MAN Energy Solutions
Future in the making

Error Mode Identification in Gas Turbines through Predictive Maintenance

MATLAB Expo 2022

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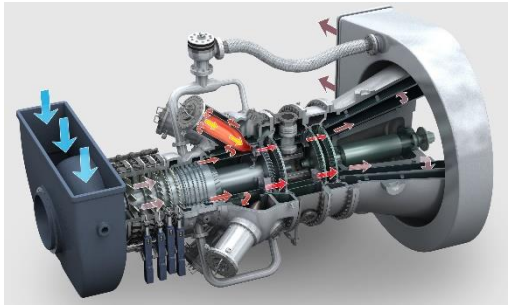
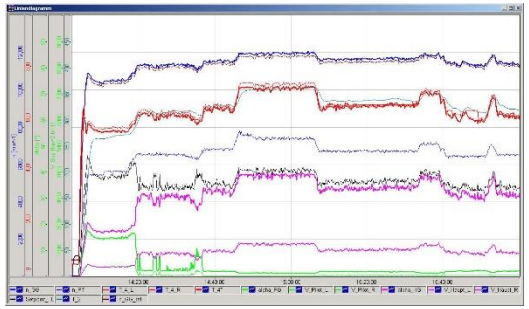
Is it Possible to Automate the Evaluation of a Gas Turbine‘s Condition?

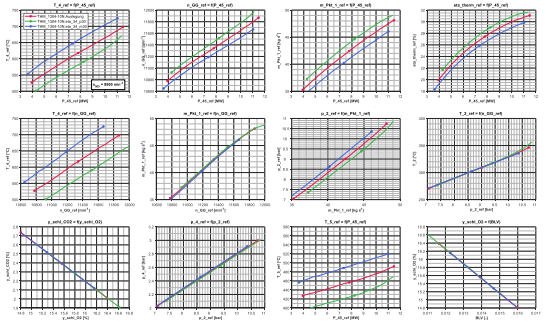


Gas Turbine



Measured Data

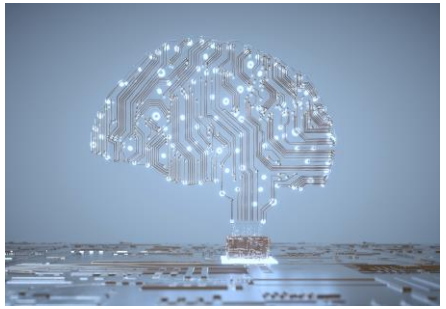
Current Workflow



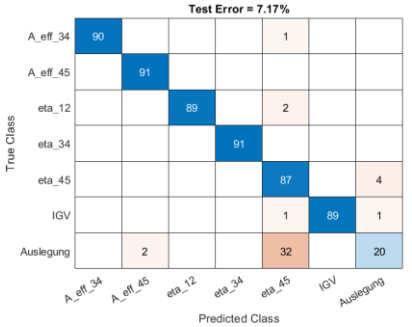
Visualization

Manual Evaluation

Envisioned Workflow



Machine Learning

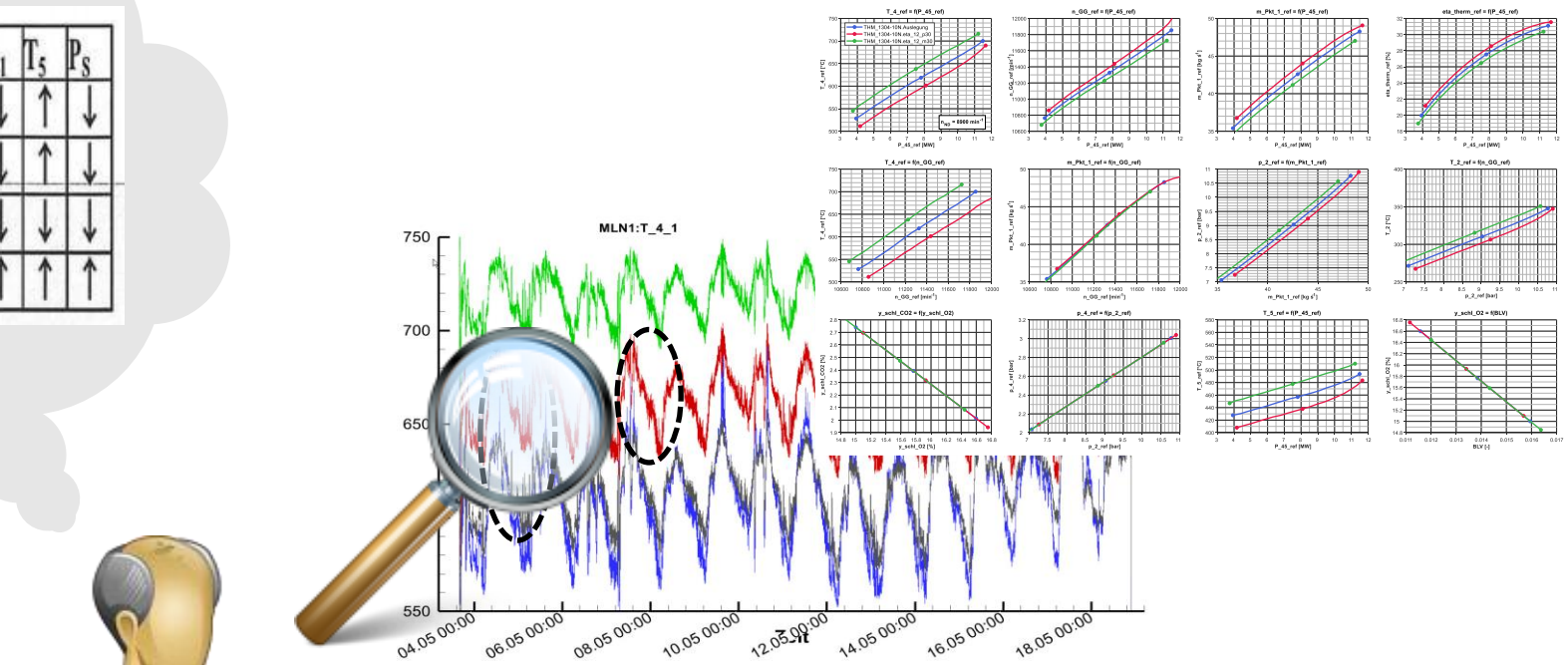


Automatic Evaluation

Manual Inspection is Tedious

Problem 1: Manual inspection of data requires **expert knowledge** and is very **time-consuming**

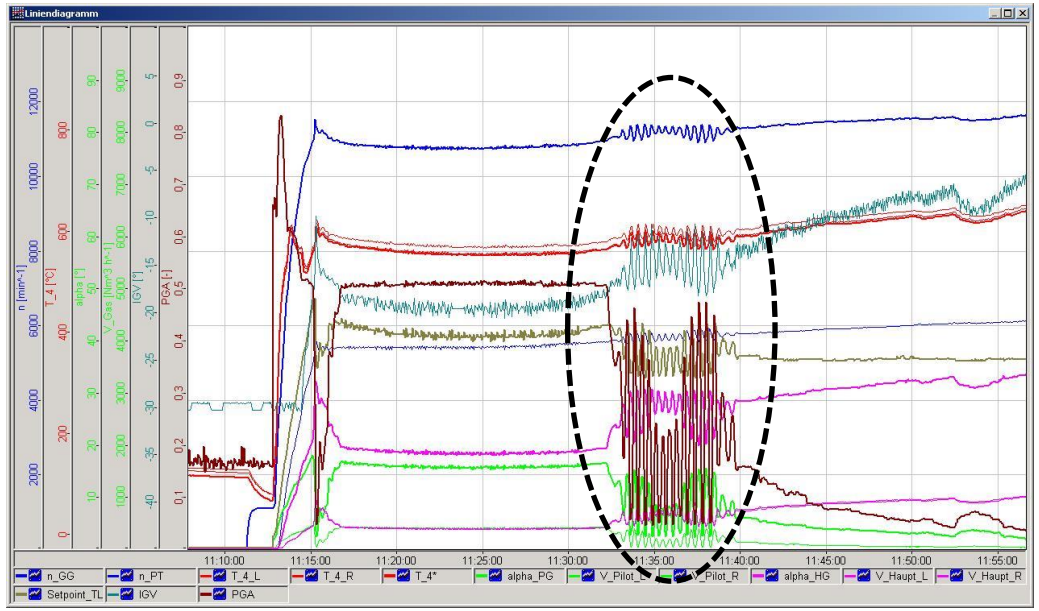
	W_a	p_3	T_3	W_f	p_{41}	T_5	P_S
(a) Mistuned IGVs	↓	↓	~	↓	↓	↑	↓
(b) Compressor Fouling	↓	↓	↑	↓	↓	↑	↓
(c) Compressor-Turbine Fou	~	↑	↑	↓	↓	↓	↓
(d) Power Turbine Fouling	~	↑	↑	↑	↑	↑	↑

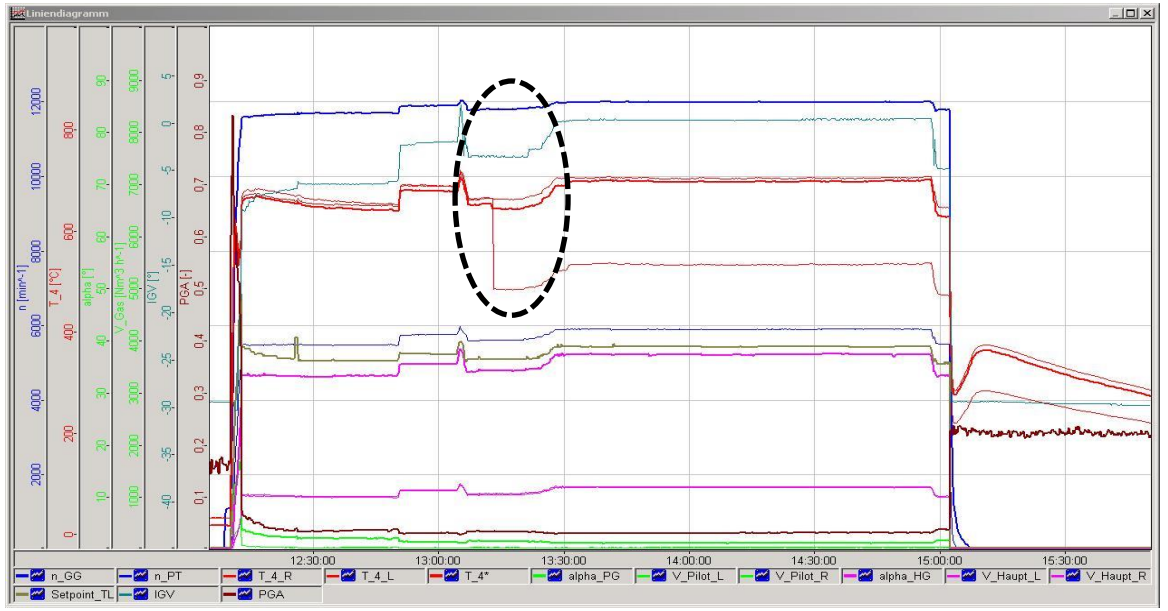


Solution: Machine learning

Real Engine Data Are Messy and not Labeled

Problem 2: Real measured data are **messy**, **incomplete** and **not labeled**

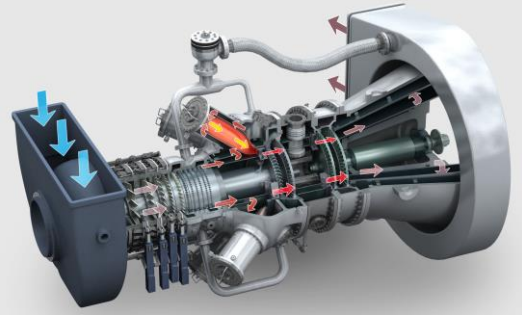




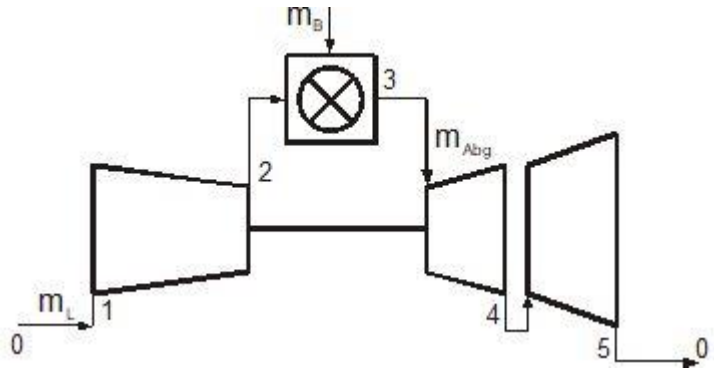
Solution: Synthetic data

Synthetic Data Are Complete, Clean and Classifiable

Gas Turbine

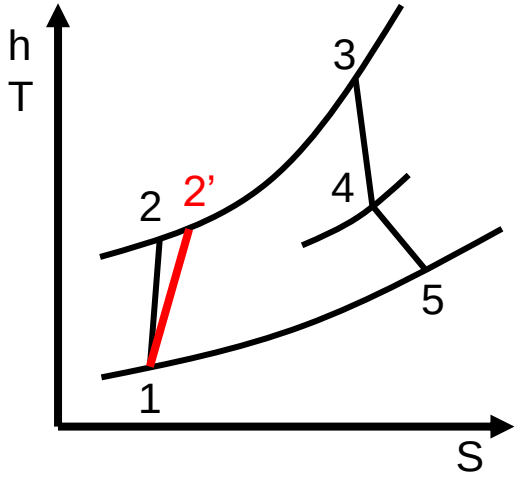


Engine Model



- Compressor and turbine maps
- Simple combustion model
- Secondary air system model

Joule Cycle



- p, T, $\dot{m}$, $\tilde{y}$ at each state point
- Cycle changes due to errors

Thermodynamic Cycle Calculations Are Used to Create Simulated Data

GateCycle™

- Engine type: THM 1304-10N
- 11 different error types
- 12 error magnitudes (± 3 %, step size 0.5 %)
- Data Sets
  - Training Data: ~50000 data points (gridded)
  - Test Data: ~2000 data points (random)

data

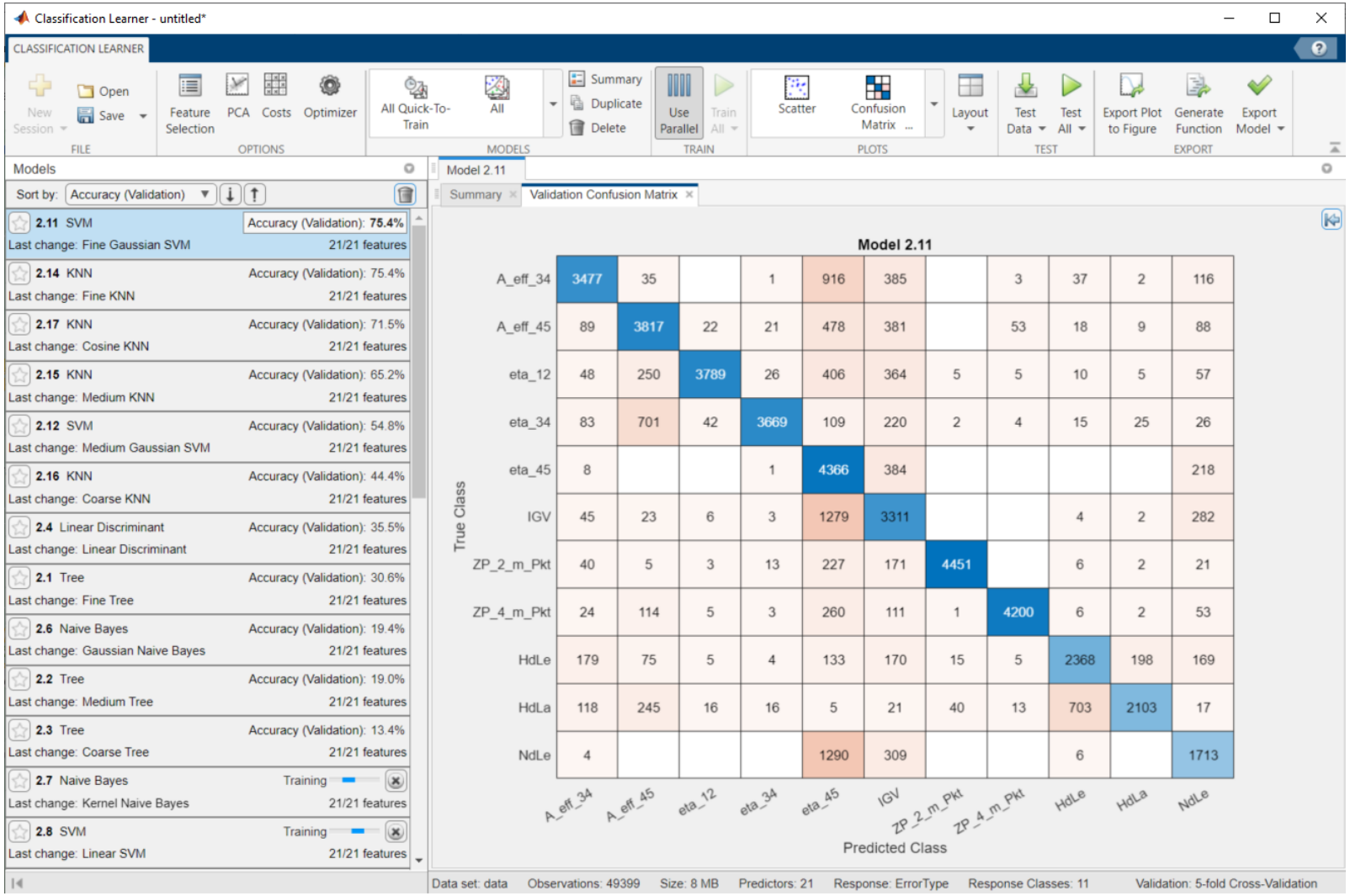
52435x23 table

	1 ErrorType	2 ErrorPerc	3 ZP_1.m_Pkt_ref	4 ZP_2.p_ref	5 ZP_2.T_ref	6 ZP_2.m_Pkt_ref	7 ZAe_23.Q_Pkt_ref	8 ZP_3.p_ref	9 ZP_3.T_ref
1	Auslegung	0	48.1530	10.7393	346.7288	48.1530	36.9600	10.3312	1.0237e+03
2	Auslegung	0	48.1998	10.7494	347.1001	48.1998	36.9600	10.3410	1.0234e+03
3	Auslegung	0	48.2674	10.7688	347.7162	48.2674	36.9600	10.3596	1.0231e+03
4	Auslegung	0	48.2887	10.7626	347.7541	48.2887	36.9600	10.3537	1.0228e+03
5	Auslegung	0	48.3310	10.7678	348.0681	48.3310	36.9600	10.3586	1.0226e+03
6	Auslegung	0	48.3544	10.7752	348.3076	48.3544	36.9600	10.3657	1.0225e+03
7	Auslegung	0	48.4047	10.7843	348.7462	48.4047	36.9600	10.3745	1.0222e+03
8	Auslegung	0	48.4391	10.7924	349.0880	48.4391	36.9600	10.3823	1.0221e+03
9	Auslegung	0	48.4760	10.7981	349.4206	48.4760	36.9600	10.3877	1.0219e+03
10	Auslegung	0	48.4948	10.8067	349.6692	48.4948	36.9600	10.3961	1.0219e+03
11	Auslegung	0	48.5295	10.8104	349.9852	48.5295	36.9600	10.3996	1.0217e+03
12	Auslegung	0	48.5501	10.8137	350.1870	48.5501	36.9600	10.4028	1.0216e+03
13	Auslegung	0	48.5661	10.8167	350.3598	48.5661	36.9600	10.4057	1.0216e+03
14	Auslegung	0	48.5805	10.8194	350.5131	48.5805	36.9600	10.4083	1.0215e+03
15	Auslegung	0	48.5926	10.8218	350.6463	48.5926	36.9600	10.4106	1.0215e+03
16	Auslegung	0	48.6015	10.8236	350.7453	48.6015	36.9600	10.4123	1.0215e+03
17	Auslegung	0	48.6081	10.8249	350.8227	48.6081	36.9600	10.4136	1.0215e+03
18	Auslegung	0	48.6119	10.8258	350.8659	48.6119	36.9600	10.4144	1.0214e+03
19	Auslegung	0	48.6130	10.8261	350.8800	48.6130	36.9600	10.4147	1.0214e+03
20	Auslegung	0	48.6113	10.8260	350.8632	48.6113	36.9600	10.4146	1.0215e+03
21	Auslegung	0	48.6067	10.8254	350.8142	48.6067	36.9600	10.4140	1.0215e+03
22	Auslegung	0	48.5995	10.8242	350.7342	48.5995	36.9600	10.4128	1.0215e+03
23	Auslegung	0	48.5893	10.8225	350.6276	48.5893	36.9600	10.4112	1.0215e+03
24	Auslegung	0	47.6585	10.5672	342.3571	47.6585	36	10.1657	1.0102e+03
25	Auslegung	0	47.6768	10.5697	342.4513	47.6768	36	10.1681	1.0102e+03

Fundamental Questions to Be Answered Using Synthetic Data

- Is it possible to identify different error types?
- Is it possibe to determine error magnitude?
- What is the best result that can be achieved?
- What effect does the number of predictors have?

Different Classification and Regression Models Were Trained and Evaluated



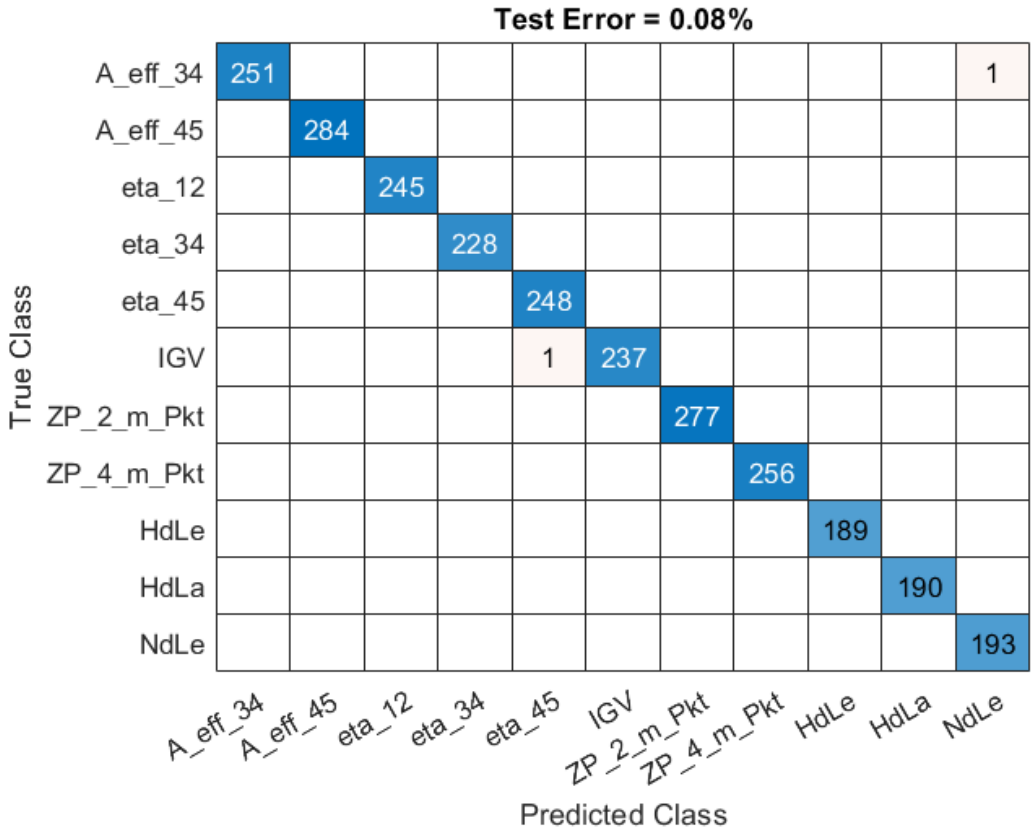
Neural Network Predicts Error Type

- Normal condition (no error) not used for training
- Error magnitude (normalized) varies from -1 to 1

Neural Net:

- Fully-connected network with two hidden layers
- Number of neurons: 21 / 50 / 25 / 8
- Datasplit: 90% / 5% / 5%

Engine Type: THM 1304-10N



Linear Regression Model Determines Error Magnitude

- Normal condition (no error) included in training data
- Normalized error magnitude varies from -1 to 1

Linear Regression Model:

- With Interaction Terms
- Data split: 95% / 5%

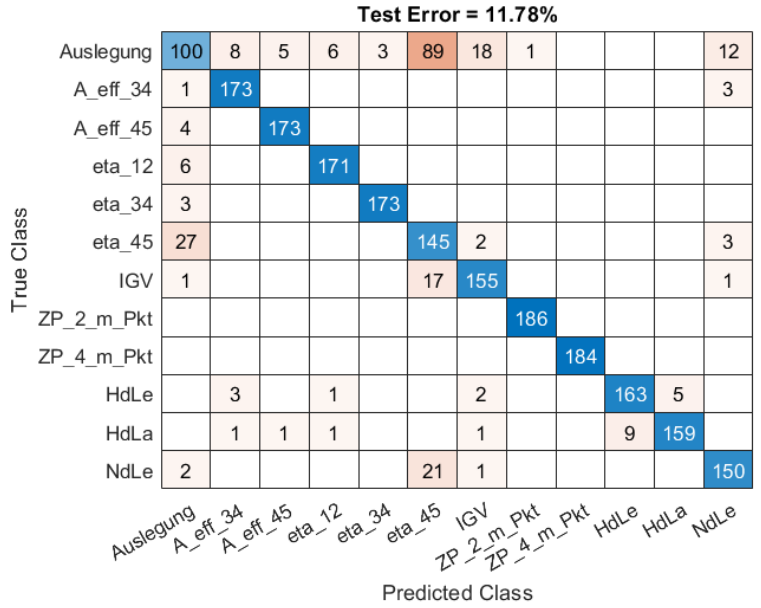
Engine Type: THM 1304-10N

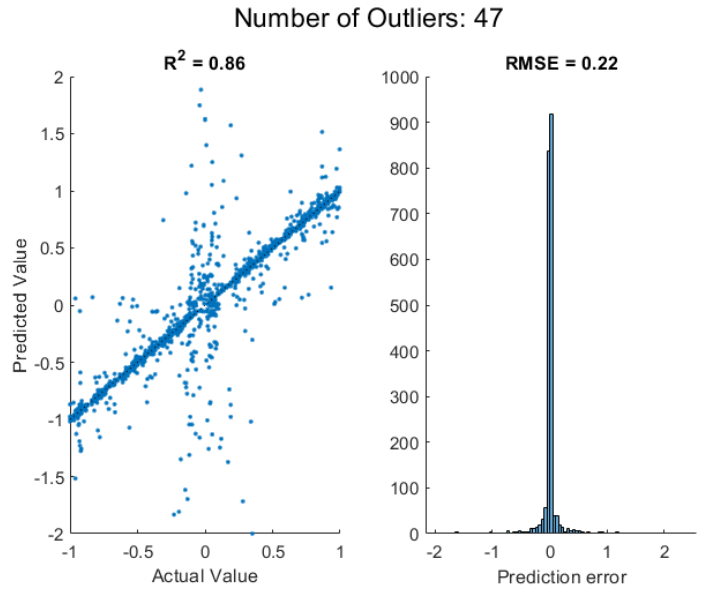
Error Type	RMSE	R^2
A_eff_34	0.11	0.97
A_eff_45	0.01	1.00
HdLa	0.00	1.00
HdLe	0.00	1.00
IGV	0.03	1.00
NdLe	0.03	1.00
ZP_2_m_Pkt	0.00	1.00
ZP_4_m_Pkt	0.00	1.00
eta_12	0.01	1.00
eta_34	0.01	1.00
eta_45	0.06	0.99

Three-Step Approach to Determine Error Type and Magnitude

1. Determine error type: 1 classification model
2. Determine error magnitude: 11 regression models
3. Subsequent identification of normal condition: normalized error magnitude < 0.1

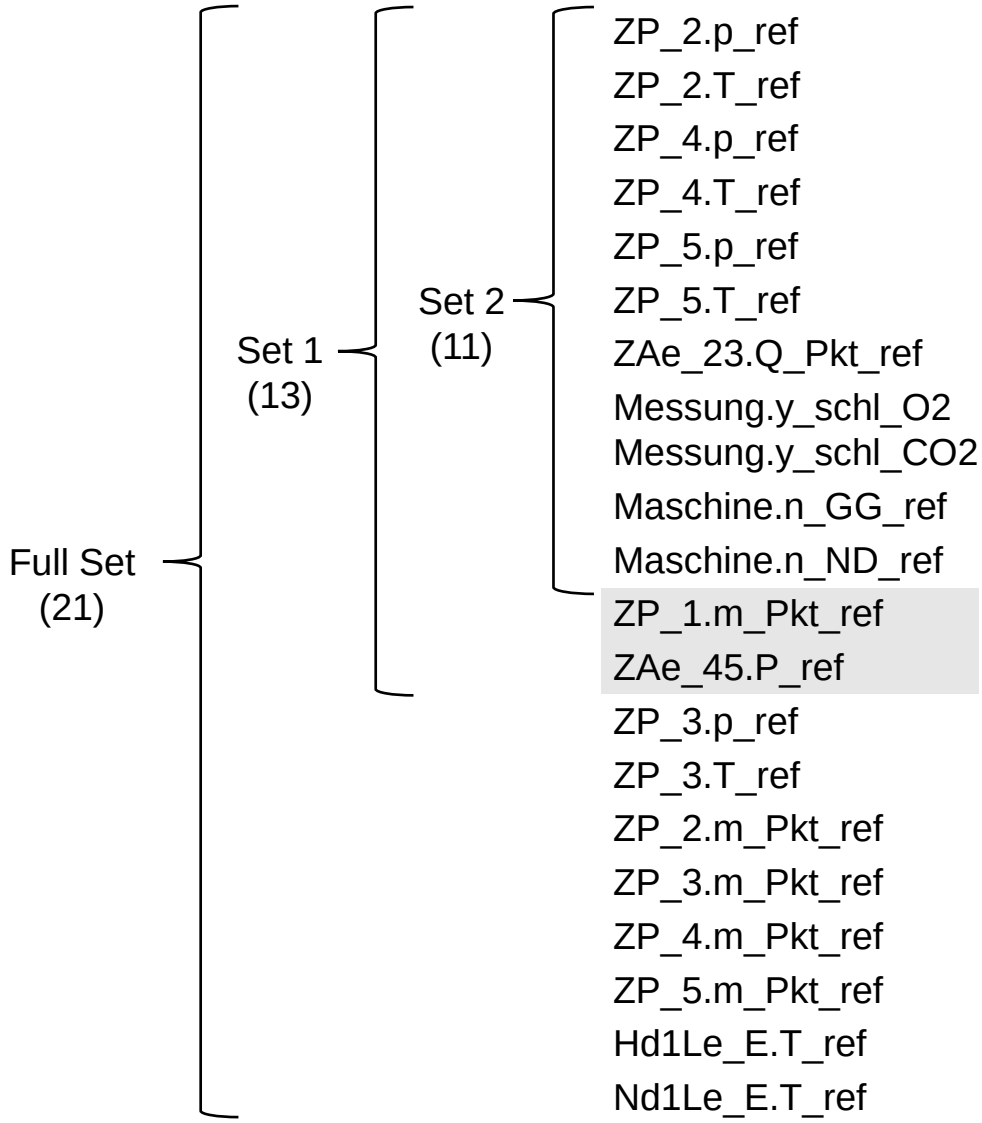
Engine Type: THM 1304-10N





What Effect Does the Number of Predictors have?

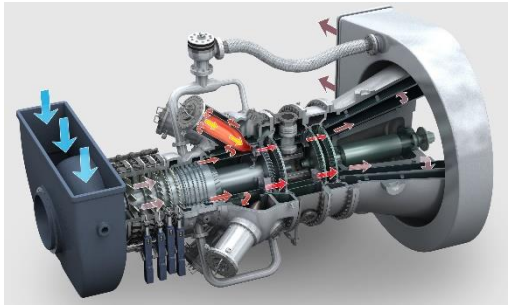
- Full set is only available on test bed
- Real-word data are much more limited
- How many and which predictors are necessary?



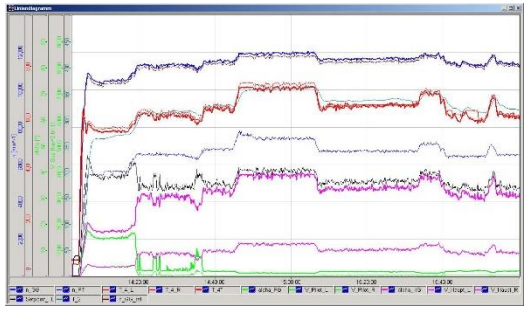
Error Detection is Possible with Reduced Data Set

	Engine Type: THM 1304-10N			
	Classification Test Error [%]	Regression RMSE	Regression R^2	Number of Outliers
Full Set (21)	11.78	0.22	0.86	47
Set 1 (13)	15.75	0.14	0.94	0
Set 2 (11)	21.60	0.24	0.83	32

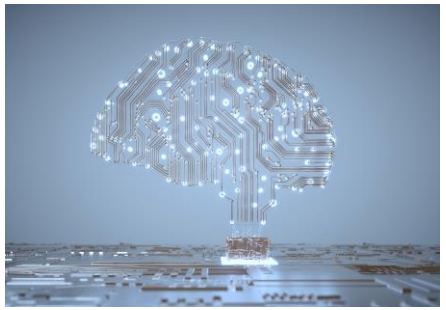
It is Possible to Determine the Condition of a Gas Turbine Using Machine Learning



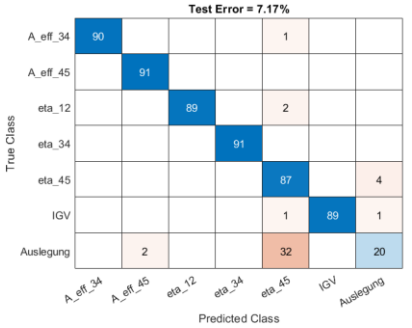
Gas Turbine



Measured Data



Machine Learning



Automatic Evaluation

Outlook

Short-term goals

- Testing the error detector on real measured data

  → Raw data of 18000 h with sample time of 20 ms

Long-term goals

- Real-time error detection at the engine’s location
- Sending reports to Oberhausen, Germany