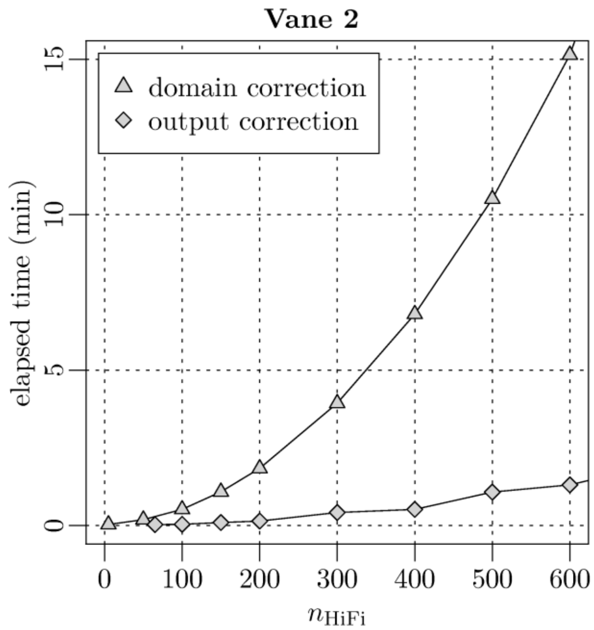


Both methods show a high correlation with only a few HiFi evaluations.
High potential for using multi-fidelity approach for optimization of Vane 2

Results

Time consumption for creation of surrogate models

- dependency on number of HiFi evaluations
- method 1: cubic dependency
- method 2: approx. linear dependency
- hardware: 1 CPU-core @ 2.6 GHz
- speed-up by parallelization is possible
- time consumption for HiFi evaluations is not included



For both methods the time consumptions are negligible in comparison to time consumption for HiFi evaluations

Outlook

Multi-Fidelity Surrogate Models

- evaluate both methods for Blade 1
- optional: take another method (“input correction”) into comparison

Optimization

- use multi-fidelity surrogate model for optimization
- benchmark performance of multi-fidelity optimization in contrast to single-fidelity optimization

Contact

Bernhard Poethke
PG GT EN LGT RC TURB TDM

Mellinghofer Str. 55
45473 Mülheim an der Ruhr

Tel.: +49 (208) 456 1726

E-Mail:
bernhard.poethke.ext@siemens.com

siemens.com/energy