Project AO-1-10549 - APPLICATION OF MACHINE LEARNING AND ARTIFICIAL INTELLIGENCE TECHNOLOGIES FOR PROCESS DATA ANALYSIS

»PANORAMA«

Process ANalysis and Optimization foR Advanced Manufacturing in Aerospace

Final Presentation

ESA-ESTEC, Noordwijk, 11/07/2023

Today's Agenda

Final Presentation of project »PANORAMA«

Overall project presentation	Use Case identification, evaluation, implementation and verification of Artificial Intelligence use cases	**1.**
Use case overview		**2.**
	MLSys 1 – Automated Live Process Monitoring	**a.**
	MLSys 2 – Robustness Assessment	**b.**
Conclusion and Outlook	Final considerations and next steps	**3.**

Fraunhofer IPT

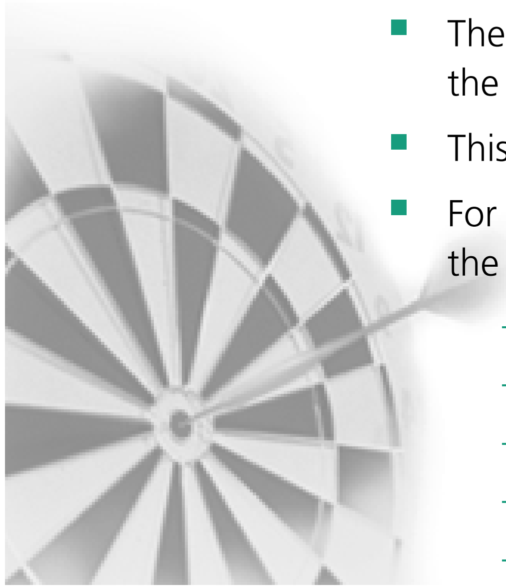
WZL | RWTH AACHEN UNIVERSITY

01 – Overall project presentation

Use Case identification, evaluation, implementation and verification of Artificial Intelligence use cases

Motivation & Outset

Overall performance enhancement by optimizing process chains via Machine Learning applications



Independent access to space, which is one key to solving global and social challenges, is a central component of the European space strategy

International competition in aerospace industries has increased sharply in recent years. For future European launch systems, this means that their reliability and performance must be increased while total system costs need to be decreased

This can be achieved by optimizing overall process chains and using advanced manufacturing technologies that lead to improvements in the cost / benefit ratio

- The overall goal of the project »PANORAMA« is the **targeted expansion of knowledge** about Machine Learning in the production environment of launch vehicles, mainly for the optimization of advanced manufacturing processes
- This **ensures** immediate and future **participation** in European space transportation systems.
- For this purpose, **AI use cases** are selected and **developed AI models** are deployed in the production environment in the following partial phases:
  - In-depth analysis of technical requirements and production system
  - Identification and evaluation of use cases
  - Development of a minimum viable product and proof of concept
  - Design and Definition of the required software architecture
  - Implementation and validation of two use cases

PANORAMA

Structure of work packages

Task 1
Analysis, design and development plan: Identification of advanced manufacturing processes, use case classes and use cases to implement. Definition of agile software development plan

Task 2
MVP's proof of concept based on the requirements analysis

Task 3
Detailed design and definition of the software architecture

Task 4
Software implementation and integration development

Task 5
Software delivery and reporting

Project presentation

Structure of work packages

Task 1

- **WP1** – Analysis of technological requirements
- **WP2** – Production system analysis
- **WP3** – Data basis analysis
- **WP4** – Use case evaluation and selection

Task 2

- **WP5** – Minimum Viable Product development
- **WP6** – Proof of concept for 2 use cases

Task 3

- **WP7** – Data preparation for 2 use cases
- **WP8** – Modelling of 2 AI use cases

Task 4

- **WP9** – Deployment of 2 AI use cases
- **WP10** – Validation

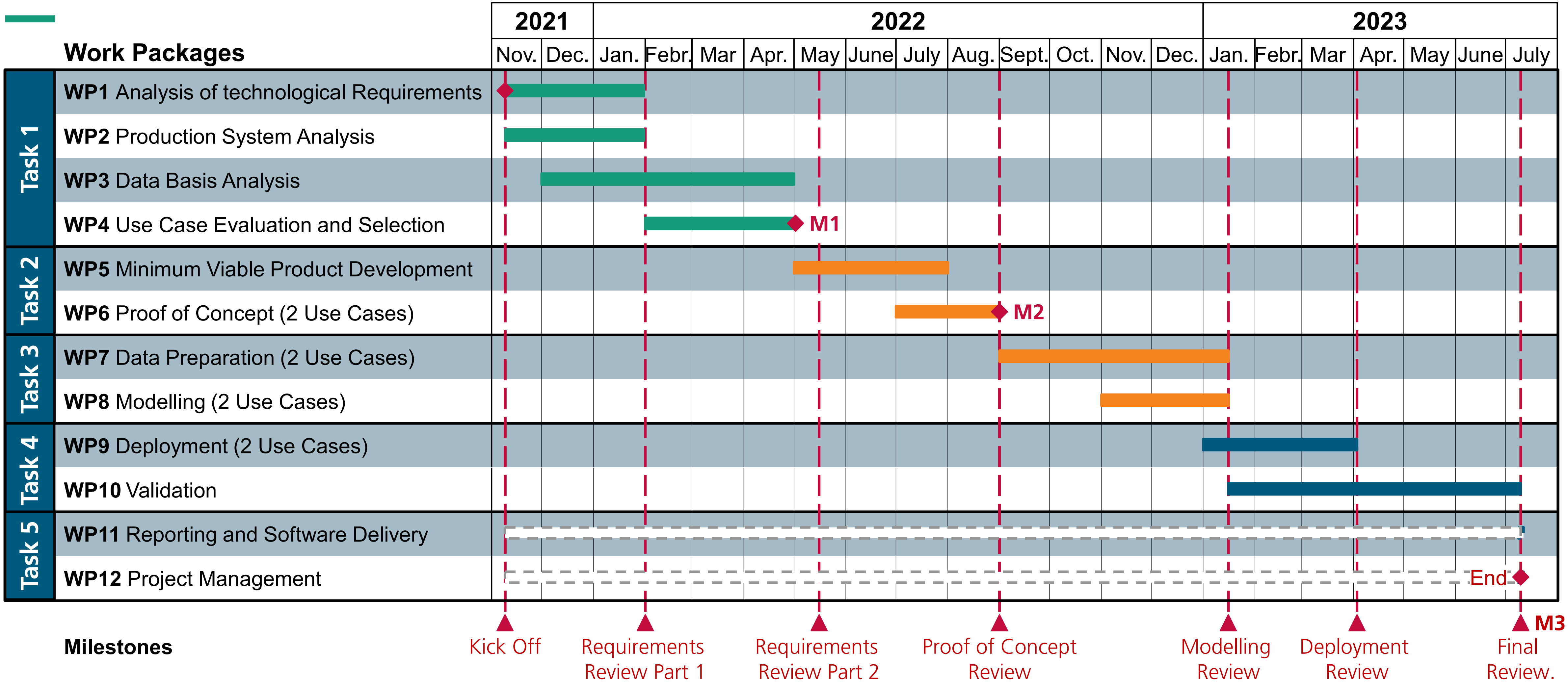
Task 5

- **WP11** – Reporting and software delivery
- **WP12** – Project management

Responsible Entity for Work Package: ArianeGroup | Fraunhofer IPT

PANORAMA

Work programme schedule



Overview of Technological Processes

Overview of analyzed process chains and corresponding parts

1) ALM* Process Chain

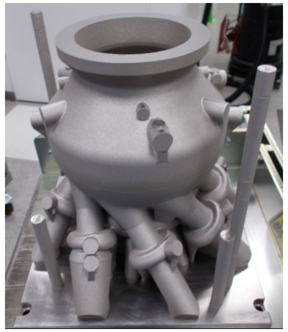
Manufacturing steps

ALM → Heat Treatment → Machining → Welding → …

Corresponding parts

Turbine Pump Casing

CC Fuel Manifold



Gas Generator

Heat Exchanger

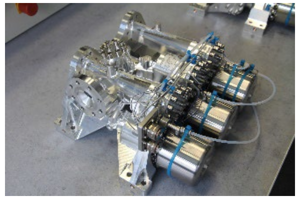
2) Electronic Valves Process Chain

Manufacturing steps

Component Manufacturing → Assembly

Corresponding parts

PPDR-H



PPDR-H

Within this project **two relevant process chains** – the manufacturing of ALM parts and electronic valves – two use cases were implemented in the ArianeGroup production environment.

*Additive Layer Manufacturing

Evaluation Model

The AI use case evaluation model considers general and specific aspects for optimal decision-making

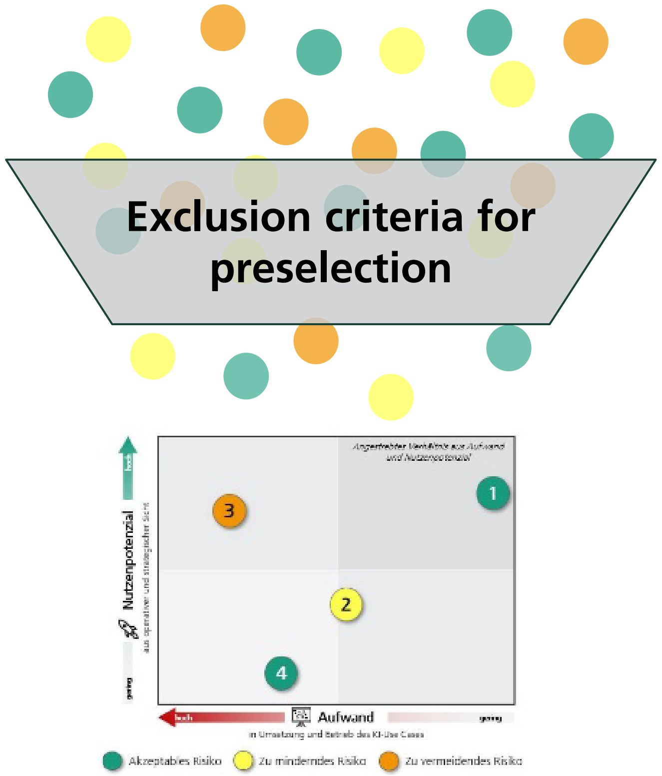
General production concepts

ArianeGroup - production system

Generic evaluation methodology

Adaption to project framework

Evaluation model for PANORAMA



Selection of Use Cases

Evaluation Model

Iterative passage and adjustment of the evaluation methodology

Recording

The characteristics of the AI use cases are recorded **qualitatively** or **quantitatively** based on the evaluation criteria.

Weighting

The **evaluation criteria** of the AI use cases **within a category** are **weighted** according to targets.

Rating

The AI use cases are **evaluated** against the target criteria for **comparative analysis**.

Selection

The two **most promising** AI use cases will be selected **based on the evaluation results** and **implemented** in the **ArianeGroup production system** after Task 1.

Preselection I

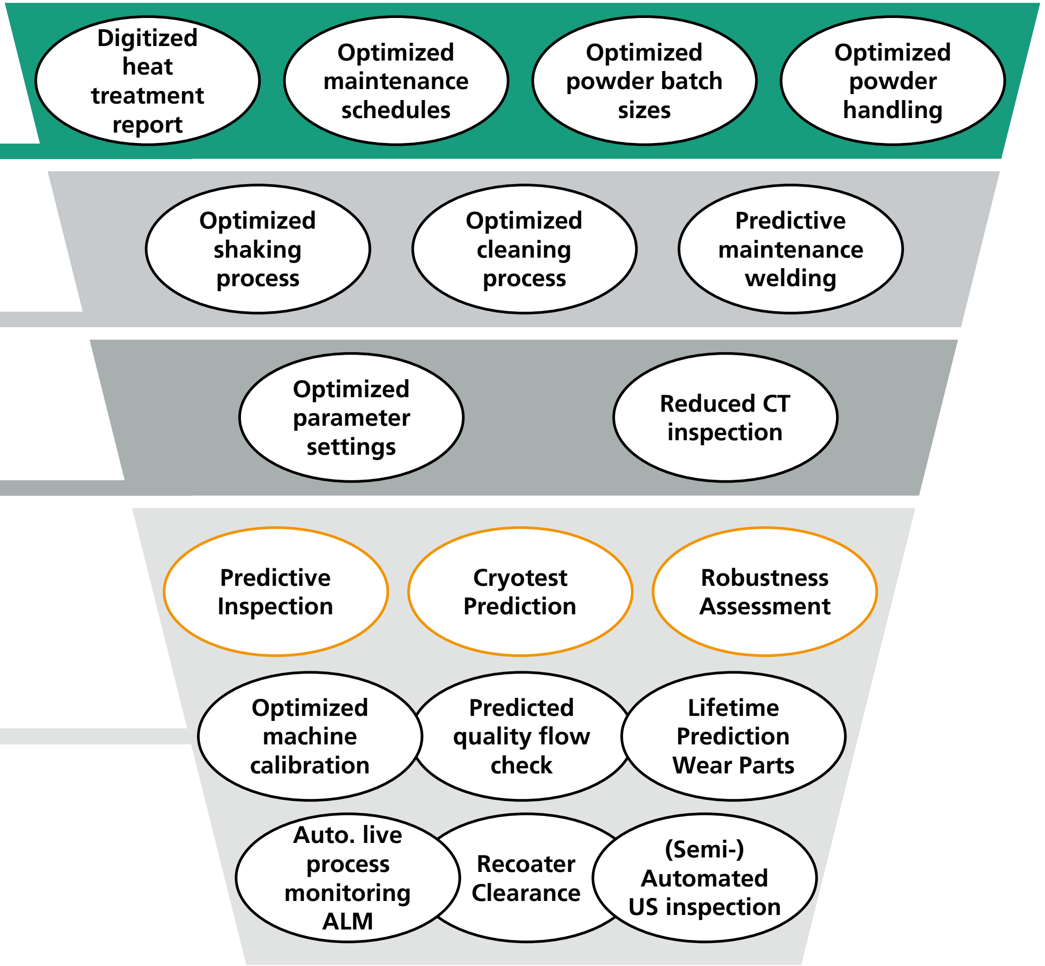
Pre-assessment based on three qualitative criteria previously discussed in the project team

Problem can be solved with **conventional statistical methods**

Pre-assessed **benefits do not justify implementation**

Implementation within project **not possible** due to severe restrictions

Use cases for **further evaluation** according to the defined criteria



Aggregation of several use cases

Preselection II

Refining the use case scope in a joint working group session

9 Use Cases (Input for working session)

Renumbering

1. *Optimized machine calibration*
2. *Lifetime Prediction Wear Parts*
3. *Recoater Clearance*
4. *Auto. live process monitoring ALM*
5. *Predictive Inspection*
6. *(Semi-) Automated US inspection*
7. *Predicted quality flow check*

Further specified use case scope
→ Revised since the updated targeted issue does not justify an implementation

8. *Cryotest Prediction*

Adapted use case scope
→ Split up into use case 8a and 8b

9. *Robustness Assessment*

Detailing of use case scope

7 Use Cases for Evaluation

1. *Optimized machine calibration*
2. *Lifetime Prediction Wear Parts*
3. *Recoater Clearance*
4. *Auto. live process monitoring ALM*

8a. *Optimized Force-Stroke Measurement*

8b. *C-ring Quality Inspection*

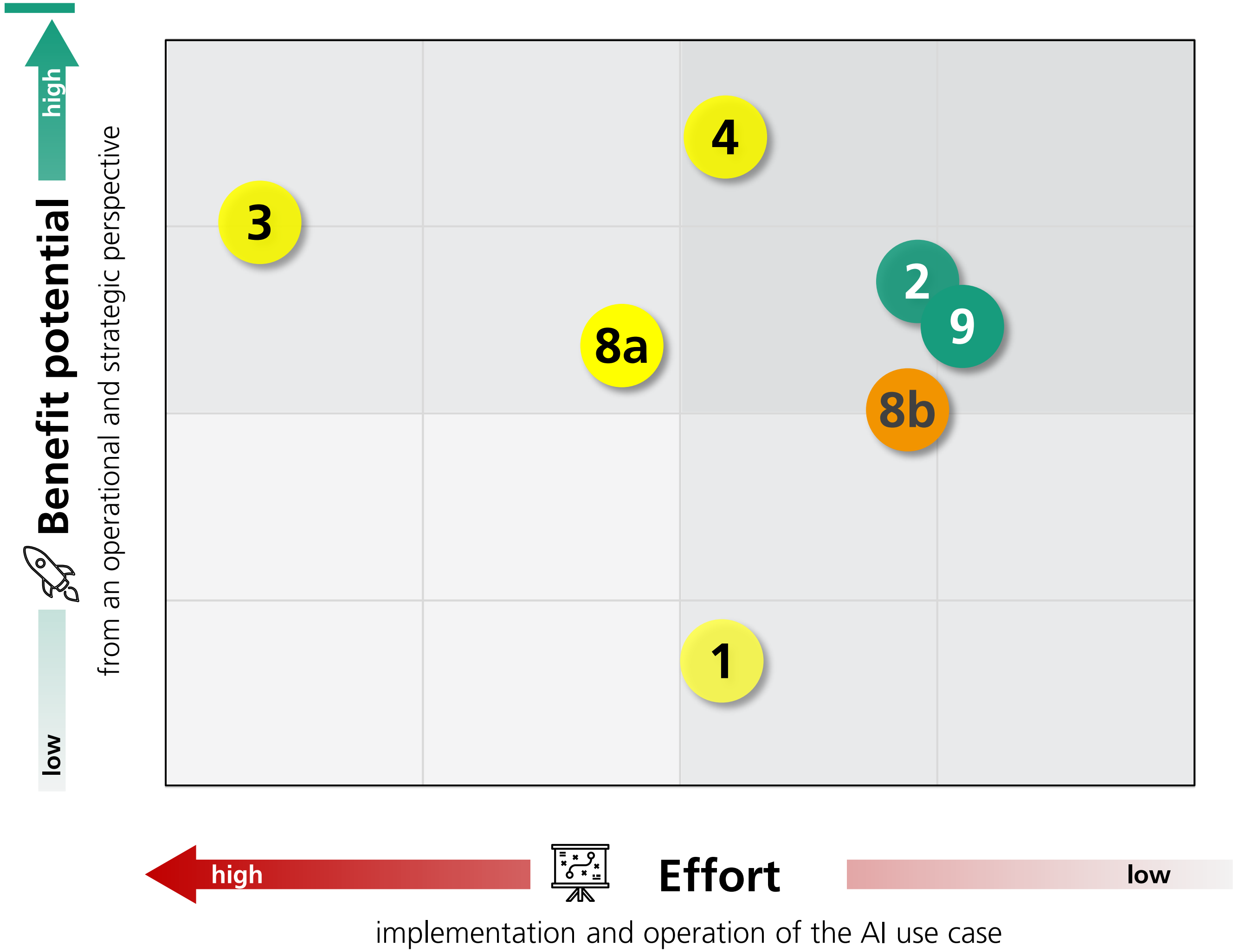
9. *Robustness Assessment*

Seven use cases serve as an input for the following **sophisticated use case evaluation**

ArianeGroup Fraunhofer IPT WZL RWTH Aachen University

Preselection I

Pre-assessment based on three qualitative criteria previously discussed in the project team



Use cases

1 Optimized Machine Calibration (ALM)

2 Lifetime Prediction Wear Parts (ALM)

3 Recoater Clearance (ALM)

4 Automated Live Process Monitoring (ALM)

8a Optimized Force Stroke Measurement (EV)

8b C-Ring Quality Inspection (EV)

9 Robustness Assessment

Acceptable risk | Risk to be reduced | Risk to be avoided

 11/07/2023

arianeGroup Fraunhofer IPT WZL RWTH AACHEN UNIVERSITY

02 – Use Case Overview

MLSys 1 – Automated Live Process Monitoring

Focus on the additive layer manufacturing (ALM) process of APU components

Initial situation

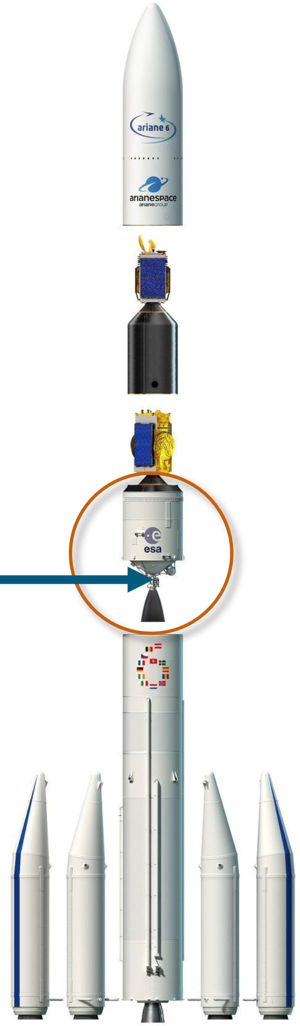
Machine Learning Use Case Applied

Additive Layer Manufacturing (ALM) Process Chain

ALM → **Heat Treatment** → **Machining** → **Welding** → **Other**

Auxiliary Power Unit

Heat Exchanger, Gas Generator, Nozzles, and Distributor



Ariane 6

Machine learning application project motivation

Live error detection for ALM processing

ALM

Status Quo

Manual error detection after processing

- Discontinuous process monitoring
- Waste of resources upon error occurrence

Target

Automated live classification of errors, e. g.

- **Non defective** – *Uncritical for product quality*
- **Hotspot Class 2** – *Medium criticality*
- **Hotspot Class 3** – *High criticality*
- **Coldspot Class 2 & 3** – *High criticality*

Execution

Live data analysis

- PBM[2] data
- OT[1] data
- M&E[3] data

Process experts are notified of critical errors immediately

[1]OT: Optical Tomography
[2]PBM: Powder Bed Monitoring
[3]M&E: Machine & Environmental

Deep dive: application of machine learning for error detection

Live error detection for ALM processing

Target

Automated live classification of errors, e. g.

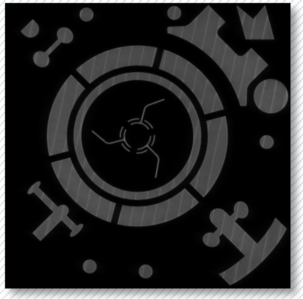
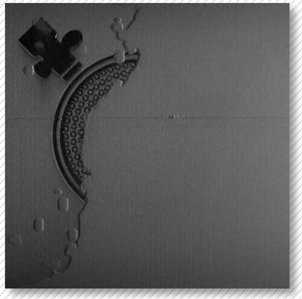
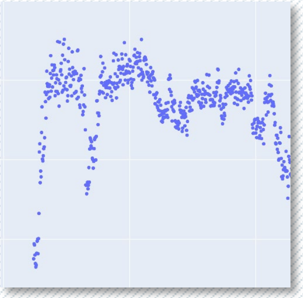
Non defective
Uncritical for product quality

Hotspot Class 2
Medium criticality

Hotspot Class 3
High criticality

Coldspot Class 2 & 3
High criticality

Input Data Streams for Machine Learning Models

	OT[1] Data Stream	*PBM[2] Data Stream*	*M&E[3] Data Stream*
Machine Learning Task	**Image classification** 	**Image classification** 	**Anomaly detection** (supervised or unsupervised) 
Objective	**Class prediction for each layer** *Non-defective* / *Class 2 hotspot* / *Class 3 hotspot* / *Coldspots*	**Class prediction for each layer** *Non-defective* / *Anomaly*	**Early detection of anomalies** *e.g. Oxygen peaks* / *e.g. Temperature peaks*

[1]OT: Optical Tomography
[2]PBM: Powder Bed Monitoring
[3]M&E: Machine & Environmental

 11/07/2023

Fraunhofer IPT | WZL | RWTH AACHEN UNIVERSITY

Deep dive: application of machine learning for error detection

Operational environment at the Ottobrunn site

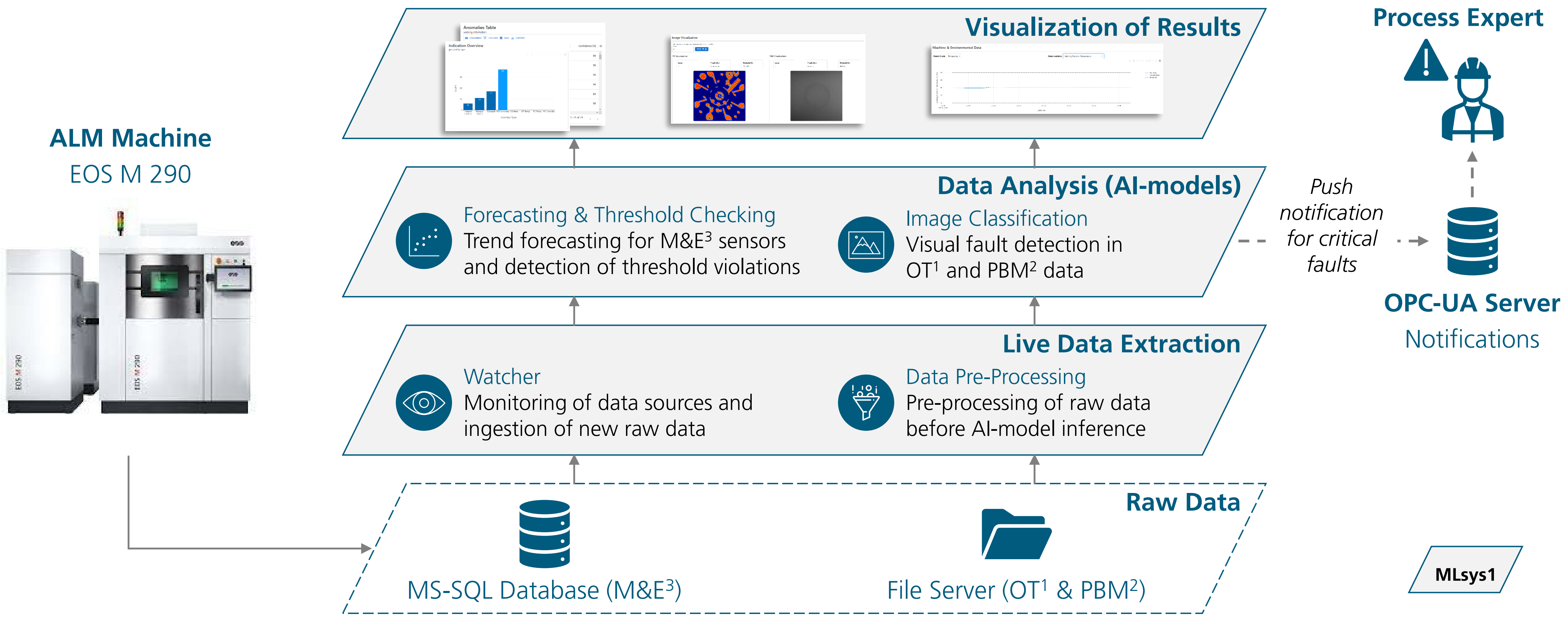


Image: EOS

[1]OT: Optical Tomography
[2]PBM: Powder Bed Monitoring
[3]M&E: Machine & Environmental

 11/07/2023

Fraunhofer IPT | WZL | RWTH AACHEN UNIVERSITY

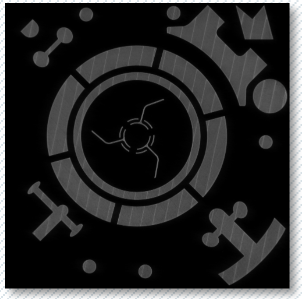
Machine learning use case along the optical tomography (OT) data stream

Use of classification for OT data stream

OT Data Stream

Task

Image classification



Objective

Class prediction for each layer

Non-defective *Class 2 hotspot*
Class 3 hotspot *Coldspots*

Batches of OT images

Sampling frequency ~ 1/min

- **Image size**: 2000x2000 (32-bit)
- **File format:** .raw
- **Channels:** Single channel (grayscale)
- **Consistent lighting** conditions across historical build jobs
- Strong **data imbalance**
- Historical data collected from **14 build jobs** from various product variants

Multiclass Classification

OT Model

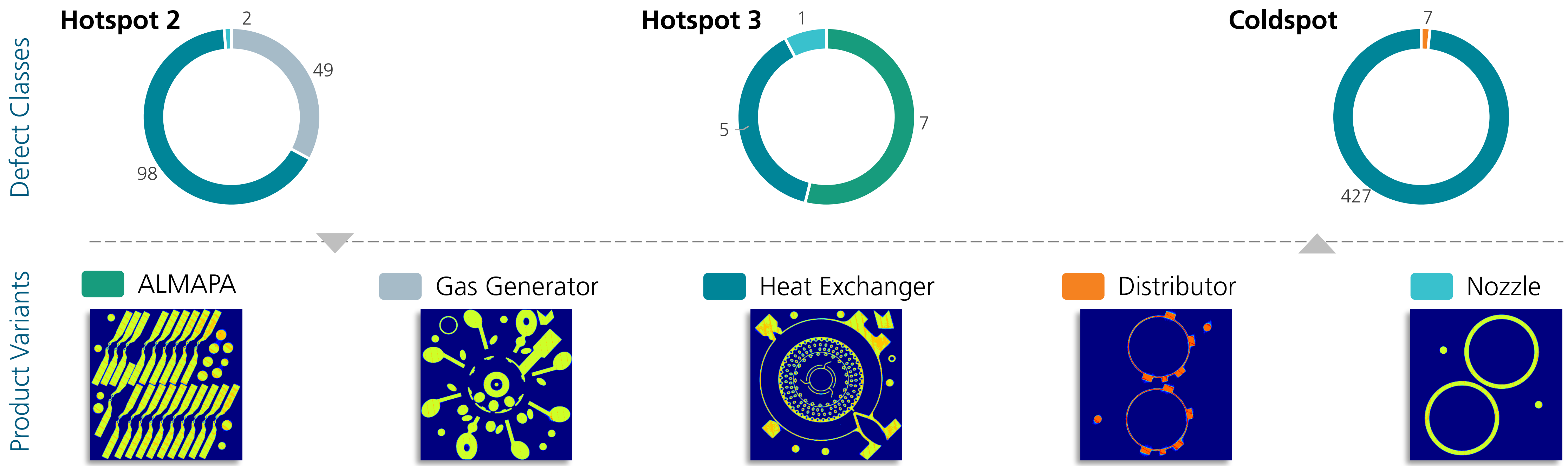
Result

- Non defective & Class 1 anomaly — *Uncritical for product quality*
- Hotspot Class 2 — *Medium criticality*
- Hotspot Class 3 — *High criticality*
- Coldspot Class 2 & 3 — *High criticality*

Optical tomography (OT) data stream

Data exploration

Distribution of product-class combinations

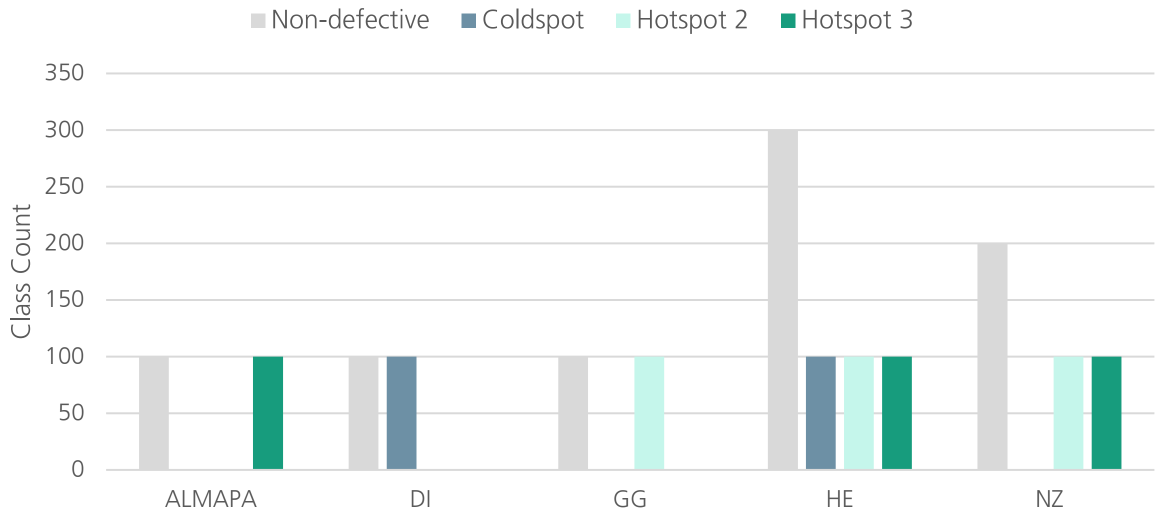


The analysis of OT data distribution revealed an **imbalance between different product-defect combinations**. This issue was **addressed during the train-test-split to avoid any bias** in the ML model for OT image classification.

Optical tomography (OT) data stream

Train-test-split, balancing, and image preprocessing

Training Dataset after Balancing

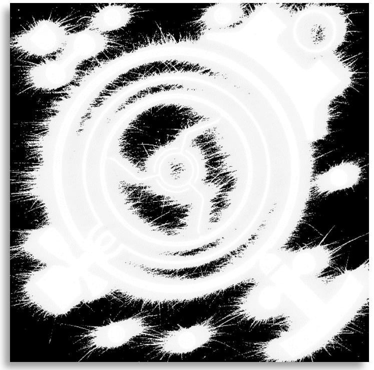


Training dataset distribution after balancing

Data split and balancing

- 80/20 train-test-split per product-class combination
- Combined class over- and undersampling to obtain balance between non-defective and defective classes per product variant

Image Preprocessing



Raw OT image (via machine interface)

Processed OT image (for analysis)

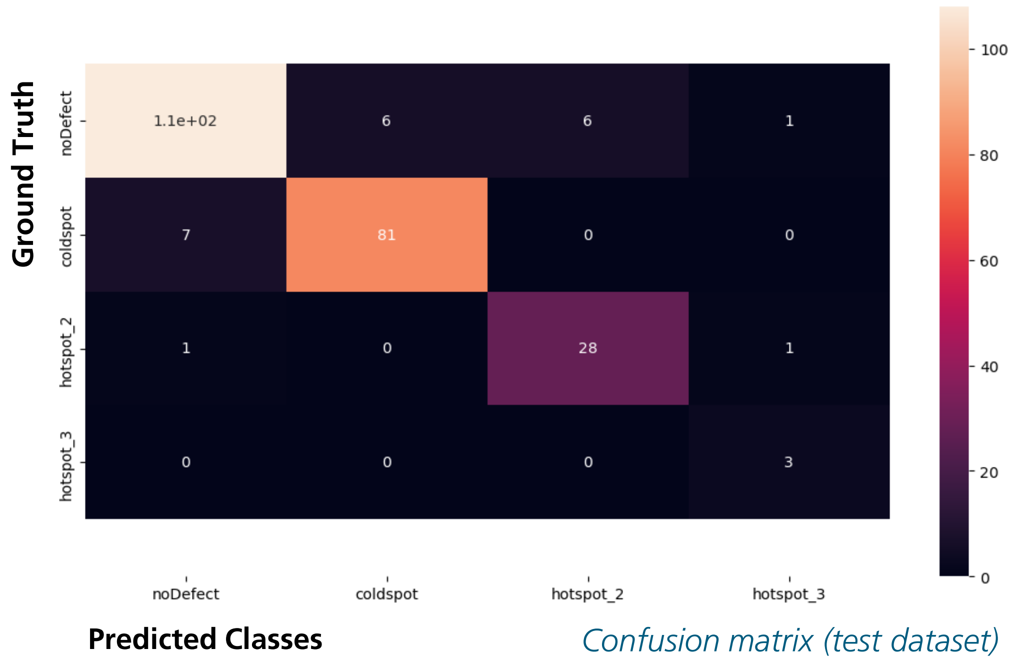
Preprocessing steps

- **Format:** .raw (32-bit) to .png (8-bit) transformation
- **Size:** 2000x2000 to 512x512
- Denoising
- RGB-transformation and Jet colormap
- Normalization and random augmentation (flip and jitter)

Optical tomography (OT) data stream

ML-Modeling results

Testing results for best model (pretrained ResNet50)



Confusion matrix (test dataset)

Class	**Precision**	**Recall**	**F1-Score**	**Support**
Non-defective & class 1 anomaly	0.93	0.89	0.91	121
Coldspot	0.93	0.92	0.93	88
Hotspot Class 2	0.82	0.93	0.87	30
Hotspot Class 3	0.60	1.00	0.75	3
Macro average	0.82	0.94	0.87	242
Weighted average	0.91	0.91	0.91	242

Classification report (test scores)

On unseen test data, the best-found **OT model detects 95% of anomalies** (95% recall / sensitivity for defect classes). Due to insufficient data of class *Hotspot Class 3*, more data is necessary to confirm the model behavior for this class.

Fraunhofer IPT WZL RWTH AACHEN UNIVERSITY

Powder bed monitoring (PBM) data stream

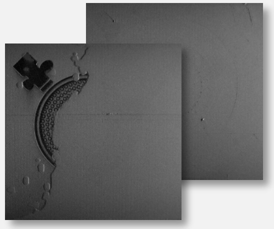
ML-Modeling results

Pipeline Objectives

Use AI / ML models to classify PBM* images of running build jobs (EOS M290) into non-defective images and images with quality-critical anomalies (soft real-time). The following classes can be distinguished:

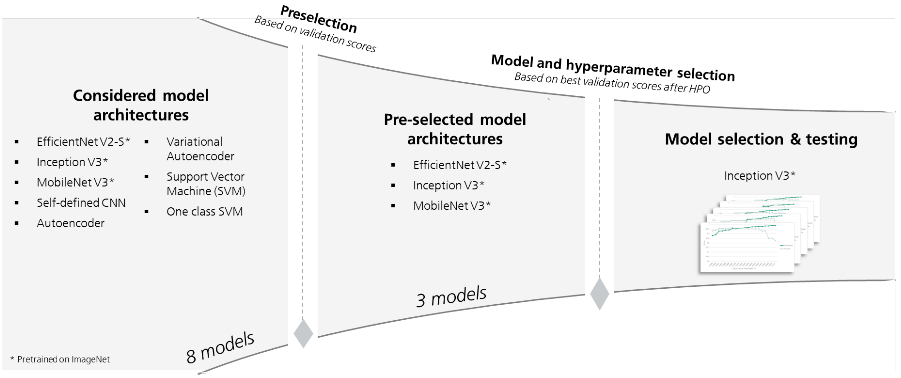
- Non-defective (i. e., no indication)
- Anomaly (i. e., powder accumulation, insufficient recoating, visible line, or critical elevated edge)

PBM DATA STREAM



Modeling Results

Model Selection: Pretrained InceptionV3 out of 8 candidates



91% Sensitivity | Detection of 91 out of 100 PBM anomalies on unseen data

100% Specificity | Robust detection of non-defective instances, characterized by a homogeneous powder bed

Note: Based on model tests on unseen data (100 defective, 100 non-defective instances)

Machine & environmental (M&E) data stream

ML-Modeling results

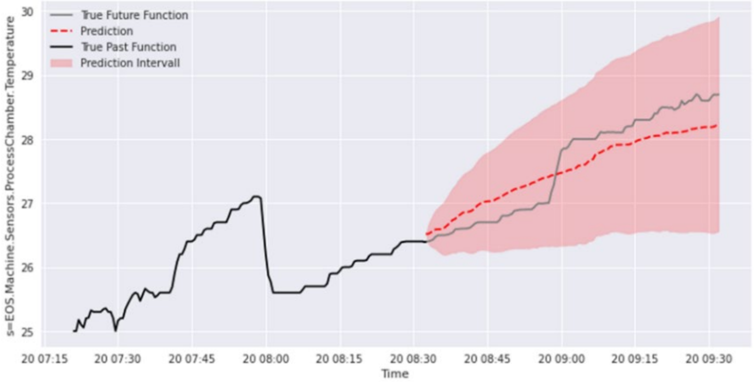
Testing Results

Mean test scores for the critical parameters with 30 second time bins, prediction frequency of ten minutes and prediction period of one hour.

Model-ID	Model Description	OC* RMSE	OC* MAE	BPT* RMSE	BPT* MAE	PCT* RMSE	PCT* MAE
MA	Moving Average	0.0623	0.0556	0.1265	0.0940	0.2208	0.2049
LR	Linear Regression	0.3274	0.3025	0.1234	0.0884	0.1408	0.1213
RR	Ridge Regression	0.3267	0.3018	0.1234	0.0884	0.1420	0.1228
RF	Random Forest	0.1893	0.1555	0.1263	0.0934	0.1410	0.1249

*Abbreviations: OC: Oxygen Concentration, BPT: Building Platform Temperature, PCT: Process Chamber Temperature

Example one hour prediction for the process chamber temperature during the SN9 build job using random forest



*The pretrained architecture **RF** achieved best results and indicates a sound prediction.*

02 – Use Case Overview

MLSys 2 – Robustness Assessment

Focus on machining capabilities through robustness assessment

Initial situation

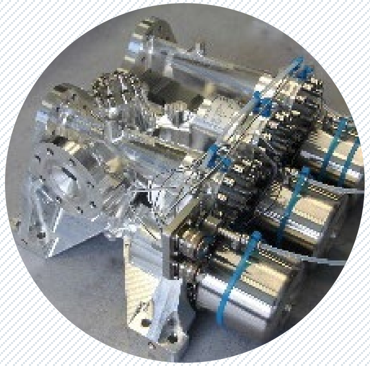
Machine Learning Use Case Applied

Process Chain

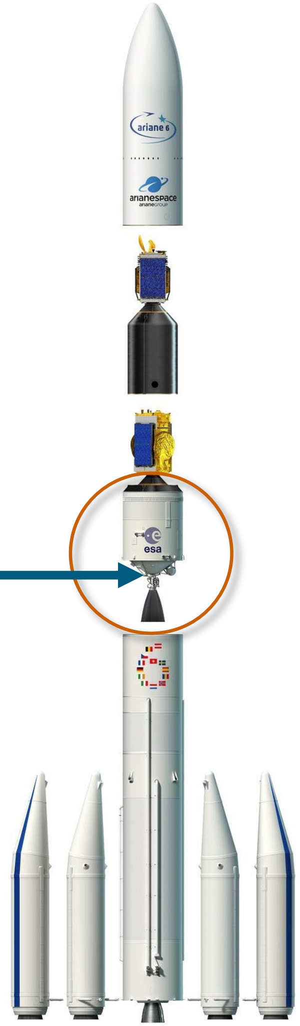
- ALM
- Machining
- Assembly

Products manufactured and inspected on site

Electronic Valves



Measurement



Ariane 6

Machine learning application project motivation

Robustness assessment of the production process

Measurement

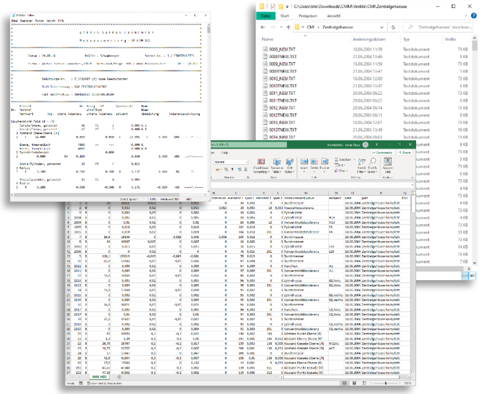
Status Quo

Existing historical measurement protocols are not utilized

- Possible hitherto correlations have not been discovered
- Unrealistic tolerance requirements generate high expenditures

Target

Identify possible relationships and optimize tolerances in production



Execution

Cluster analysis

Data points and corresponding meta information of historical measurements

Correlations and optimization possibilities are identified

 11/07/2023

Deep dive: application of machine learning for robustness assessment

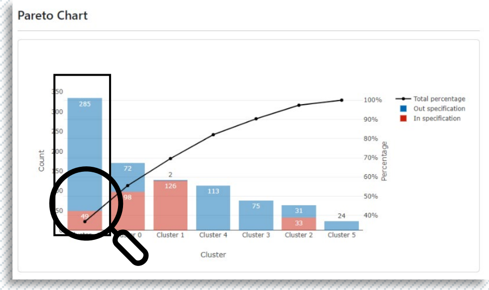
Clustering of measurement data points from historical measurement protocols

Target

Identify possible relationships and optimize tolerances in production

- Identification of problematic features
- Identification of problematic sizes
- Identification of special influences

Tasks for robustness assessment

	Correlation Analysis	*Optimization of tolerances*
Machine Learning Task	**Scatter Plot** 	**What if …** 
Objective	**Identify clusters for correlation analysis of specific properties**	**Evaluate the impact of tolerance requirement changes**

Deep dive: application of machine learning for error classification

Operation at the Ottobrunn site

CMM

Wenzel LH

Robustness Assessment

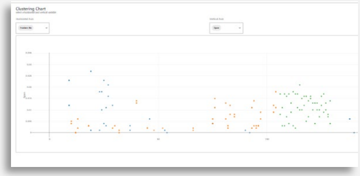
Visualization
Identification of possible causality-based correlations

Conducting analysis
Investigation of the impact of tolerance adjustments on the scrap rate

Process Expert

Clustering

Derivation of clusters by the system and mapping of correlations

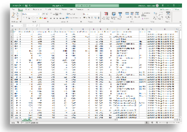


Properties Preselection

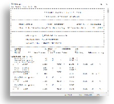
Model specifications
Setting general conditions like time period, algorithm and investigated correlation

Preselection of focus
Selection of features of interest and focus e.g. assemblies, parts

Raw Data Import



Preprocessed .csv measurement protocol



Raw .txt measurement protocol

MLsys2

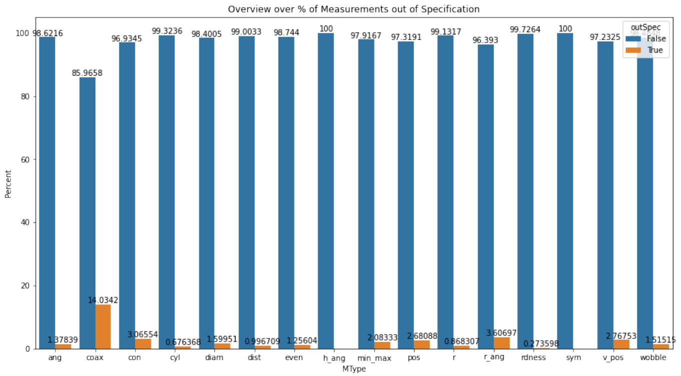
Image: Wenzel

CMM measurement data

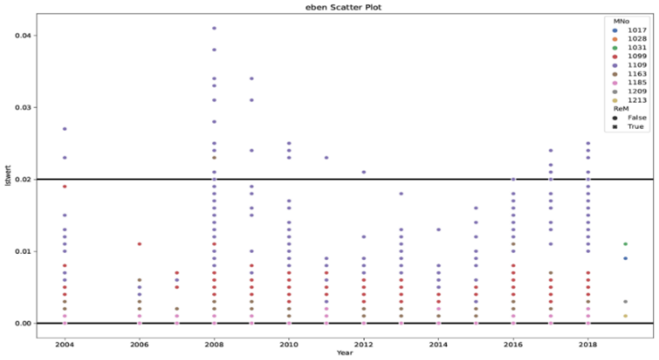
Data exploration

- File format: .txt and .csv
- Strong data imbalance
  - Low overall number for out of specification, ~2.0%
  - Numerous remeasurements, usually without recording of remeasured value
  - Varying out of specification ratio over years, components and features

Overview of relative number of out of specification measurements



Trends within groups in the example of "even" measurement



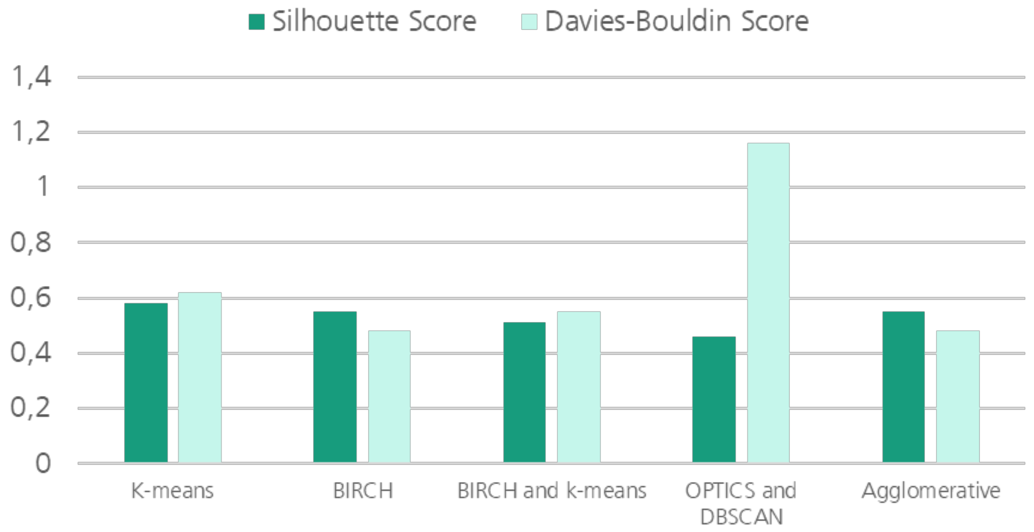
 11/07/2023

Fraunhofer IPT

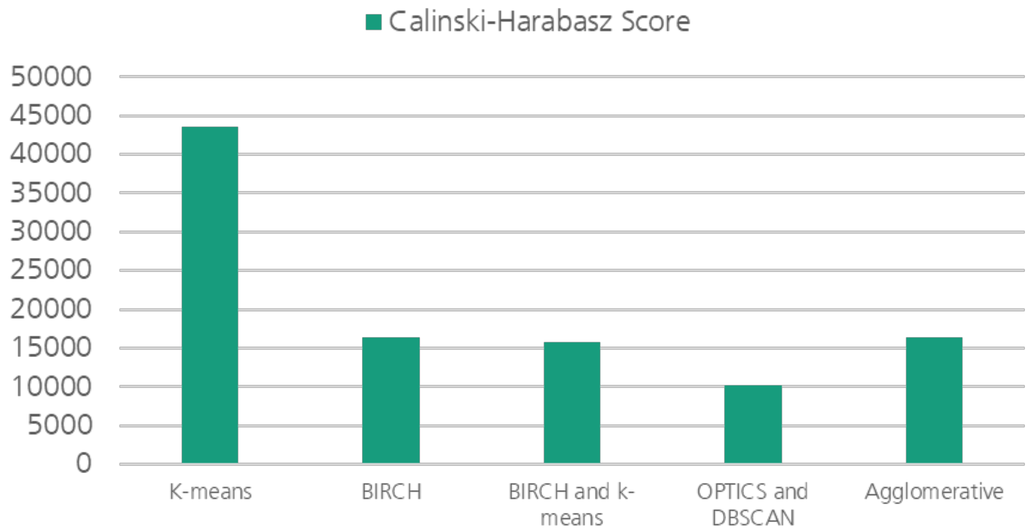
CMM measurement data

ML-Modeling results

Silhouette & Davies-Bouldin Score



Calinski-Harabasz Score



The most suitable models are K-means and DBSCAN, where K-means gives the option to predefine the number of clusters and DBSCAN selects the number of clusters itself.

03 – Conclusion and Outlook

Utilization of Artificial Intelligence in Advanced Manufacturing Processes in Aerospace

Project conclusion

Use of artificial intelligence in aerospace production

Key takeaways in the use of artificial intelligence in aerospace manufacturing in project »PANORAMA«

- In the future, space production will continue to be low-volume production from a relative perspective. Low data volumes will continue to be a hurdle.
- Due to the relatively low amount of manufacturing volume, technologies with large amounts of process data in each manufacturing step should mostly be considered.
- The main effort of implementing Machine Learning in aerospace production is due to adapting the models to highly individual infrastructure environments.

Possible next steps

Path ahead after the project

1 Use case 1 is individually implemented at the first ALM machine at ArianeGroup‘s site. An extension to further ALM machines is possible with modifications to the software.

2 Use case 2 is suitable to be extended to other databases and technologies to gain further insights into process chains, possibly other production sites.

3 The initial recording of Machine Learning use cases should be reviewed and updated periodically with the goal to implement more use cases and scale up the technology.

4 Finally, in the fast-paced developments within the field of AI, new use cases in production are emerging, especially through the application of Large Language Models.

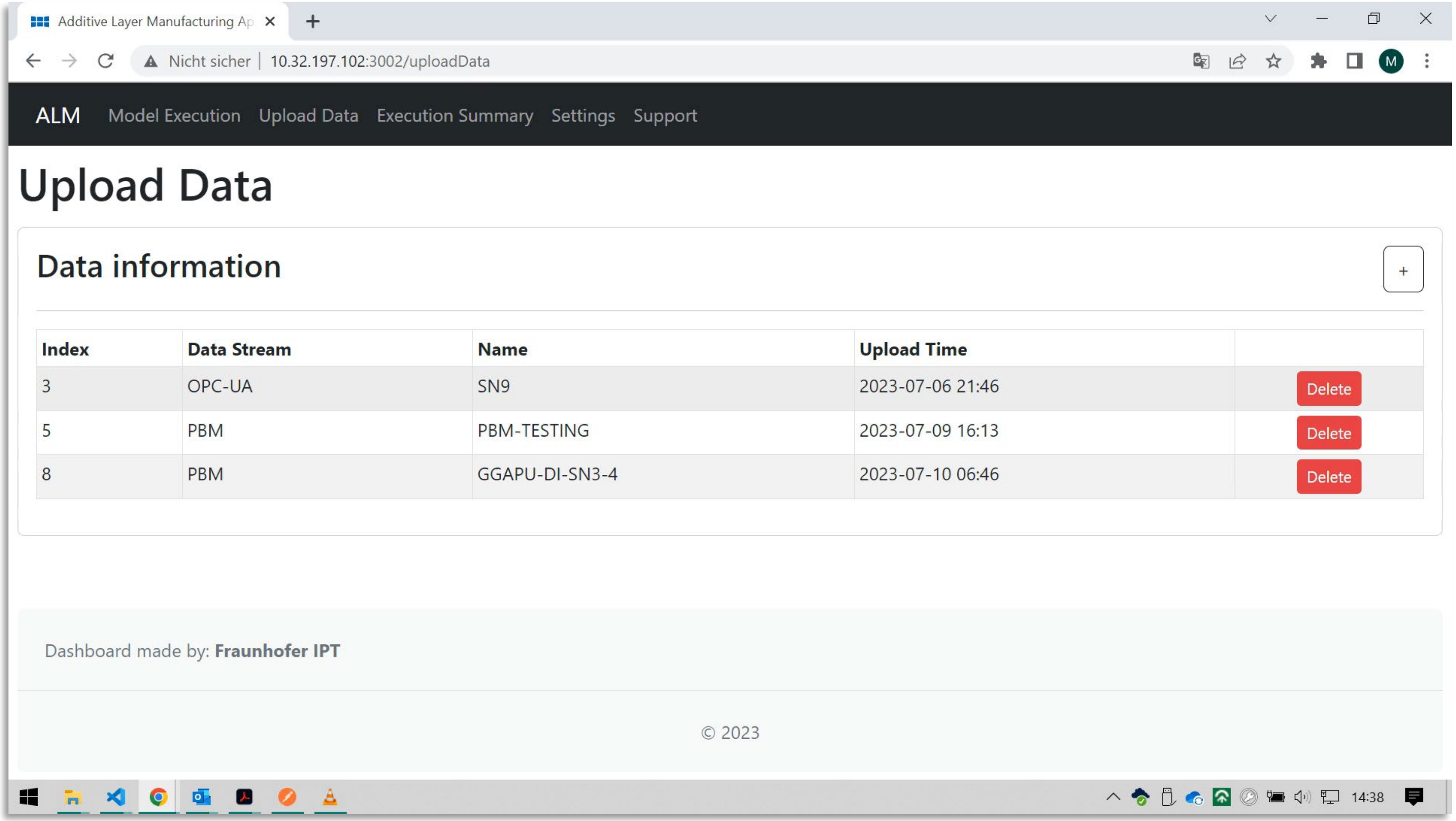
Backup

Use Case Demonstration

MLSys 1 – Automated Live Process Monitoring

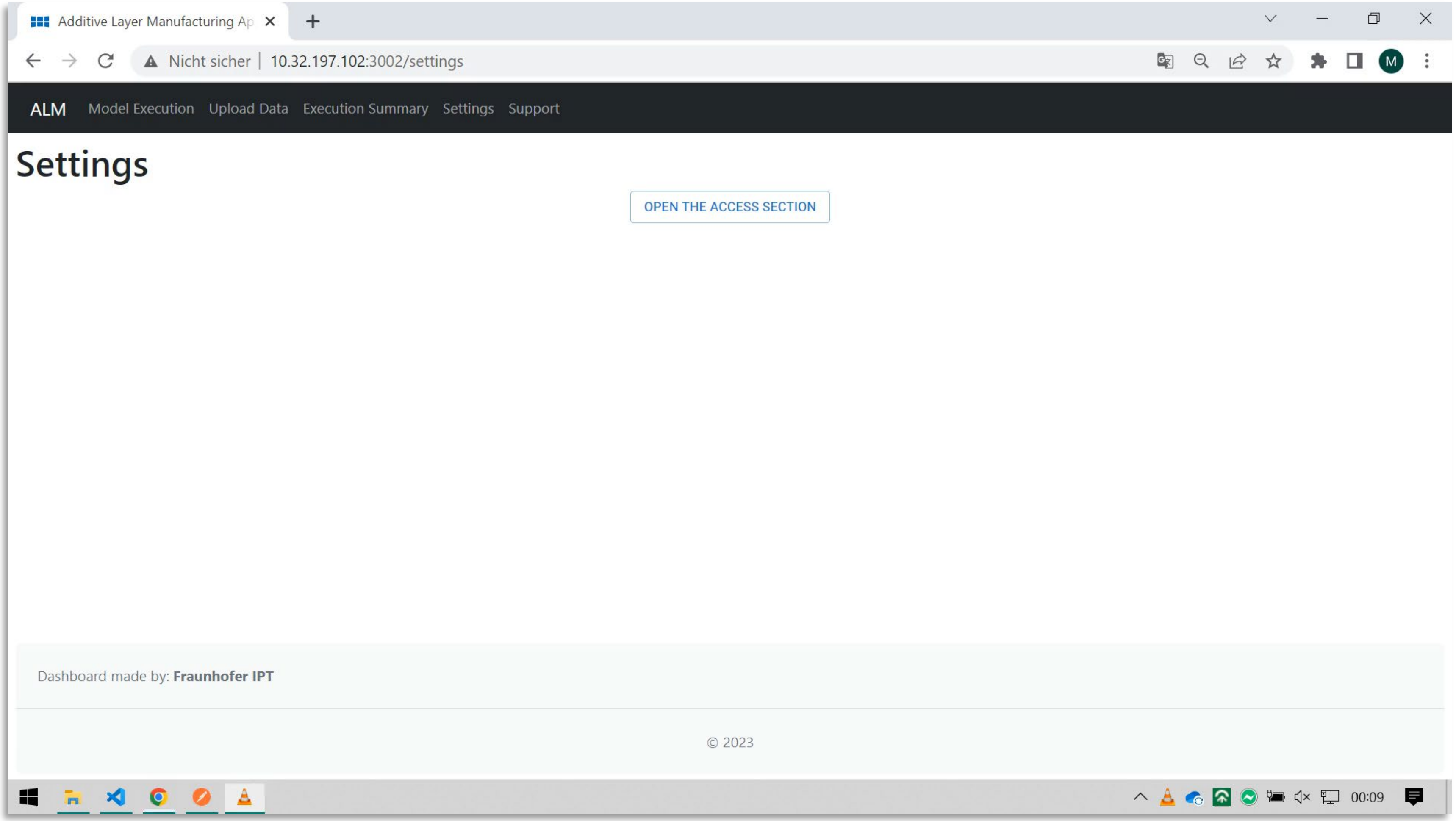
MLSys 1 – Automated Live Process Monitoring

Data & Model Management



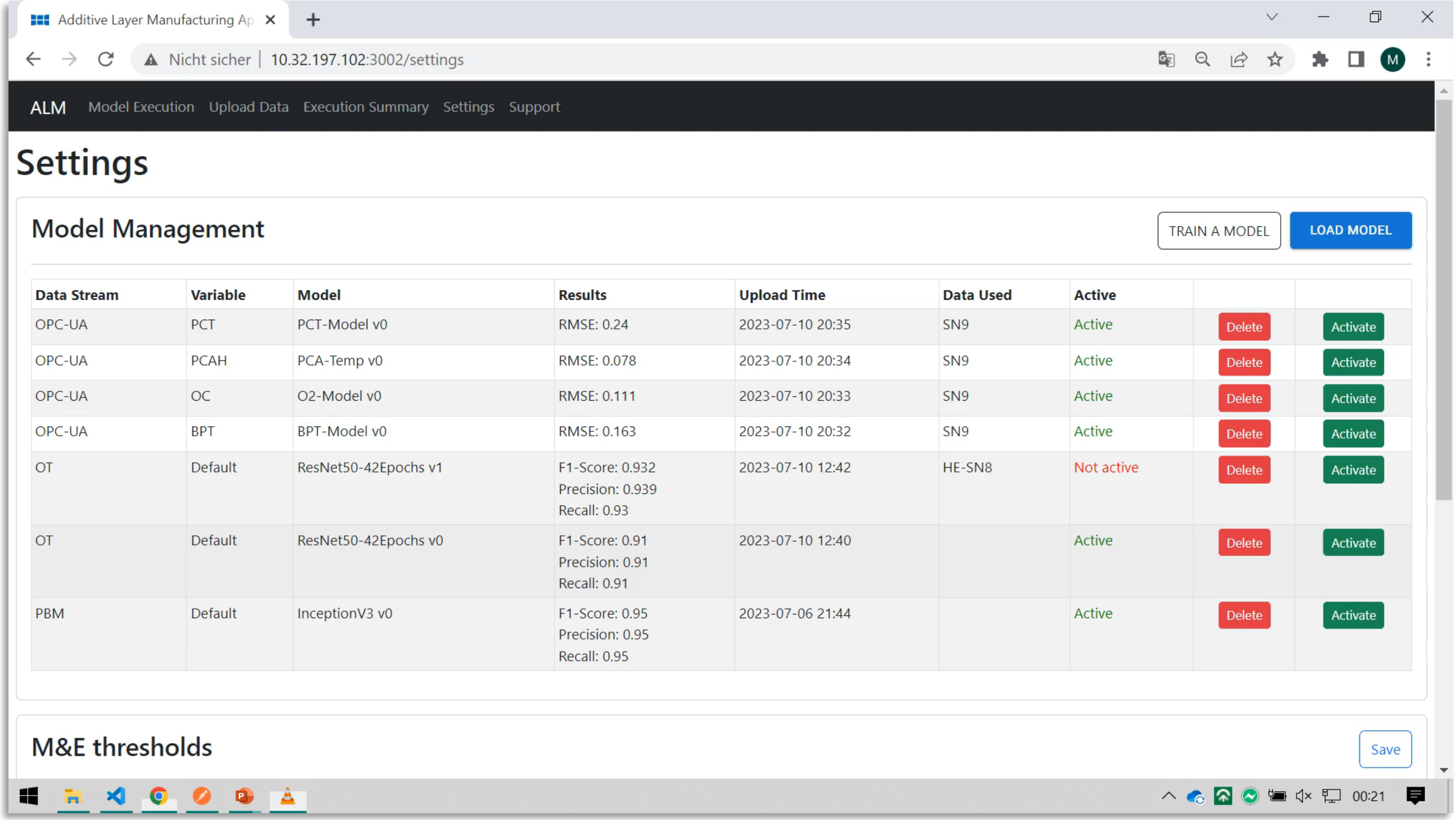
MLSys 1 – Automated Live Process Monitoring

Model Execution (Live Monitoring)



MLSys 1 – Automated Live Process Monitoring

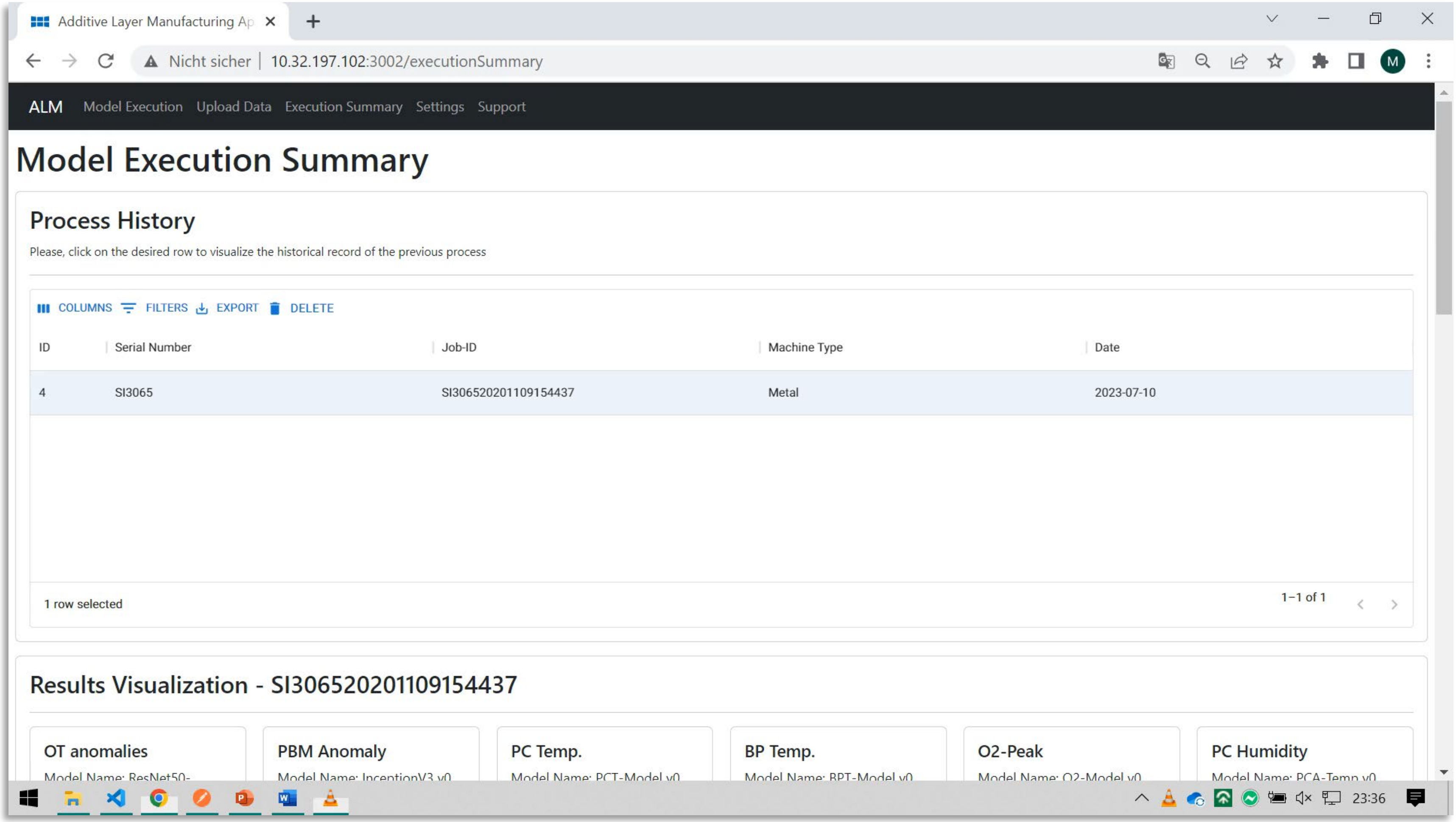
Model Execution (Live Monitoring) – M&E Forecasting



Data Stream	Variable	Model	Results	Upload Time	Data Used	Active		
OPC-UA	PCT	PCT-Model v0	RMSE: 0.24	2023-07-10 20:35	SN9	Active	Delete	Activate
OPC-UA	PCAH	PCA-Temp v0	RMSE: 0.078	2023-07-10 20:34	SN9	Active	Delete	Activate
OPC-UA	OC	O2-Model v0	RMSE: 0.111	2023-07-10 20:33	SN9	Active	Delete	Activate
OPC-UA	BPT	BPT-Model v0	RMSE: 0.163	2023-07-10 20:32	SN9	Active	Delete	Activate
OT	Default	ResNet50-42Epochs v1	F1-Score: 0.932 Precision: 0.939 Recall: 0.93	2023-07-10 12:42	HE-SN8	Not active	Delete	Activate
OT	Default	ResNet50-42Epochs v0	F1-Score: 0.91 Precision: 0.91 Recall: 0.91	2023-07-10 12:40		Active	Delete	Activate
PBM	Default	InceptionV3 v0	F1-Score: 0.95 Precision: 0.95 Recall: 0.95	2023-07-06 21:44		Active	Delete	Activate

MLSys 1 – Automated Live Process Monitoring

Post-Process Analysis of Results

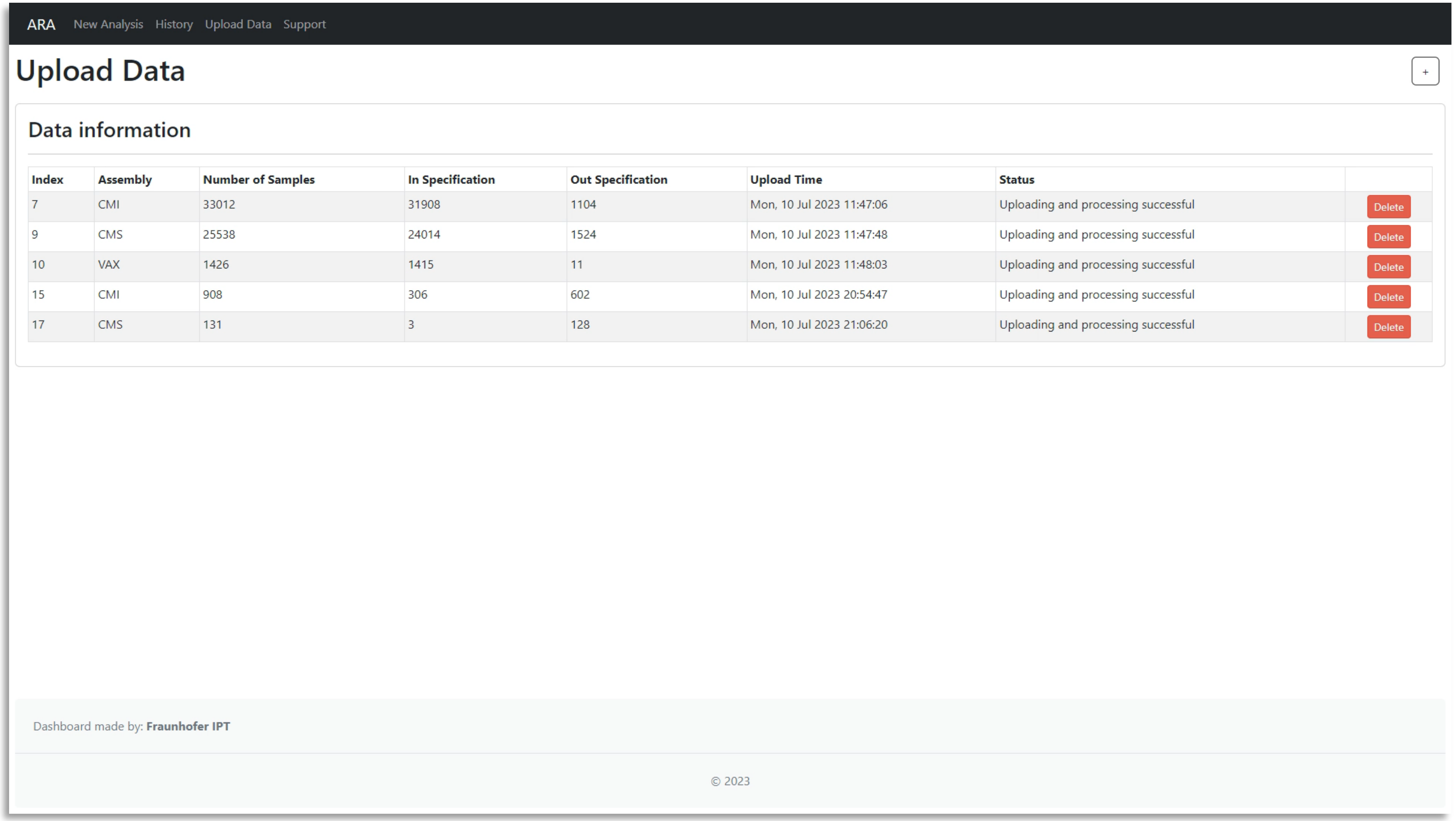


Use Case Demonstration

MLSys 2 – Robustness Assessment

MLSys 2 – Robustness Assessment

Upload Data



ARA New Analysis History Upload Data Support

Upload Data

+

Data information

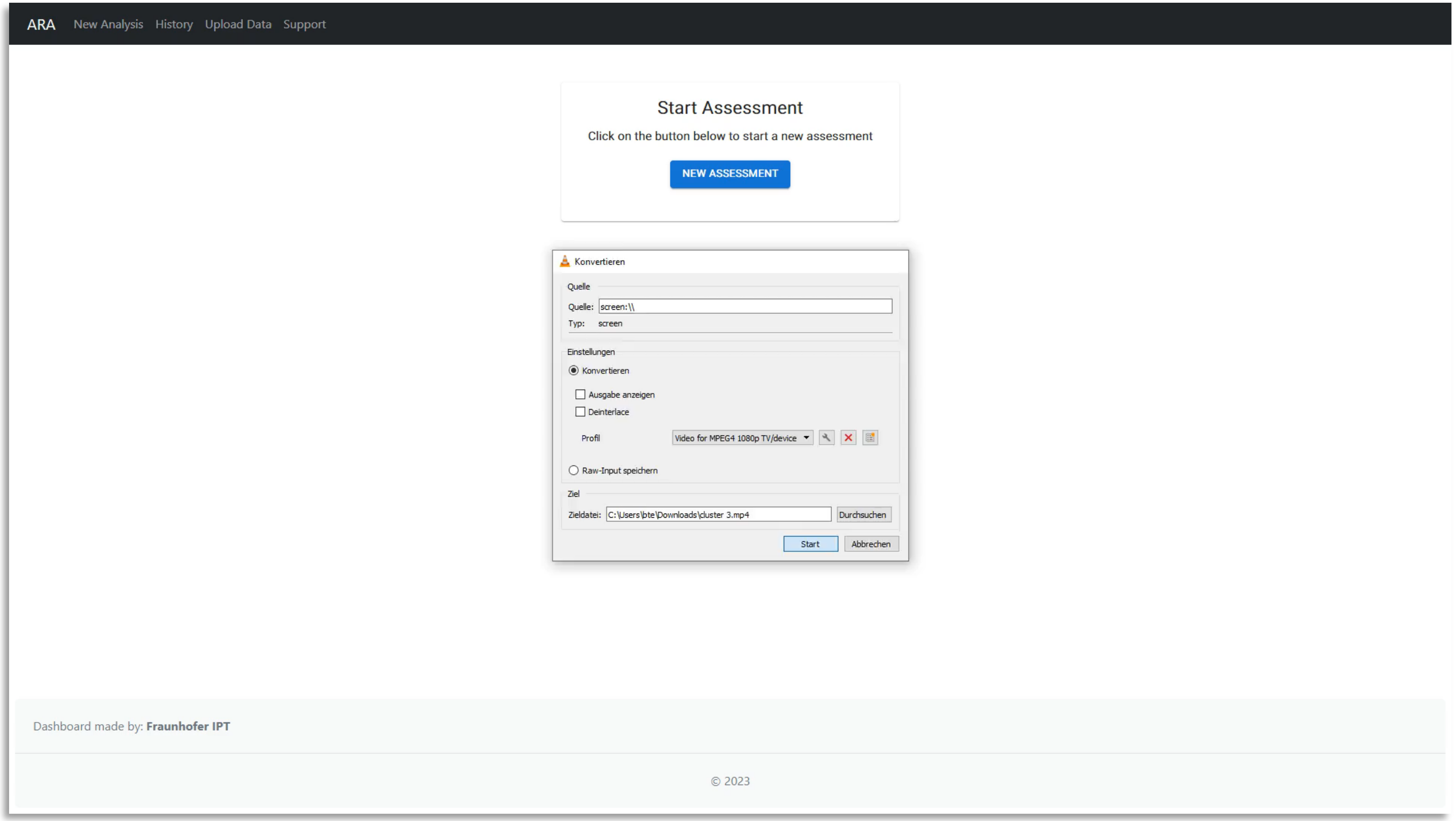
Index	Assembly	Number of Samples	In Specification	Out Specification	Upload Time	Status	
7	CMI	33012	31908	1104	Mon, 10 Jul 2023 11:47:06	Uploading and processing successful	Delete
9	CMS	25538	24014	1524	Mon, 10 Jul 2023 11:47:48	Uploading and processing successful	Delete
10	VAX	1426	1415	11	Mon, 10 Jul 2023 11:48:03	Uploading and processing successful	Delete
15	CMI	908	306	602	Mon, 10 Jul 2023 20:54:47	Uploading and processing successful	Delete
17	CMS	131	3	128	Mon, 10 Jul 2023 21:06:20	Uploading and processing successful	Delete

Dashboard made by: **Fraunhofer IPT**

© 2023

MLSys 2 – Robustness Assessment

Cluster Analysis



MLSys 2 – Robustness Assessment

Customization of Thresholds

Customization of Thresholds

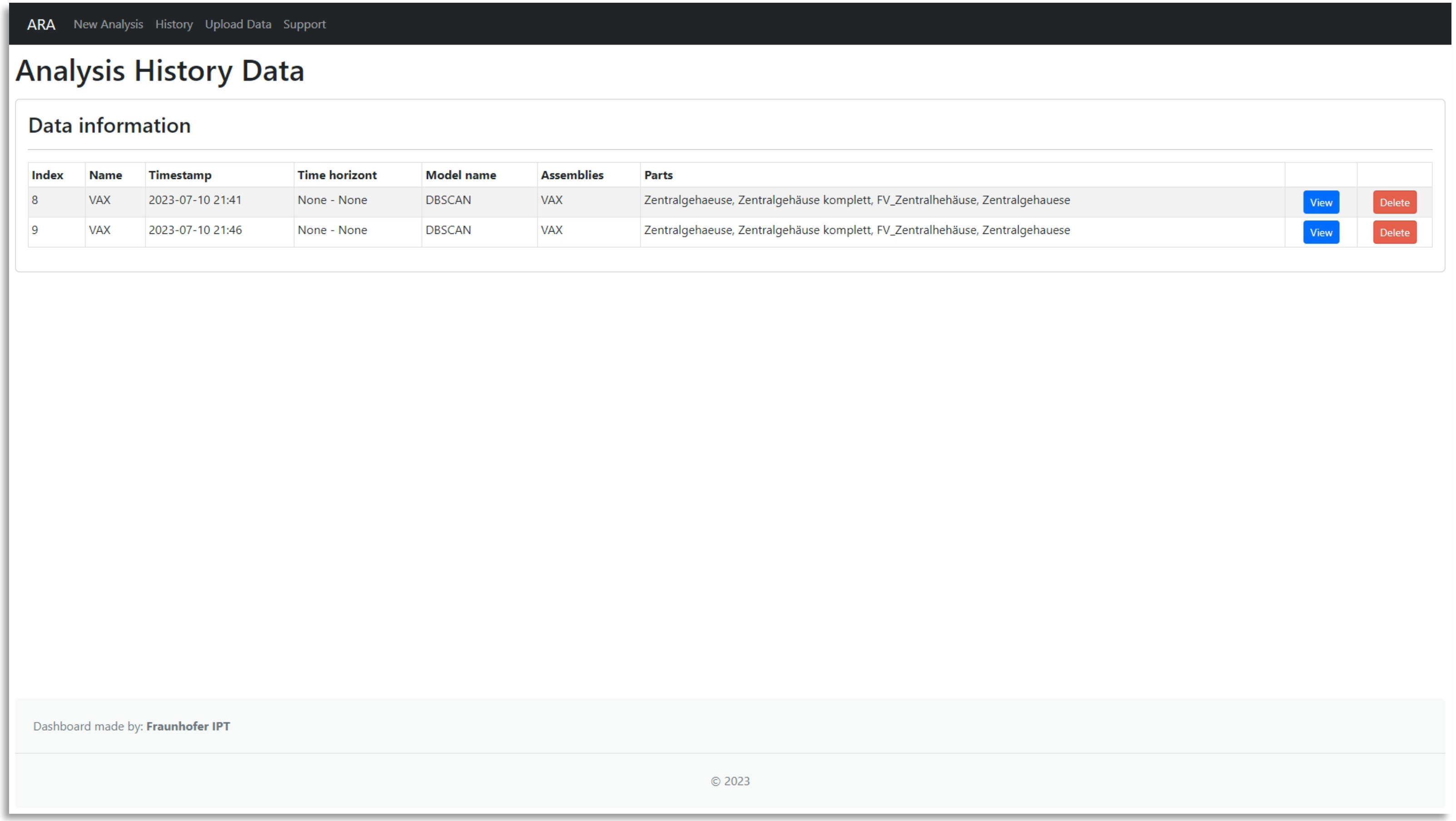
Lower Threshold Factor
Type Here
.95

Upper Threshold Factor
Type Here

Year	Number of Measurements	Out of Sepc	In Spec	Lower Threshold Factor	Upper Threshold Factor	New Out of Sepc	New In Spec
2004	2178	462	1716	.95		468	1710
2005	108	108	0	.95		108	0
2006	1210	130	1080	.95		132	1078
2007	3469	444	3025	.95		454	3015
2008	50	36	14	.95		36	14
2009	1360	126	1234	.95		128	1232
2010	1688	18	1670	.95		18	1670
2011	1564	28	1536	.95		32	1532
2012	1426	70	1356	.95		72	1354
2013	2378	34	2344	.95		38	2340
2014	938	18	920	.95		18	920
2015	2700	66	2634	.95		70	2630
2016	1858	12	1846	.95		28	1830
2017	1880	22	1858	.95		22	1858
2018	1128	40	1088	.95		40	1088
2019	776	14	762	.95		18	758
2020	958	24	934	.95		24	934

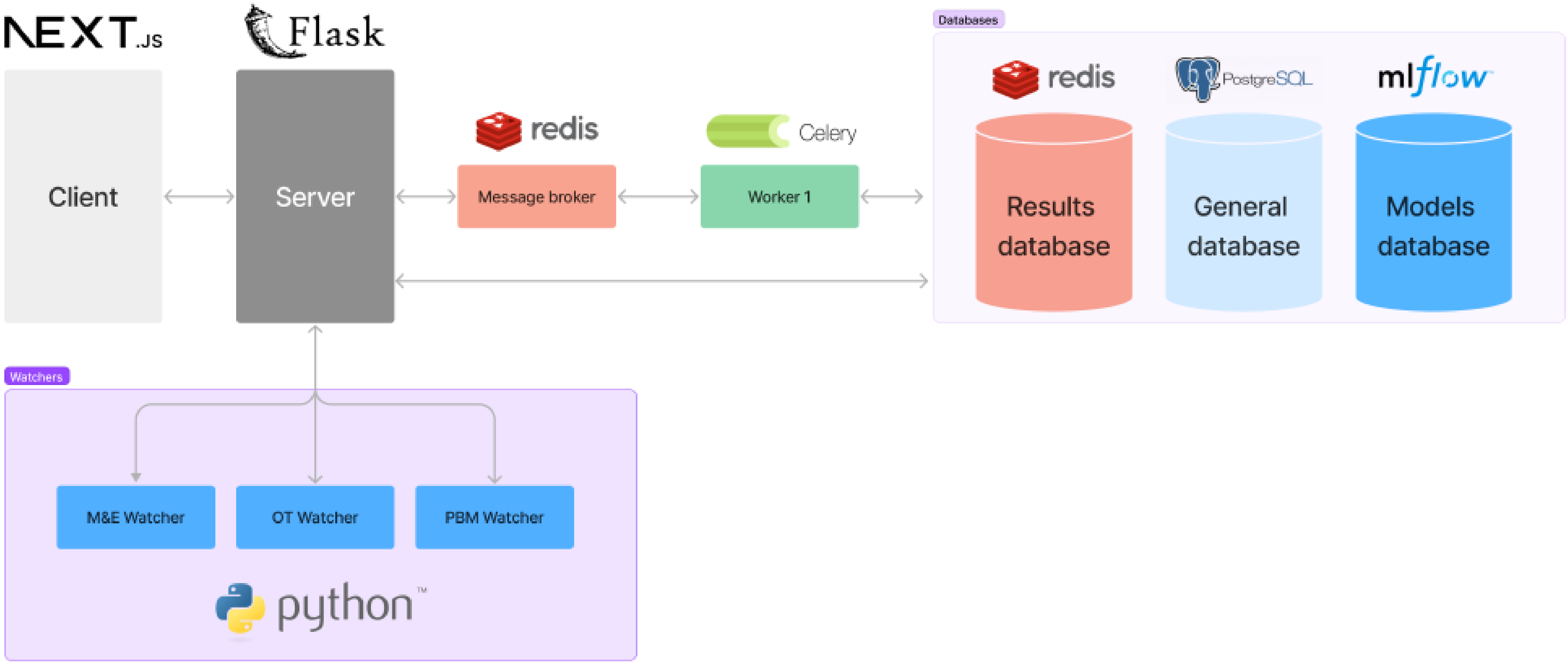
MLSys 2 – Robustness Assessment

Recall History



Index	Name	Timestamp	Time horizont	Model name	Assemblies	Parts		
8	VAX	2023-07-10 21:41	None - None	DBSCAN	VAX	Zentralgehaeuse, Zentralgehäuse komplett, FV_Zentralhehäuse, Zentralgehauese	View	Delete
9	VAX	2023-07-10 21:46	None - None	DBSCAN	VAX	Zentralgehaeuse, Zentralgehäuse komplett, FV_Zentralhehäuse, Zentralgehauese	View	Delete

MLsys1
Software architecture overview

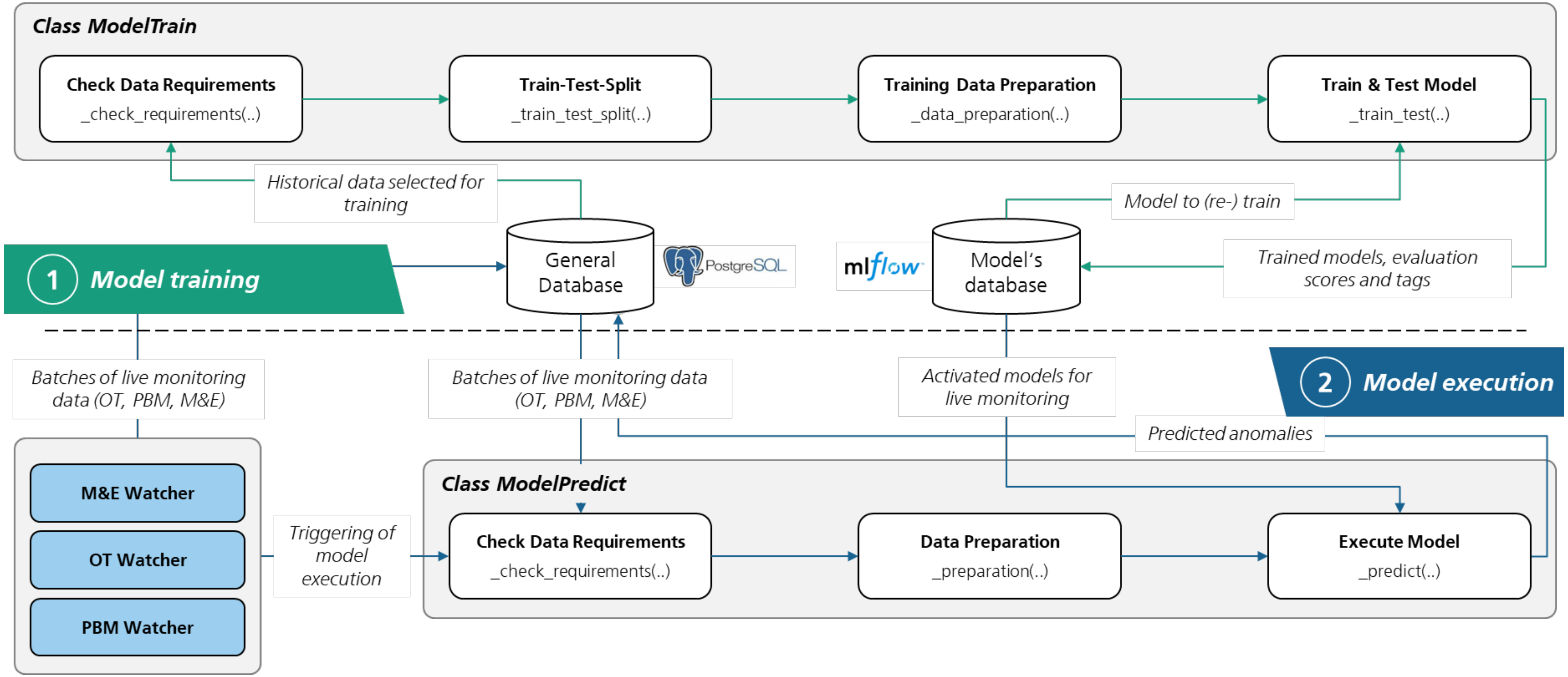


 11/07/2023

Fraunhofer IPT | WZL | RWTH AACHEN UNIVERSITY

MLsys1

ML-model lifecycle management



 11/07/2023

Selection of ML-model architectures

Three step approach prior to final selection

Considered model architectures

- AlexNet*
- DenseNet 161*
- EfficientNet V2-S*
- GoogleNet*
- Inception V3*
- MobileNet V3-L*
- MobileNet V2*
- ResNet 50*
- Self-defined CNN
- ShuffleNet V2-x0_5*
- SqueezeNet 1.1*
- VGG 11*

* Pretrained on ImageNet

12 models

Preselection
Based on validation scores

Pre-selected model architectures

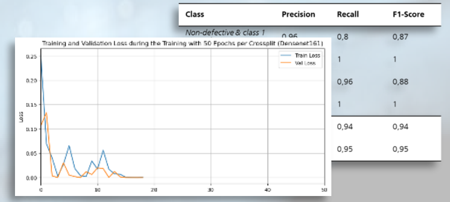
- DenseNet 161*
- EfficientNet V2-S*
- GoogleNet*
- MobileNet V3-L*

4 models

Model and hyperparameter selection
Based on best validation scores after HPO[1]

Model selection & testing

DenseNet 161*



First OT-Model

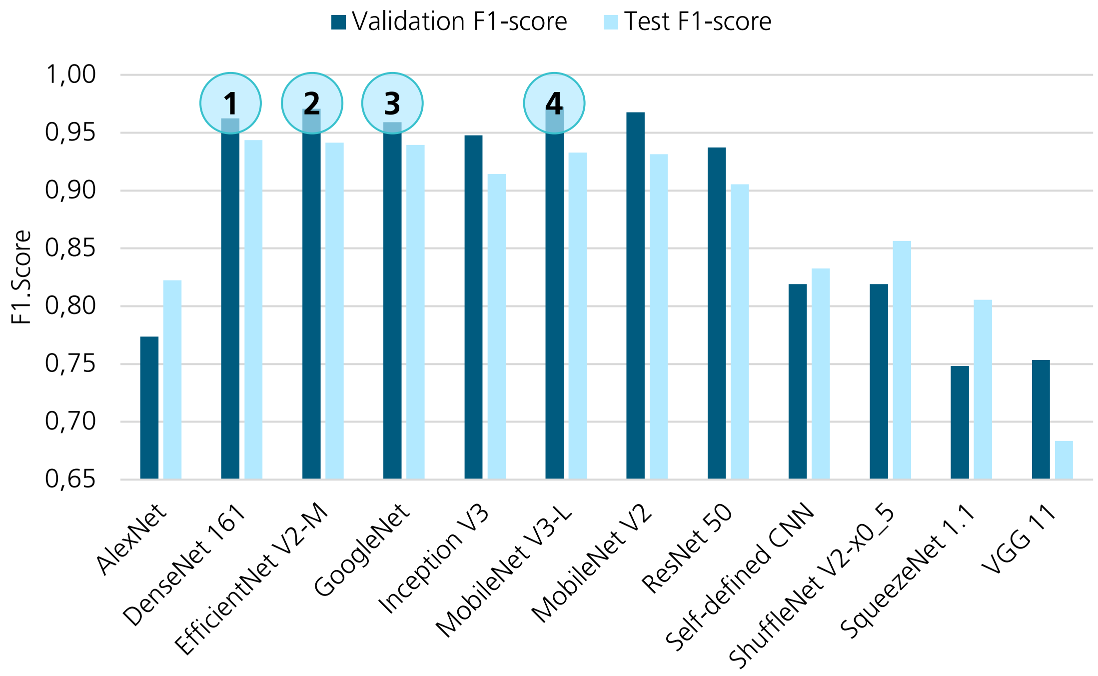
[1]HPO: Hyperparameter Optimization

Considered model architectures

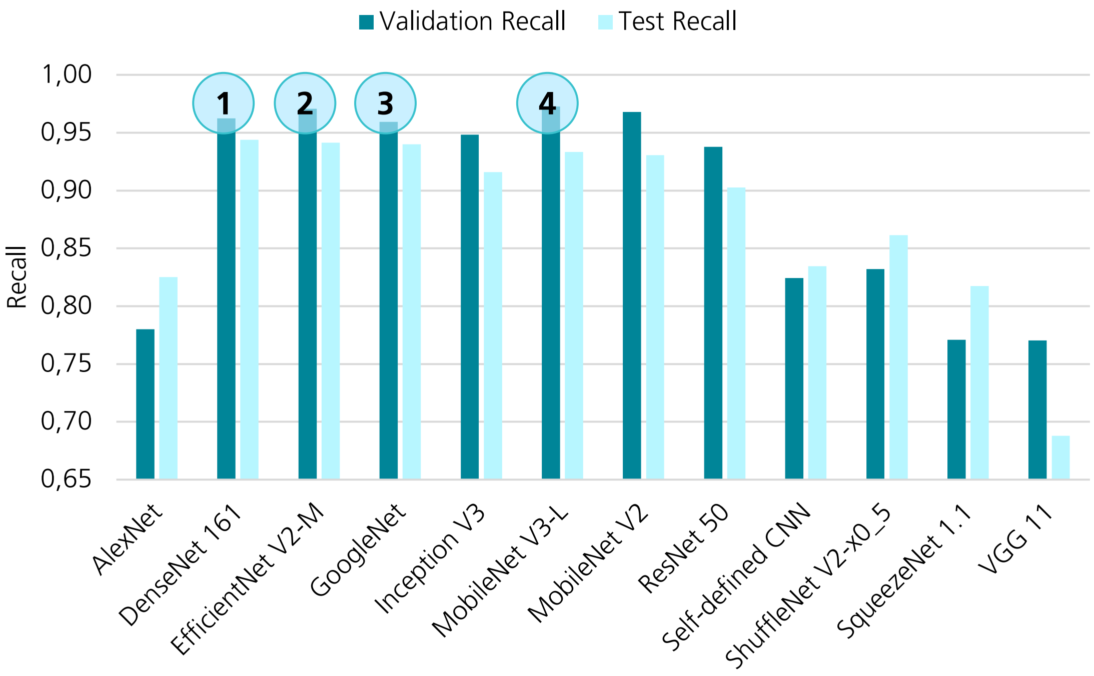
12 models in total

First OT-Model

Validation and test F1-scores for OT multiclass classification[1]



Validation and test recall for OT multiclass clas



1) Non-sequential classification with 4 classes: non-defective, hotspot 2, hotspot 3, and coldspot 2 & 3 (without hyperparameter optimization)

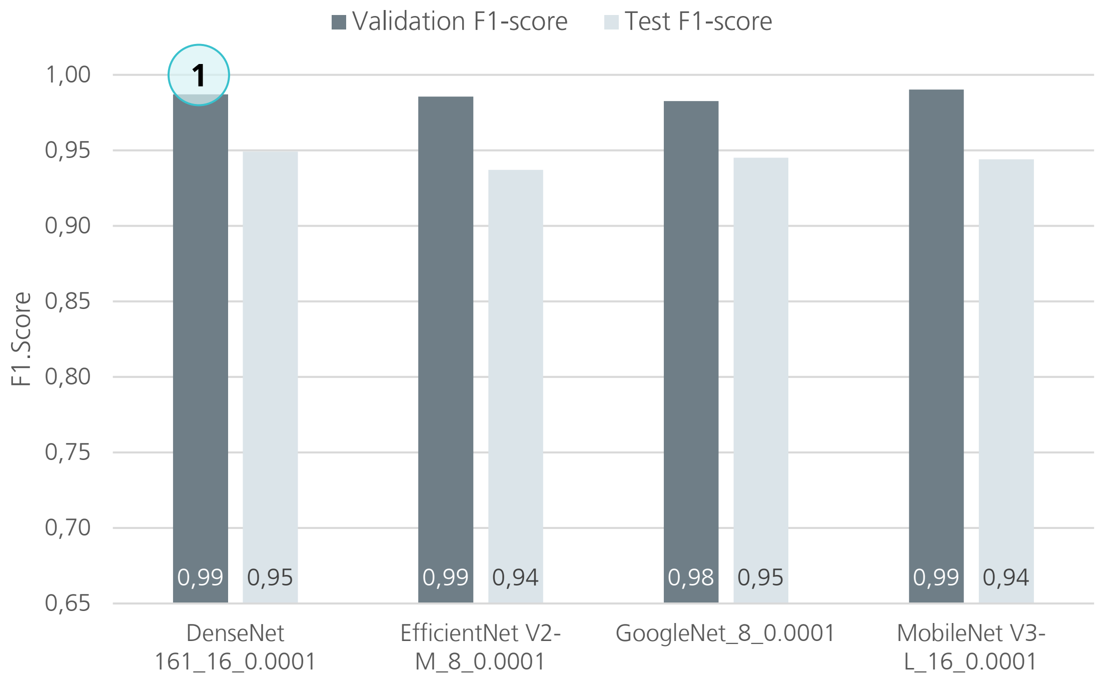
Pre-selected models

Pre-selected model architectures

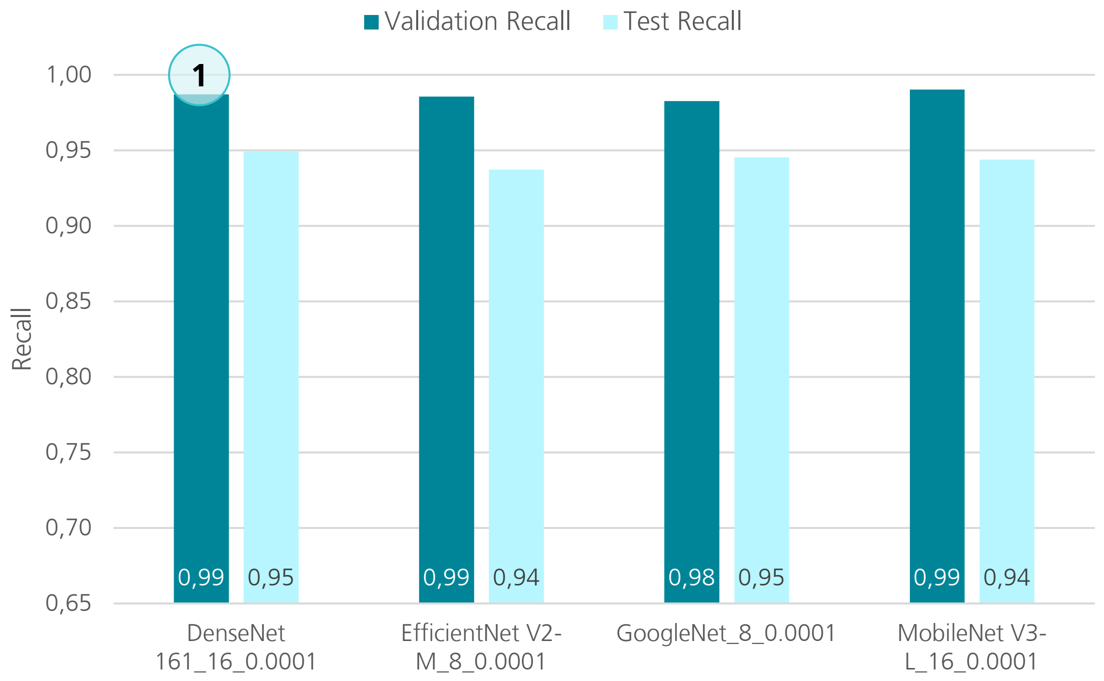
4 models after preselection

First OT-Model

Validation and test F1-scores after hyperparameter optimization



Validation and test recall after hyperparameter optimization



Based on the validation scores after hyperparameter optimization, a pretrained version of DenseNet has been selected.

Pre-selected models

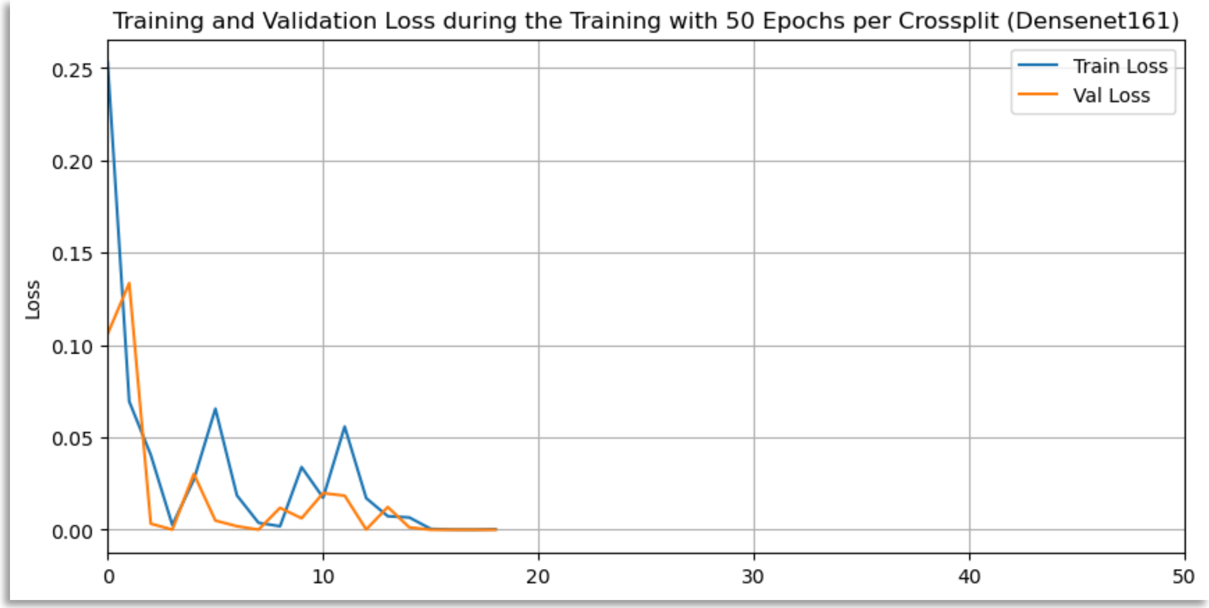
Model selection & testing

Final selection

First OT-Model

Testing & error analysis for best model

- DenseNet 161 (Batch size:16, Learning rate: 0.0001)
- Training for 50 epochs with early stopping (1:59 h of training on GPU-based machine)

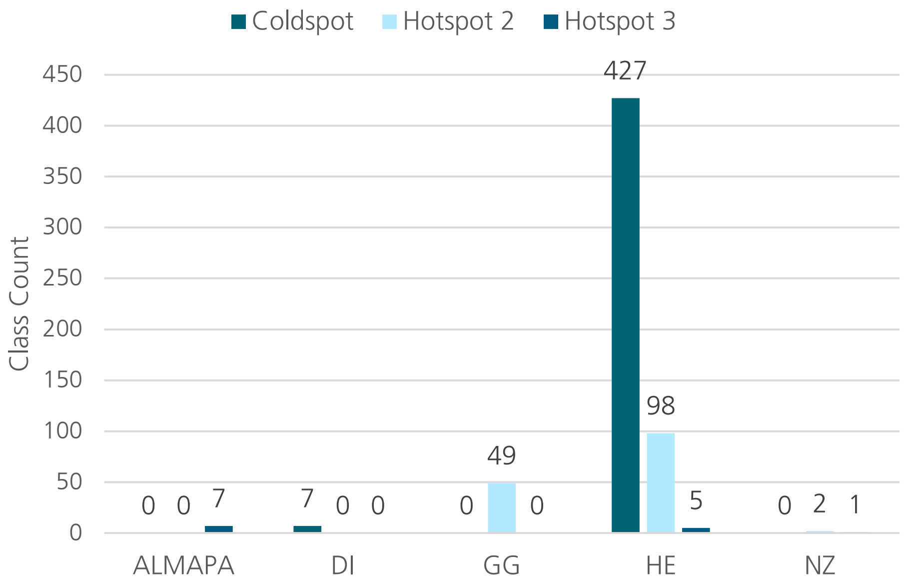


Class	**Critical to Quality**	**Precision**	**Recall**	**F1-Score**
Non-defective & Class 1 anomaly	*Low*	0,96	0,8	0,87
Hotspot Class 2	*Medium*	0,81	0,96	0,88
Hotspot Class 3	*High*	1	1	1
Coldspot Class 2 & Class 3	*High*	1	1	1
Macro average		0,94	0,94	0,94
Weighted average		0,96	0,95	0,95

Classification report (test scores)

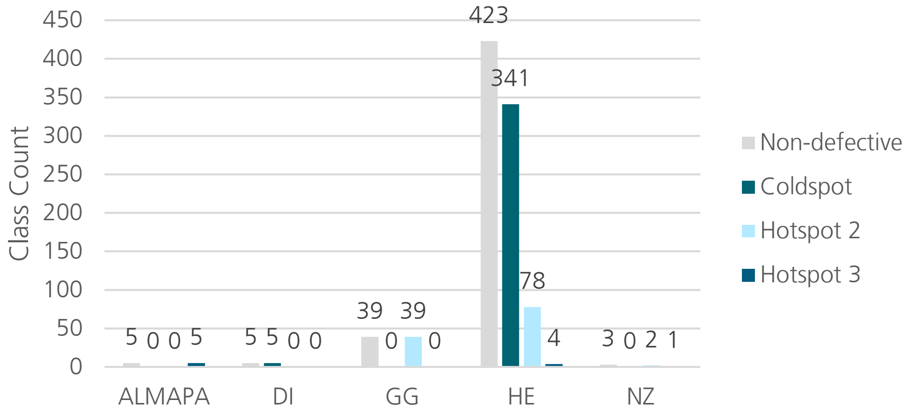
Monitoring of OT data stream
Updated Train-Test-Split (Version 2.0)

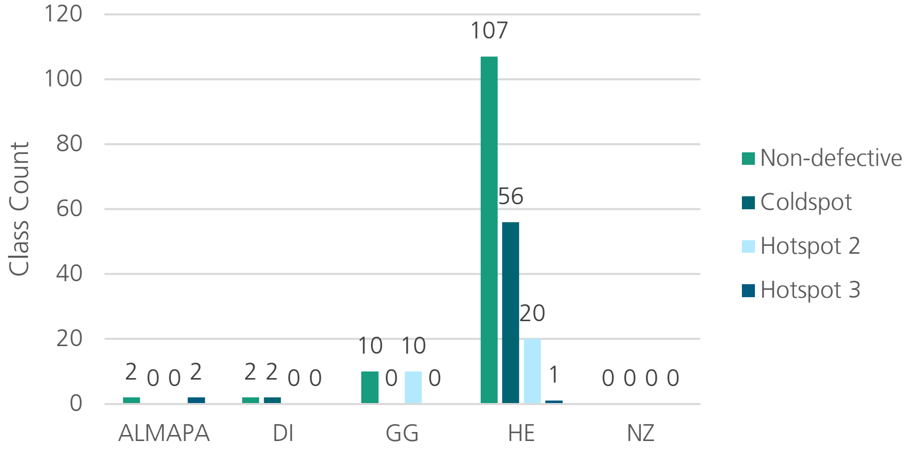
Exploration of product-class distribution in training data



Strong imbalance of product-class combinations, e. g. coldspots were mainly observed for the HE variant

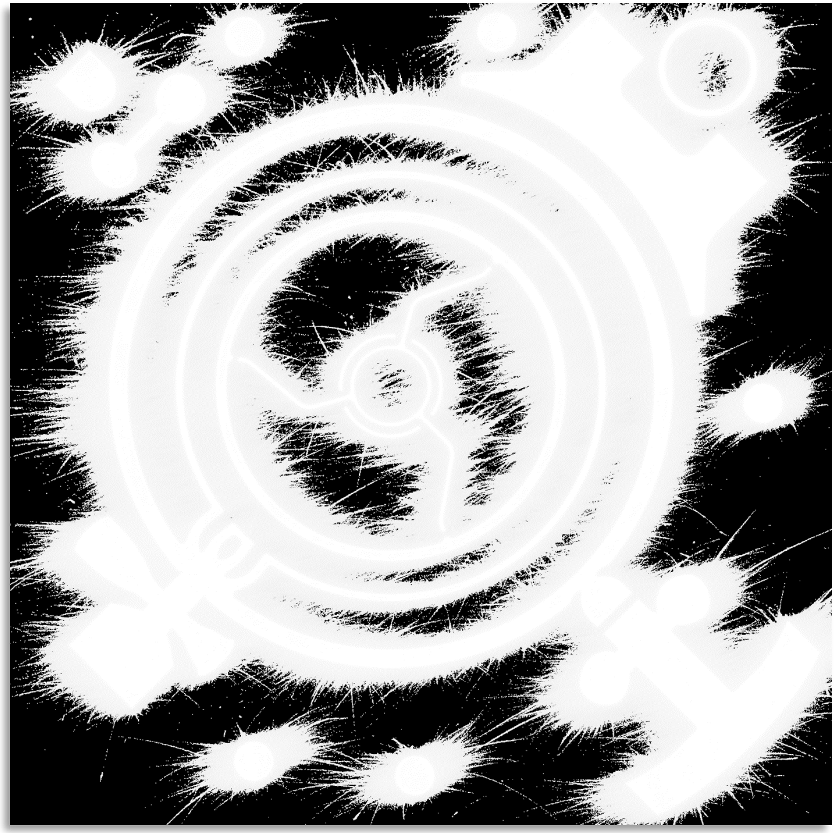
Update of the train-test split to obtain a product-class balance





Monitoring of OT data stream

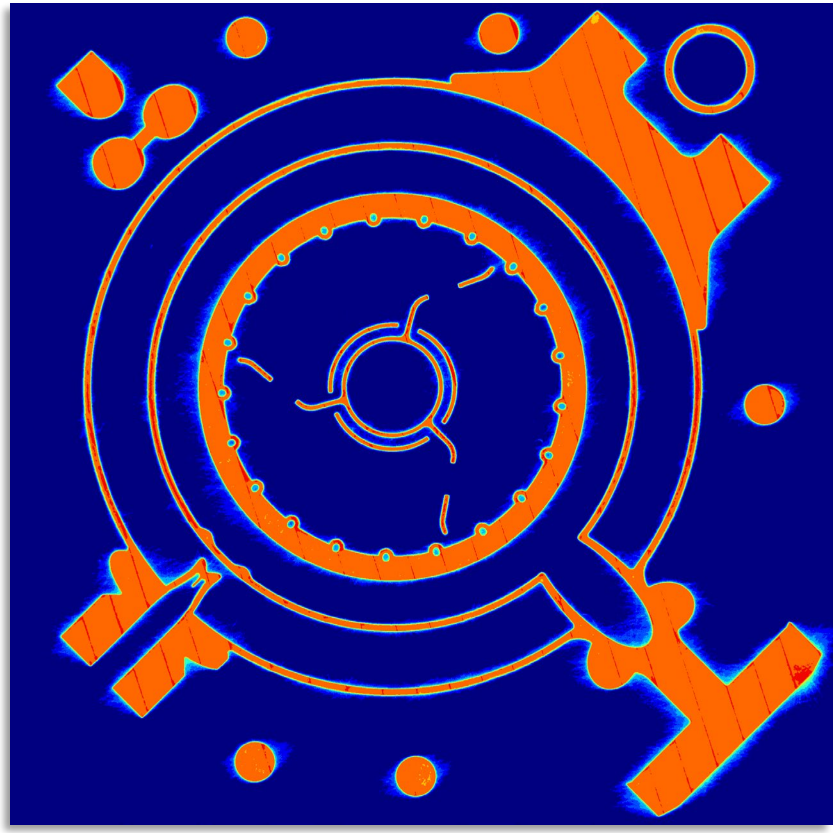
Updated OT pipeline I – Image preprocessing



Input images (provide by EOS machine)

Image Transformations

- .raw (32-bit) to .png (8-bit) transformation
- Denoising
- RGB transformation
- Jet colormap

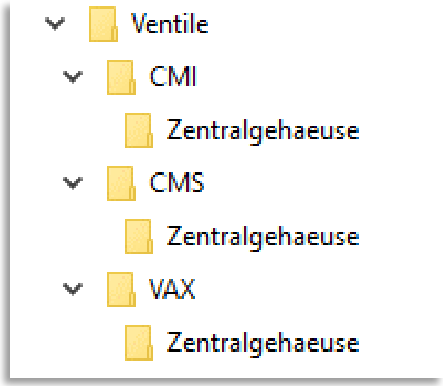


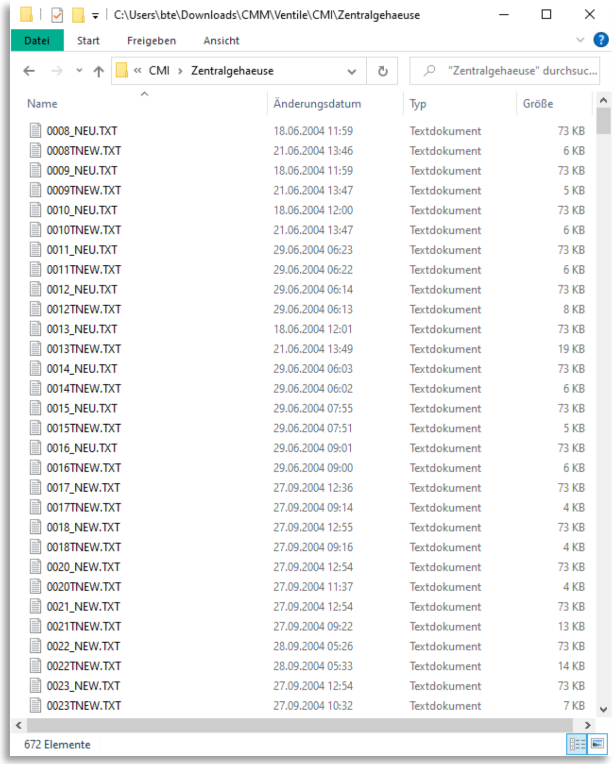
Pre-processed images (processed by model)

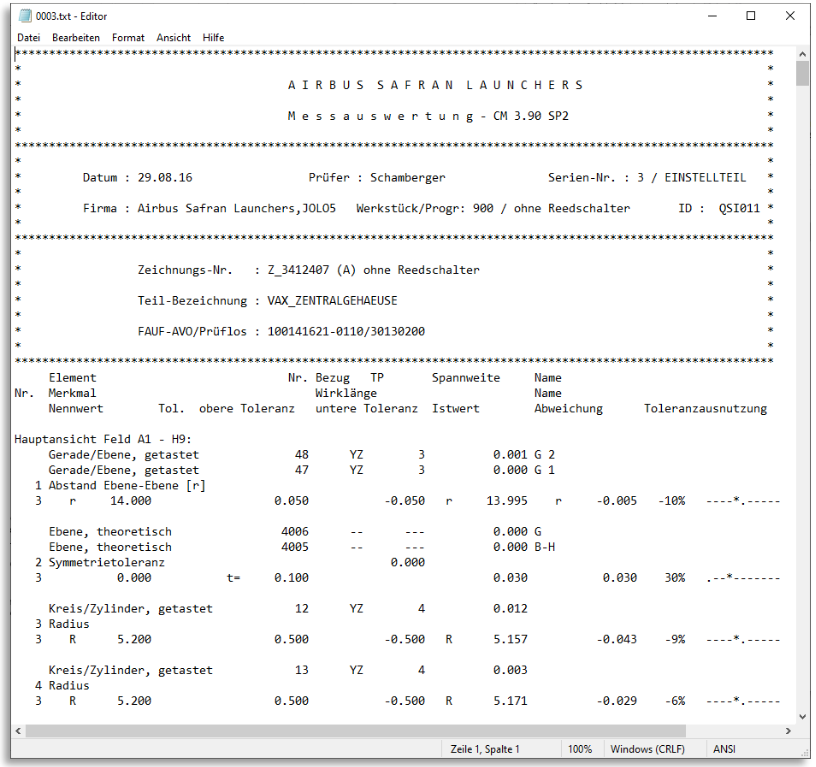
MLsys2: Robustness Assessment

Demonstration of Robustness Assessment in the Target Environment

Release v1.0





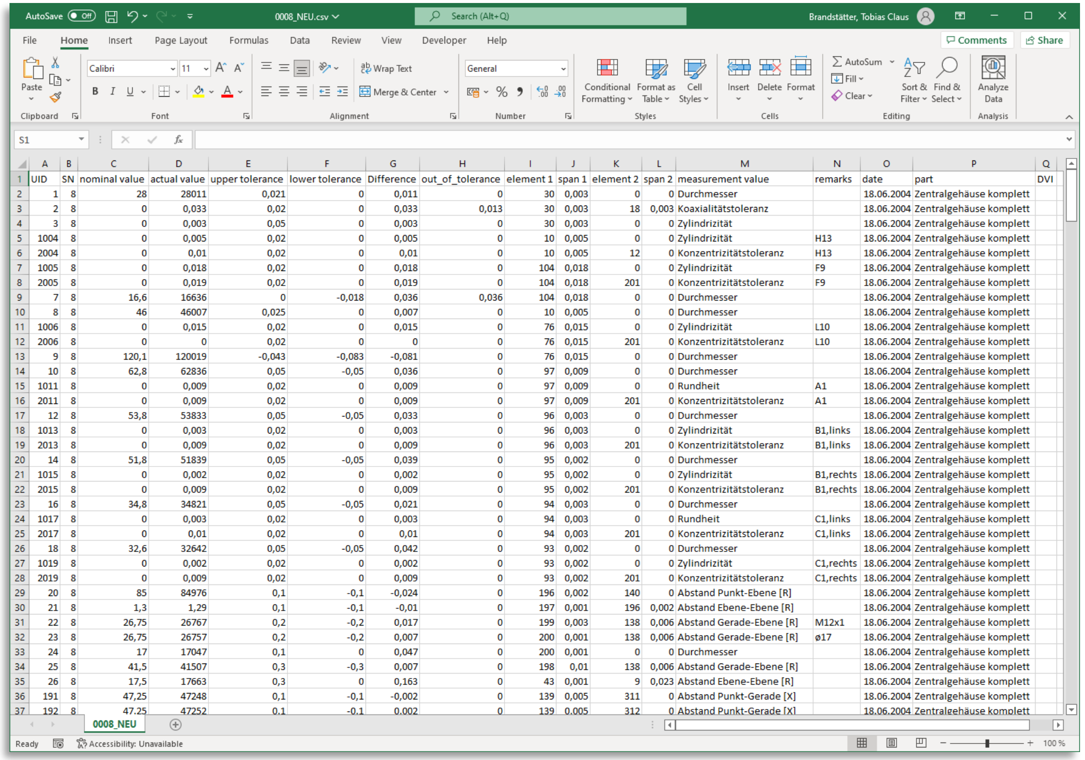


The upload of the measurement protocols follows the structure assembly – type – part.

MLsys2: Robustness Assessment

Demonstration of Robustness Assessment in the Target Environment

Release v1.0



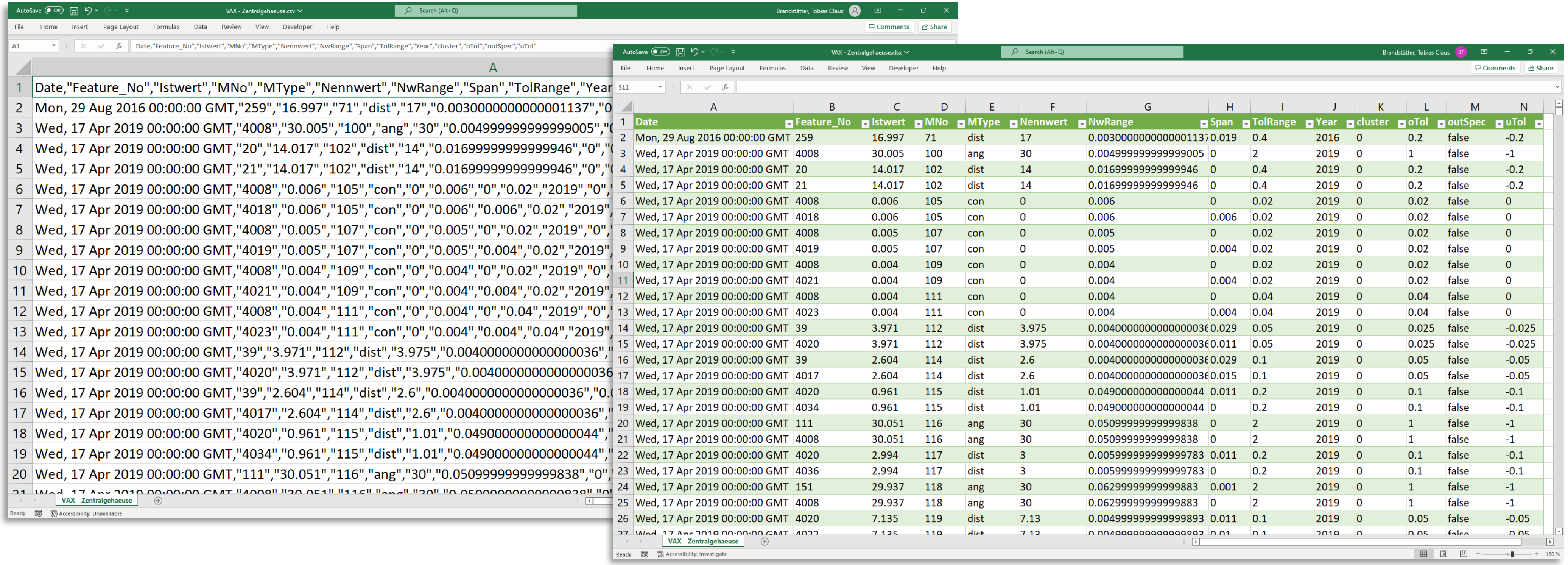
UID	SN	nominal value	actual value	upper tolerance	lower tolerance	Difference	out_of_tolerance	element 1	span 1	element 2	span 2	measurement value	remarks	date	part	DVI
1	8	28	28011	0,021	0	0,011	0	30	0,003	0	0	Durchmesser		18.06.2004	Zentralgehäuse komplett	
2	8	0	0,033	0,02	0	0,033	0,013	30	0,003	18	0,003	Koaxialitätstoleranz		18.06.2004	Zentralgehäuse komplett	
3	8	0	0,003	0,05	0	0,003	0	30	0,003	0	0	Zylindrizität		18.06.2004	Zentralgehäuse komplett	
1004	8	0	0,005	0,02	0	0,005	0	10	0,005	0	0	Zylindrizität	H13	18.06.2004	Zentralgehäuse komplett	
2004	8	0	0,01	0,02	0	0,01	0	10	0,005	12	0	Konzentrizitätstoleranz	H13	18.06.2004	Zentralgehäuse komplett	
1005	8	0	0,018	0,02	0	0,018	0	104	0,018	0	0	Zylindrizität	F9	18.06.2004	Zentralgehäuse komplett	
2005	8	0	0,019	0,02	0	0,019	0	104	0,018	201	0	Konzentrizitätstoleranz	F9	18.06.2004	Zentralgehäuse komplett	
7	8	16,6	16636	0	-0,018	0,036	0,036	104	0,018	0	0	Durchmesser		18.06.2004	Zentralgehäuse komplett	
8	8	46	46007	0,025	0	0,007	0	10	0,005	0	0	Durchmesser		18.06.2004	Zentralgehäuse komplett	
1006	8	0	0,015	0,02	0	0,015	0	76	0,015	0	0	Zylindrizität	L10	18.06.2004	Zentralgehäuse komplett	
2006	8	0	0	0,02	0	0	0	76	0,015	201	0	Konzentrizitätstoleranz	L10	18.06.2004	Zentralgehäuse komplett	
9	8	120,1	120019	-0,043	-0,083	-0,081	0	76	0,015	0	0	Durchmesser		18.06.2004	Zentralgehäuse komplett	
10	8	62,8	62836	0,05	-0,05	0,036	0	97	0,009	0	0	Durchmesser		18.06.2004	Zentralgehäuse komplett	
1011	8	0	0,009	0,02	0	0,009	0	97	0,009	0	0	Rundheit	A1	18.06.2004	Zentralgehäuse komplett	
2011	8	0	0,009	0,02	0	0,009	0	97	0,009	201	0	Konzentrizitätstoleranz	A1	18.06.2004	Zentralgehäuse komplett	
12	8	53,8	53833	0,05	-0,05	0,033	0	96	0,003	0	0	Durchmesser		18.06.2004	Zentralgehäuse komplett	
1013	8	0	0,003	0,02	0	0,003	0	96	0,003	0	0	Zylindrizität	B1,links	18.06.2004	Zentralgehäuse komplett	
2013	8	0	0,009	0,02	0	0,009	0	96	0,003	201	0	Konzentrizitätstoleranz	B1,links	18.06.2004	Zentralgehäuse komplett	
14	8	51,8	51839	0,05	-0,05	0,039	0	95	0,002	0	0	Durchmesser		18.06.2004	Zentralgehäuse komplett	
1015	8	0	0,002	0,02	0	0,002	0	95	0,002	0	0	Zylindrizität	B1,rechts	18.06.2004	Zentralgehäuse komplett	
2015	8	0	0,009	0,02	0	0,009	0	95	0,002	201	0	Konzentrizitätstoleranz	B1,rechts	18.06.2004	Zentralgehäuse komplett	
16	8	34,8	34821	0,05	-0,05	0,021	0	94	0,003	0	0	Durchmesser		18.06.2004	Zentralgehäuse komplett	
1017	8	0	0,003	0,02	0	0,003	0	94	0,003	0	0	Rundheit	C1,links	18.06.2004	Zentralgehäuse komplett	
2017	8	0	0,01	0,02	0	0,01	0	94	0,003	201	0	Konzentrizitätstoleranz	C1,links	18.06.2004	Zentralgehäuse komplett	
18	8	32,6	32642	0,05	-0,05	0,042	0	93	0,002	0	0	Durchmesser		18.06.2004	Zentralgehäuse komplett	
1019	8	0	0,002	0,02	0	0,002	0	93	0,002	0	0	Zylindrizität	C1,rechts	18.06.2004	Zentralgehäuse komplett	
2019	8	0	0,009	0,02	0	0,009	0	93	0,002	201	0	Konzentrizitätstoleranz	C1,rechts	18.06.2004	Zentralgehäuse komplett	
20	8	85	84976	0,1	-0,1	-0,024	0	196	0,002	140	0	Abstand Punkt-Ebene [R]		18.06.2004	Zentralgehäuse komplett	
21	8	1,3	1,29	0,1	-0,1	-0,01	0	197	0,001	196	0,002	Abstand Ebene-Ebene [R]		18.06.2004	Zentralgehäuse komplett	
22	8	26,75	26767	0,2	-0,2	0,017	0	199	0,003	138	0,006	Abstand Gerade-Ebene [R]	M12x1	18.06.2004	Zentralgehäuse komplett	
23	8	26,75	26757	0,2	-0,2	0,007	0	200	0,001	138	0,006	Abstand Gerade-Ebene [R]	ø17	18.06.2004	Zentralgehäuse komplett	
24	8	17	17047	0,1	0	0,047	0	200	0,001	0	0	Durchmesser		18.06.2004	Zentralgehäuse komplett	
25	8	41,5	41507	0,3	-0,3	0,007	0	198	0,01	138	0,006	Abstand Gerade-Ebene [R]		18.06.2004	Zentralgehäuse komplett	
26	8	17,5	17663	0,3	0	0,163	0	43	0,001	9	0,023	Abstand Ebene-Ebene [R]		18.06.2004	Zentralgehäuse komplett	
191	8	47,25	47248	0,1	-0,1	-0,002	0	139	0,005	311	0	Abstand Punkt-Gerade [X]		18.06.2004	Zentralgehäuse komplett	
192	8	47,25	47252	0,1	-0,1	0,002	0	139	0,005	312	0	Abstand Punkt-Gerade [X]		18.06.2004	Zentralgehäuse komplett	

The existing file parser for measurement protocols of AGG is compatible with the System

MLsys2: Robustness Assessment

Demonstration of Robustness Assessment in the Target Environment

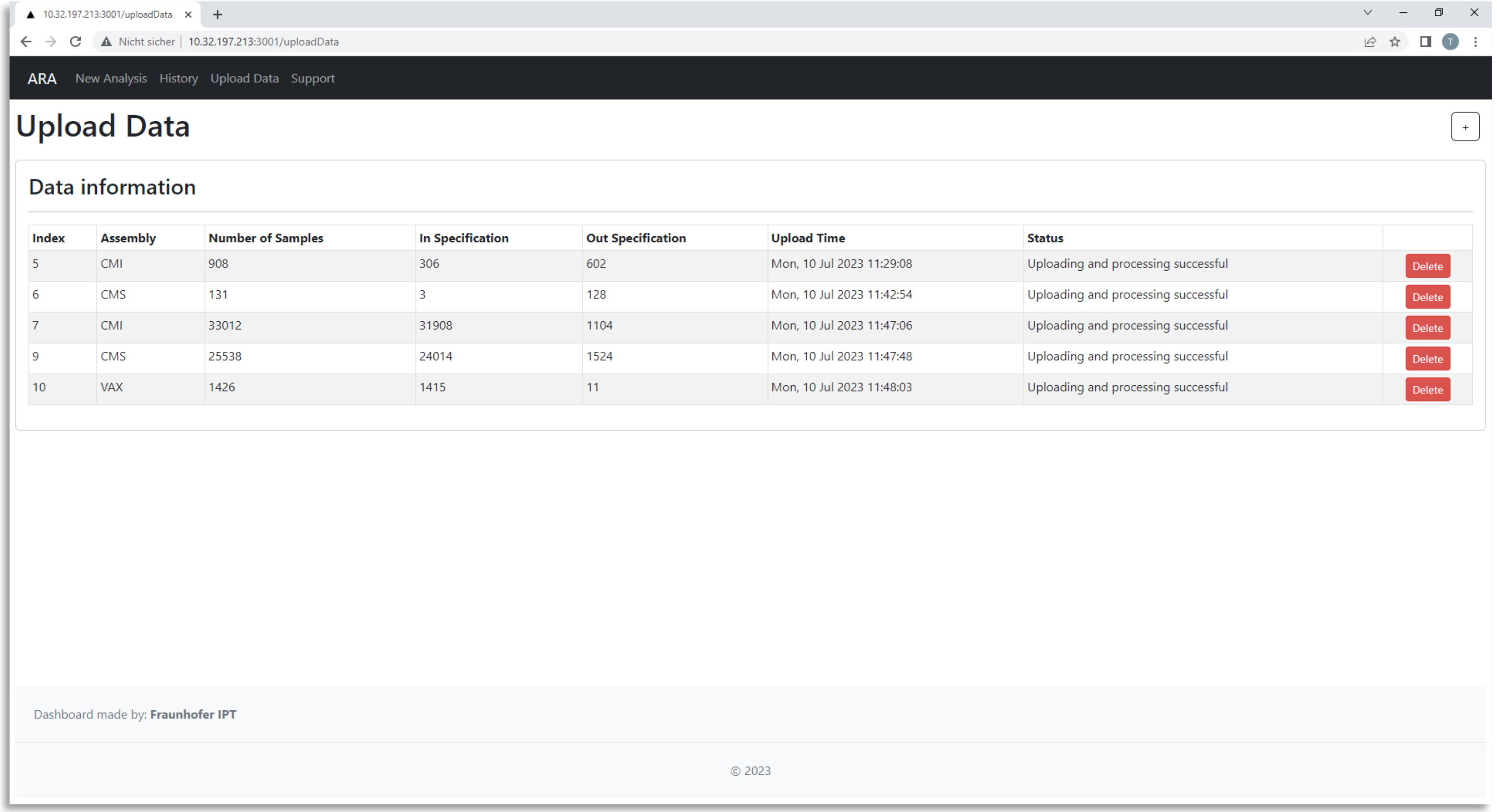
Release v1.0



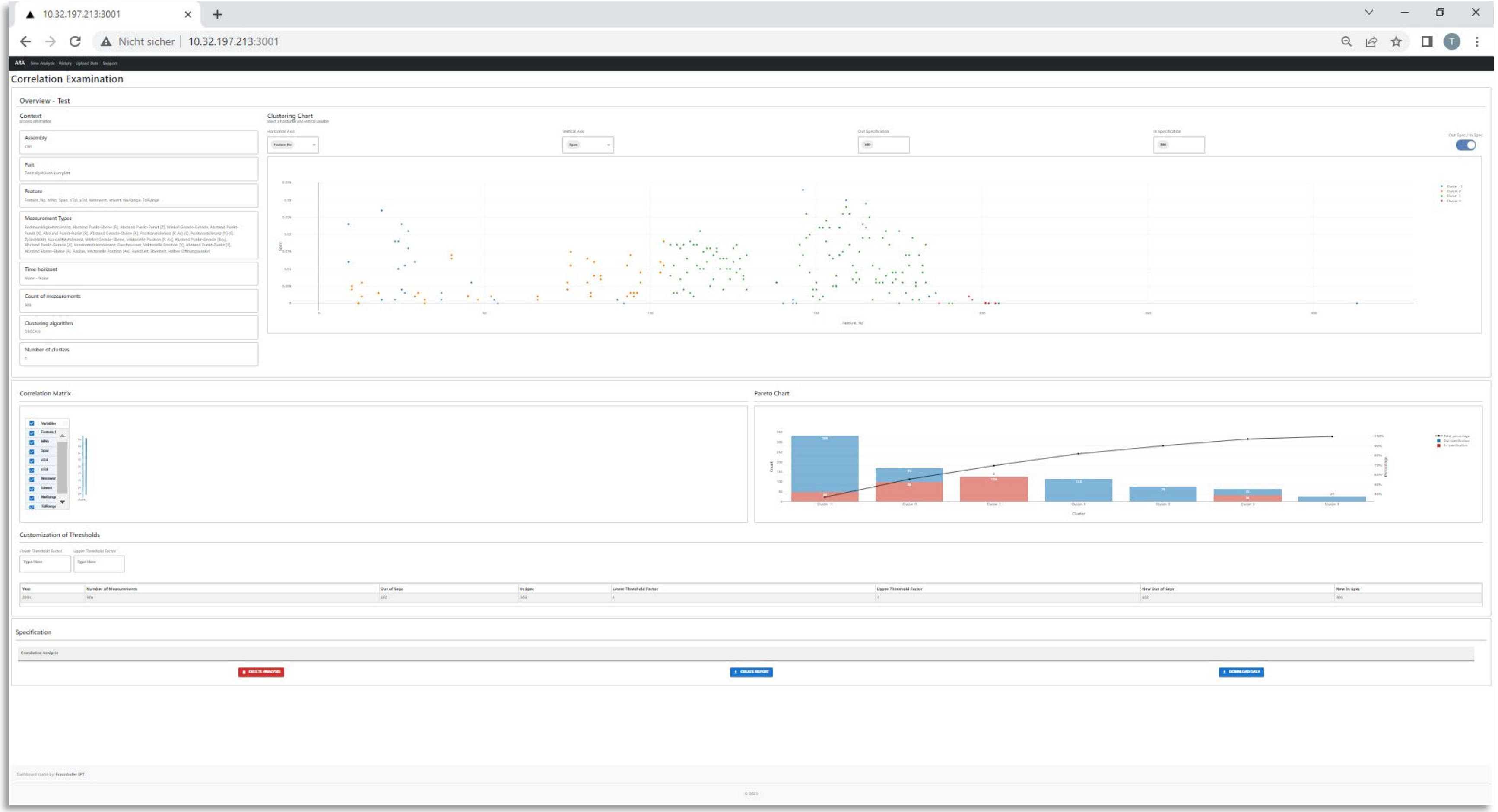
```
Date,"Feature_No","Istwert","MNo","MType","Nennwert","NwRange","Span","TolRange","Year
Mon, 29 Aug 2016 00:00:00 GMT,"259","16.997","71","dist","17","0.0030000000000001137","0
Wed, 17 Apr 2019 00:00:00 GMT,"4008","30.005","100","ang","30","0.004999999999999005","0
Wed, 17 Apr 2019 00:00:00 GMT,"20","14.017","102","dist","14","0.01699999999999946","0","
Wed, 17 Apr 2019 00:00:00 GMT,"21","14.017","102","dist","14","0.01699999999999946","0","
Wed, 17 Apr 2019 00:00:00 GMT,"4008","0.006","105","con","0","0.006","0","0.02","2019","0",
Wed, 17 Apr 2019 00:00:00 GMT,"4018","0.006","105","con","0","0.006","0.006","0.02","2019",
Wed, 17 Apr 2019 00:00:00 GMT,"4008","0.005","107","con","0","0.005","0","0.02","2019","0",
Wed, 17 Apr 2019 00:00:00 GMT,"4019","0.005","107","con","0","0.005","0.004","0.02","2019",
Wed, 17 Apr 2019 00:00:00 GMT,"4008","0.004","109","con","0","0.004","0","0.02","2019","0",
Wed, 17 Apr 2019 00:00:00 GMT,"4021","0.004","109","con","0","0.004","0.004","0.02","2019",
Wed, 17 Apr 2019 00:00:00 GMT,"4008","0.004","111","con","0","0.004","0","0.04","2019","0",
Wed, 17 Apr 2019 00:00:00 GMT,"4023","0.004","111","con","0","0.004","0.004","0.04","2019",
Wed, 17 Apr 2019 00:00:00 GMT,"39","3.971","112","dist","3.975","0.0040000000000000036",
Wed, 17 Apr 2019 00:00:00 GMT,"4020","3.971","112","dist","3.975","0.0040000000000000036
Wed, 17 Apr 2019 00:00:00 GMT,"39","2.604","114","dist","2.6","0.0040000000000000036","0.
Wed, 17 Apr 2019 00:00:00 GMT,"4017","2.604","114","dist","2.6","0.0040000000000000036",
Wed, 17 Apr 2019 00:00:00 GMT,"4020","0.961","115","dist","1.01","0.049000000000000044",
Wed, 17 Apr 2019 00:00:00 GMT,"4034","0.961","115","dist","1.01","0.049000000000000044",
Wed, 17 Apr 2019 00:00:00 GMT,"111","30.051","116","ang","30","0.05099999999999838","0",
```

Date	Feature_No	Istwert	MNo	MType	Nennwert	NwRange	Span	TolRange	Year	cluster	oTol	outSpec	uTol
Mon, 29 Aug 2016 00:00:00 GMT	259	16.997	71	dist	17	0.003000000000000113	0.019	0.4	2016	0	0.2	false	-0.2
Wed, 17 Apr 2019 00:00:00 GMT	4008	30.005	100	ang	30	0.004999999999999005	0	2	2019	0	1	false	-1
Wed, 17 Apr 2019 00:00:00 GMT	20	14.017	102	dist	14	0.01699999999999946	0	0.4	2019	0	0.2	false	-0.2
Wed, 17 Apr 2019 00:00:00 GMT	21	14.017	102	dist	14	0.01699999999999946	0	0.4	2019	0	0.2	false	-0.2
Wed, 17 Apr 2019 00:00:00 GMT	4008	0.006	105	con	0	0.006	0	0.02	2019	0	0.02	false	0
Wed, 17 Apr 2019 00:00:00 GMT	4018	0.006	105	con	0	0.006	0.006	0.02	2019	0	0.02	false	0
Wed, 17 Apr 2019 00:00:00 GMT	4008	0.005	107	con	0	0.005	0	0.02	2019	0	0.02	false	0
Wed, 17 Apr 2019 00:00:00 GMT	4019	0.005	107	con	0	0.005	0.004	0.02	2019	0	0.02	false	0
Wed, 17 Apr 2019 00:00:00 GMT	4008	0.004	109	con	0	0.004	0	0.02	2019	0	0.02	false	0
Wed, 17 Apr 2019 00:00:00 GMT	4021	0.004	109	con	0	0.004	0.004	0.02	2019	0	0.02	false	0
Wed, 17 Apr 2019 00:00:00 GMT	4008	0.004	111	con	0	0.004	0	0.04	2019	0	0.04	false	0
Wed, 17 Apr 2019 00:00:00 GMT	4023	0.004	111	con	0	0.004	0.004	0.04	2019	0	0.04	false	0
Wed, 17 Apr 2019 00:00:00 GMT	39	3.971	112	dist	3.975	0.00400000000000003	0.029	0.05	2019	0	0.025	false	-0.025
Wed, 17 Apr 2019 00:00:00 GMT	4020	3.971	112	dist	3.975	0.00400000000000003	0.011	0.05	2019	0	0.025	false	-0.025
Wed, 17 Apr 2019 00:00:00 GMT	39	2.604	114	dist	2.6	0.00400000000000003	0.029	0.1	2019	0	0.05	false	-0.05
Wed, 17 Apr 2019 00:00:00 GMT	4017	2.604	114	dist	2.6	0.00400000000000003	0.015	0.1	2019	0	0.05	false	-0.05
Wed, 17 Apr 2019 00:00:00 GMT	4020	0.961	115	dist	1.01	0.049000000000000044	0.011	0.2	2019	0	0.1	false	-0.1
Wed, 17 Apr 2019 00:00:00 GMT	4034	0.961	115	dist	1.01	0.049000000000000044	0	0.2	2019	0	0.1	false	-0.1
Wed, 17 Apr 2019 00:00:00 GMT	111	30.051	116	ang	30	0.05099999999999838	0	2	2019	0	1	false	-1
Wed, 17 Apr 2019 00:00:00 GMT	4008	30.051	116	ang	30	0.05099999999999838	0	2	2019	0	1	false	-1
Wed, 17 Apr 2019 00:00:00 GMT	4020	2.994	117	dist	3	0.005999999999999783	0.011	0.2	2019	0	0.1	false	-0.1
Wed, 17 Apr 2019 00:00:00 GMT	4036	2.994	117	dist	3	0.005999999999999783	0	0.2	2019	0	0.1	false	-0.1
Wed, 17 Apr 2019 00:00:00 GMT	151	29.937	118	ang	30	0.06299999999999883	0.001	2	2019	0	1	false	-1
Wed, 17 Apr 2019 00:00:00 GMT	4008	29.937	118	ang	30	0.06299999999999883	0	2	2019	0	1	false	-1
Wed, 17 Apr 2019 00:00:00 GMT	4020	7.135	119	dist	7.13	0.004999999999999893	0.011	0.1	2019	0	0.05	false	-0.05

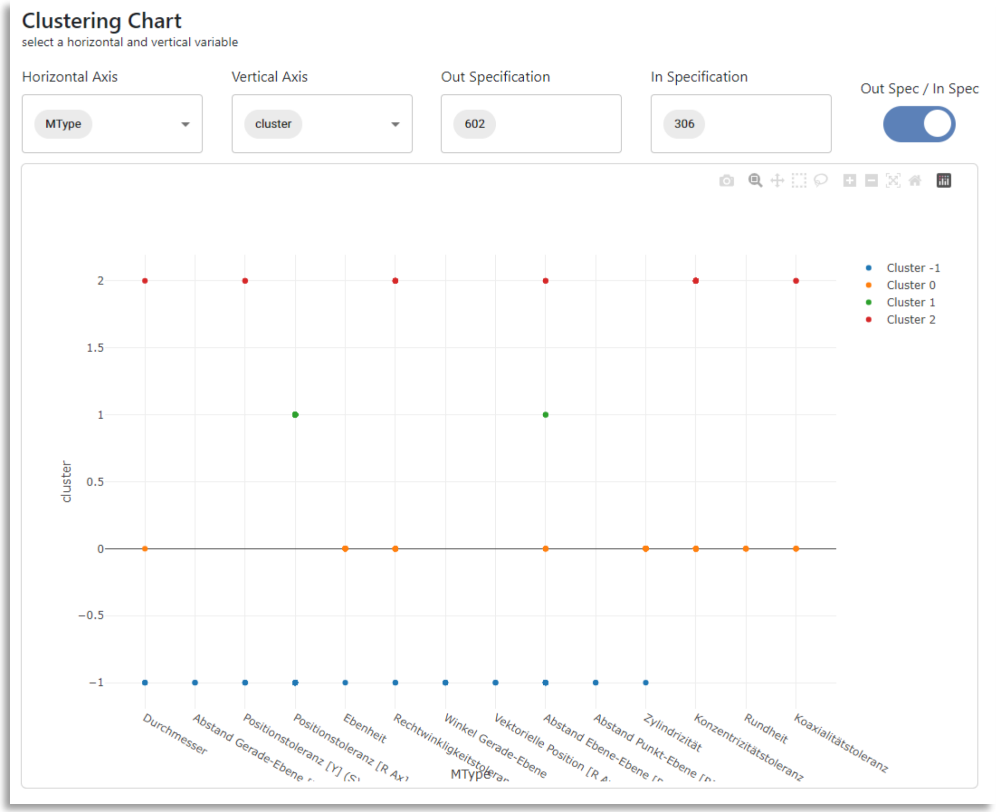
All parsed measurements can be exported as a .csv file.
During parsing, all relevant metadata and information is automatically extracted from the protocols.

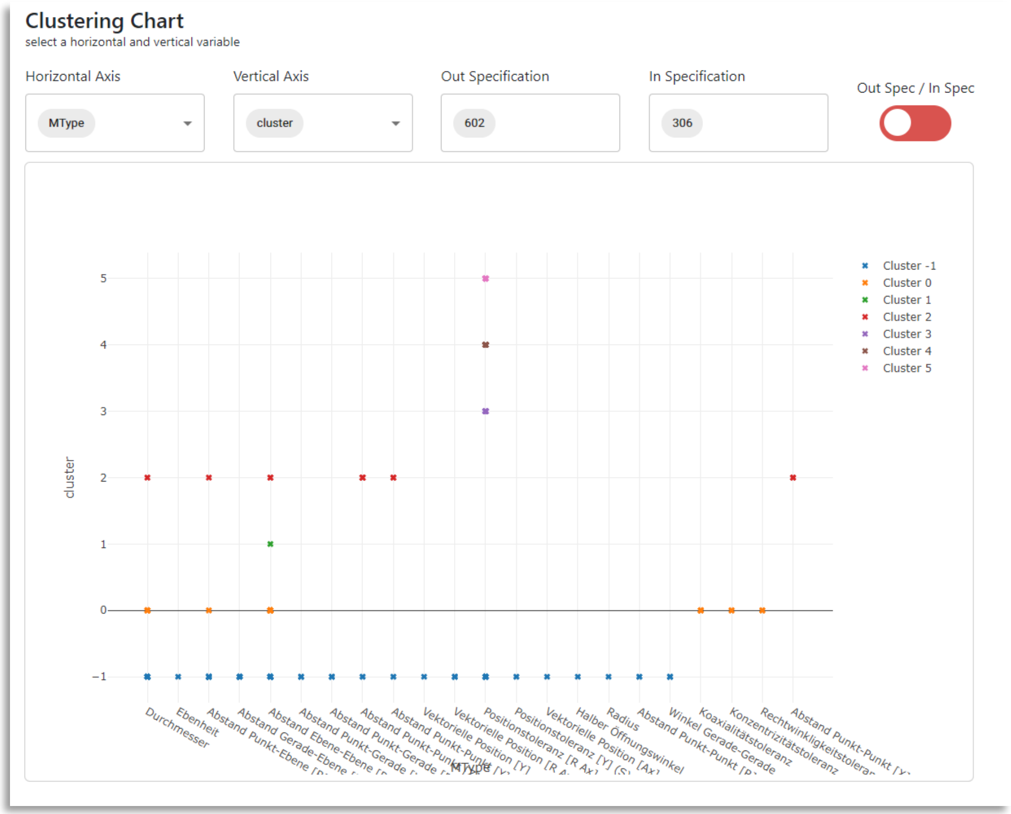


Index	Assembly	Number of Samples	In Specification	Out Specification	Upload Time	Status	
5	CMI	908	306	602	Mon, 10 Jul 2023 11:29:08	Uploading and processing successful	Delete
6	CMS	131	3	128	Mon, 10 Jul 2023 11:42:54	Uploading and processing successful	Delete
7	CMI	33012	31908	1104	Mon, 10 Jul 2023 11:47:06	Uploading and processing successful	Delete
9	CMS	25538	24014	1524	Mon, 10 Jul 2023 11:47:48	Uploading and processing successful	Delete
10	VAX	1426	1415	11	Mon, 10 Jul 2023 11:48:03	Uploading and processing successful	Delete

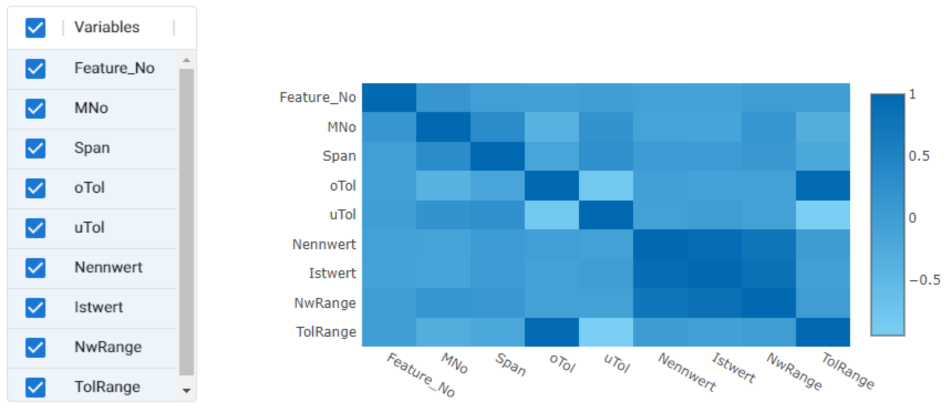

10.32.197.213:3001
Nicht sicher
10.32.197.213:3001
Correlation Examination
Overview - Test
Context
Clustering Chart
Assembly
Part
Feature
Measurement Types
Time horizont
Count of measurements
Clustering algorithm
Number of clusters
Correlation Matrix
Pareto Chart
Customization of Thresholds
Specification

 11/07/2023

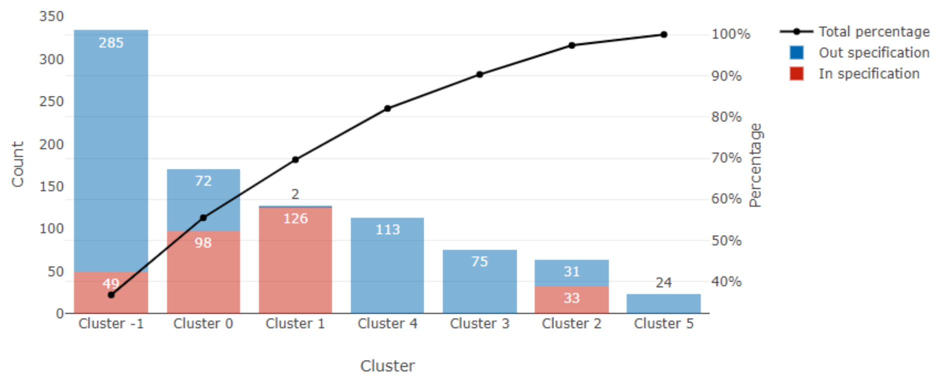

Clustering Chart
select a horizontal and vertical variable
Horizontal Axis
MType
Vertical Axis
cluster
Out Specification
602
In Specification
306
Out Spec / In Spec
Cluster -1
Cluster 0
Cluster 1
Cluster 2
cluster
MType
Durchmesser
Ebenheit
Zylindrizität
Konzentrizitätstoleranz
Rundheit
Koaxialitätstoleranz


Clustering Chart
select a horizontal and vertical variable
Horizontal Axis
MType
Vertical Axis
cluster
Out Specification
602
In Specification
306
Out Spec / In Spec
Cluster -1
Cluster 0
Cluster 1
Cluster 2
Cluster 3
Cluster 4
Cluster 5
cluster
MType
Durchmesser
Ebenheit
Radius
Halber Öffnungswinkel
Koaxialitätstoleranz
Konzentrizitätstoleranz

Correlation Matrix



Pareto Chart



Customization of Thresholds

Lower Threshold Factor

Type Here

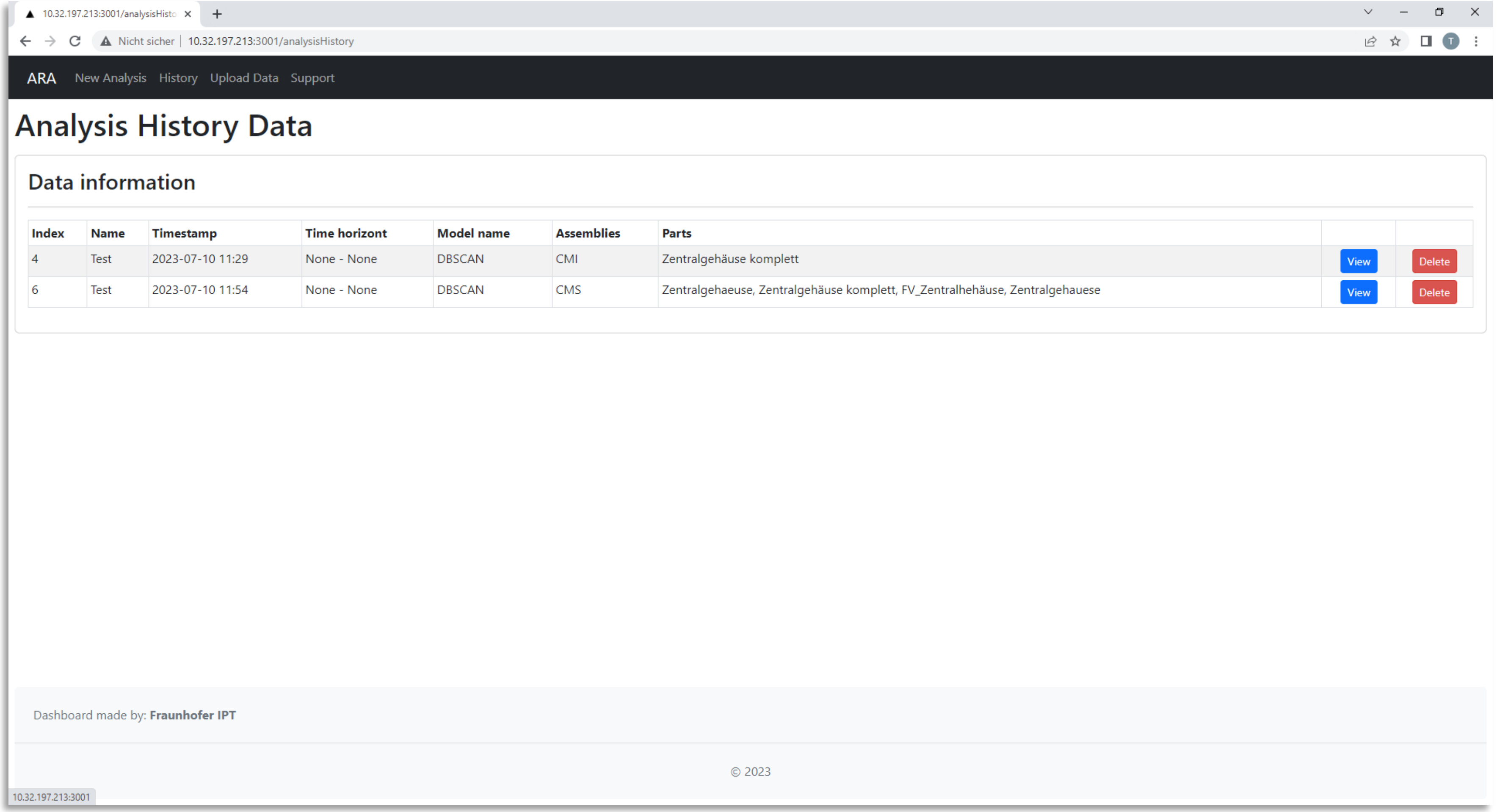
1

Upper Threshold Factor

Type Here

1.05

Year	Number of Measurements	Out of Sepc	In Spec	Lower Threshold Factor	Upper Threshold Factor	New Out of Sepc	New In Spec
2004	908	602	306	1	1.05	598	310



10.32.197.213:3001/analysisHisto

Nicht sicher | 10.32.197.213:3001/analysisHistory

ARA New Analysis History Upload Data Support

Analysis History Data

Data information

Index	Name	Timestamp	Time horizont	Model name	Assemblies	Parts		
4	Test	2023-07-10 11:29	None - None	DBSCAN	CMI	Zentralgehäuse komplett	View	Delete
6	Test	2023-07-10 11:54	None - None	DBSCAN	CMS	Zentralgehaeuse, Zentralgehäuse komplett, FV_Zentralhehäuse, Zentralgehauese	View	Delete

Dashboard made by: **Fraunhofer IPT**

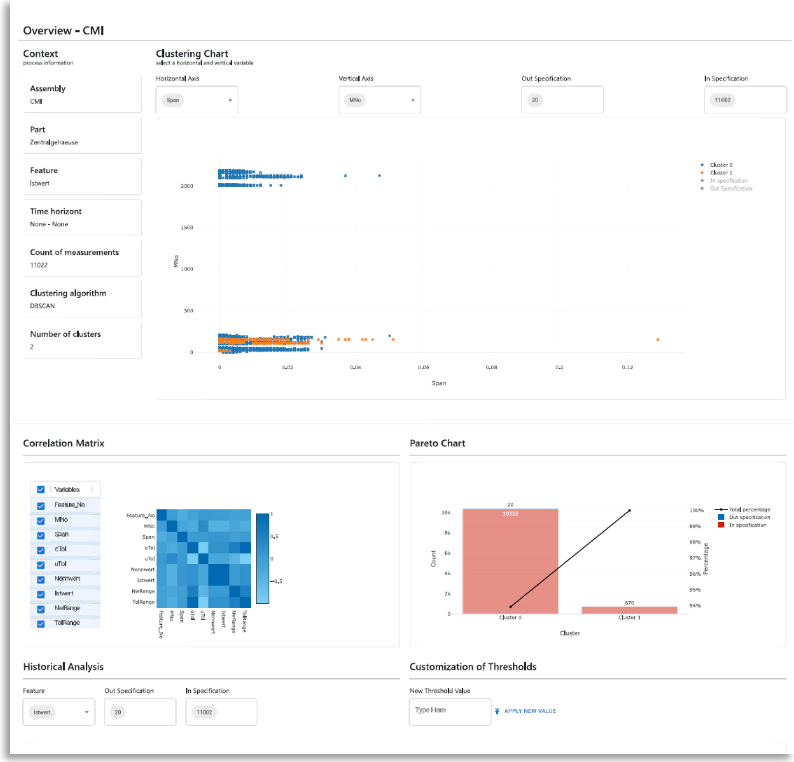
© 2023

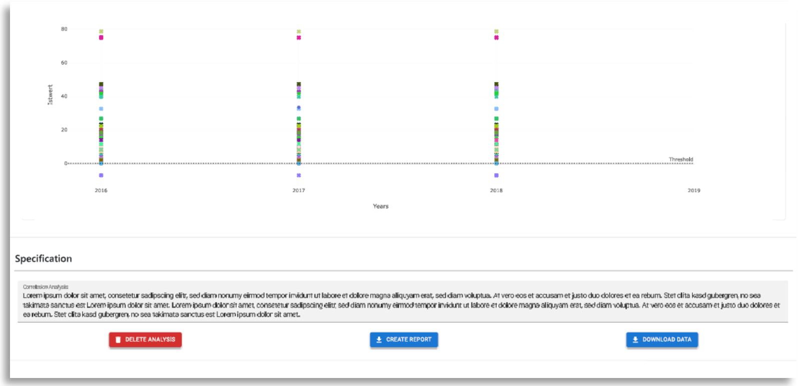
10.32.197.213:3001

MLsys2: Robustness Assessment

Demonstration of Robustness Assessment in the Target Environment

Release v1.0





A conducted robustness assessment can be supplemented with comments and exported as a report in form of a .pdf-file.

Clustering analysis

Pipeline objectives

CMM DATA STREAM

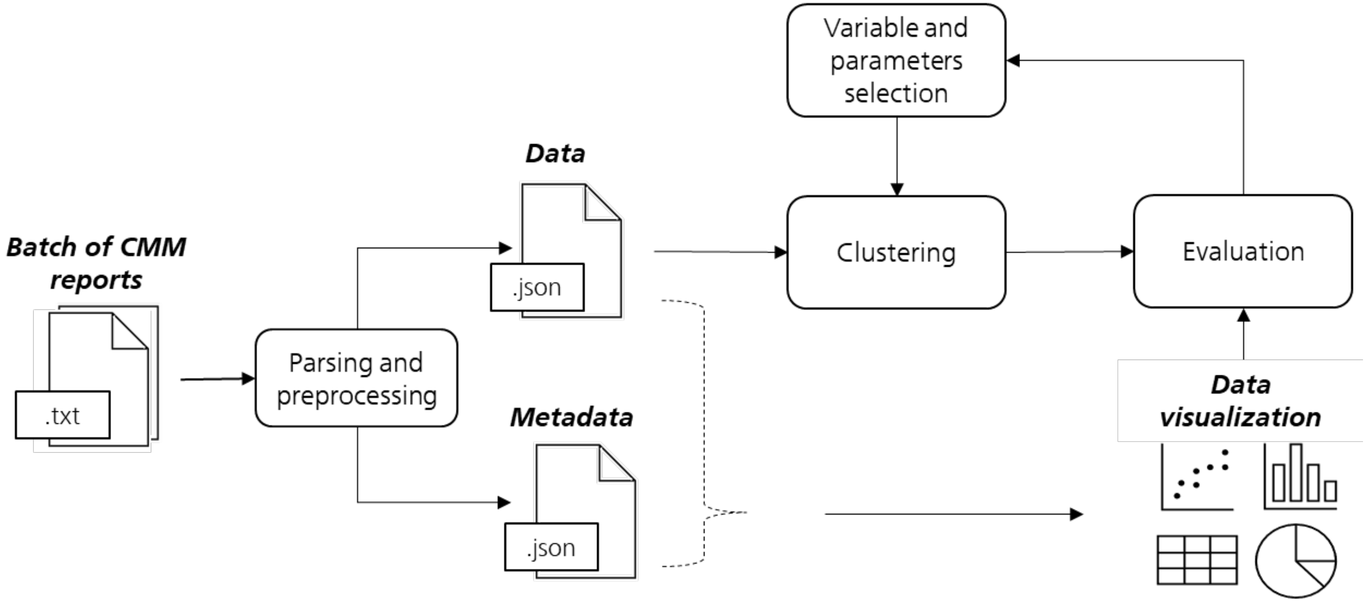
Pipeline Objectives

Provide an insight into underlying patterns in historic CMM to make deductions regarding the feasibility of manufacturing specifications for various components.

The task of this pipeline is to:

- Execute clustering using preconfigured clustering algorithms to test hypotheses
- Provide interpretation aids (visualizations and descriptive statistics)

Enable in-depth analysis of production capabilities using cluster analysis.



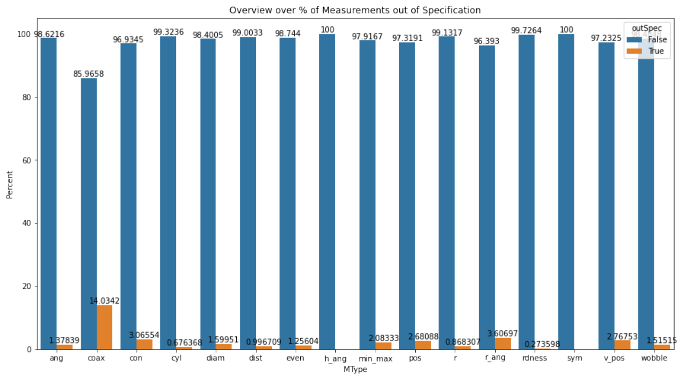
Clustering analysis

Data preparation

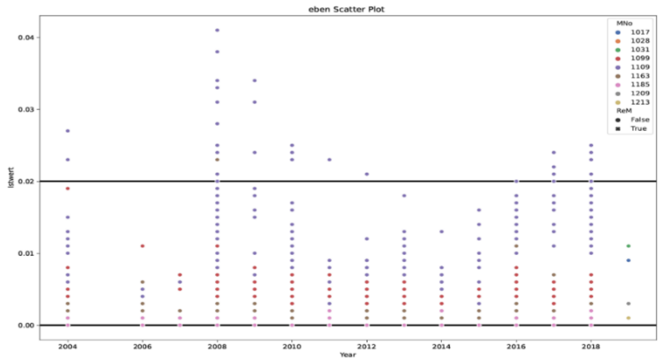
Data Characteristics

- File format: .txt
- Strong data imbalance
  - Low overall number for out of specification, ~2.0%
  - Numerous remeasurements, usually without recording of remeasured value
  - Varying out of specification ratio over years, components and features

Overview of relative number of out of specification measurements



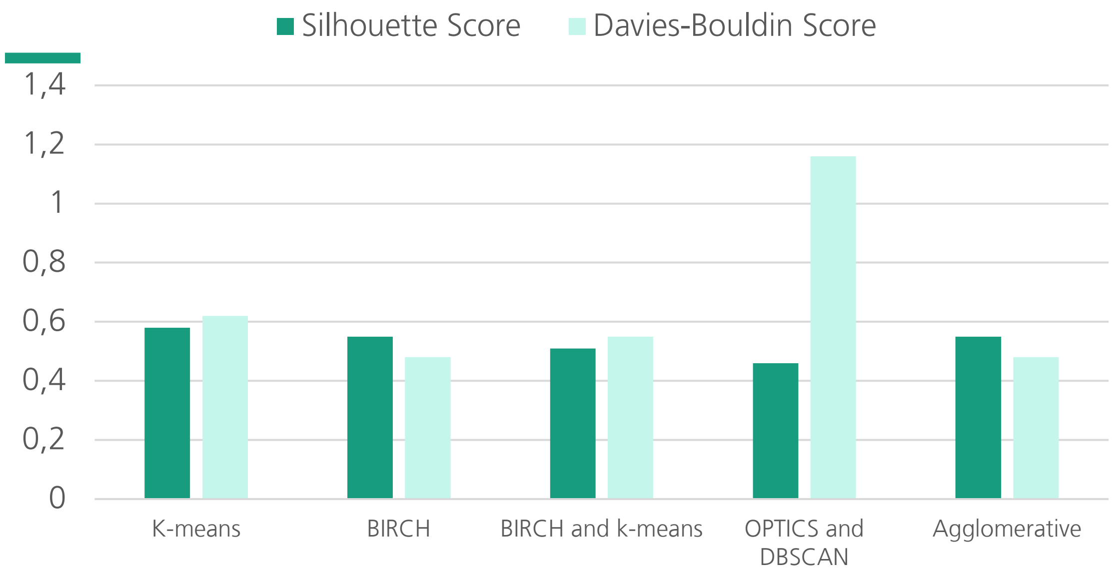
Trends within groups in the example of "even" measurement



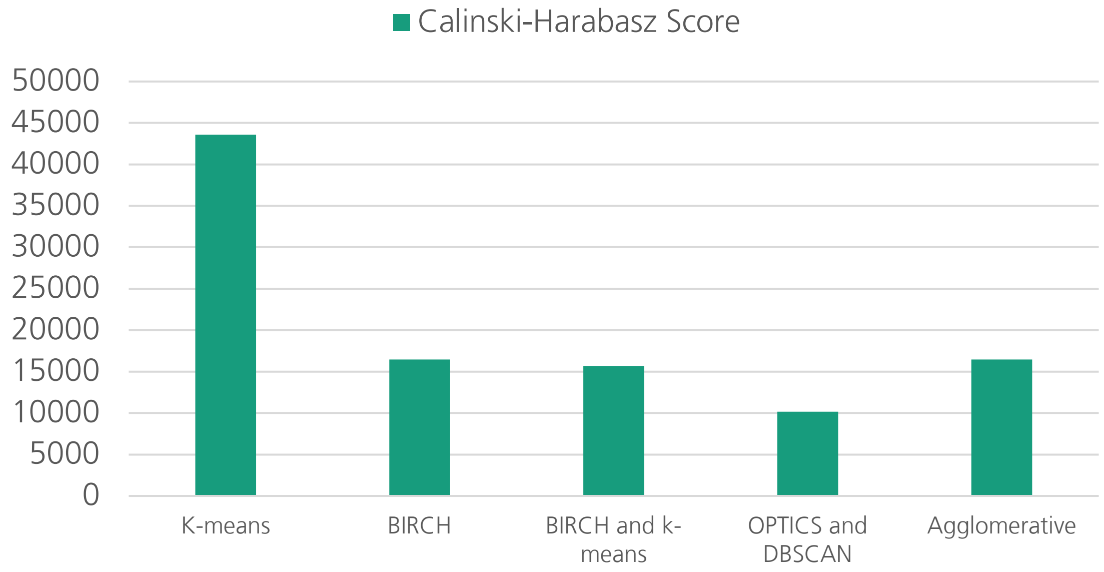
Data Preparation Steps

- Remove duplicate and incomplete measurements
- Divide data into groups (e.g. measurement types -> compare angle of vectorial position with other angle measurements)
- Engineer additional features: range between upper and lower tolerance, difference between actual value and nominal value, tolerance range relative to tolerance range of other measurements a feature is involved in, tolerance range relative to other tolerance ranges within measurement group, nominal value in ratio to other nominal values within measurement group, group membership
- Scale data using sklearn.StandardScaler to prevent bias due to different scales of the features

MLsys2 – robustness assessment | PoC modeling results



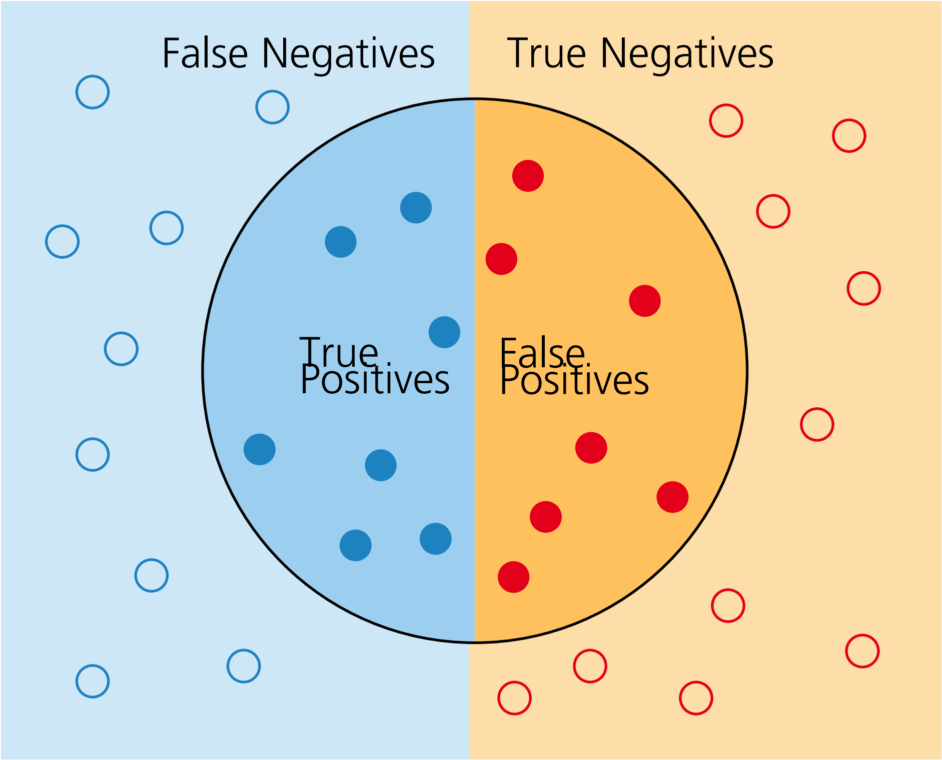
- Silhouette Score
  - Silhouette coefficient summarizes the intra/inter cluster distance comparison to a score between -1 to 1.
  - A value close to 1 indicates a very promising clustering result, where the inter-cluster distances are much larger that the intra-cluster distances.
- Davies-Bouldin Score
  - The Davies-Bouldin index is similar to the Calinski-Harabasz Score, but the inter/intra cluster distance ratio calculation is reverse.
  - The smaller the score is, the better the cluster separation is.
- Calinski-Harabasz Score
  - The Calinski-Harabasz index is defined as a ratio of the squared inter-cluster distance sum and the squared intra-cluster distance sum for all clusters.
  - The higher the score, the better the clusters are separated from each other, and there is no upper bound for the score.



Modeling Status

Performance metrics for classification problems 1/3

1 ***Automated Live Monitoring***

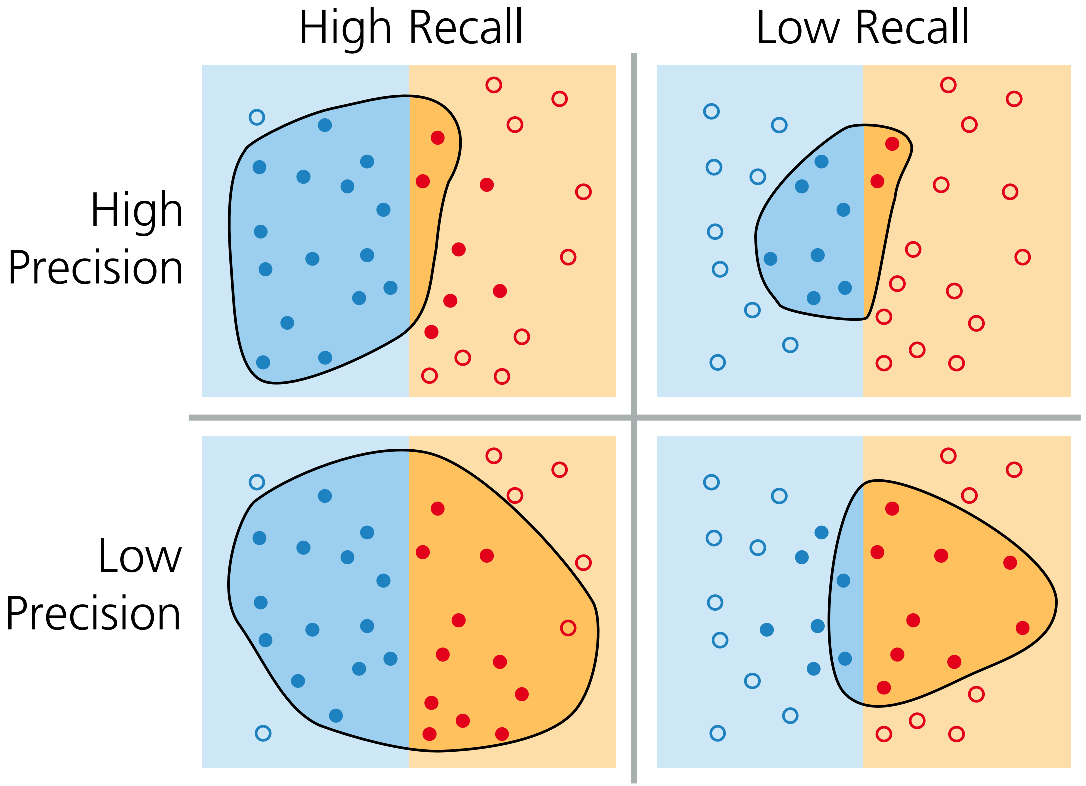


- True Positives (**TP**)
  - Actually positive cases that were correctly assigned positive class
- True Negatives (**TN**)
  - Actually negative cases that were correctly assigned negative class
- False Positives (**FP**)
  - Actually negative cases that were wrongly assigned positive class (Type 1 error)
- False Negatives (**FN**)
  - Actually positive cases that were wrongly assigned negative class (Type 2 Error)

Modeling Status

Performance metrics for classification problems 2/3

1 *Automated Live Monitoring*



Precision

- $Precision = \frac{TP}{TP+FP}$
  - „Confidence“
  - How many predicted „positives“ are actually positive?

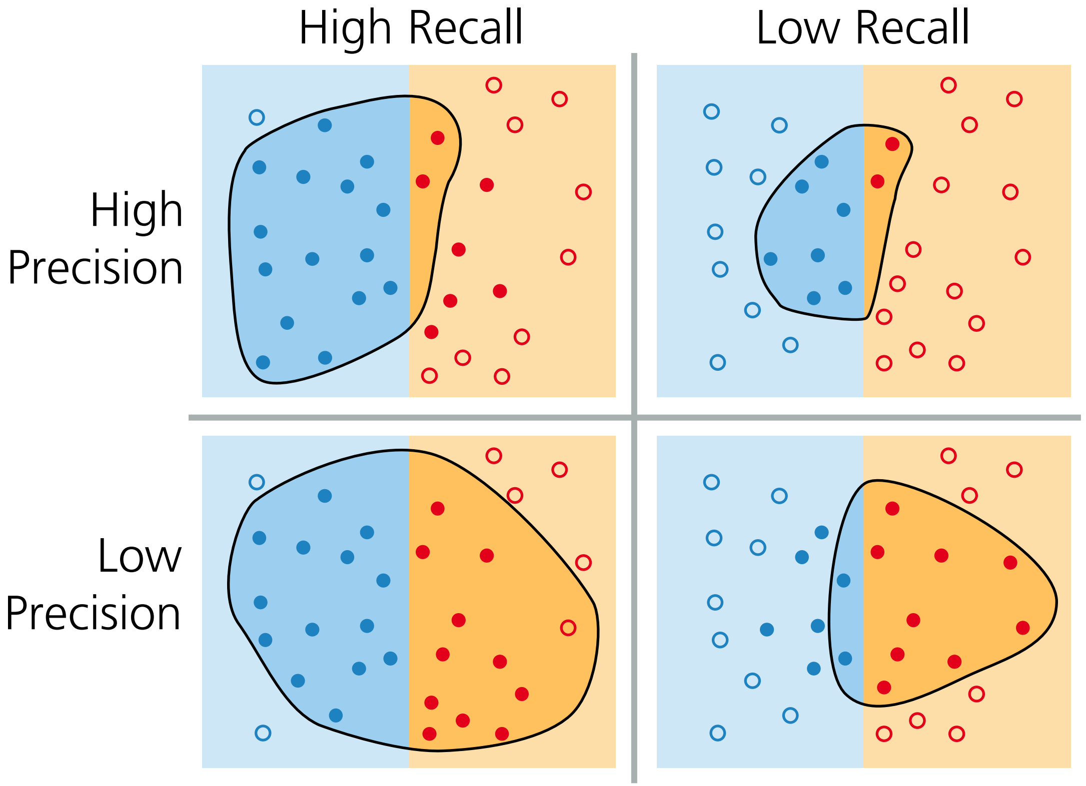
Recall

- $Recall = \frac{TP}{TP+FN}$
  - „Sensitivity“
  - How well does the model recognize positive cases?

Modeling Status

Performance metrics for classification problems 3/3

1 ***Automated Live Monitoring***



F1-score

- $F_1\ score = \frac{2 \cdot TP}{2 \cdot TP + FN + FP} = 2 \cdot \frac{Precision \cdot Recall}{Precision + Recall}$
  - Harmonic mean of precision and recall
  - Favors classifiers with similar precision and recall

Focus on F1-score and recall as the key metrics for the performance assessment of OT and PBM model.