Project **RUBY**

Robust and reliable general management tool for performance and durability improvement of fuel cell stationary units

ROBUST DIAGNOSIS OF PEMFC BASED ON ARTIFICIAL INTELLIGENCE AND EIS

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Context

Lifetime of fuel cells

- DOE Objectives
  - 2020 : 40 000h Stationary / 5000h Vehicle
  - Ultimate: 80 000h / 8000h

- Tools :
  - Diagnosis → Detection of degrading conditions
  - Prognosis → Prediction of future performance

↓

  - Control → Changes in operating conditions

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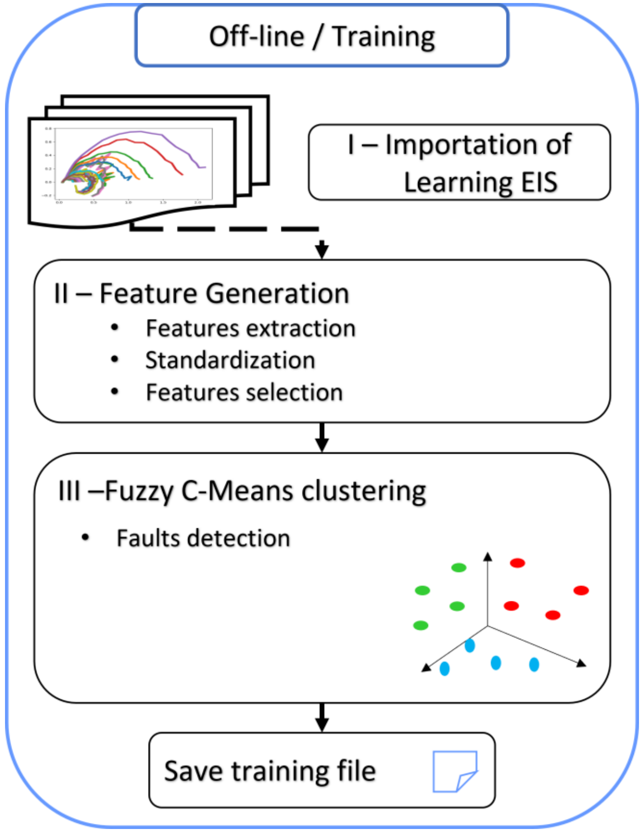
Diagnostic approach

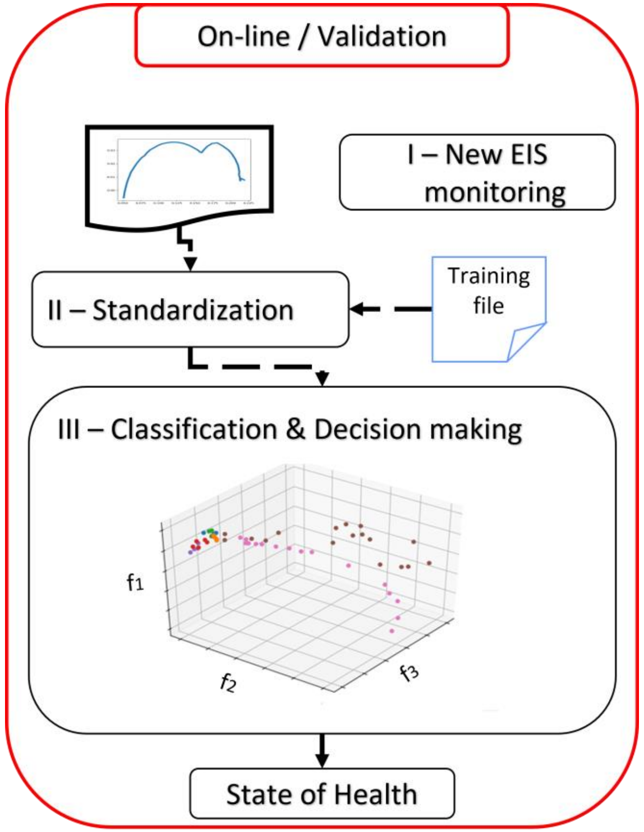
Why using diagnosis ?

- Determine the State of Health of a system
- Quickly detect any abnormal conditions
  - Operation to be done regularly
  - Plan maintenance operations

Operation :

- Model-based:
  - Equations and/or artificial intelligence
  - Relationship(s) between input(s) and output(s)
    - Calculation of residuals
- Non model-based:
  - Statistical analysis and artificial intelligence
  - Relationship(s) between known conditions and data





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Diagnostic approach

European "Health Code" project

Training of the algorithm

Database

The key point of Machine Learning algorithms

- Clean data are needed to have powerfull algorithms
- Complexity of obtaining noiseless data on an industrial scale

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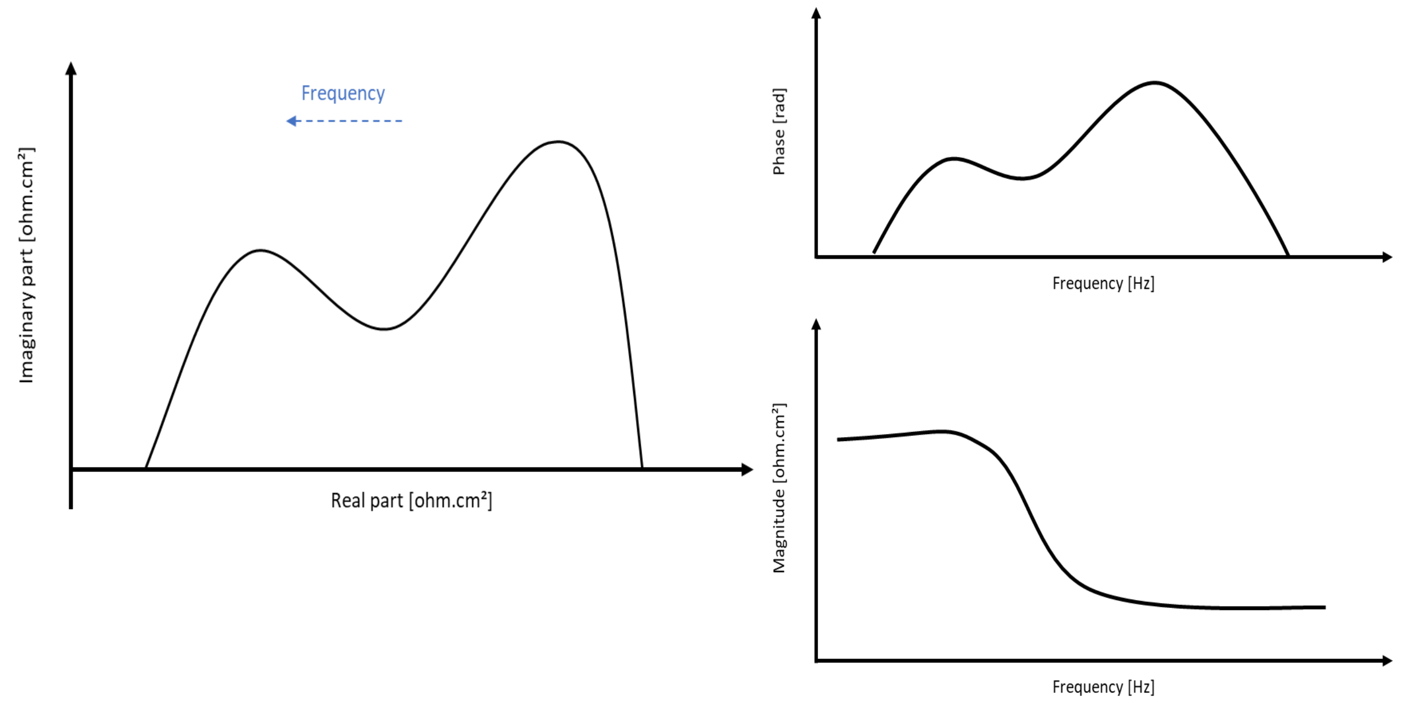
Diagnostic approach – Databases

Databases:

- Composed by electrochemical impedance spectra (EIS)
- Two PEMFC technologies tested by 2 different laboratories
  - 5 - 7 conditions tested
    - Nominal conditions
    - Water management (+/-)
    - Reagent management (-)
    - Poisoning (CO and Sulfur)
  - More than 80 EIS per technology

Typical EIS representation in Nyquist (left) & Bode (right) diagramns



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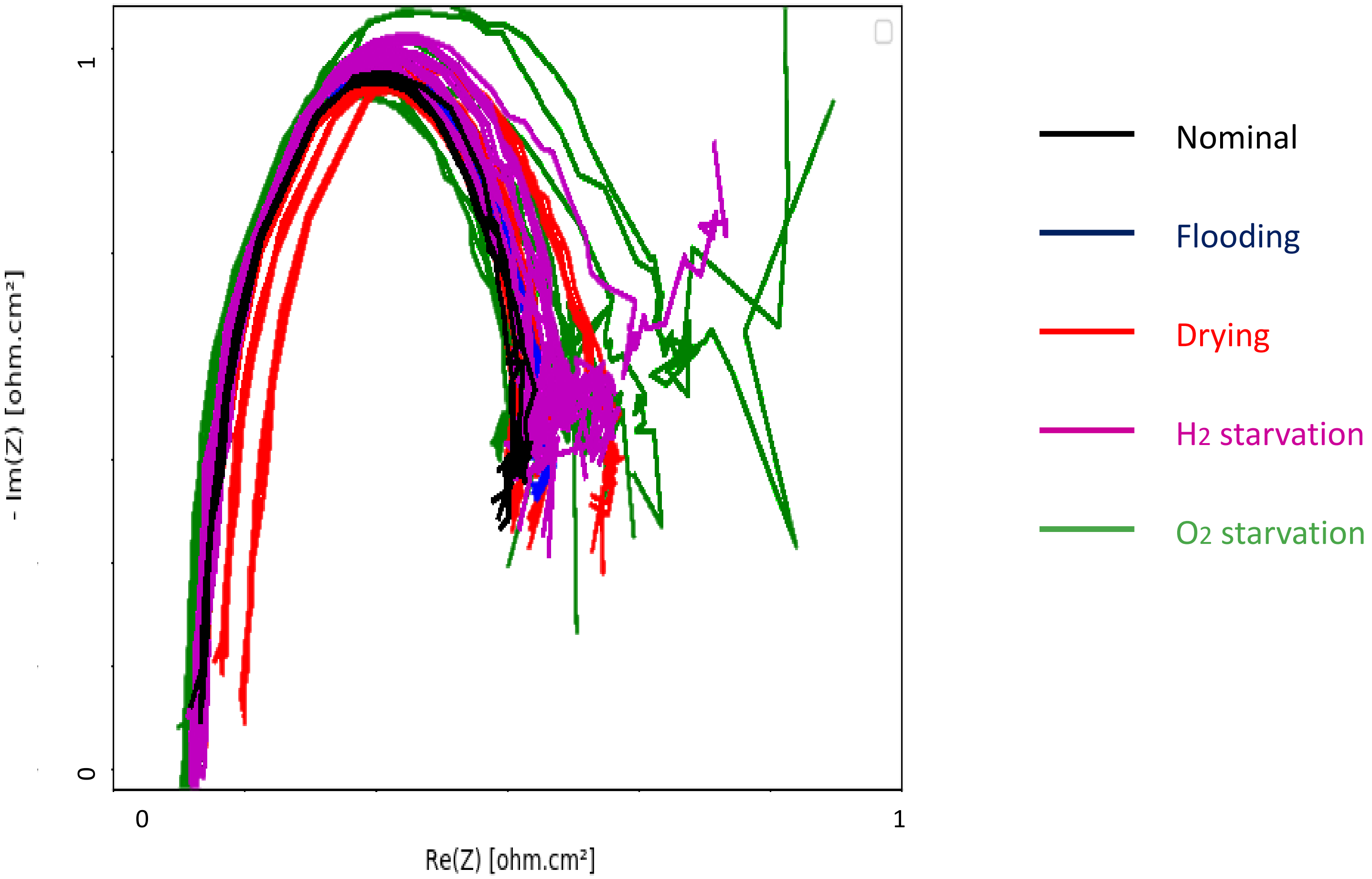
Diagnostic approach – Databases

EIS spectra obtained with an H_2 – O_2 stack



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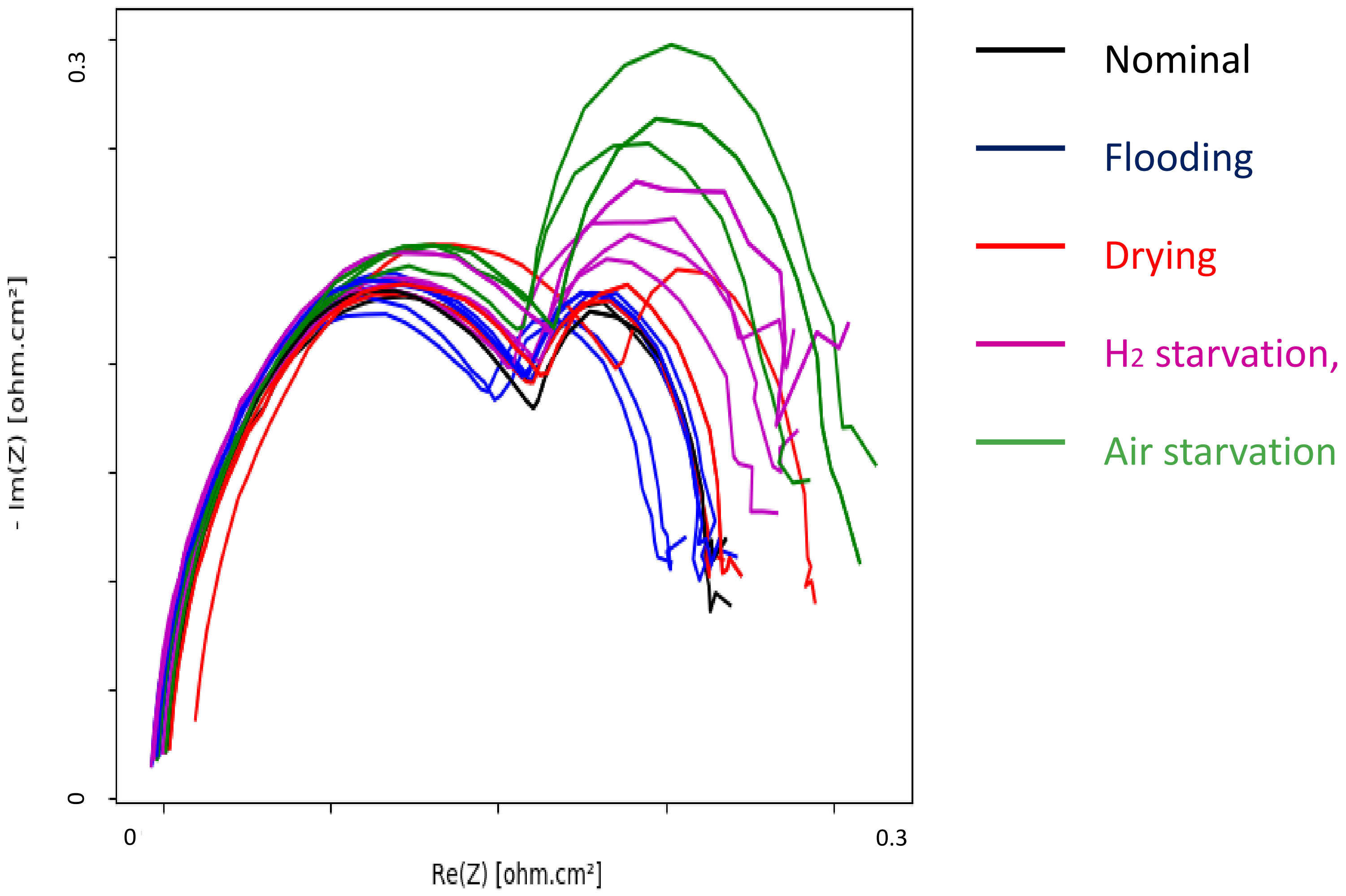
Diagnostic approach – Databases

EIS spectra obtained with an H_2 – Air



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Diagnostic approach – Databases

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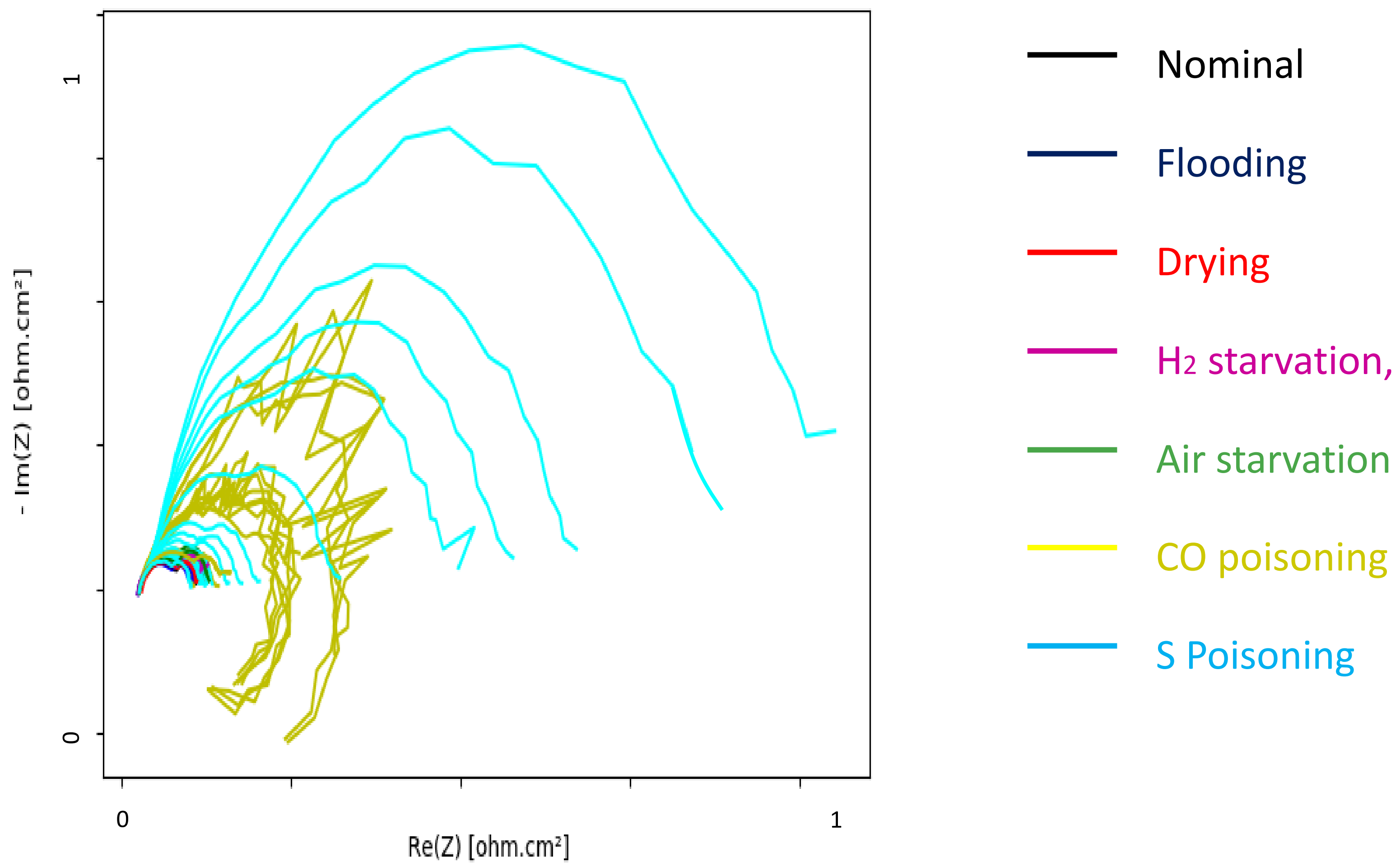

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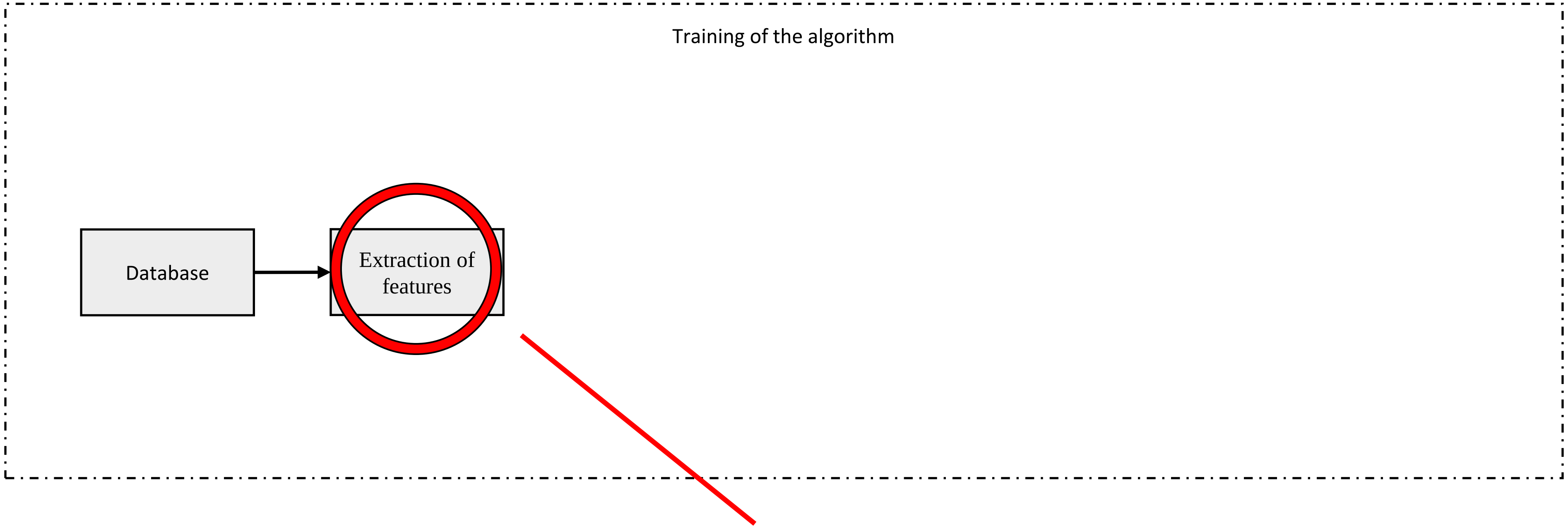
Diagnostic approach



Generate a Fault Detection & Identification (FDI) space to separate each fault

- **Extraction based on physics knowledge and/or statistical test**

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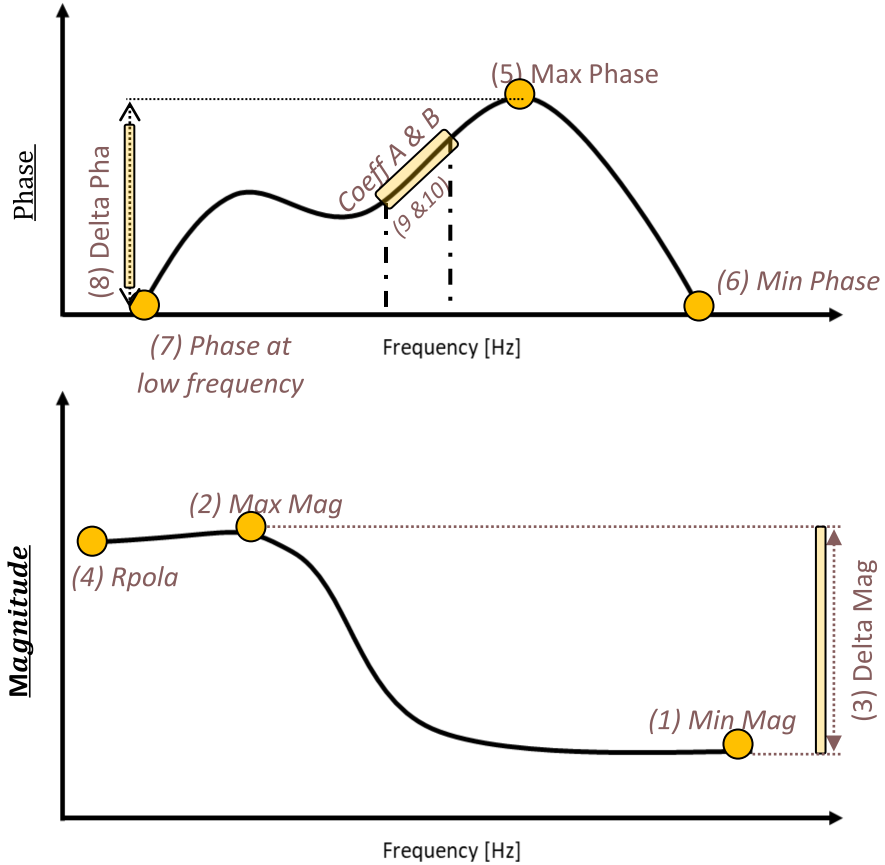
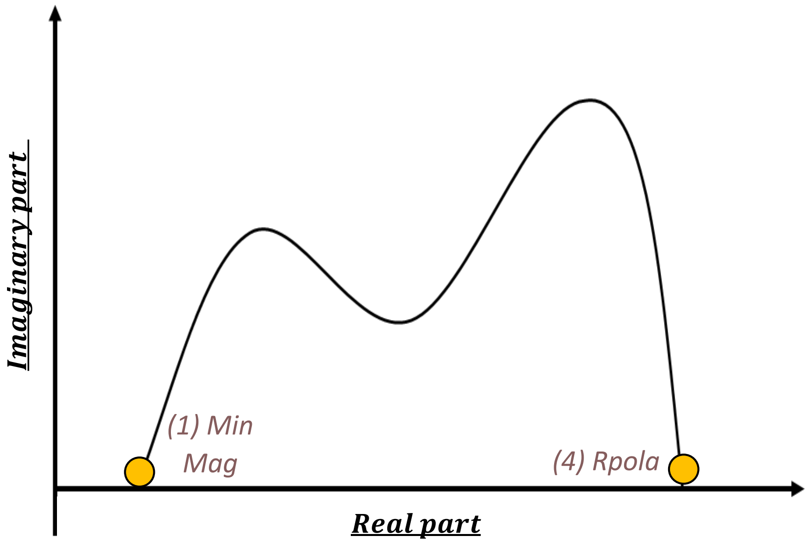
Diagnostic approach - Feature extraction

(1) Min Magnitude ; (2) Max Magnitude; (3) Delta Magnitude, (4) Polarization resistance; (5) Max Phase
(6) Min Phase; (7) Phase at low frequency (~0.1) ; (8) Delta Phase,
(9 &10) Phase analysis: Phase = A. freq + B [1, 10] Hz

Representation of features extracted on Nyquist (left) & Bode (right) diagramns





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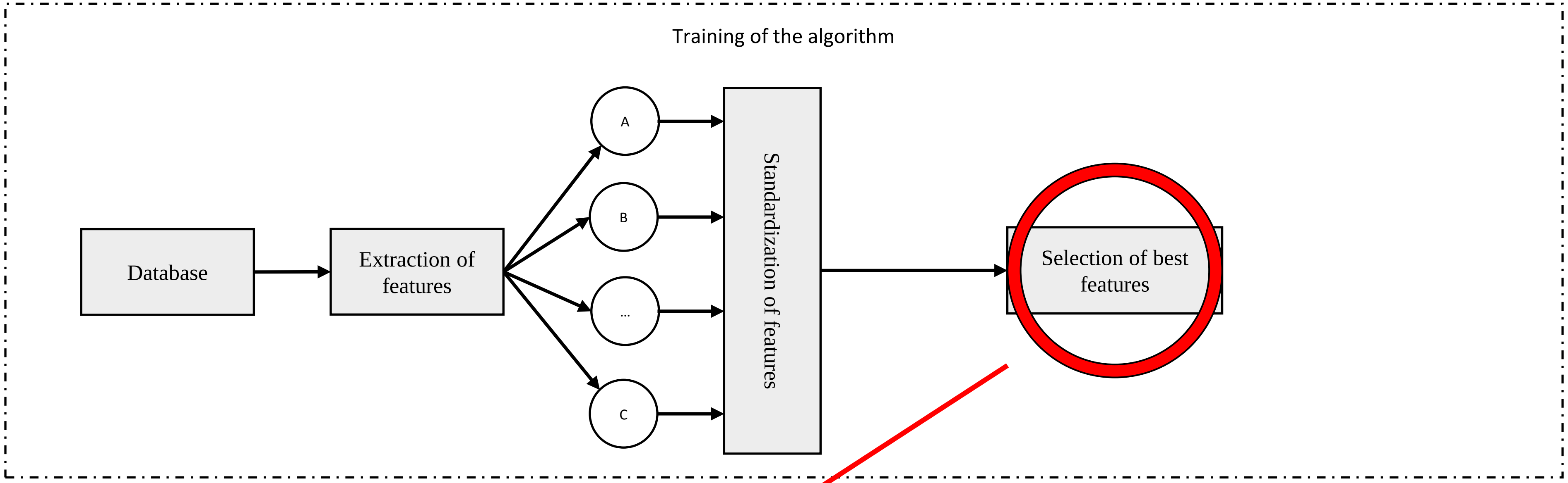
Diagnostic approach



Optimisation of the FDI space

- **Keeping only relevant information**
- **Too much: Overfitting → Redundant information, computation time ↗**
- **Not enough: Underfitting → Poor performances**

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Diagnostic approach - Feature selection

- *Filtering*
  - Objective :
    - To limit redundant information
    - To reduce the feature space
  - Process :
    - Measure of correlation between features (Pearson)
    - Variance to determine which one to delete

- *Ranking*
  - Objective :
    - To simplify the need for empirical testing
    - Basic process: testing all feature combinations
    - With ranking : adding features 1 by 1 until reaching the maximum accuracy.
  - Process :
    - Statistical test ANOVA F-Test
    - Measuring the relationship between the condition being tested and each feature

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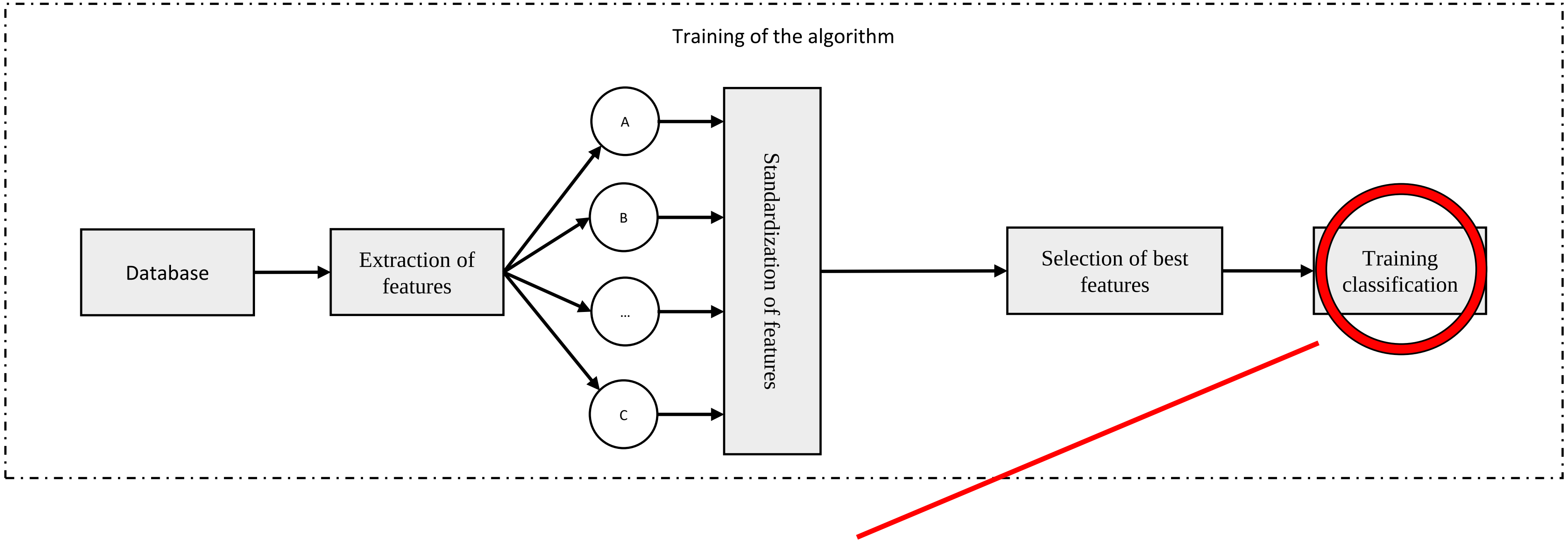
Diagnostic approach



Determining the condition associated with a known data to evaluate the performance

- Need for a low computational time algorithm
- To reduce user expertise for ease of use → How much is the prediction correct ?
- To be able to adapt during operation

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Diagnostic approach - Classification

Classification

- Use of fuzzy c-means clustering
  - **Reduce the user expertise and add incertitude in the prediction of data**
  - Non supervised algorithm
    - The class of each individual is unknown
    - Separates a database into X desired clusters
    - Determines the coordinates of the centers of each cluster
- Adaptation
  - Creation of groups for each condition tested
    - Level of faults
  - To know the condition associated with each center (but not the level)
  - To optimize positioning
  - To facilitate the classification of new points
- The case of CO poisoning
  - High intensity positive imaginary part

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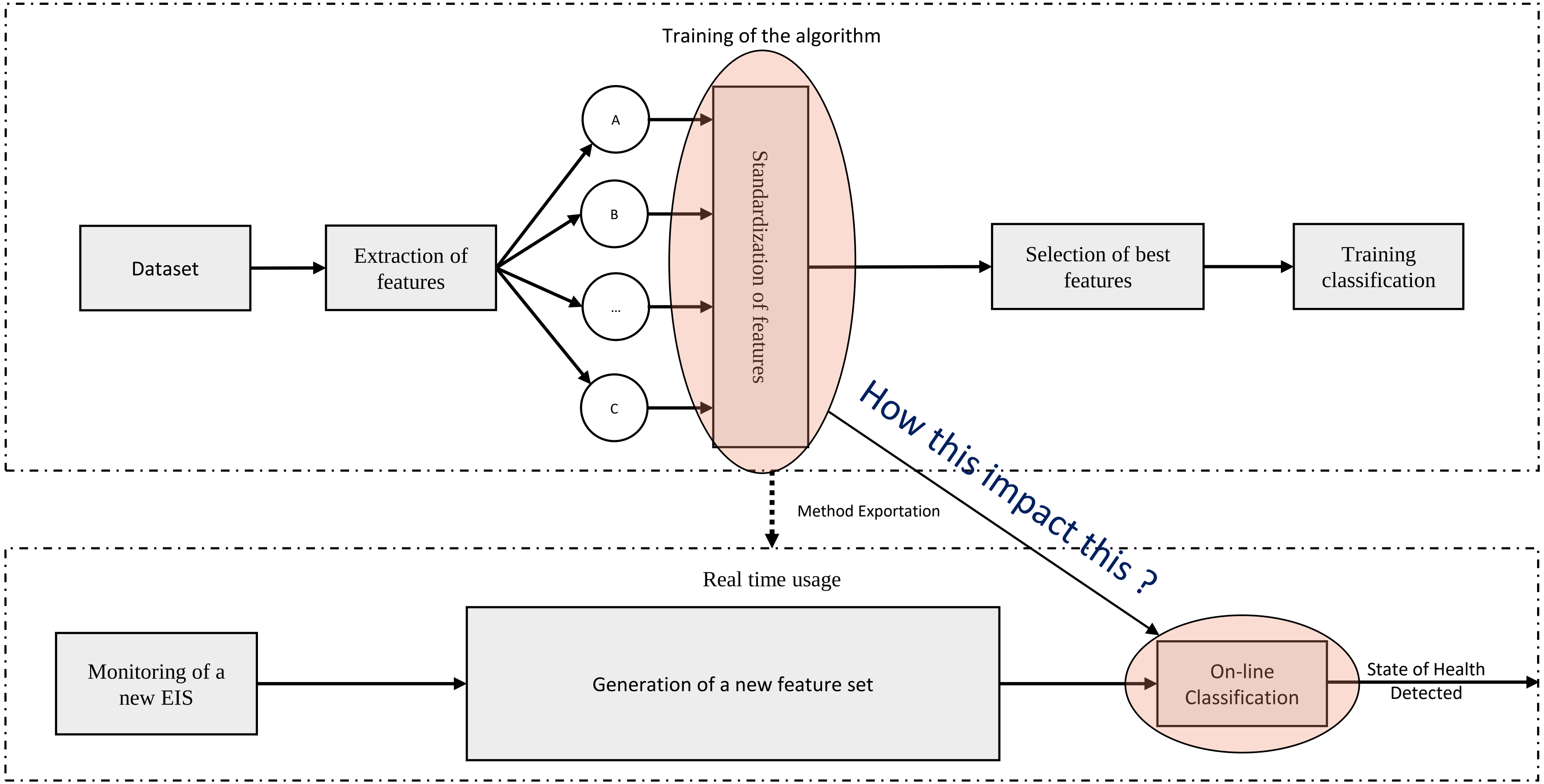
Diagnostic approach



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Principle of standardization

Main interest of standardization:

Scaling the data	Reduce computational time
Reduce the importance of outliers	Improve performances

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Overview of methods

	Type of transformation	Standardized data	Sensitive to outliers	Operation	Usefulness	Comments
Normalizers	Normalizer	Samples	Yes	Divide the samples by their norm (L1, L2, inf).	Quantifies similarities between samples	-
Min-Max	Linear	Features	Yes	Features are scaled in the range [0, 1] using Min-Max values	Same scale for all features [0, 1]	-
Max-Abs	Linear	Features	Yes	Divides the data by the maximum absolute value	Same scale for all features [0 or -1, 1]	-
Standard	Linear	Features	Yes	Center the features using the mean and standard deviation	Features centered around the mean	Mean = 0, Standard deviation = 1
Robust	Linear	Features	No	Same principle as Standard but uses the median and interquartile range	Outliers not taken into account to center the features	-
Box-Cox	Non-linear	Features	No	Transforms the data to follow a Gaussian distribution	Low outlier weight	Strictly positive data
Yeo - Johnson	Non-linear	Features	No	Transforms the data to follow a Gaussian distribution	Low outlier weight	-
Quantile uniforme & normal	Non-linear	Features	No	The features follow a uniform or normal distribution	Same scale for all features + Low outlier weight	-

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Classification metrics

- Confusion matrix:

	Real condition	
Detected condition	*True*	*False*
True	*Tp*	*Fp*
False	*Fn*	*Tn*

- Accuracy score :
  - $\text{Accuracy} = \frac{\text{Tp} + \text{Tn}}{\text{Tp} + \text{Tn} + \text{Fp} + \text{Fn}}$
- Recall score :
  - $\text{Recall} = \frac{\text{Tp}}{\text{Tp} + \text{Fn}}$
- Precision score :
  - $\text{Precision} = \frac{\text{Tp}}{\text{Tp} + \text{Fp}}$
- F1 score
  - $\text{F1} = \frac{2 \times \text{Recall} \times \text{Precision}}{\text{Recall} + \text{Precision}}$

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Results obtained

Database 1 : H_2/O_2

Tested conditions: nominal (1), flooding (1), drying (3), H_2 starvation (3), O_2 starvation (3)

Cross-validation : Leave One Out

		Normalizer			Linear scaler				Non Linear transformer		
	Raw data	*Normalizer L2*	*Normalizer L1*	*Normalizer inf*	*Min-Max scaler*	*Max Absolute scaler*	*Standard scaler*	*Robust scaler*	*Yeo-Johnson*	*Normal Quantile*	*Uniform Quantile*
Accuracy	0.852	0.784	0.784	0.750	0.943	0.852	0.920	0.977	0.966	0.943	0.955
F1 score	0.852	0.781	0.780	0.745	0.943	0.853	0.920	0.977	0.966	0.943	0.954
Recall score	0.852	0.784	0.784	0.750	0.943	0.852	0.920	0.977	0.966	0.943	0.955
Precision score	0.859	0.797	0.797	0.759	0.947	0.856	0.922	0.979	0.966	0.948	0.961
Number of features	4	8	7	7	5	5	5	6	6	6	5

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Results obtained

Database 2 : H_2/Air

Tested conditions : nominal (1), flooding (2), drying (2), H_2 starvation (2), Air starvation (2), carbon monoxide poisoning (3), sulphur poisoning (4)

Cross-validation : Leave One Out

		Normalizer			Linear scaler				Non Linear transformer		
	Raw data	*Normalizer L2*	*Normalizer L1*	*Normalizer inf*	*Min-Max scaler*	*Max Absolute scaler*	*Standard scaler*	*Robust scaler*	*Yeo-Johnson*	*Normal Quantile*	*Uniform Quantile*
Accuracy	0.776	0.829	0.882	0.868	0.882	0.855	0.750	0.842	0.908	0.882	0.961
F1 score	0.774	0.832	0.883	0.864	0.879	0.851	0.753	0.842	0.908	0.883	0.961
Recall score	0.776	0.829	0.882	0.868	0.882	0.855	0.750	0.842	0.908	0.882	0.961
Precision score	0.816	0.855	0.886	0.866	0.891	0.861	0.763	0.866	0.909	0.891	0.961
Number of features	5	4	7	5	4	4	4	4	6	6	6

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Analysis of the results

Impact of standardization

- Beneficial for any type of database
  - + 10 to 15%
- Normalizer not effective for EIS
- Linear method sufficient when data are similar
- Non-linear method works well in all types of configurations
- Uniform quantile transformation offers the best performance
  - Significance of strongly reduced outliers
  - Data at the same scale
  - (-) impact on the relationships between features
  - (+) easy comparison between features

	Score F1	
	H_2 / O_2	H_2 / Air
Raw data	*0.852*	*0.774*
Normalizer L2	*0.781*	*0.832*
Normalizer L1	*0.780*	*0.883*
Normalizer inf	*0.745*	*0.864*
Min-max	*0.943*	*0.879*
Max absolute	*0.853*	*0.851*
Standard	*0.920*	*0.753*
Robust	*0.977*	*0.842*
Yeo-Johnson	*0.966*	*0.908*
Quantile normal	*0.943*	*0.883*
Quantile uniform	*0.954*	*0.961*

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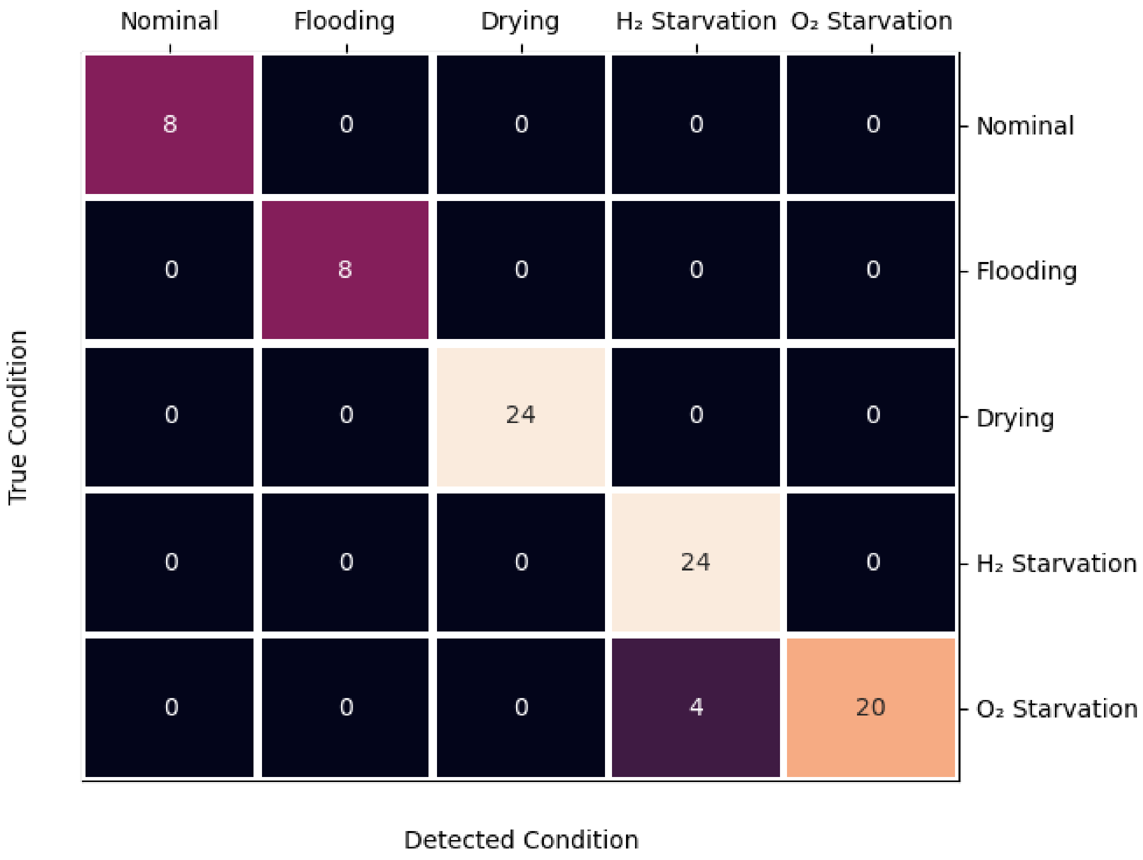
Confusion matrixes



H2 / O2 Database

Confusion between air and oxygen shortages

- Similar faults

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Confusion matrixes

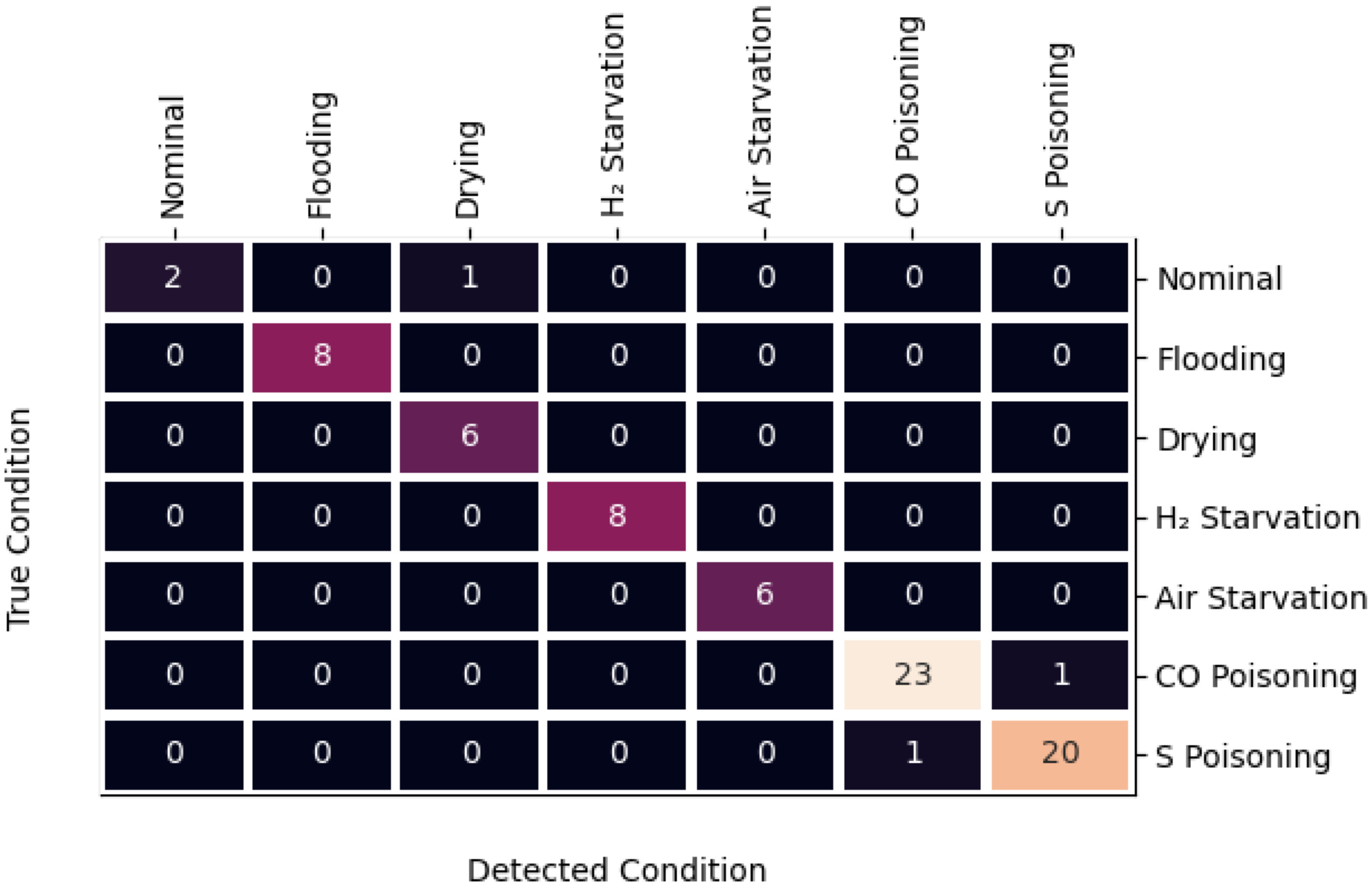
H_2 / Air Database

Confusion between the two poisonings

- Incipient and similar defects

Confusion between nominal / drying

- Incipient faults
- Lack of data



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Conclusion

Synopsis:

- Main families of standardization
- Non-model-based diagnostic approach
- The impact of standardization on two different databases

Standardization has a strong influence on the results

- Increasing or reducing distortions
- Basic linear methods are limited
- Use of non-linear methods → Increasing the robustness

Future prospects:

- Automatic detection of the number of clusters
- Increasing in the non-supervised portion

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Thank you for your attention

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