41. EFB-Kolloquium Blechverarbeitung 8. / 9. Mai 2023

Fraunhofer IWU

Fraunhofer-Institut für Werkzeugmaschinen und Umformtechnik IWU

Digitalisierung in Umform- und Fügetechnik

Christian Schwarz, Patrick Ackert, Reinhard Mauermann, Welf-Guntram Drossel

Fraunhofer IWU

Agenda

- Gegenstand
- Ziele
- CPA – Coupled Process Analysis
- Praxisbeispiele

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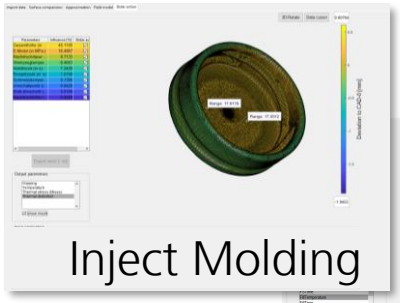
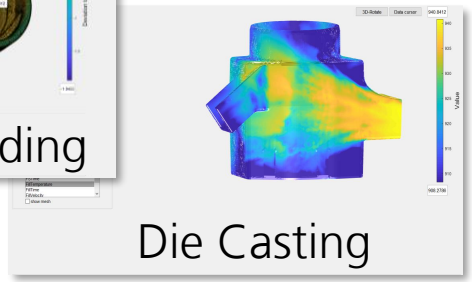
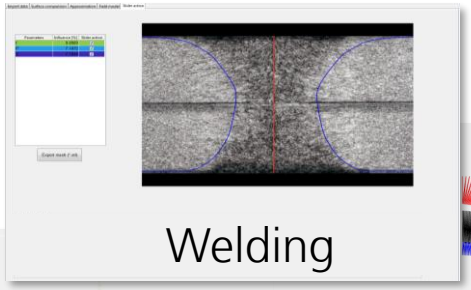
Gegenstand

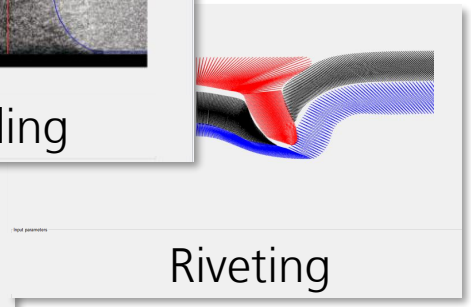
Beispielgebiete mit CPA-Modellen

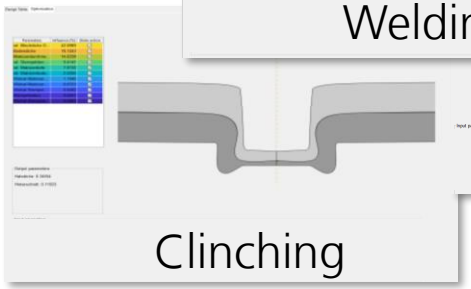




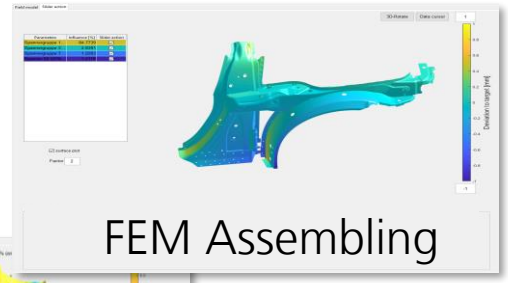
Urformen

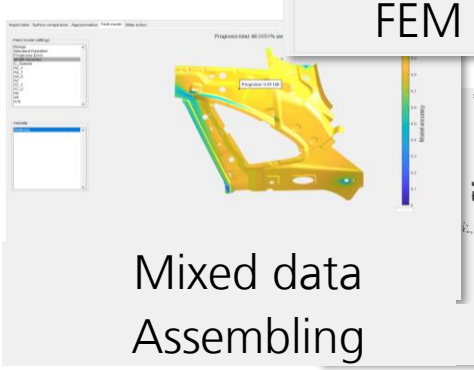


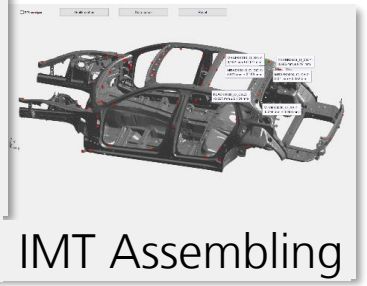




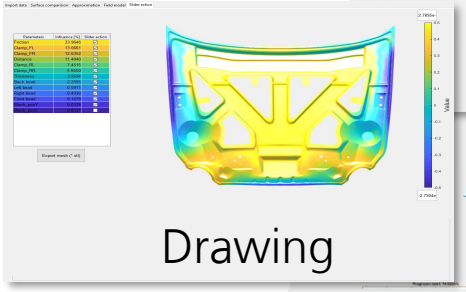
Fügen

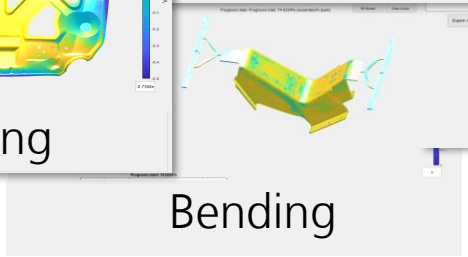






Prozesskettenanalyse





Umformen

Gegenstand

Wann macht Digitalisierung mit CPA Sinn?

- Anzahl **Prozessparameter hoch;** z.B. >5; **Kreuzkorrelationen** auch für Experten schwierig zu übersehen
- **Geringer Datenumfang**; Aufwand für Versuch & Irrtum groß
- **Räumliche Auflösung** erwünscht
- Zusammenhänge **ohne Zeitverzögerung** erwünscht
- **Gute Daten** vorhanden; Input-/Output beschreiben den Prozess gut
- Daten sind **maschinenlesbar**

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Gegenstand

Welche Verfahren werden analysiert

CPA Industrial Data Modeling

- PLASTIC INJECTION MOLDING
- LASER BEAM WELDING
- CLINCHING
- SELF-PIERCE RIVETING
- VIRTUAL MULTI-STAGE CAR BODY PROCESS CHAIN
- REAL MULTI-STAGE CAR BODY PROCESS CHAIN
- HOTFORMING/FORGING
- SHEET METAL FORMING
- PRESS HARDENING
- DIE CASTING

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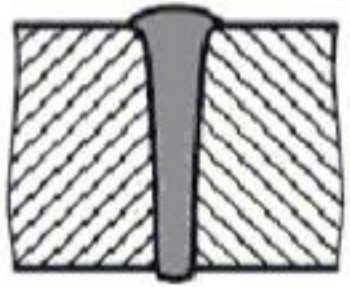
Gegenstand Elektronenstrahlschweißen

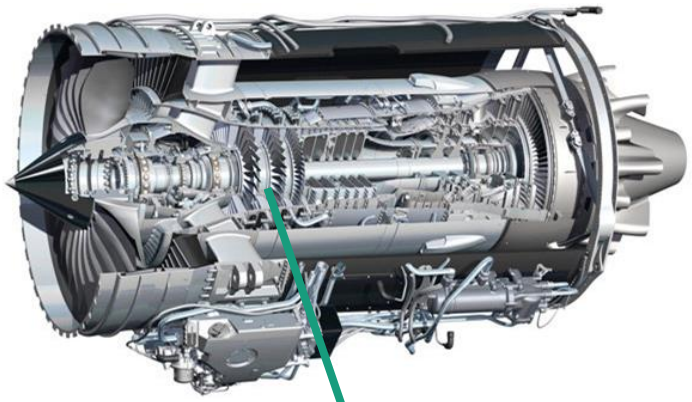
Prinzip

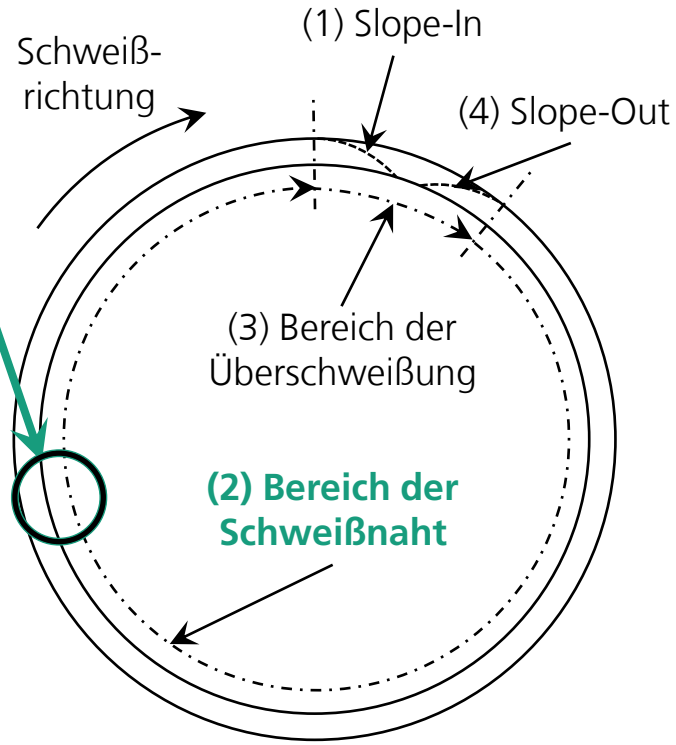
1 **Umwandlung von kinetischer in thermische Energie**

2 **Aufschmelzen des Materials**



3 **Schweißnaht nach beendeter Erstarrung**





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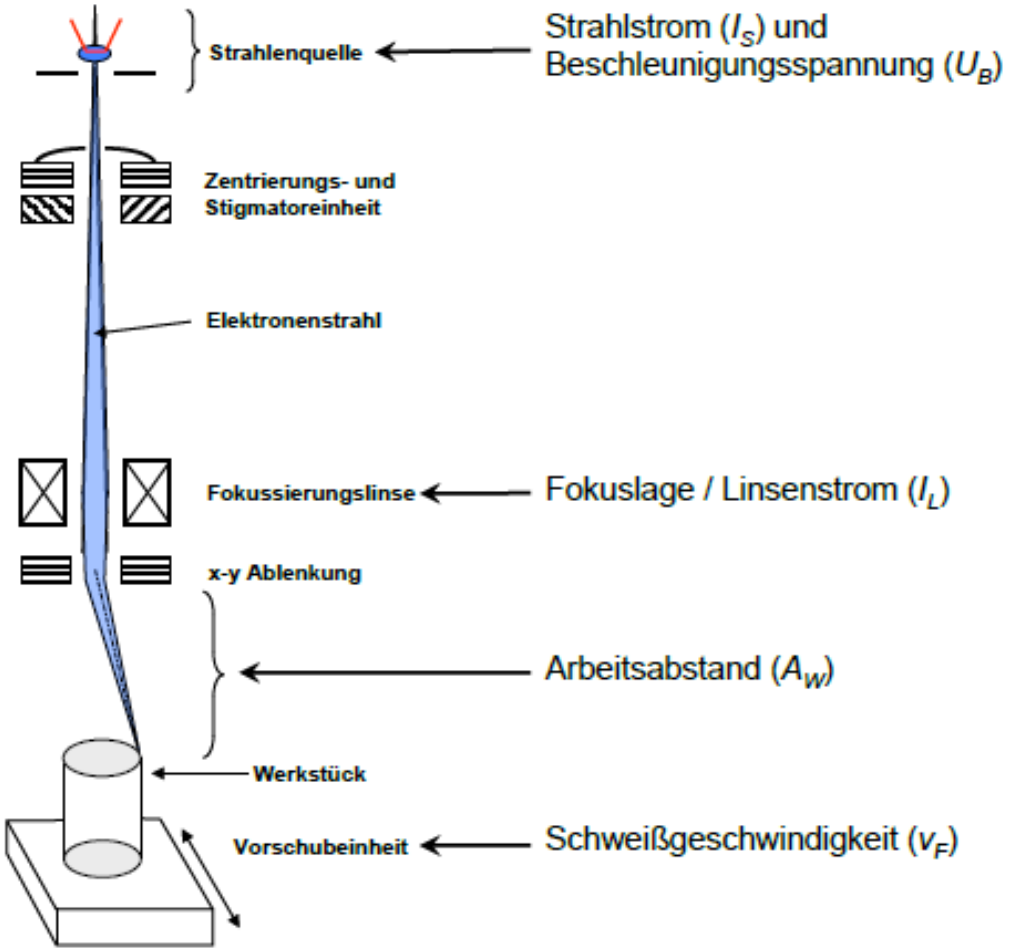
Gegenstand Elektronenstrahlschweißen

Einflussfaktoren und Variationsgrenzen



Variationsgrenzen:

- Arbeitsabstand (AW) 350 … 400 mm
- Schweißgeschwindigkeit (VF) 30 … 60 mm/s
- Strahlstrom (IS) 40 … 60 mA
- Beschleunigungsspannung (UB) 120 … 150 kV
- Linsenstrom (IL) 25 … 40 mA

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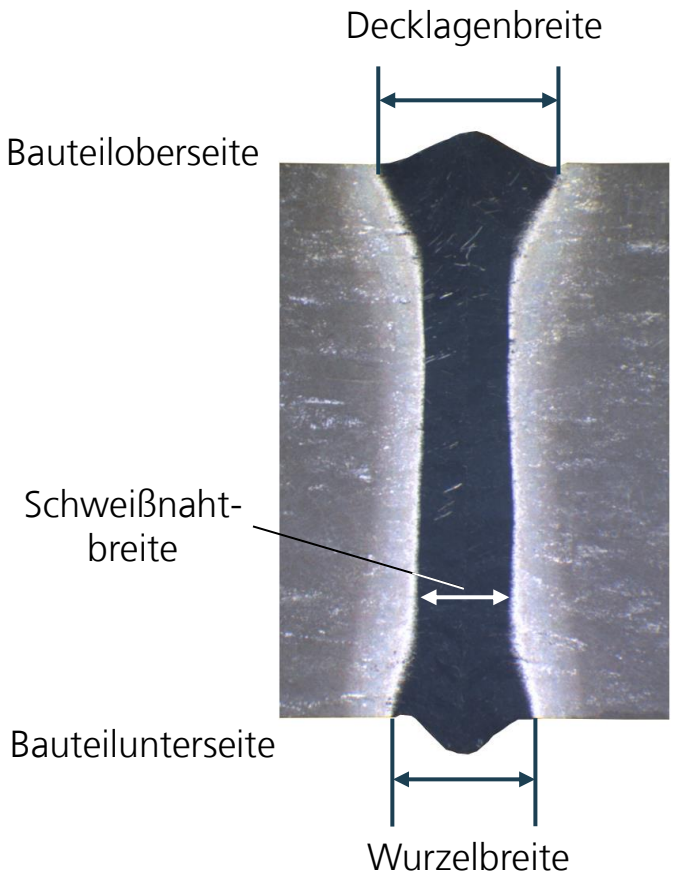
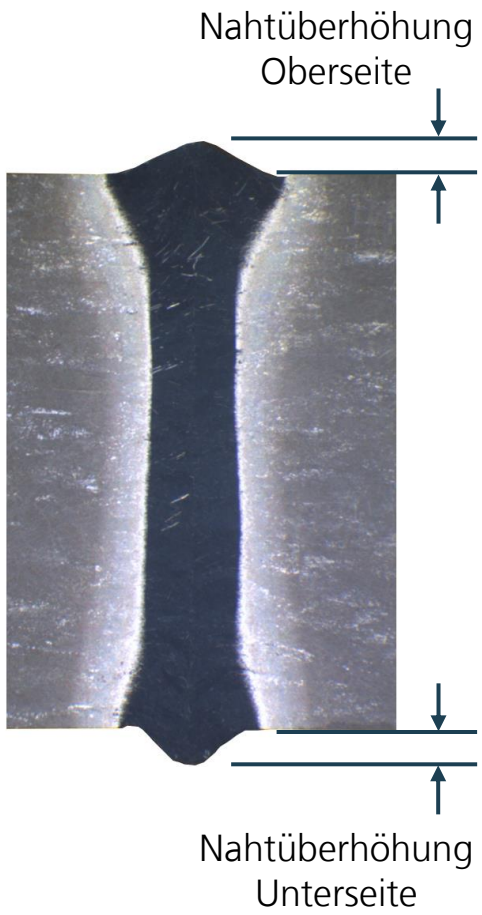
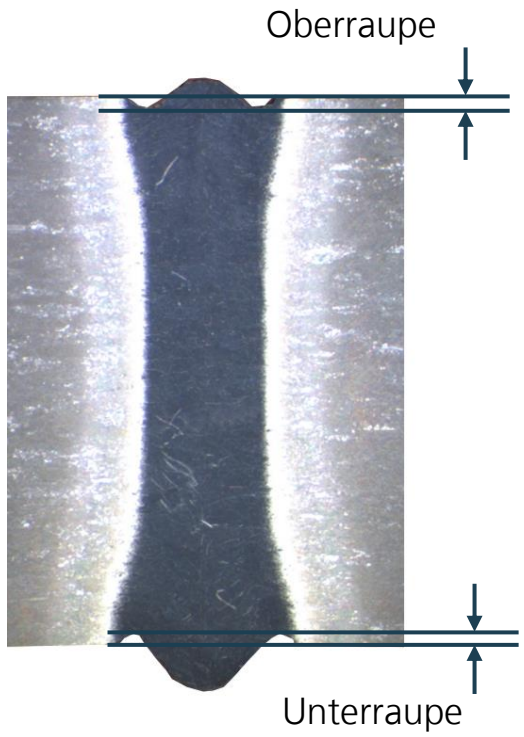
Gegenstand Elektronenstrahlschweißen

Bewertungskriterien (Querschliff)







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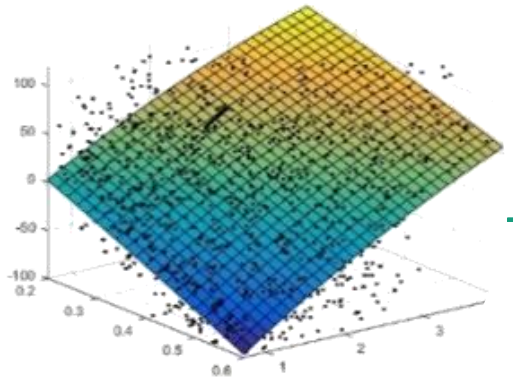
Ziele

Modellbasierte Prognose der finalen Nahtgeometrie

Inputs:

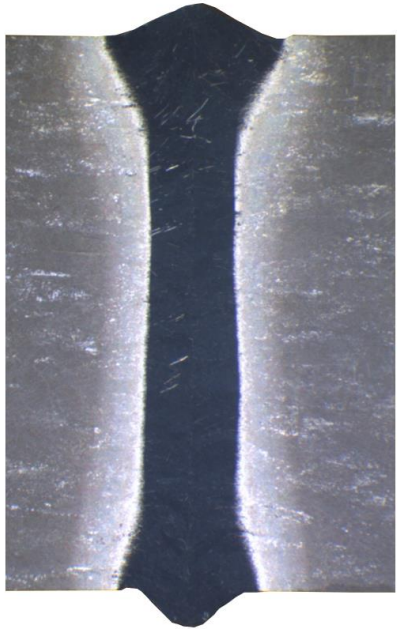
- Strahlstrom (IS) 40 … 60 mA
- Beschleunigungsspannung (UB) 120 … 150 kV
- Linsenstrom (IL) 25 … 40 mA
- Arbeitsabstand (AW) 350 … 400 mm
- Schweißgeschwindigkeit (VF) 30 … 60 mm/s

5 Schweißparameter



Metamodell

Output (Querschliff):



Multivariates Schliffbild

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Ziele

Modellbasierte Prognose der finalen Nahtgeometrie

Inputs:

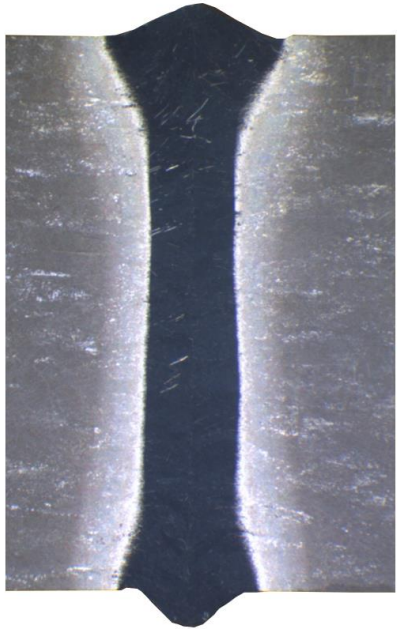
- Strahlstrom (IS) 40 … 60 mA
- Beschleunigungsspannung (UB) 120 … 150 kV
- Linsenstrom (IL) 25 … 40 mA
- Arbeitsabstand (AW) 350 … 400 mm
- Schweißgeschwindigkeit (VF) 30 … 60 mm/s

5 Schweißparameter

Von den Eingaben wird auf das Ergebnis geschlossen

CPA Industrial Data Modeling

Output (Querschliff):



Multivariates Schliffbild

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Ziele

Nutzung aller Simulations- und Meßdaten

- …auch mit **kleinen Stichprobengrößen**
- … mit flexiblen **Schnittstellen** (z. B. zu FE-Solvern)
- … mit flexiblen **Datentypen** (Oberflächen, Kurven, diskrete Werte)
- … mit **beliebiger Anzahl** an In- und Outputgrößen
- …mit einfacher Oberfläche

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Ziele

Modellierung Prozesswissen

- **Planung**: für die **Prognose**; hauptsächlich aus **FE-Daten**
  - **Eigenschaften werden vorausgesagt; z.B.Toleranzen**
  - **Prozeßparameter können optimiert werden**
  - **Schnellere Produkteinführung**
- **Serie**: für die **Qualitätssicherung**; hauptsächlich aus **Meßdaten**
  - **Prozessstabilität für laufende Produktion**
  - **Regelkreise bei Verfügbarkeit eines Stellgliedes**

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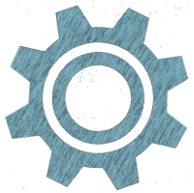
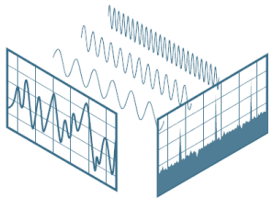
Coupled Process Analysis CPA

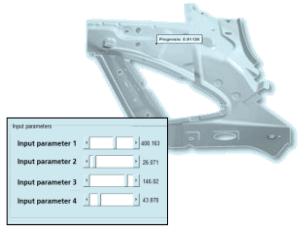
Workflow



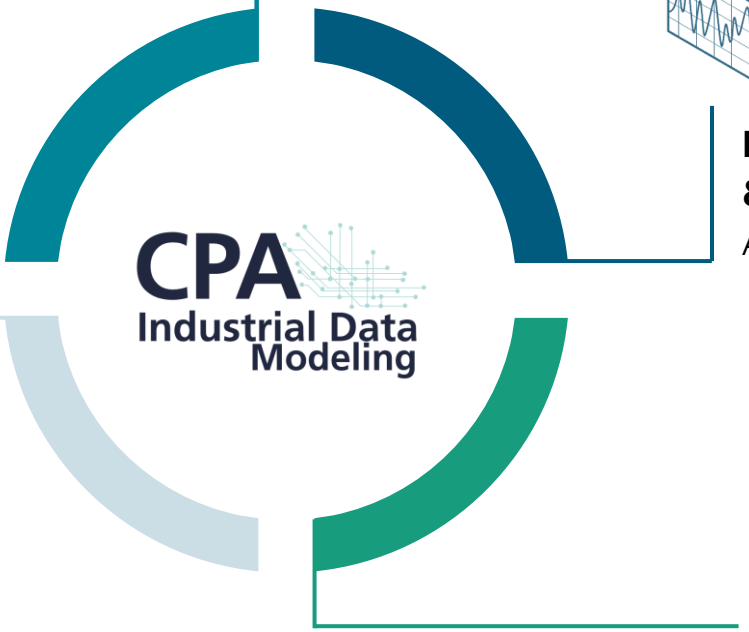
Data Collecting
Users Task
50-90% of Work scope



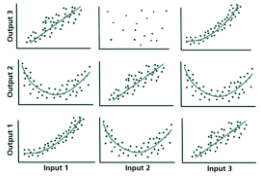
Data standardization & Data Compression
Assignment target values



Visualisation
User-friendly visualisation



Supervised Learning
Selection/ Validation of modeling approach



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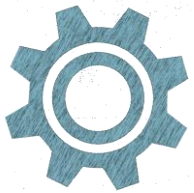
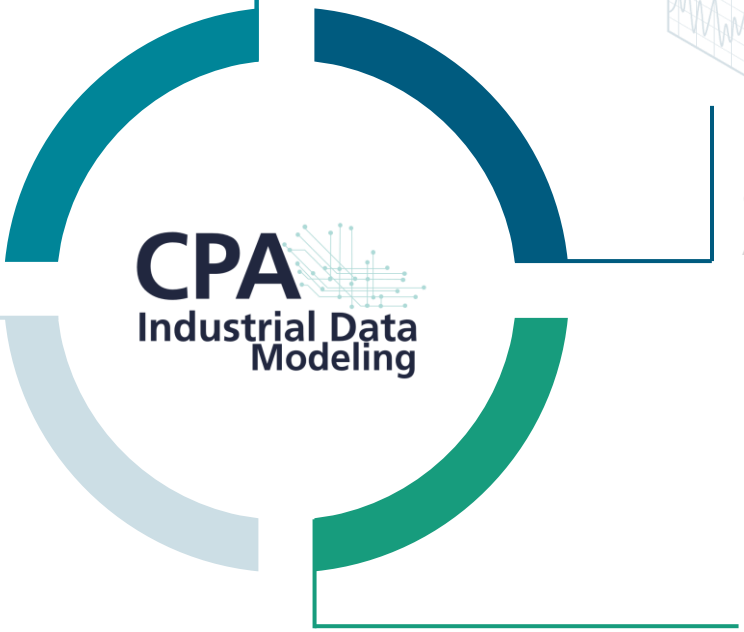
Coupled Process Analysis CPA

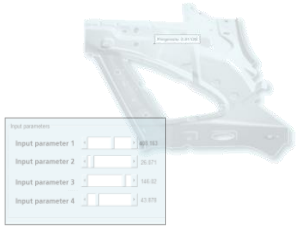
Data Collection



Data Collecting
Users Task
80% of Work scope

Data standardization & Data Compression
Assignment target values





Visualisation
User-friendly visualisation

Supervised Learning
Selection/ Validation of modeling approach

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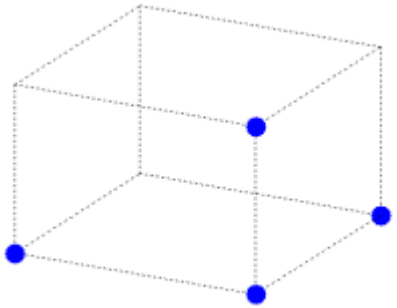
Coupled Process Analysis CPA

Data collection

D-optimales Design (DOE)

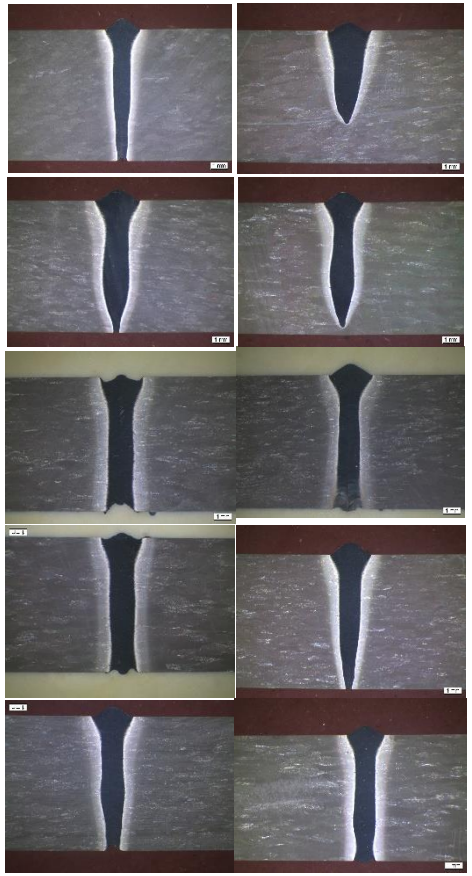


Versuchsplan (64 Stichproben)

Vers-#	Vers.-folge	I_S [mA]	U_B [kV]	OF+ [mA]	A_W [mm]	v_F $\left[\frac{mm}{s}\right]$
1	27	50	120	40	450	45
2	21	50	120	25	350	45
3	49	60	120	40	450	30
⋮						
62	43	60	120	25	350	30
63	56	60	135	40	450	60
64	52	60	135	25	350	60

Experiment (Flachprobe)

64 Schliffbilder



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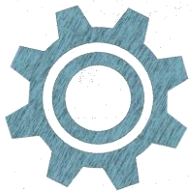
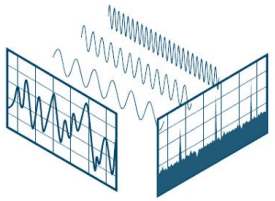
Coupled Process Analysis CPA

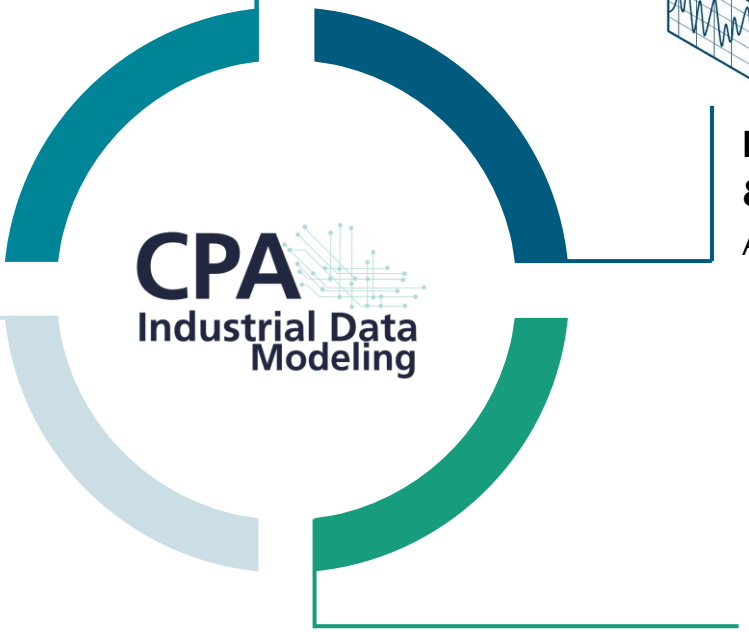
Data standardization & Data compression

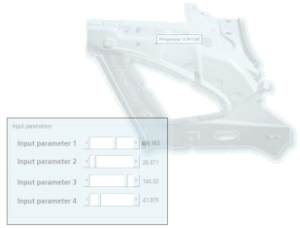


Data Collecting
Users Task
80% of Work scope



Data standardization & Data Compression
Assignment target values





Visualisation
User-friendly visualisation

Supervised Learning
Selection/ Validation of modeling approach

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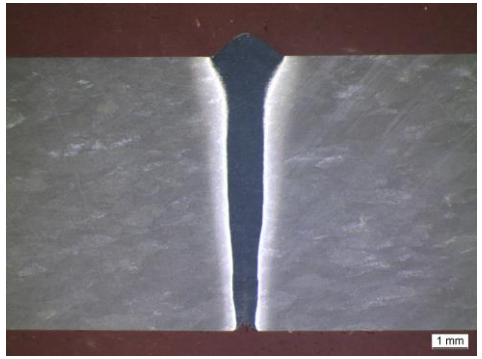
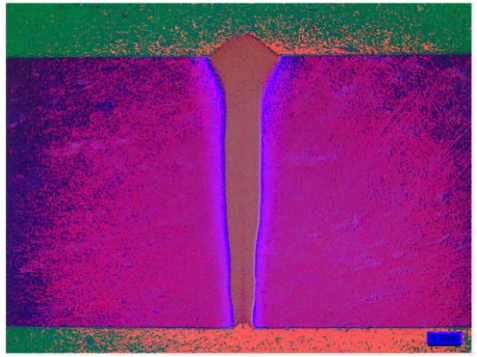
Coupled Process Analysis CPA

Data standardization

1. Schliffbild

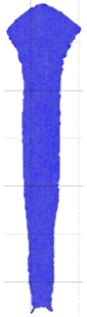


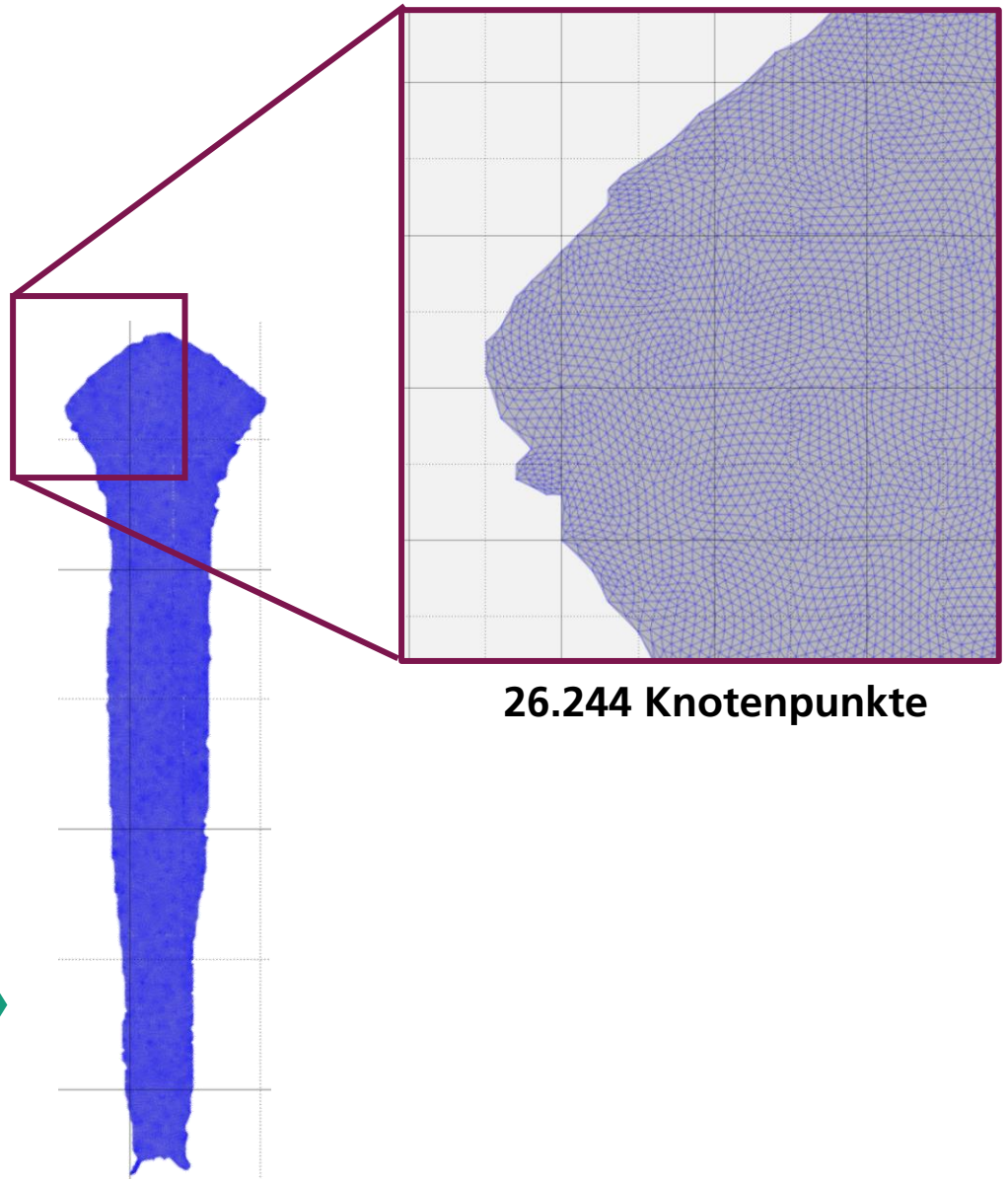
2. Farbfilter



3. Isolierung der Schweiß-naht

4. Umwandlung in Dreiecks-netz (STL)





26.244 Knotenpunkte

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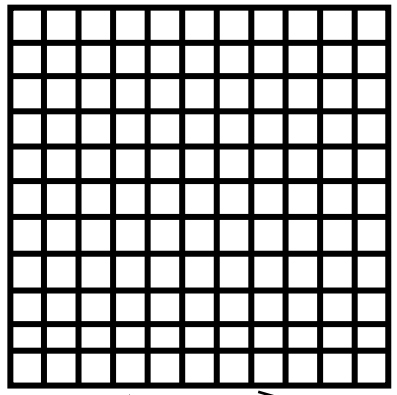
Coupled Process Analysis CPA

Data standardization



Einheitsquadrat mit 26.244 Knotenpunkten

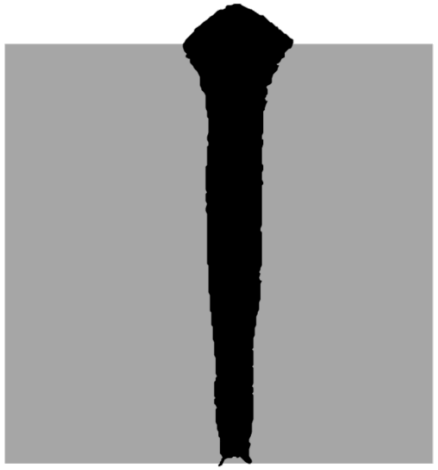
Design 1

STL-Netz mit 26.244 Knotenpunkten

Design 2

STL-Netz mit 26.244 Knotenpunkten

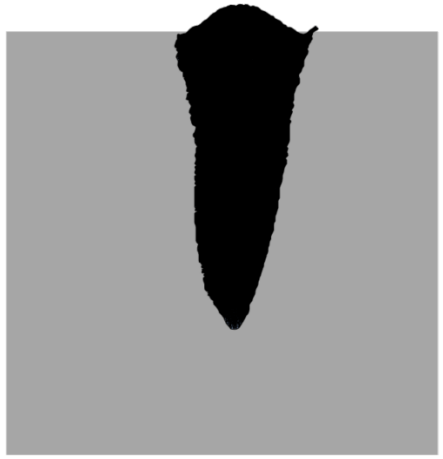
Design 3



STL-Netz mit 26.244 Knotenpunkten

...

Design 64



STL-Netz mit 26.244 Knotenpunkten

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Coupled Process Analysis CPA

Data standardization

Design 1 **Design 2** **Design 3** **Design 64**

		Design			
		1	2	3	n
Node	1	t_{11}	t_{12}	t_{13}	t_{1n}
	2	t_{21}	t_{22}	t_{23}	t_{2n}
	3	t_{31}	t_{32}	t_{33}	t_{3n}
	d	t_{d1}	t_{d2}	t_{d3}	t_{dn}

(n x d) - Multivariate Datenmatrix
→ 64 x 26.244 = 1.679.616 Matrixeinträge

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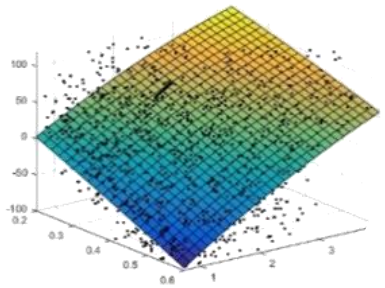
Coupled Process Analysis CPA

Data compression

- Strahlstrom
- Beschleunigungsspannung (UB)
- Linsenstrom (IL)
- Arbeitsabstand (AW)
- Schweißgeschwindigkeit (VF)



Multivariate Datenmatrix
(→ 26.244 X 64)

		Design			
		1	2	3	n
Node	1	t_{11}	t_{12}	t_{13}	t_{1n}
	2	t_{21}	t_{22}	t_{23}	t_{2n}
	3	t_{31}	t_{32}	t_{33}	t_{3n}
	d	t_{d1}	t_{d2}	t_{d3}	t_{dn}

26.244 Metamodelle für die Beschreibung der Schweißnaht notwendig!!!!

→ Lösung: Datenkompression

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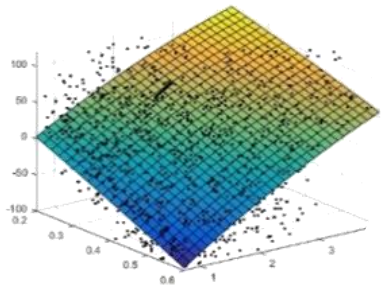
Coupled Process Analysis CPA

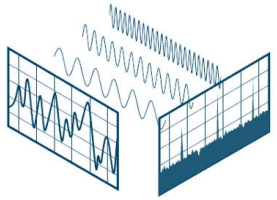
Data compression

- Strahlstrom
- Beschleunigungsspannung (UB)
- Linsenstrom (IL)
- Arbeitsabstand (AW)
- Schweißgeschwindigkeit (VF)



Multivariate Datenmatrix (→ 26.244 X 64)

		Design			
		1	2	3	n
Node	1	t_{11}	t_{12}	t_{13}	t_{1n}
	2	t_{21}	t_{22}	t_{23}	t_{2n}
	3	t_{31}	t_{32}	t_{33}	t_{3n}
	d	t_{d1}	t_{d2}	t_{d3}	t_{dn}



Fourier-Transformation

		Design			
		1	2	3	n
CPA-Mode	1	t_{11}	t_{12}	t_{13}	t_{1n}
	2	t_{21}	t_{22}	t_{23}	t_{2n}
	3	t_{31}	t_{32}	t_{33}	t_{3n}
	k	t_{d1}	t_{d2}	t_{d3}	t_{dn}

Reduzierte Datenmatrix (→ 10 X 64)

10 signifikante Variationsmuster identifiziert

→ Nur 10 Metamodelle für die Beschreibung der Schweißnaht notwendig!!!!

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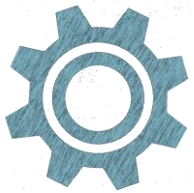
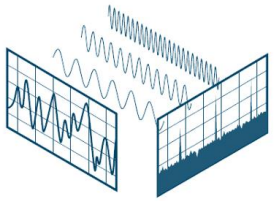
Coupled Process Analysis CPA

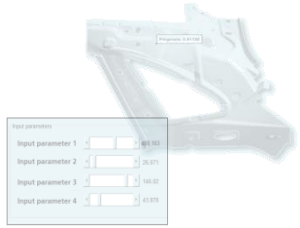
Supervised Learning



Data Collecting
Users Task
80% of Work scope

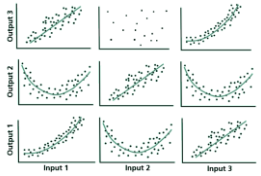


Data standardization
& Data Compression
Assignment target values



Visualisation
User-friendly visualisation

Supervised Learning
Selection/ Validation of
modeling approach



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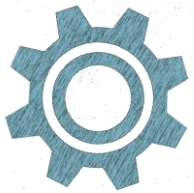
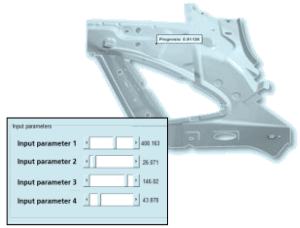
Coupled Process Analysis CPA

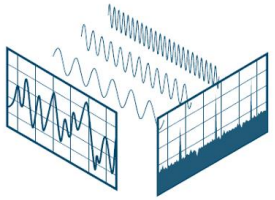
Visualiziation



Data Collecting
Users Task
80% of Work scope

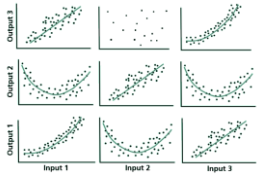


Visualisation
User-friendly visualisation



Data standardization
& Data Compression
Assignment target values

Supervised Learning
Selection/ Validation of
modeling approach



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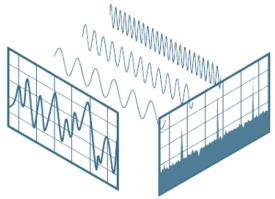
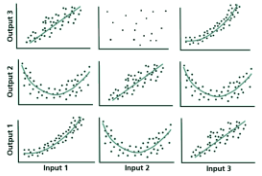
Coupled Process Analysis CPA

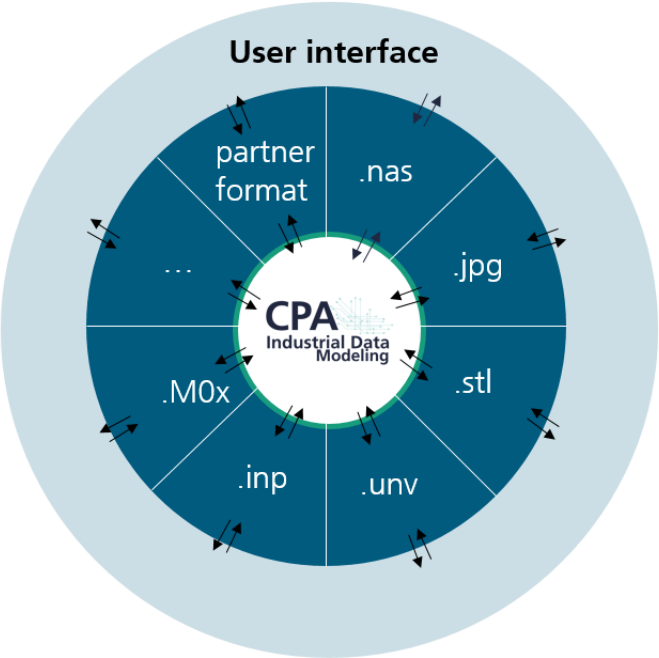
Concept



Data standardization
& Data Compression
Assignment target values

Supervised Learning
Selection/ Validation of
modeling approach





CPA Software Structure

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Agenda

- Gegenstand
- Ziele
- CPA – Coupled Process Analysis
- Praxisbeispiele

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Urformen

Numerical analysis HIGH PRESSURE DIE CASTING

Use cases: Porosity; solidification rate, fill temperature

Data Source: MAGMASOFT®

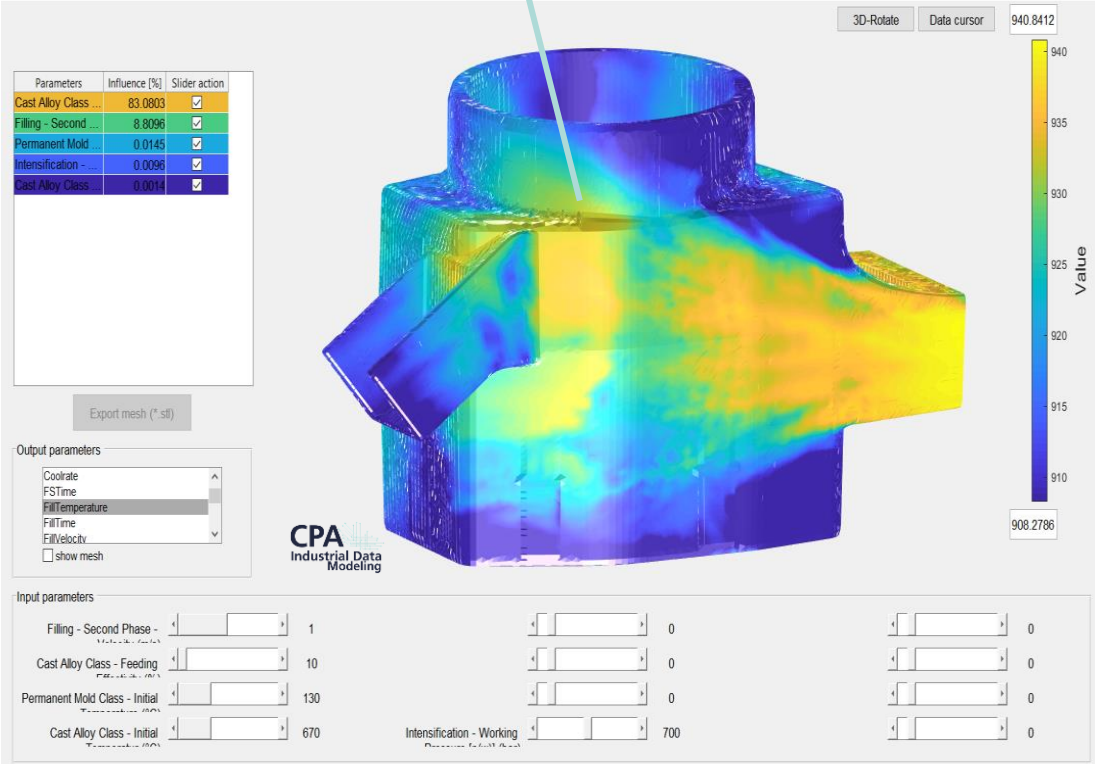
Inputs: 13 parameters

Samples: 15 simulations

Advantages:

- Spatially-resolved model for component-related visualization of process sensitivities
- Model-based generation of arbitrary virtual variants in real time (without new solver runs)

3D output variable (Fill Temperature) predicted by the model



process parameters

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Urformen

Numerical analysis of PLASTIC INJECTION MOLDING

Use cases: Thermal stress; deviation to CAD

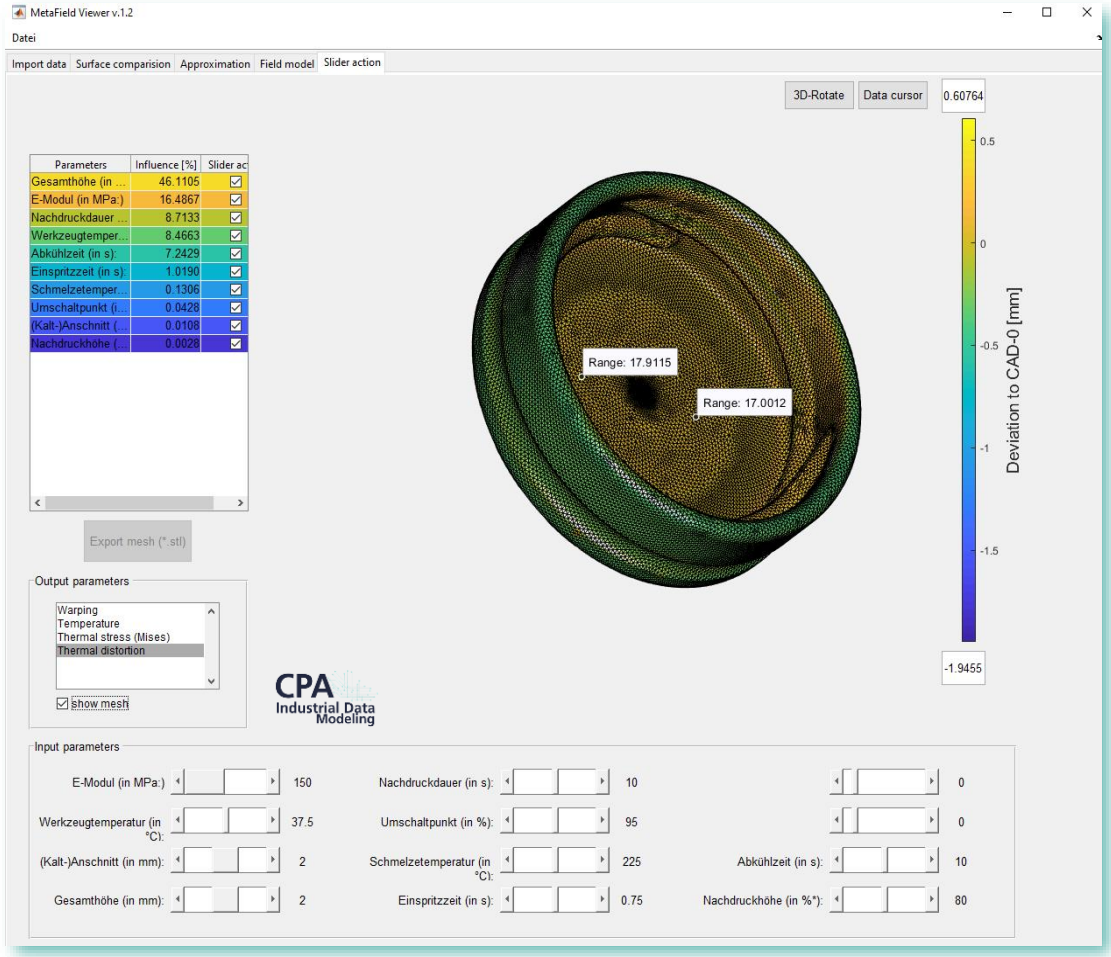
Data Source: Moldex3D®

Inputs: 10 parameters

Samples: 31 simulations

Advantages:

- All causal relationships (distortion, thermal stress, temperature)
- Reduction of bottle cap distortion in contrast to the starting design



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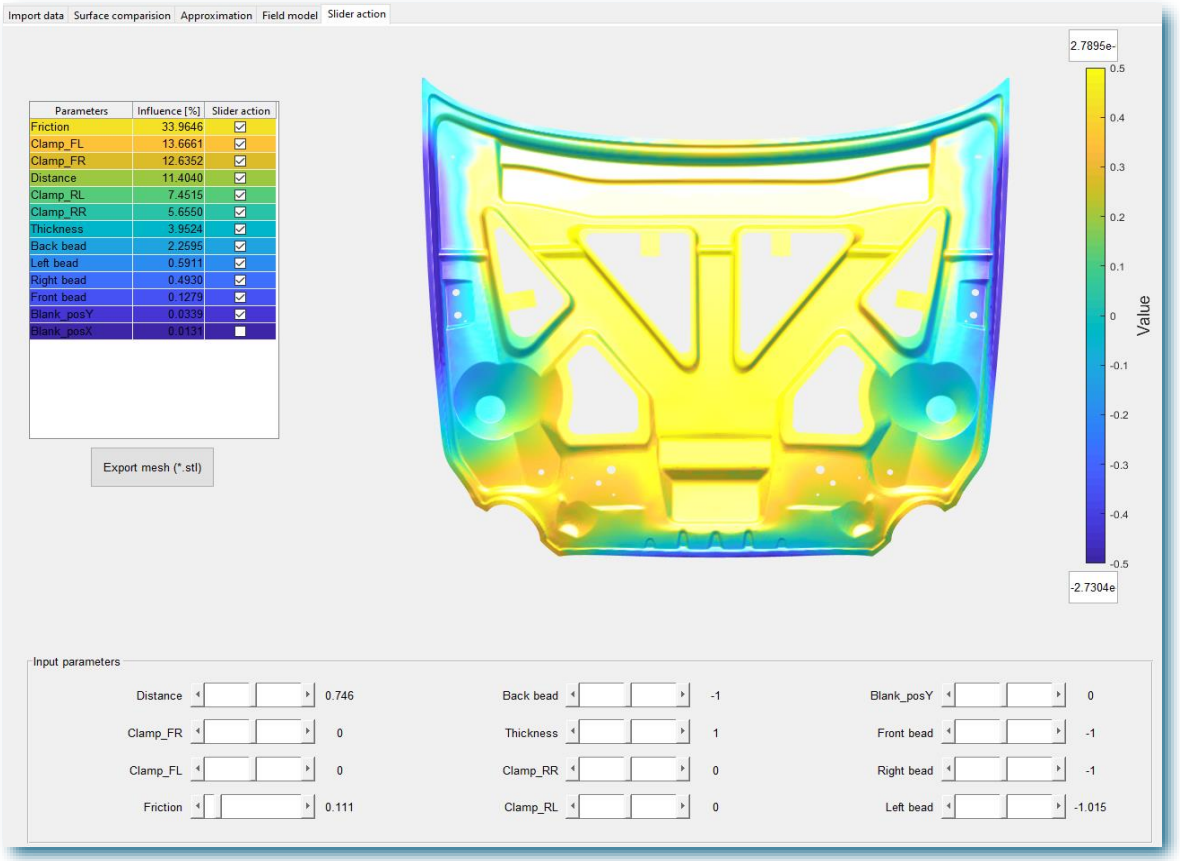
Umformen

Numerical analysis DRAWING

Use cases:	Springback	Wrinkeling // Waves
Data Source:	ESI PAM-STAMP®	AutoForm®
Inputs:	13 parameters	9 Parameter
Samples:	30 simulations	40 Simulation

Advantages:

- Small amount of samples (AutoForm Sigma min12/Input)
  - correlation-free DOE extension by SLHS
  - standardisation capability



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Umformen

Numerical analysis PRESS HARDENING

Use cases: Hardness

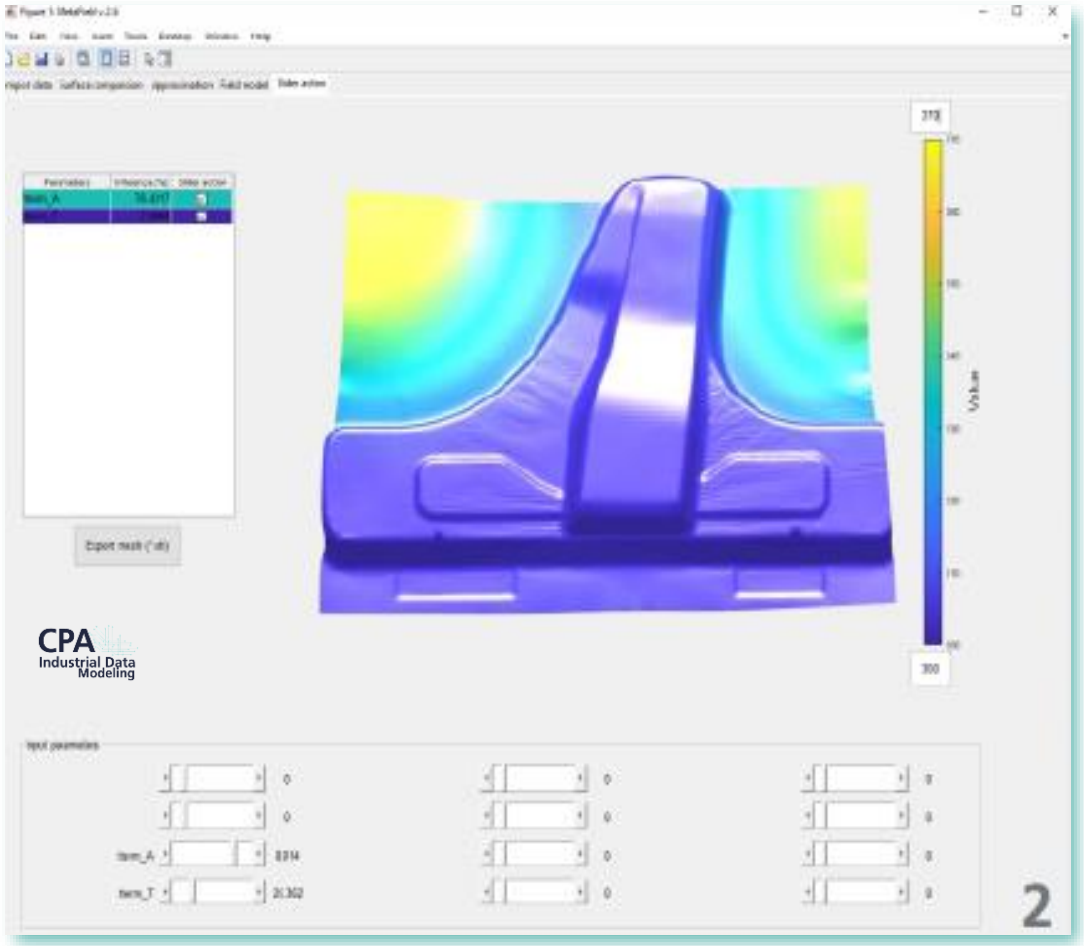
Data Source: LS-DYNA®

Inputs: 4 parameters

Samples: 25 simulations

Advantages:

- Predict hardness in the 3D model



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Fügen

Numerical analysis HALF TUBE RIVETING

Use cases: 2D image result

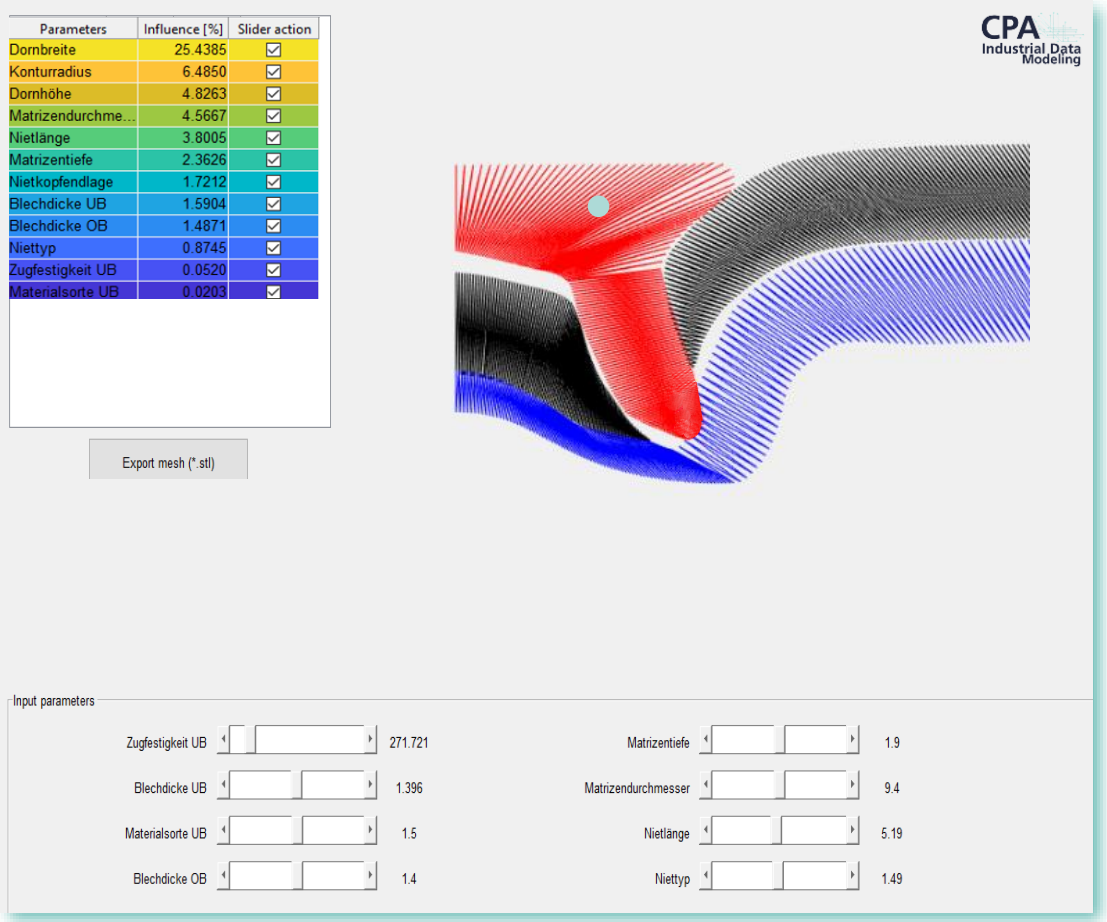
Data Source: SIMUFACT®

Inputs: 12 parameters

Samples: 4.000 simulations

Advantages:

- Statistical model, which mathematically generates the 2D cross-sectional geometry of the SPR joint in real time with free change of the tool parameters.



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Fügen

Modeling micrographs of LASER BEAM WELDING

Use cases: Process Capability

Data Source: Micrograph Images

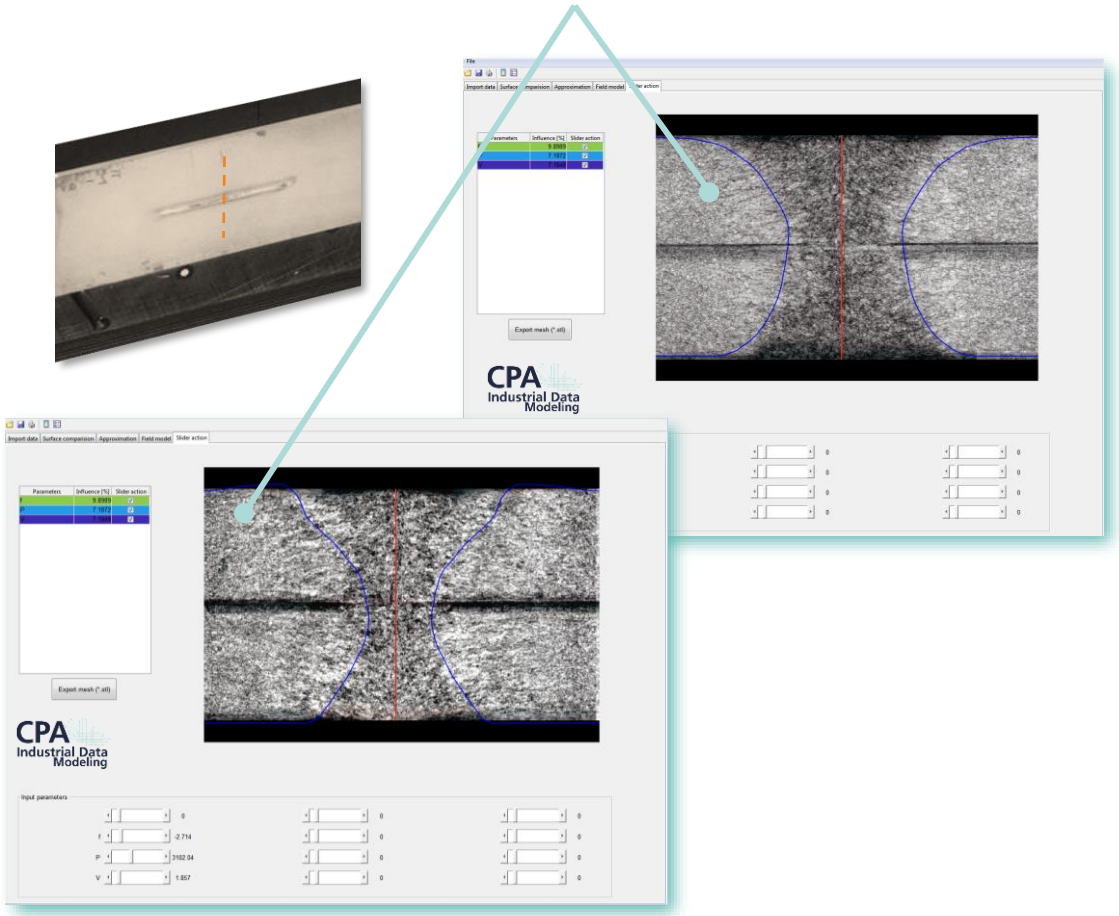
Inputs: 3 parameters

Samples: 12 pictures (12MP)

Advantages:

- Model-based 2D image (virtual micrograph)
- Laser weld seam parameter combinations in real time
- Model calculation < 2 min (office notebook)

2D micrograph images predicted by the model



welding process parameters

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Fügen

Modeling micrographs of ELECTRON BEAM WELDING

Use cases: Process Capability

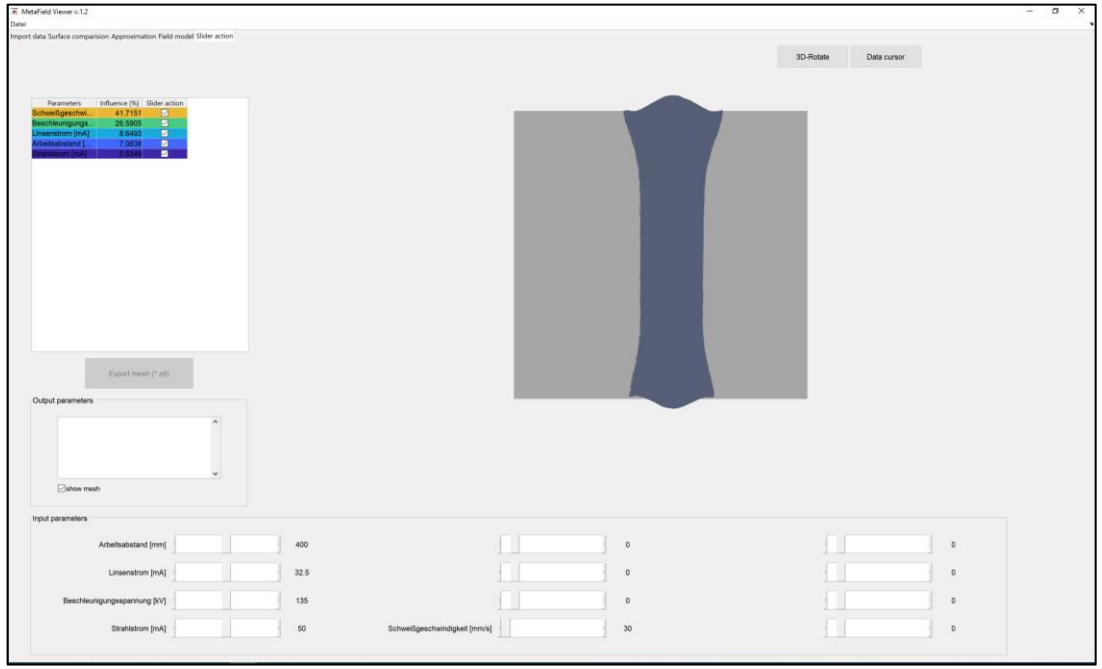
Data Source: Micrograph Images

Inputs: 3 parameters

Samples: 64 pictures

Advantages:

- Cross corelations are visible
- Model-based 2D image (virtual micrograph) from process parameters combinations in real time



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Assembling

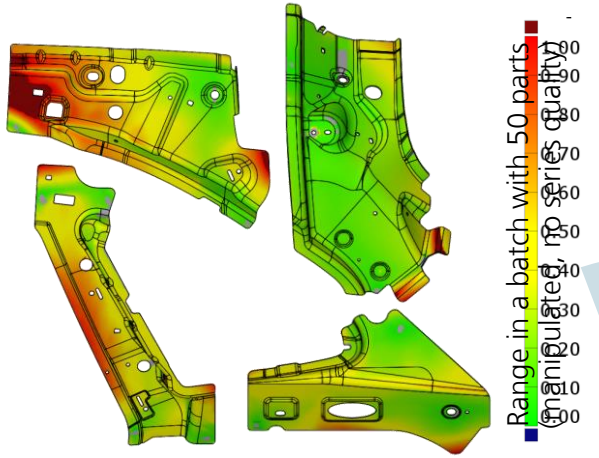
Experimental and numerical analysis window corner

Use cases: Springback

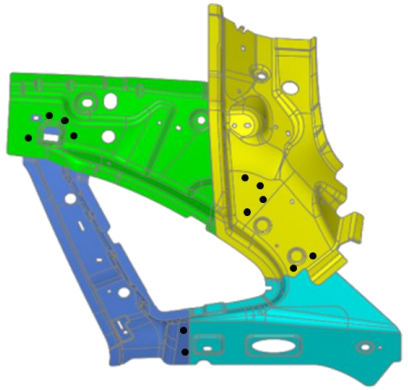
Data Source: GOM ATOS® + ESI PAM-STAMP®

Inputs: 2 parameters (Clamps & Pins) & 4 Parts

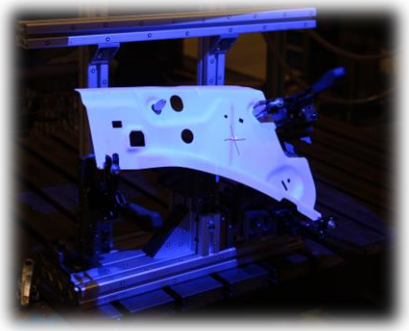
Samples: 50 simulations



Single Part Variation Range



Variant Simulation



Measurement (5 pcs / Type)

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Assembling

Experimental and numerical analysis window corner

Use cases: Springback

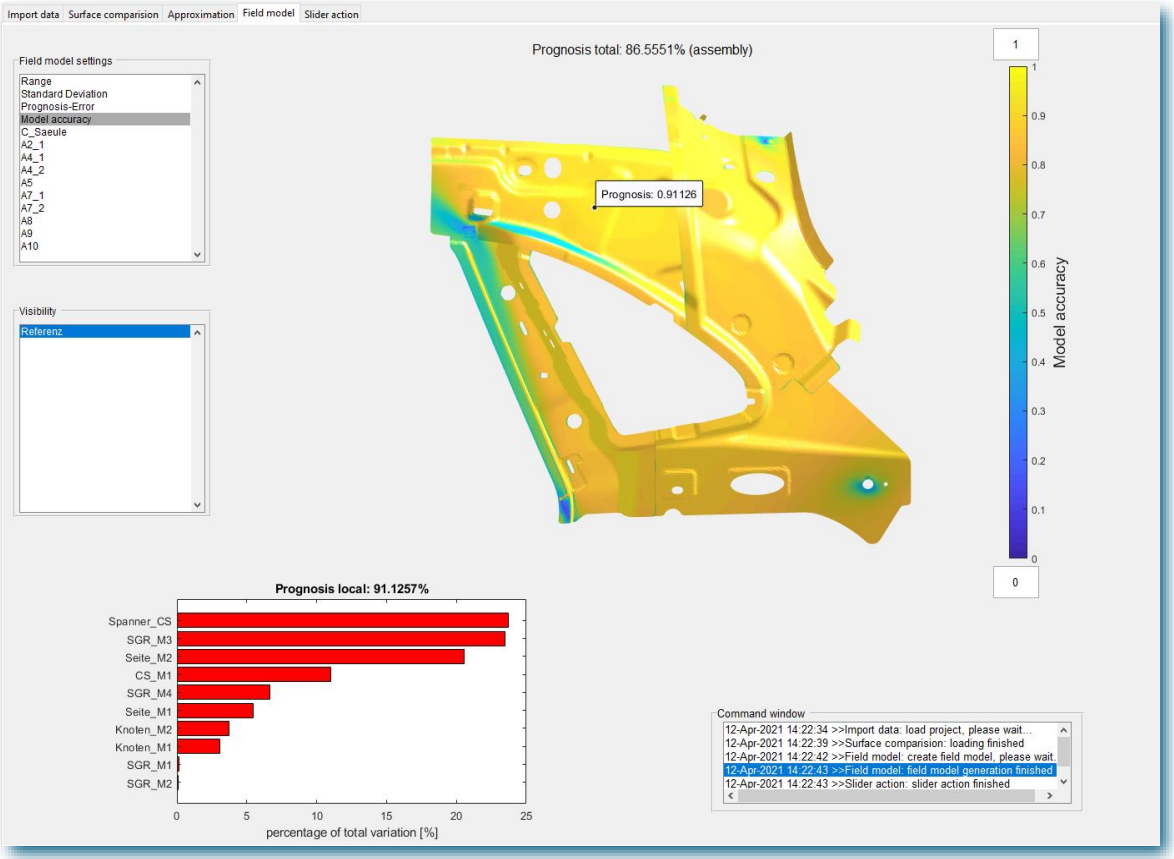
Data Source: GOM ATOS® + ESI PAM-STAMP®

Inputs: 2 parameters (Clamps & Pins) & 4 Parts

Samples: 50 simulations

Advantages:

- Presentation of the influence of single part variations and possibilities for dimensional stability compensation through clamping point variation



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Assembling

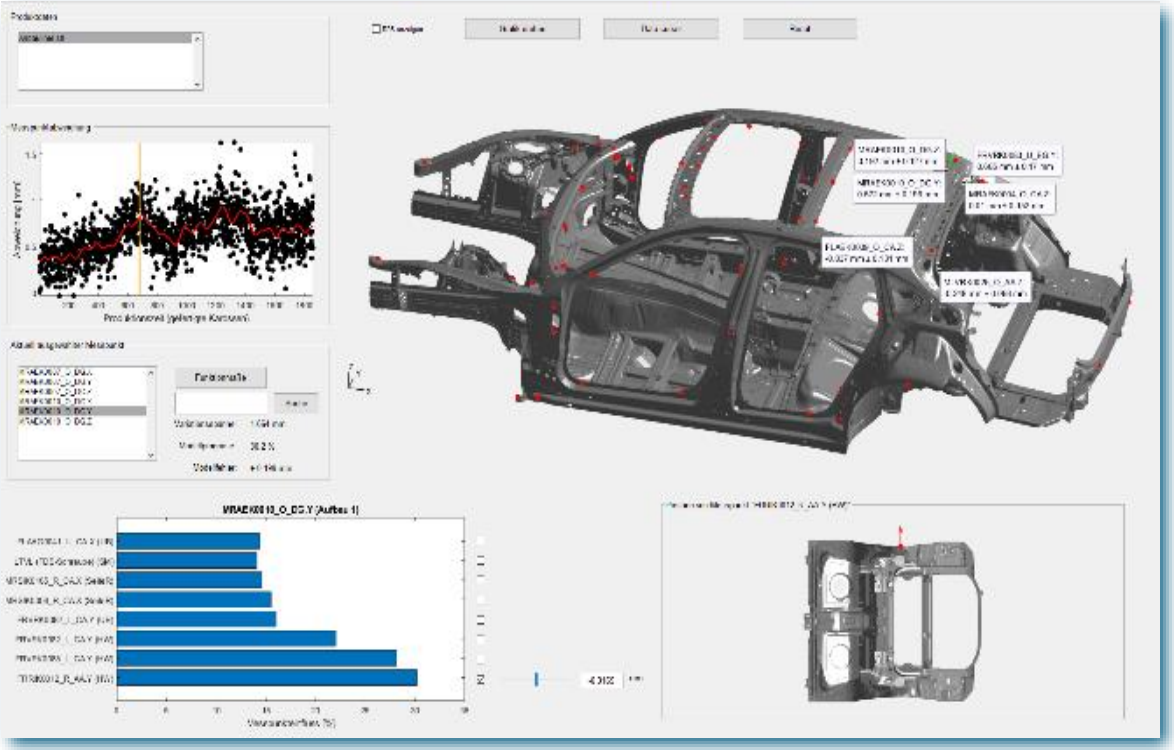
Serial Assembling Process

Use cases: Springback

Data Source: ZEISS IMT

Inputs: 7 substructure Measurement Stations
about 1800 Points

Samples: one week of production



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Getting started with CPA

in 3 steps to your analysis solution

POC

STEP 1

On the basis of submitted data, a **compiled CPA viewer** is generated for testing at the project partner's site
(available in a few weeks)

PROTOTYPE

STEP 2

Compiled CPA application, which allows the loading and evaluation of data by the project partner

PROFESSIONAL

STEP 3

Professionalized CPA software tool for the standalone analysis of cause-effect relationships by the project partner

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Vielen Dank für Ihre Aufmerksamkeit!