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Non-parametric trend analysis of condition monitoring indicators

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Adrien Marsick, Hugo Andre, Ilyes Khelf, Quentin Leclere, Jérôme Antoni. Non-parametric trend analysis of condition monitoring indicators. Wind Energy Science Conference 2023, May 2023, Glasgow- University of Strathclyde, United Kingdom. <hal-04533312>

HAL Id: hal-04533312

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Submitted on 4 Apr 2024

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WESC
25th May 2023



Adrien MARSICK

Non-parametric trend analysis of condition monitoring indicators

A. Marsick^{1,2}, H. Andre³, I. Khelf², Q. Leclere¹, J. Antoni¹



Context on condition-based maintenance

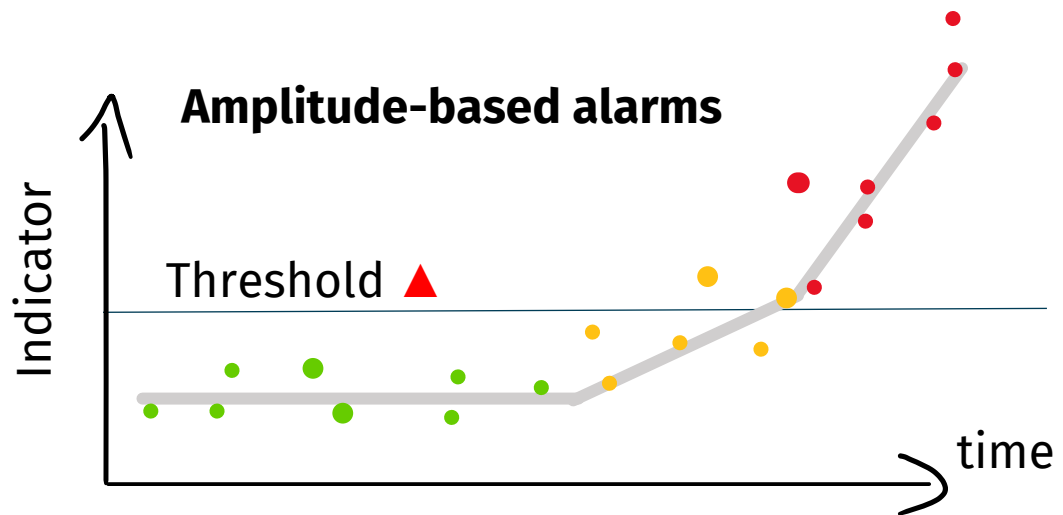


Monitoring workflow

Physical signals

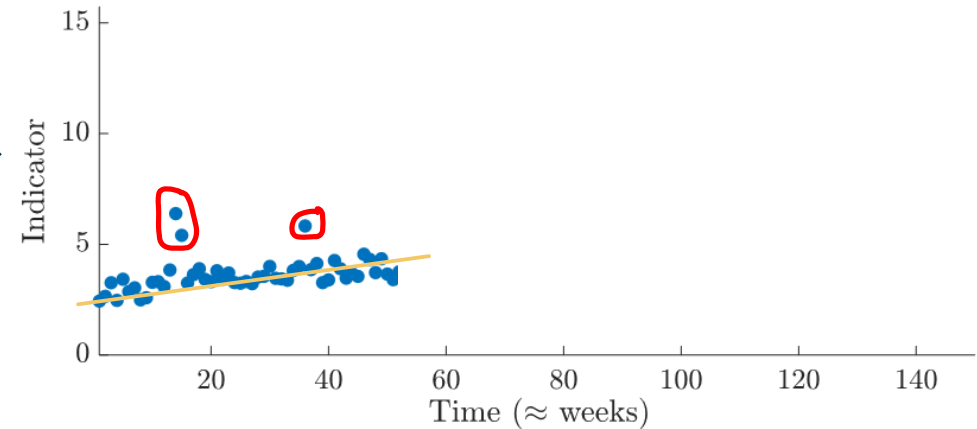
Health indicators

Alarms



- Compromise between early replacement and catastrophic failure
- Fleet scale surveillance
- Usual monitoring
 - Statistical threshold
 - Learnt from “healthy” state

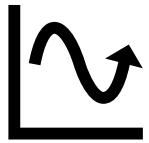
Challenges



- Small increasing trends & Outliers
- Multiple episodes (Degradation process)

Need of trend analysis and segmentation

Qualitative analysis of trend



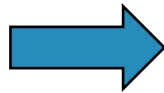
Benefits of studying trend

Fault gravity information

Indicator fusion

Input for machine learning

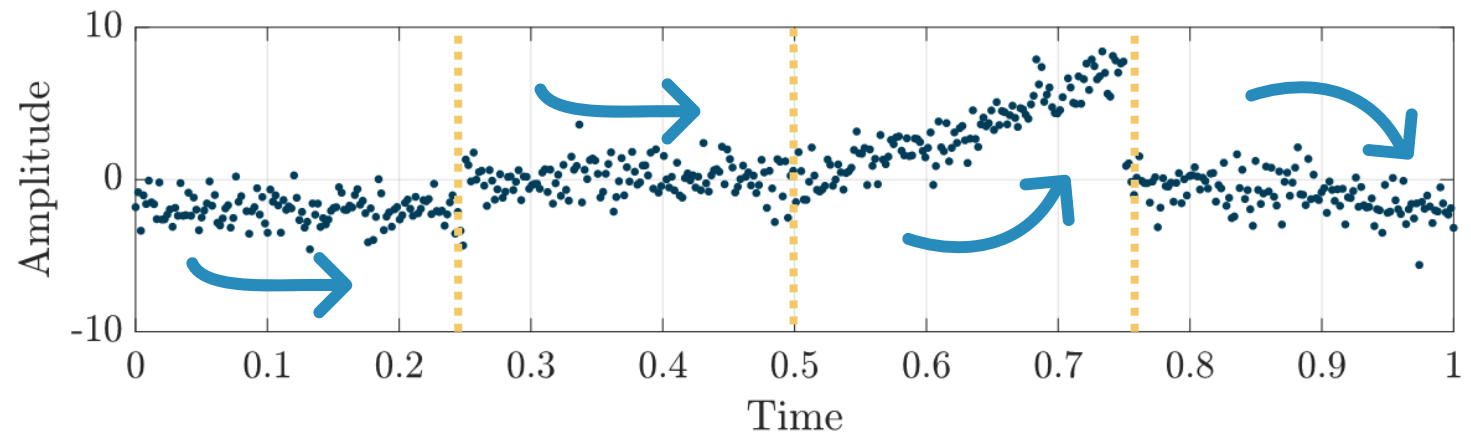
What is a trend ?



A trend is a consecutive **sequence of episodes** in which the beginning and end time instants are uniquely determined to manifest a time of **qualitative state change**

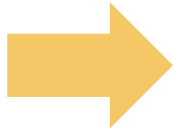
Tasks

1. Segment episodes
2. Characterise

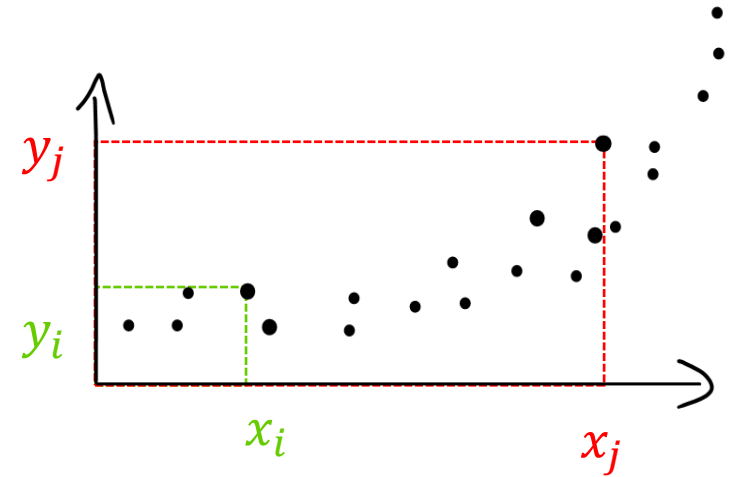


Rank-based statistics

How to detect a trend without assumption on the distribution of the data?



Test the tidiness of the data!



Pair test If $x_i < x_j$, does

$y_j > y_i$?

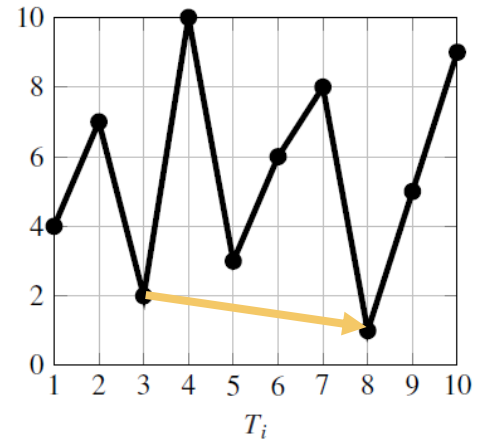
Concordant pair

$y_j < y_i$?

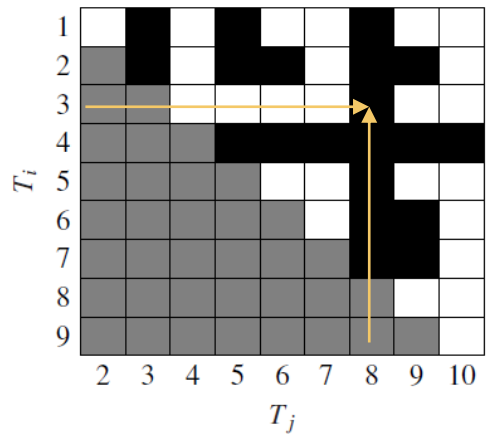
Discordant pair



Pair to pair comparison



Rank Matrix



A view on two rank tests

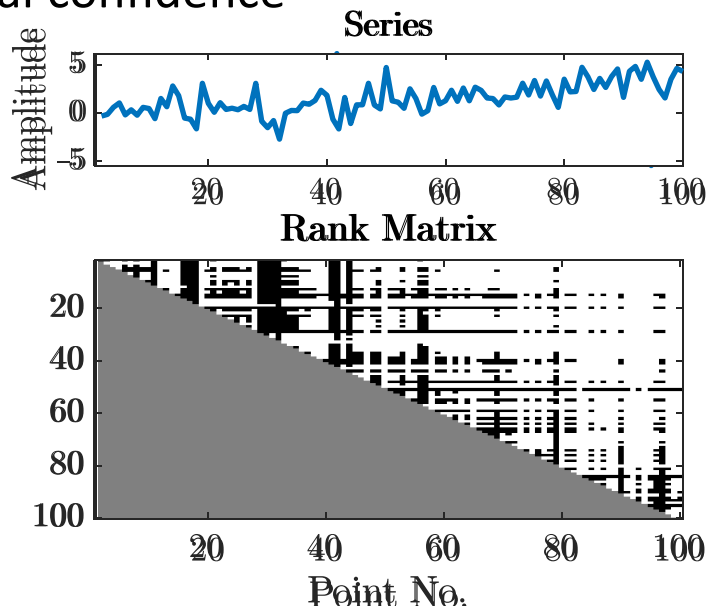
Stationarity: Mann-Kendall test

- Sum of the rank matrix
- Stationarity given by concordance / discordance of pairs
- Statistical confidence

Concordant



Discordant

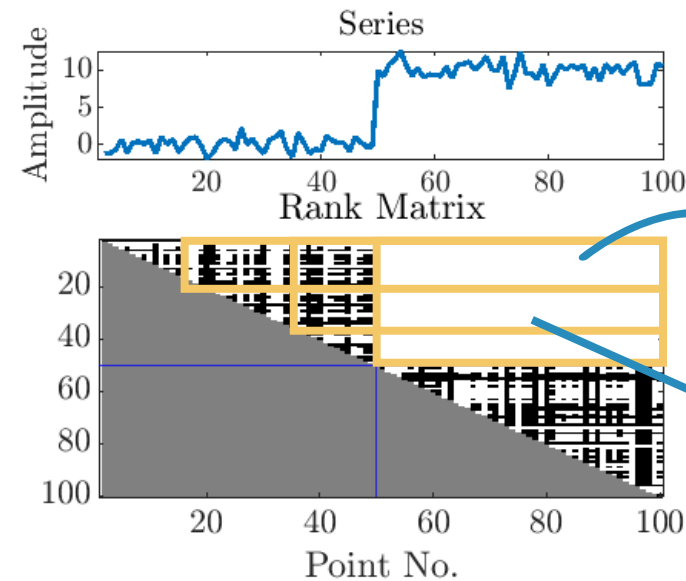


Equal pairs on average

Non parametric, independent of amplitude, robust to outliers

Change-point: Pettitt test

- Blocks of concordance
- Gives the most probable change-point
- Statistical confidence

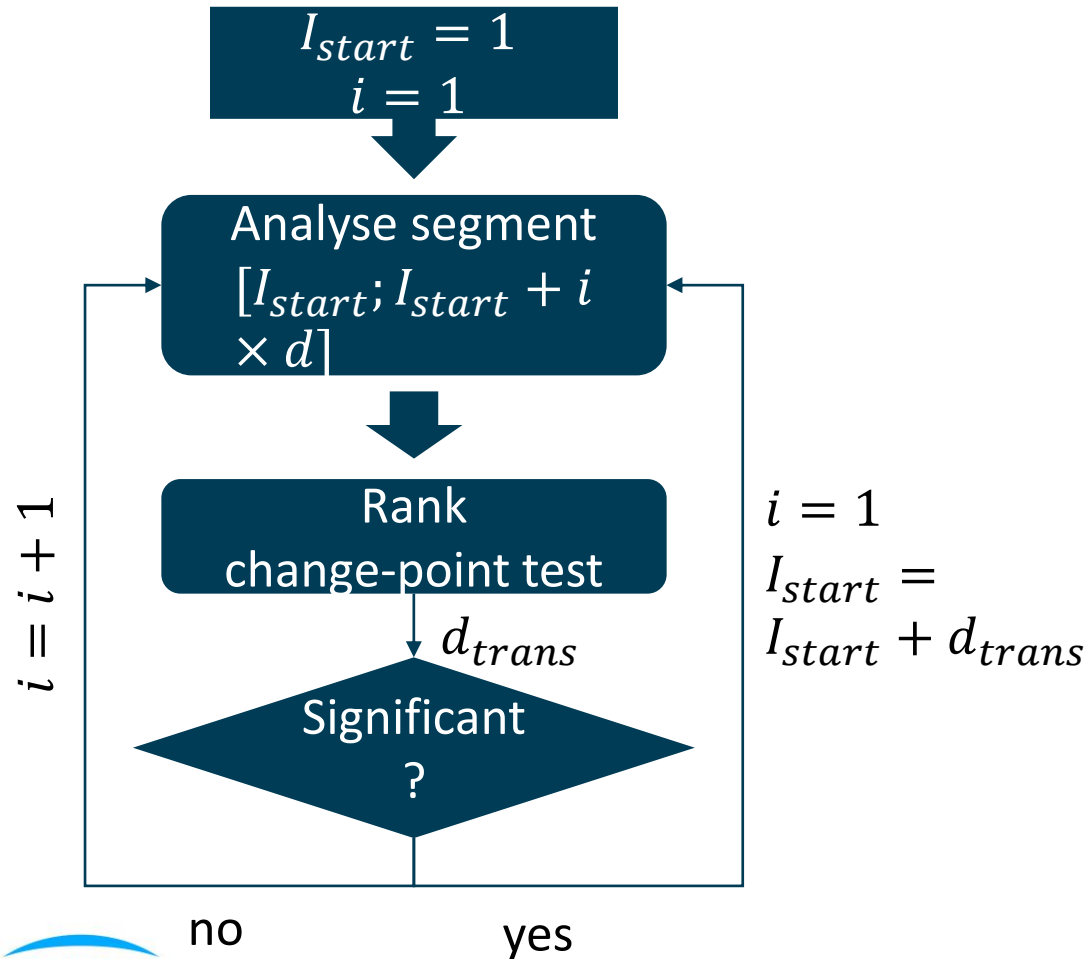


Sum of rectangle

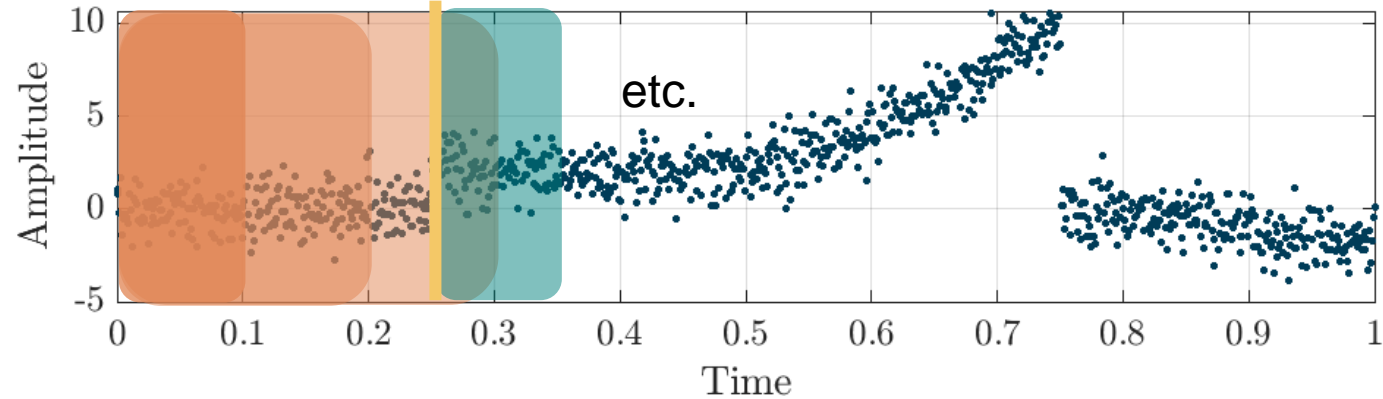
Maximum at transition

Segmentation algorithm

Sliding window with Pettitt change point test



- Output: list of transition dates
- Labelling of segments & transition

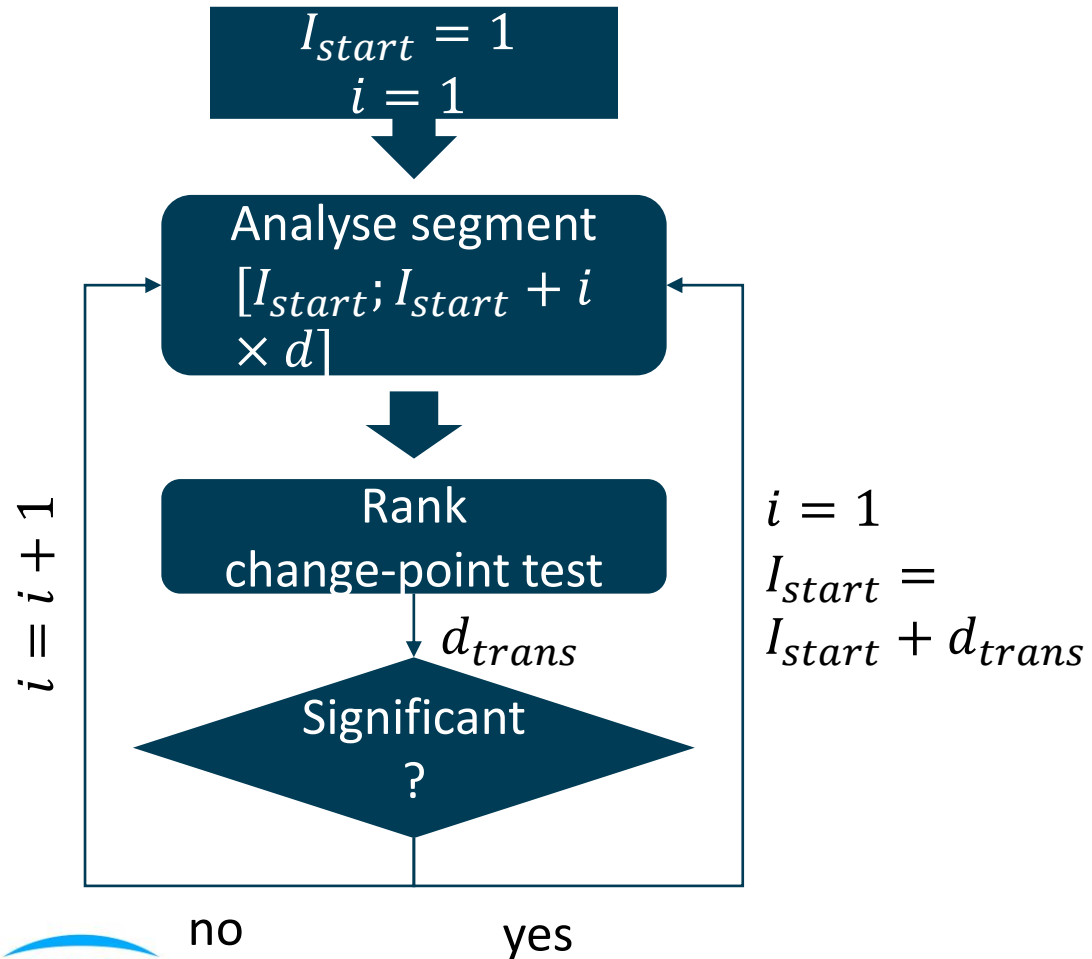


Algorithm

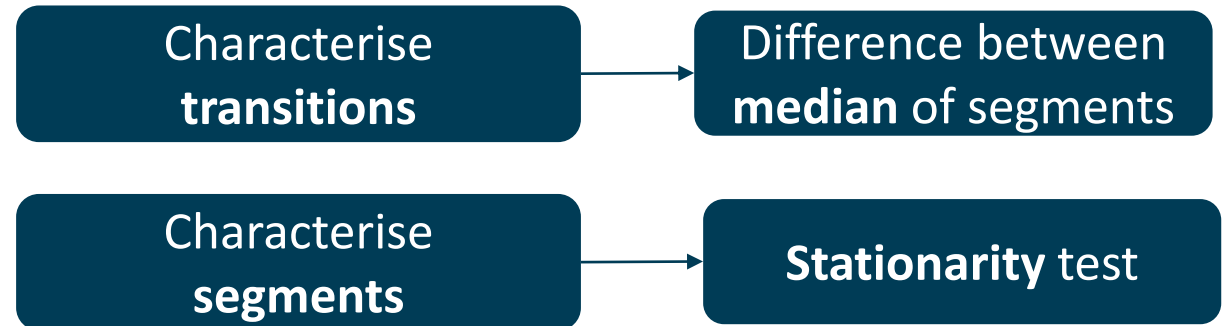
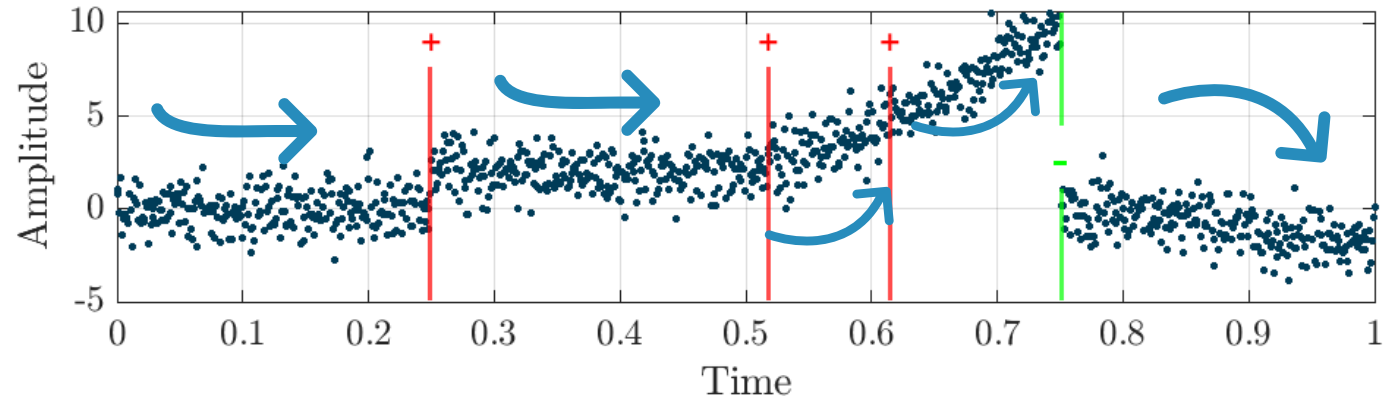
Segment $\rightarrow [0; 0.1]$ $i = 1$ $d = 0.1$ Change point \rightarrow NO	Segment $\rightarrow [0; 0.2]$ $i = 2$ $d = 0.1$ Change point \rightarrow NO	Segment $\rightarrow [0; 0.3]$ $i = 3$ $d = 0.1$ Change point \rightarrow YES $I_{start} = 0.25$
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Segmentation algorithm

Sliding window with Pettitt change point test



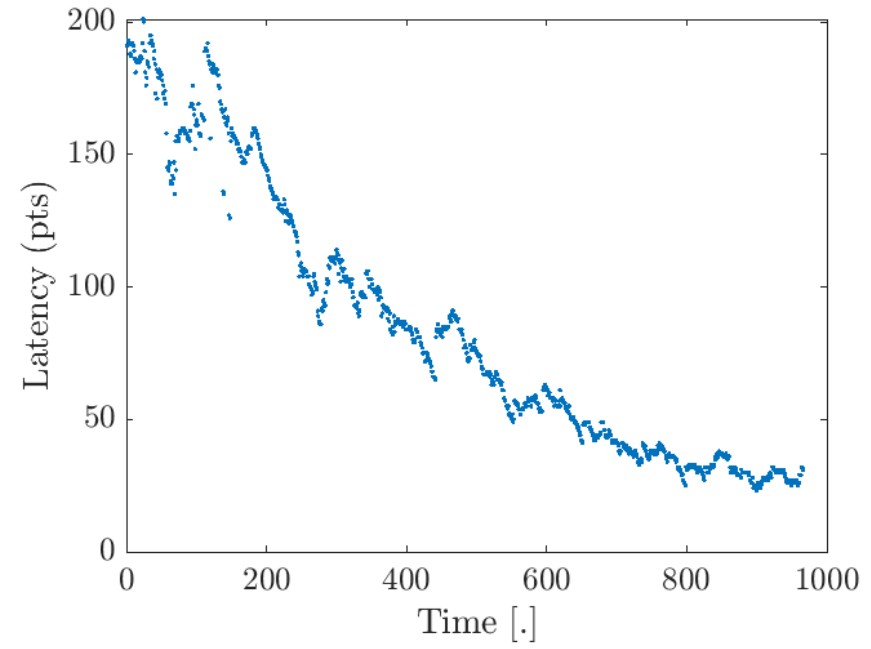
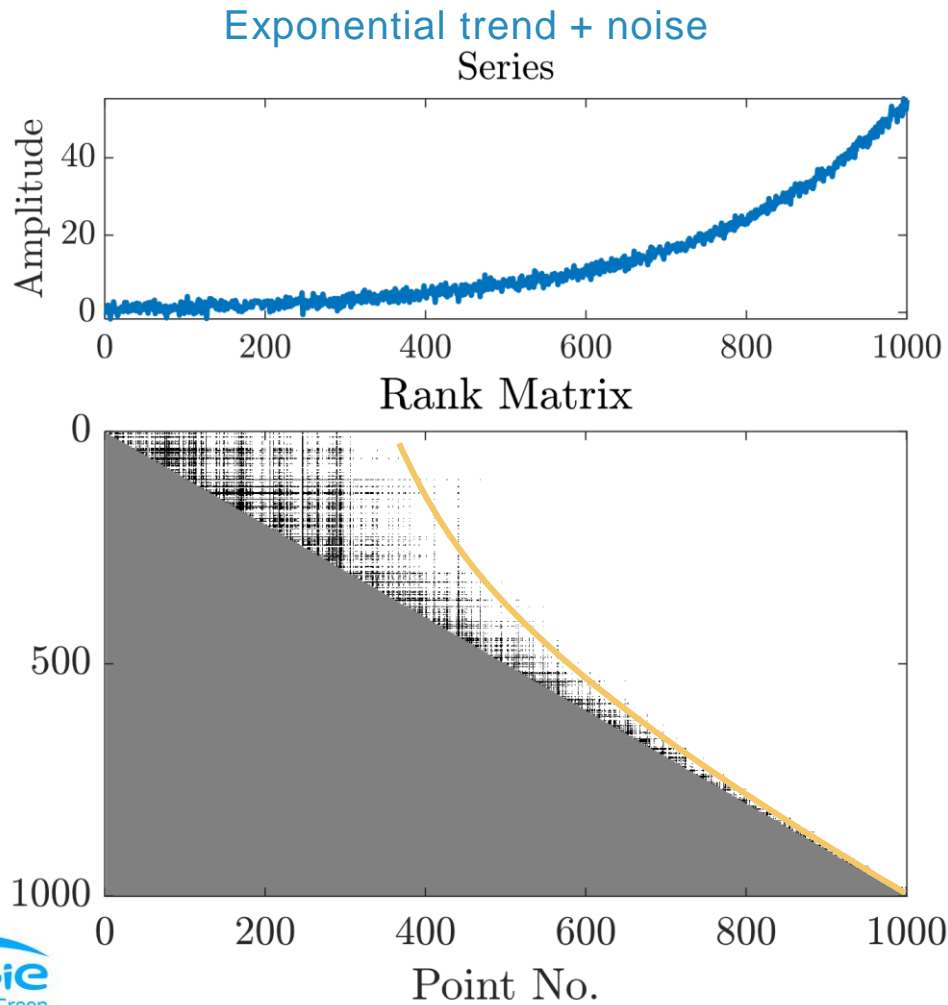
- Output: list of transition dates
- Labelling of segments & transition



A rank-based evaluation of the slope

Non-parametric dynamic → Slope to Noise Ratio

- For an increasing trend, more points are needed for small hidden trends
- Latency = number of points needed to reject the stationarity hypothesis



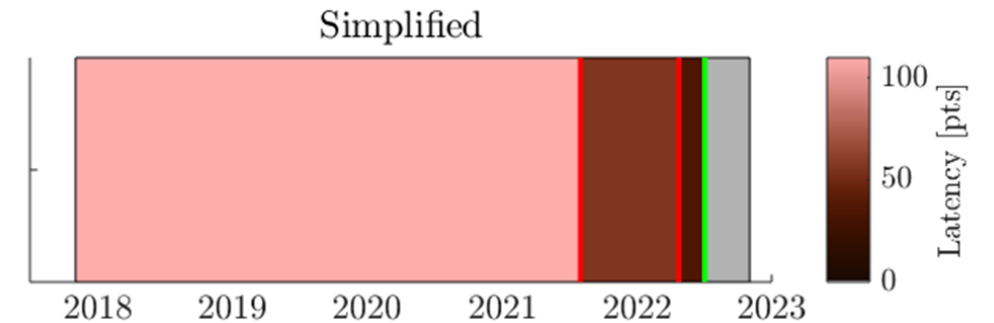
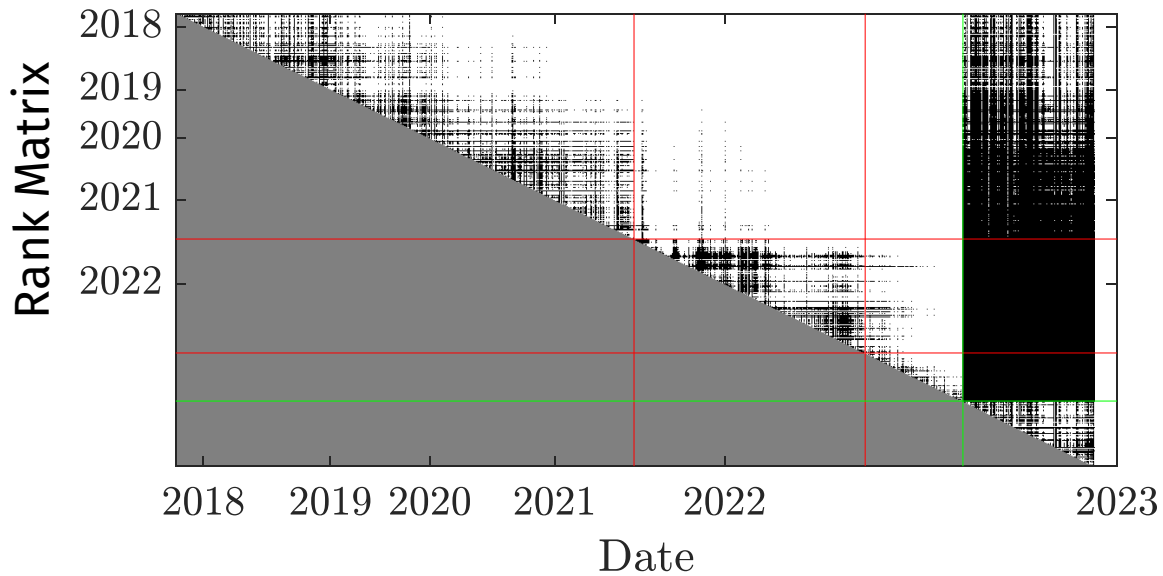
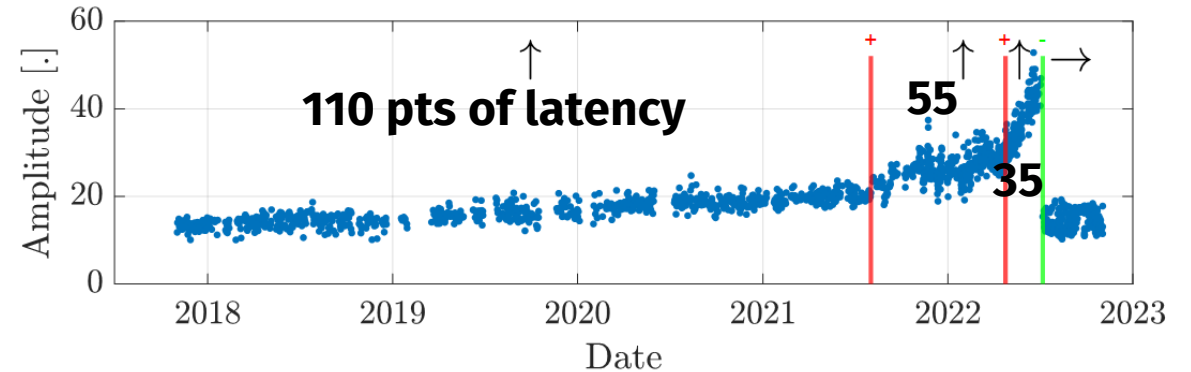
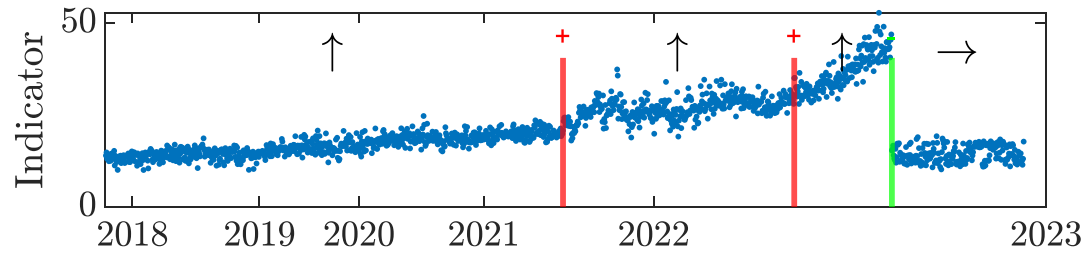
Non-parametric measure of Slope to Noise Ratio

Example vibration-based indicator



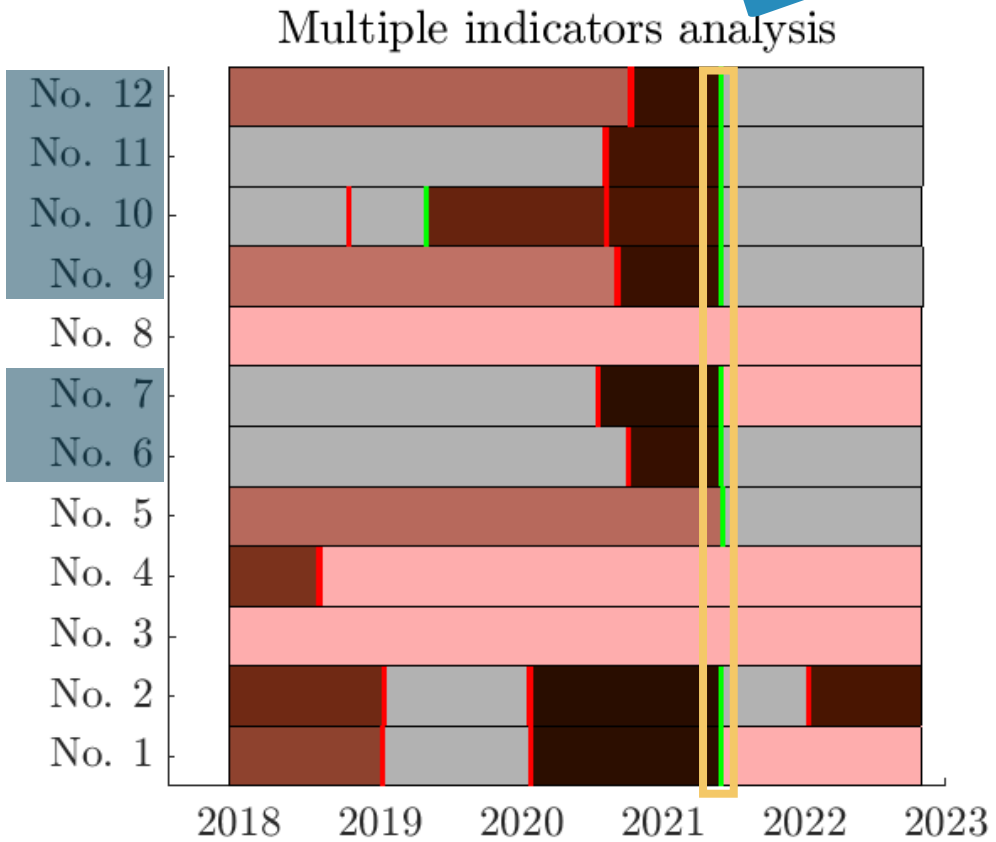
Damaged bearing

Condition indicator



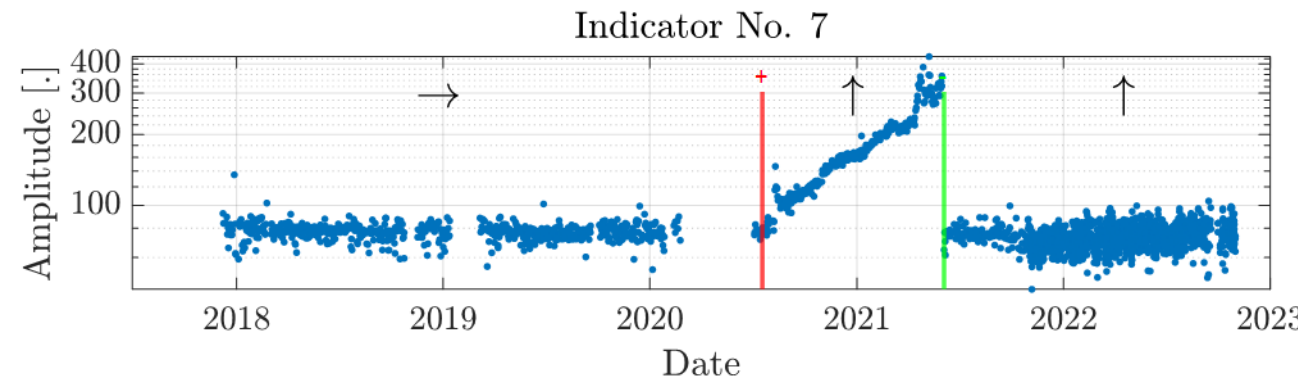
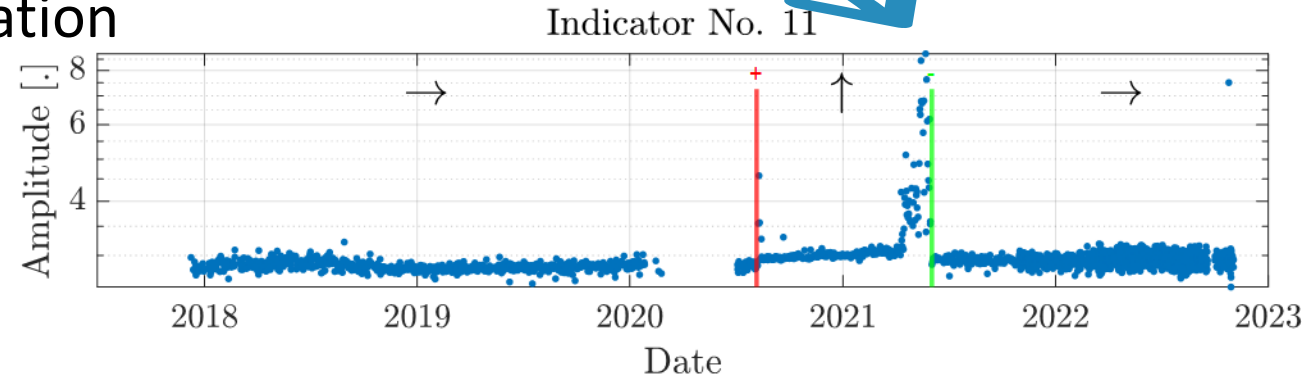
- Robust segmentation
- Qualitative characterisation of episodes
- Information on latency

Multi-indicators monitoring



| Decreasing median
| Increasing median

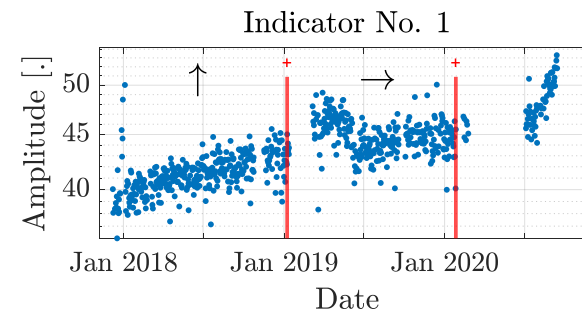
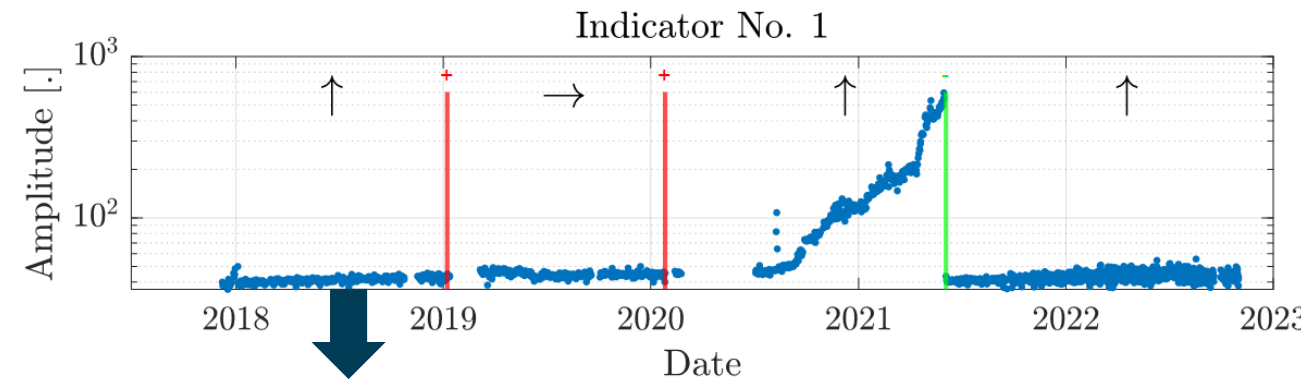
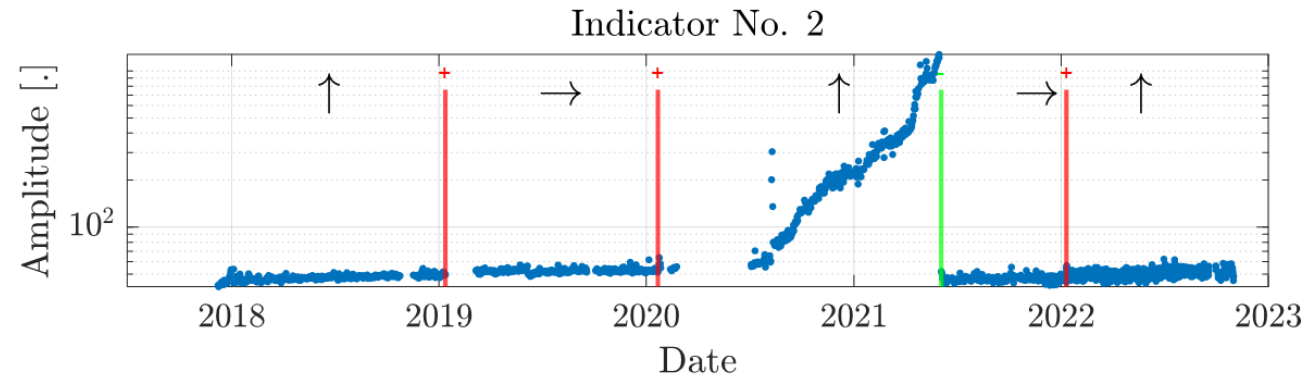
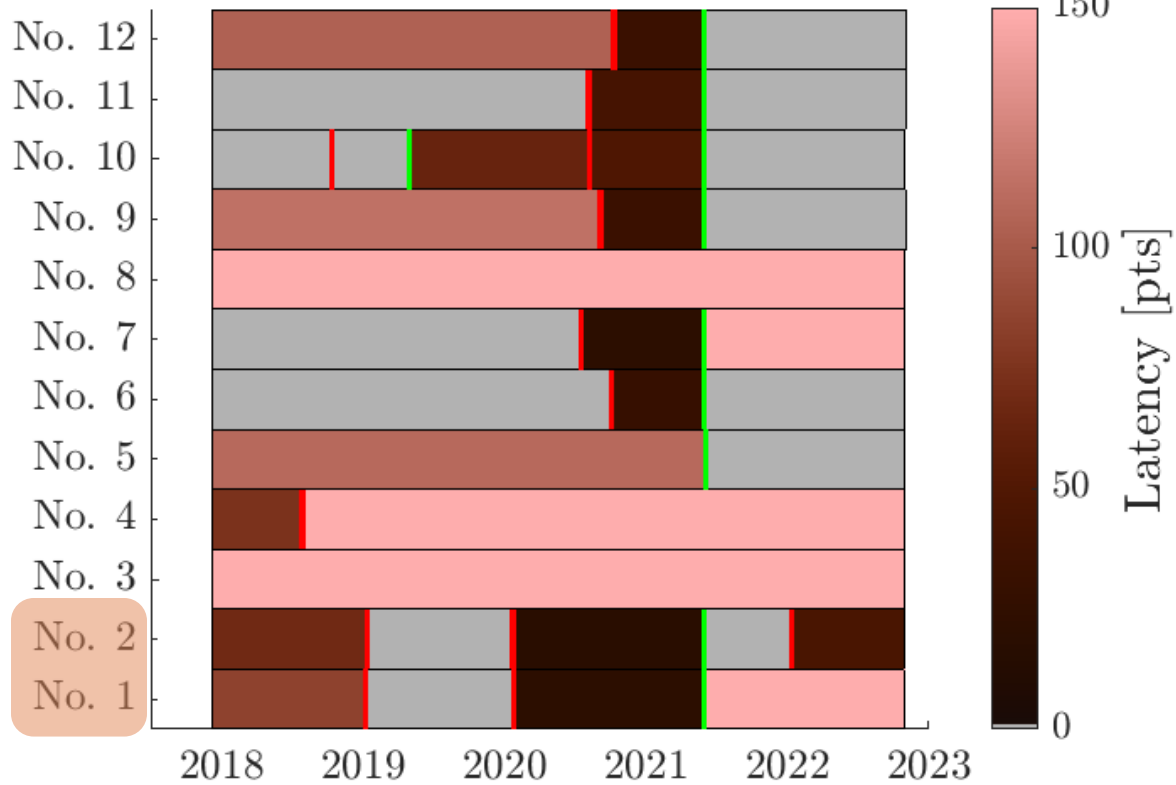
Maintenance operation



Similar dynamic
 Rise in diagnostic confidence

Multi-indicators monitoring

Multiple indicators analysis



Zoom
Early trend detection

Conclusion

- ⇒ Need for a **qualitative trend analysis** tool
- ⇒ **Rank-based** statistics offers a **non-parametric** framework
- ⇒ A **segmentation and characterisation** method has been proposed

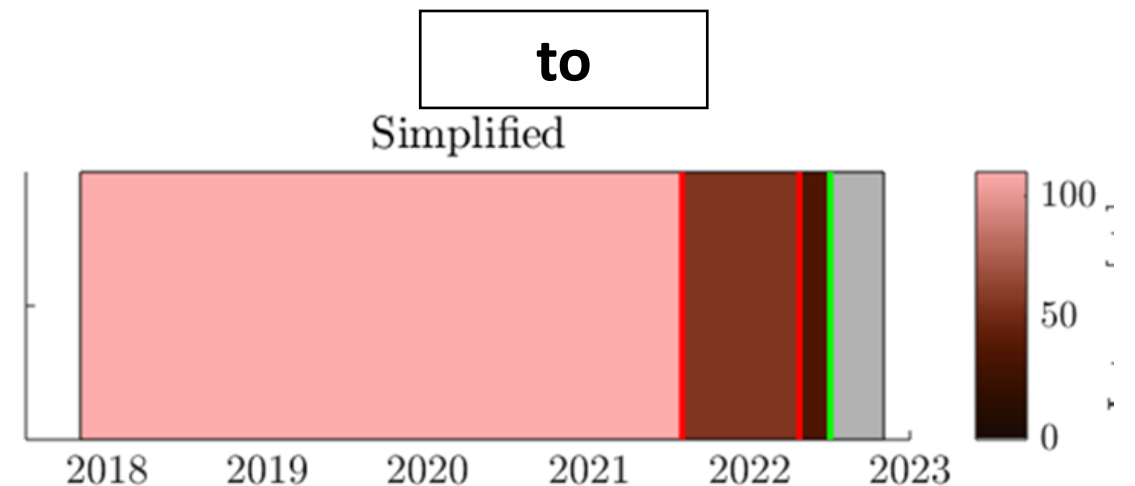
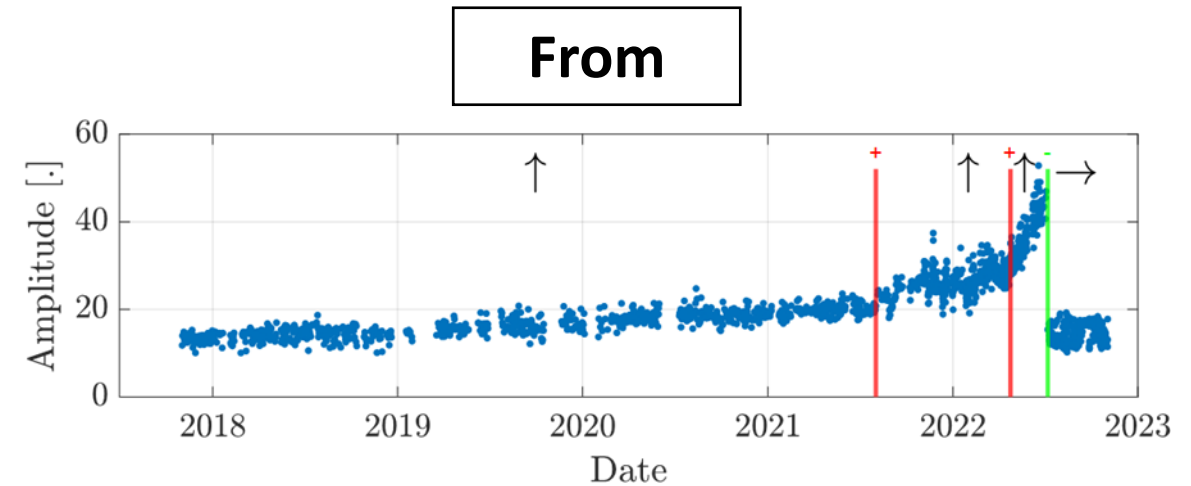
Gains of the method:



- simplified language, robust to outliers
- multi indicator analysis
- added information for maintenance decision



- **Input** for large study of **historical defects**
- **Not limited to** vibration-based indicators series
- **Room for improvement** : selection of hyperparameters, online implementation

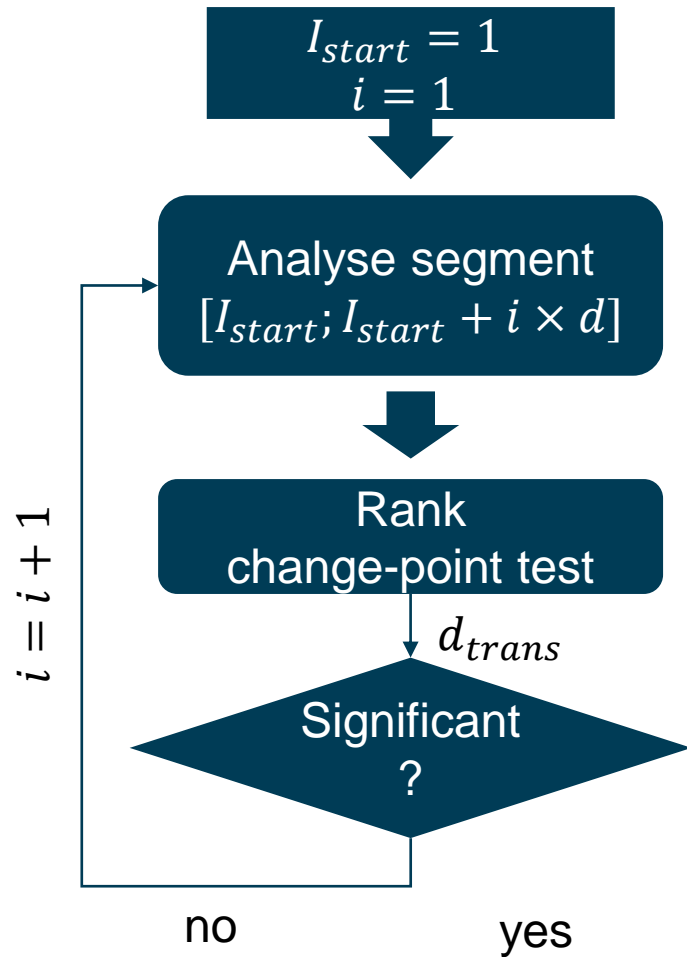


Thank You

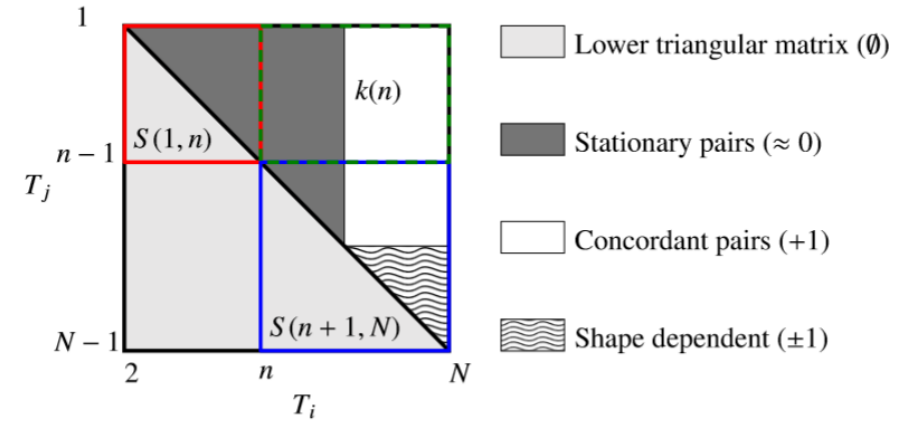
- [1] A.N. Pettitt, A Non-Parametric Approach to the Change-Point Problem, *Journal of the Royal Statistical Society. Series C (Applied Statistics)*. 28 (1979) 126–135. <https://doi.org/10.2307/2346729>.
- [2] H.B. Mann, Nonparametric Tests Against Trend, *Econometrica*. 13 (1945) 245–259. <https://doi.org/10.2307/1907187>.



Tunable parameters



Length of the segment d
Significance confidence $1 - \alpha$



$$k(n) = \sum_{i=1}^n \sum_{i=n+1}^N \text{sgn}(t_i - t_j) \text{sgn}(x_i - x_j). \quad (6)$$

The Pettitt statistic $k(n)$ is maximised for the most probable change point T , that is

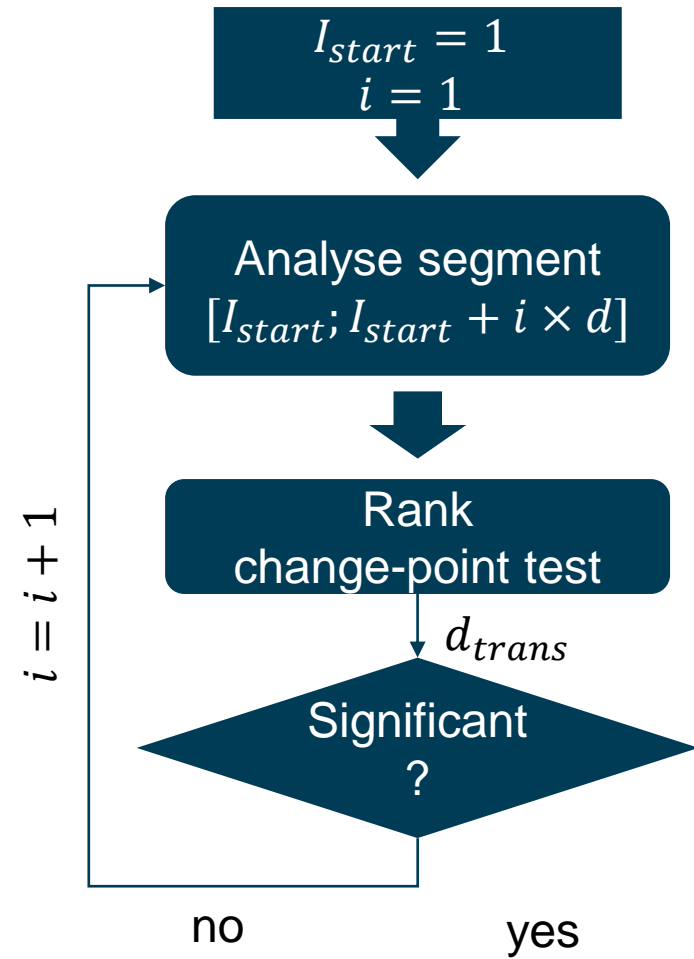
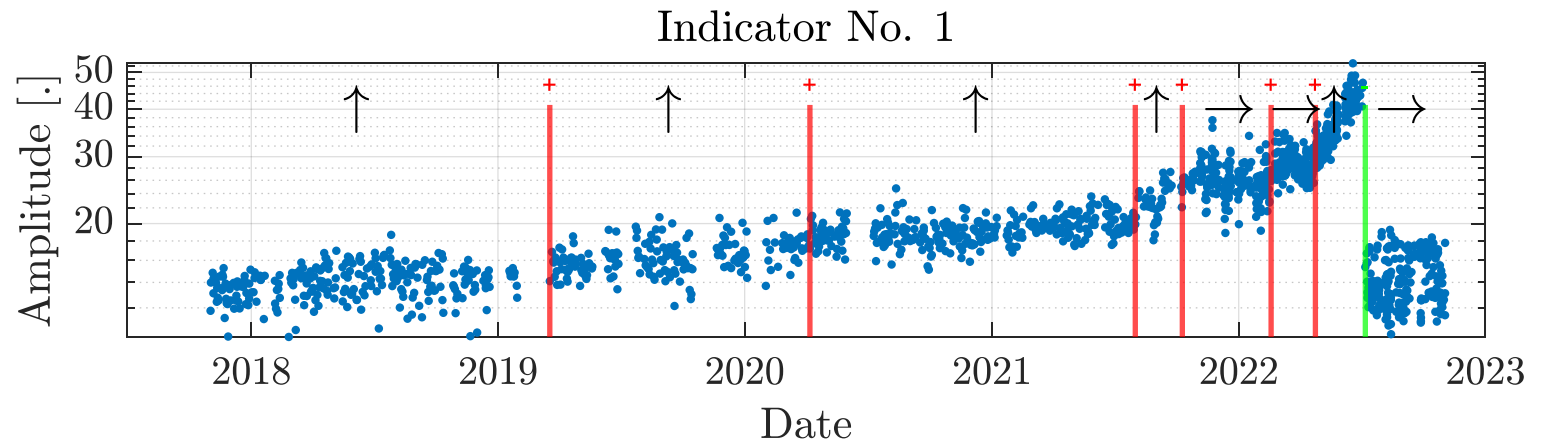
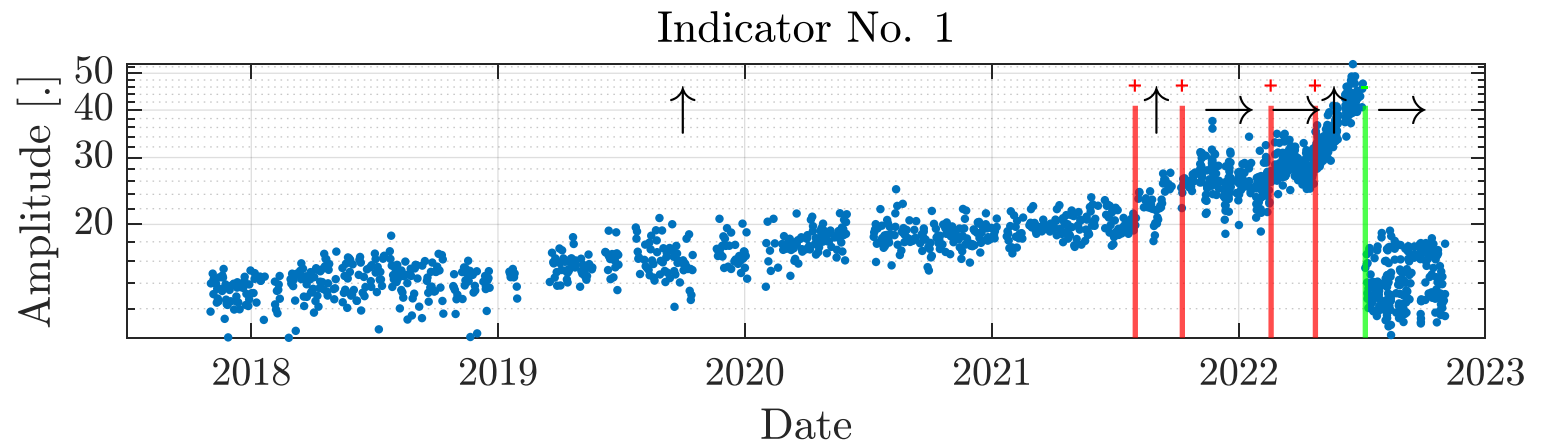
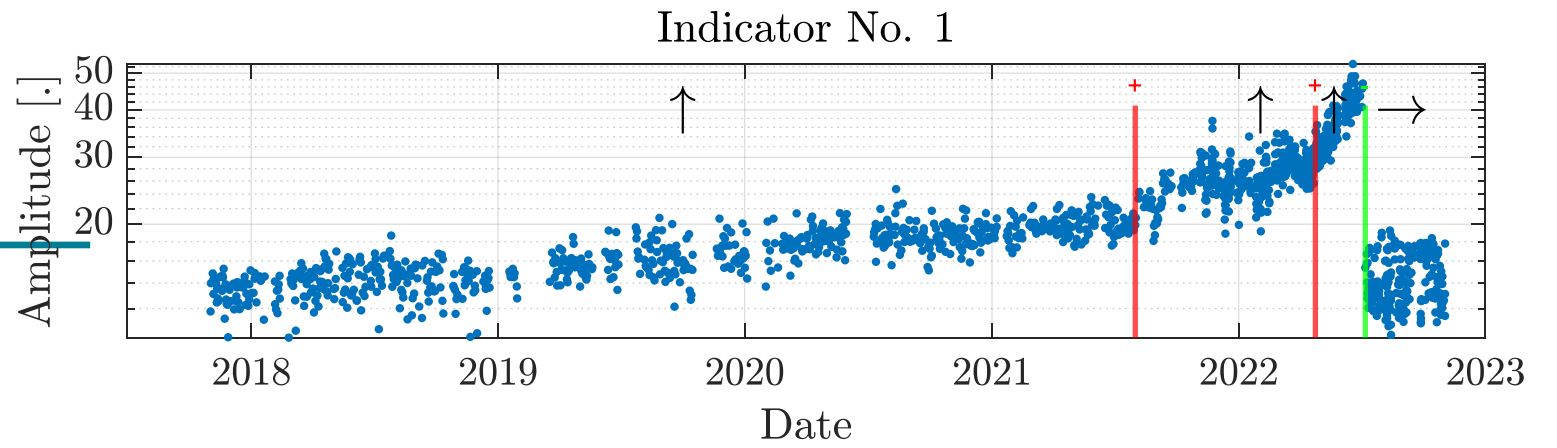
$$K = \max_{1 \leq n \leq N} (|k(n)|), \quad (7)$$

$$T = \arg \max_{1 \leq n \leq N} (|k(n)|). \quad (8)$$

Most importantly, using the well-defined properties of stationary series, Pettitt proposed a significance test for the rejection of H_0 where the p-value for rejection is approximated by

$$p \approx 2 \exp\left(-\frac{6K^2}{n^3 + n^2}\right), \quad (9)$$

Tunable parameters



Mann Kendall

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(y_j - y_k)$$

Avec $\tau = \frac{S}{S_{\text{total number of pairs}}} = \frac{2S}{n(n-1)}$

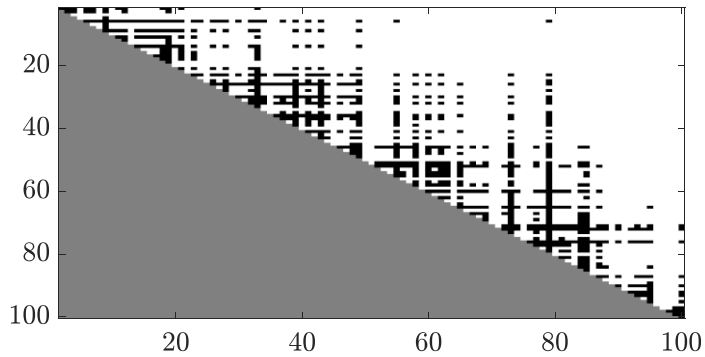
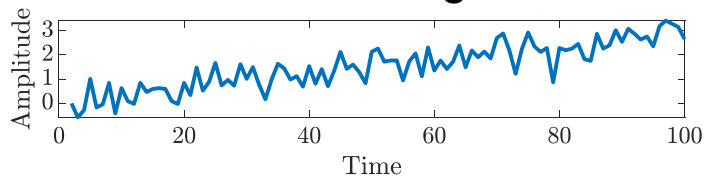
Variance of the sum is

$$\sigma_S^2 = \frac{n(n-1)(2n+5)}{18}$$

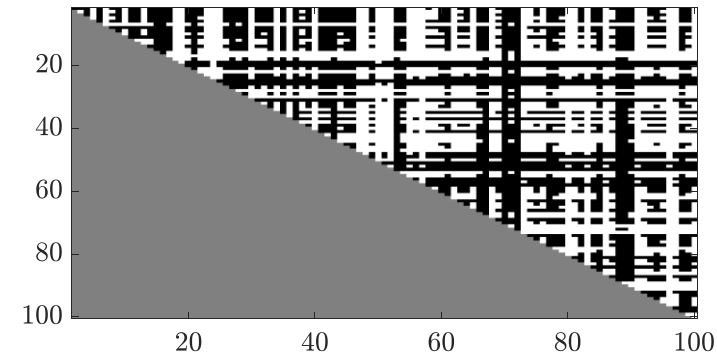
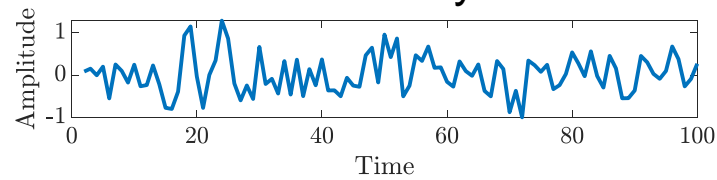
With null mathematical expectation

Deviation from gaussian

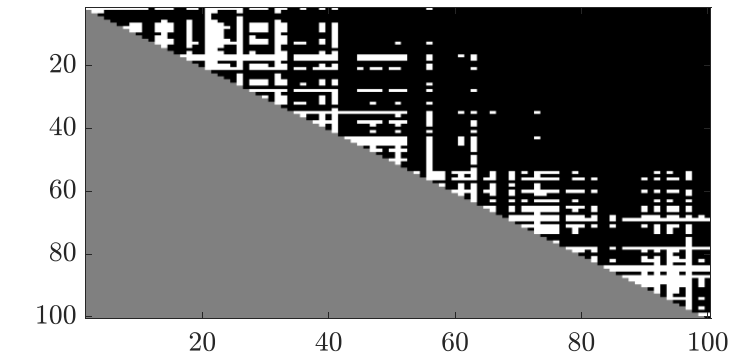
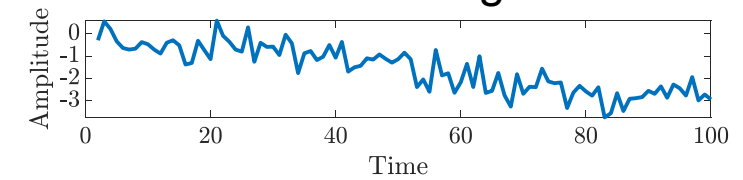
Increasing



Stationary



Decreasing



Statistically more +1 pairs

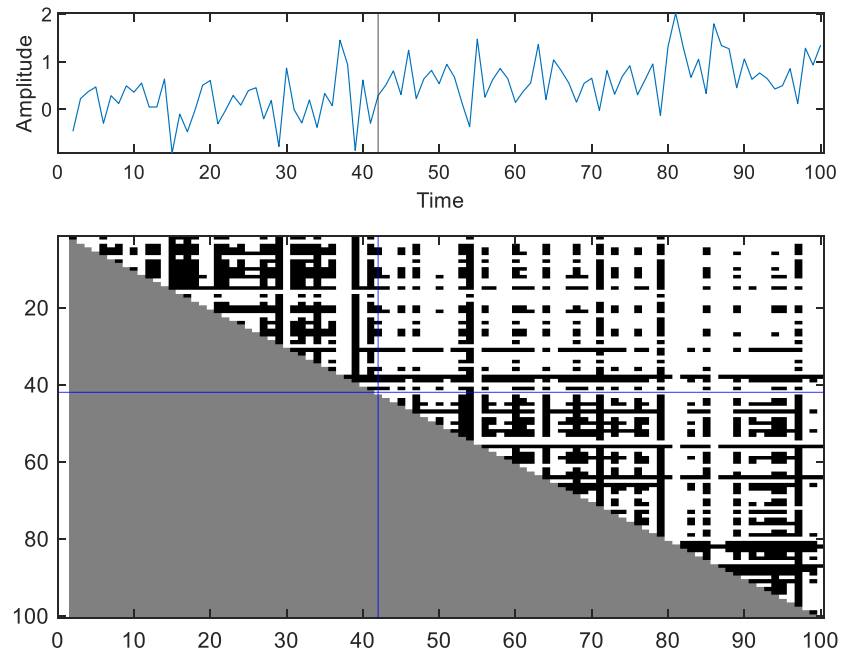
Statistically equal +/-1 pairs

Statistically more -1 pairs

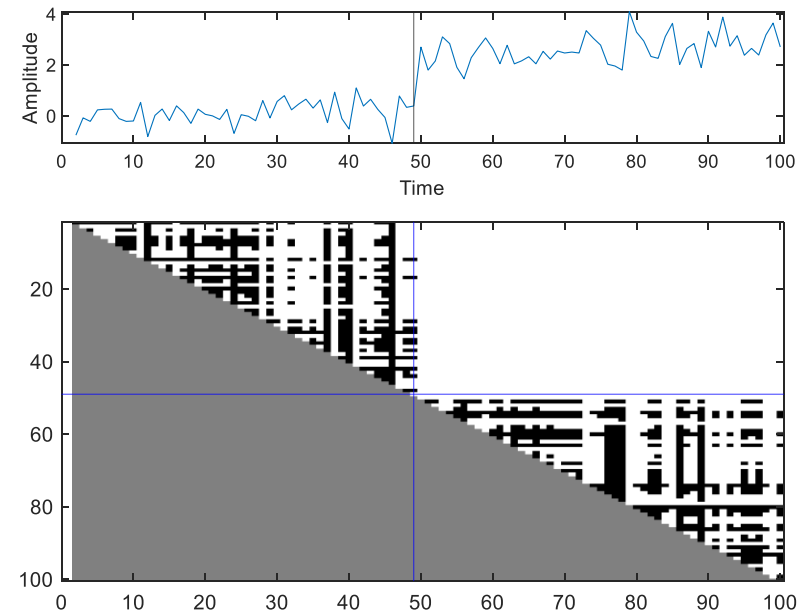
The issue of increasing trends

- Pettitt test : detection of change in median

Linear increase + noise



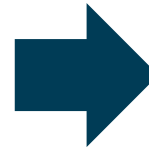
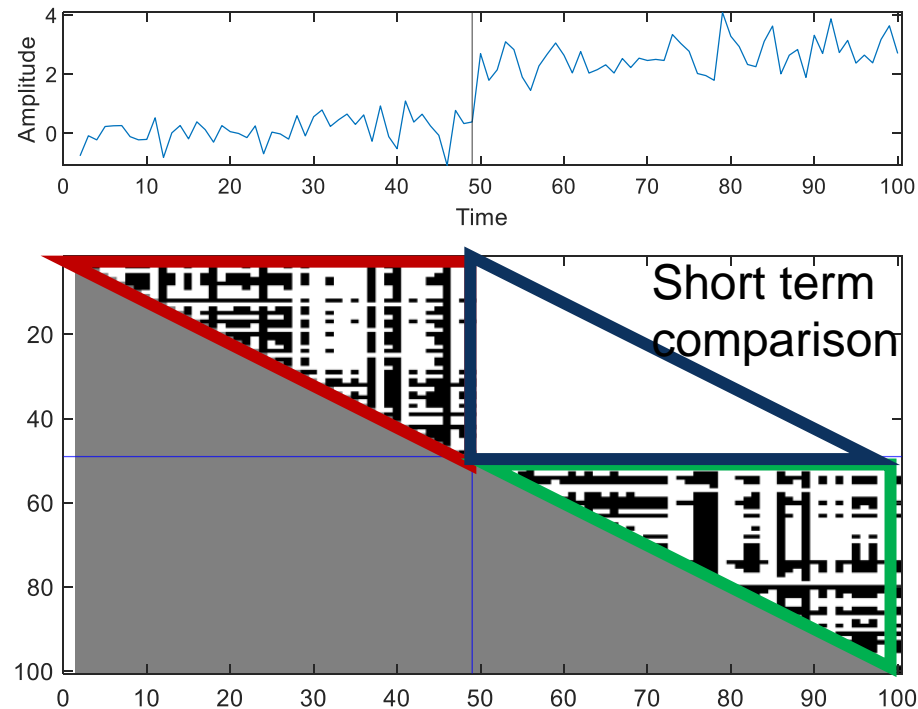
Linear increase + step



How to differentiate the two ?

The issue of increasing trends

- Pettitt test : detection of change in median

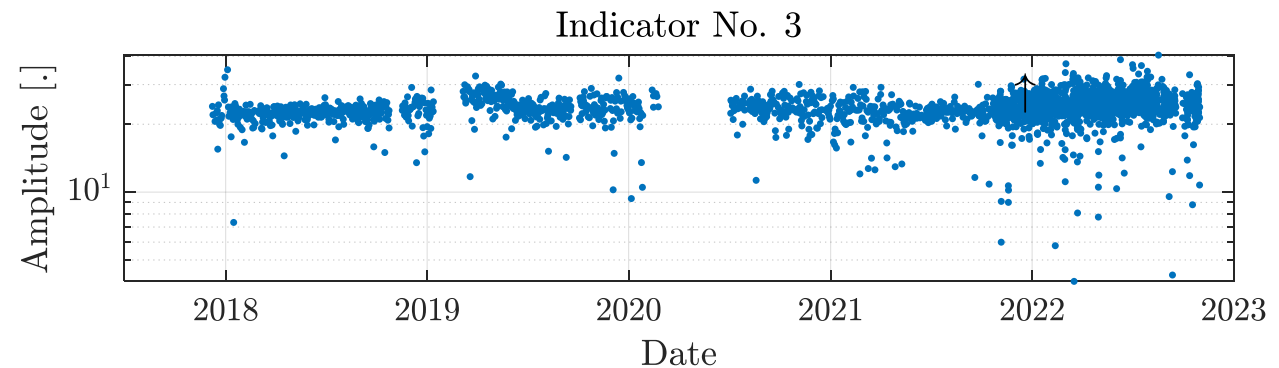
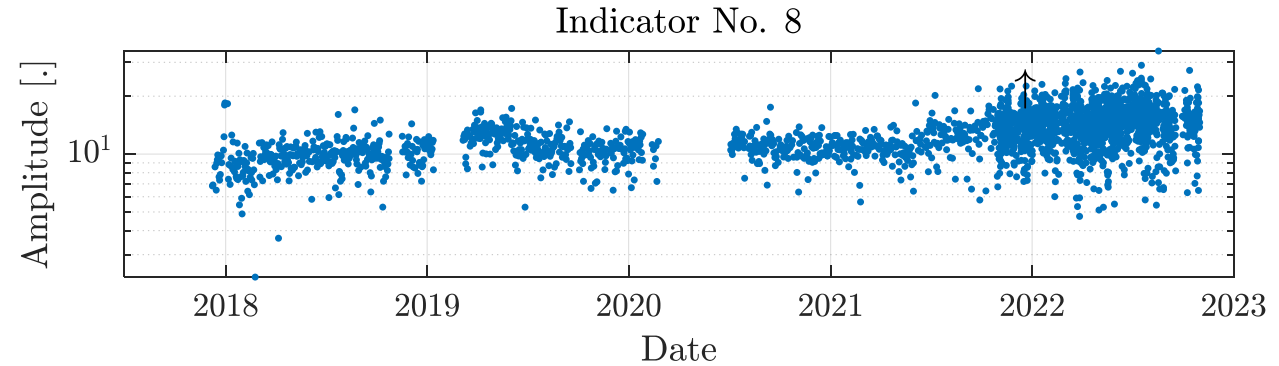
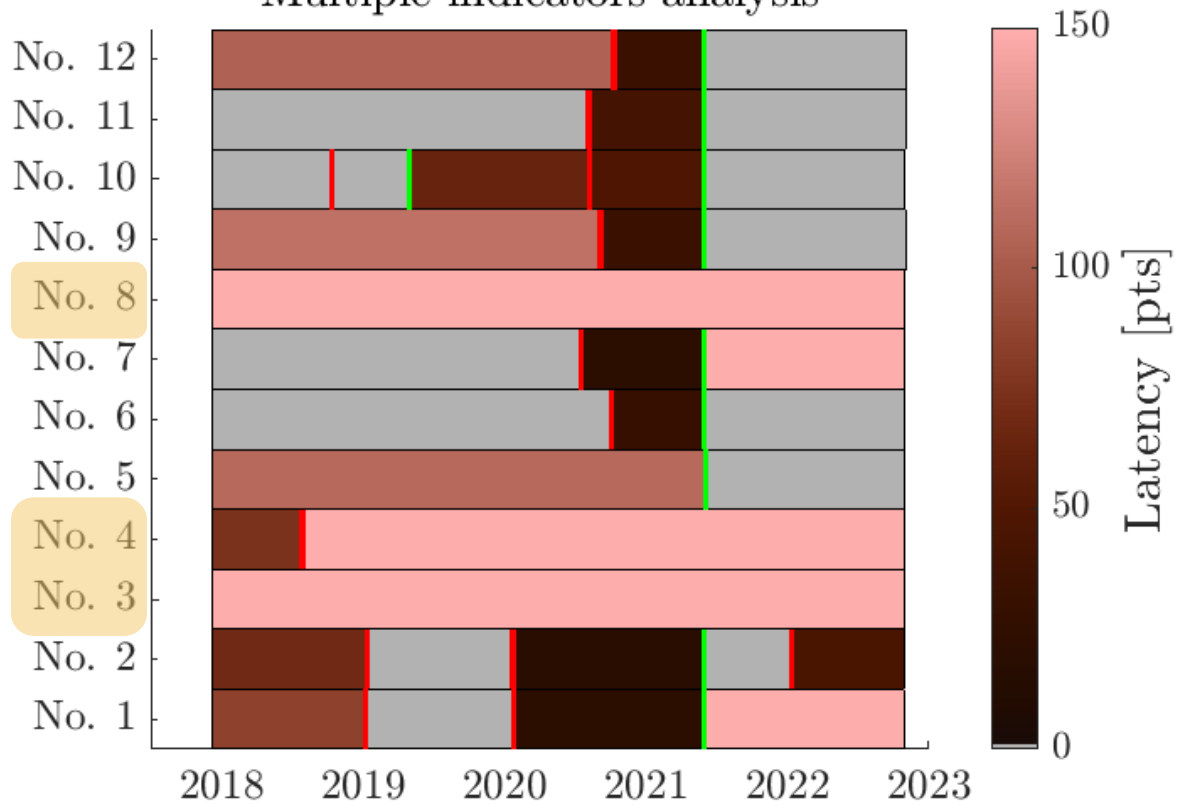


Criteria on rank correlation

Global surveillance and industrial application

Segmentation on multiple indicators

Multiple indicators analysis

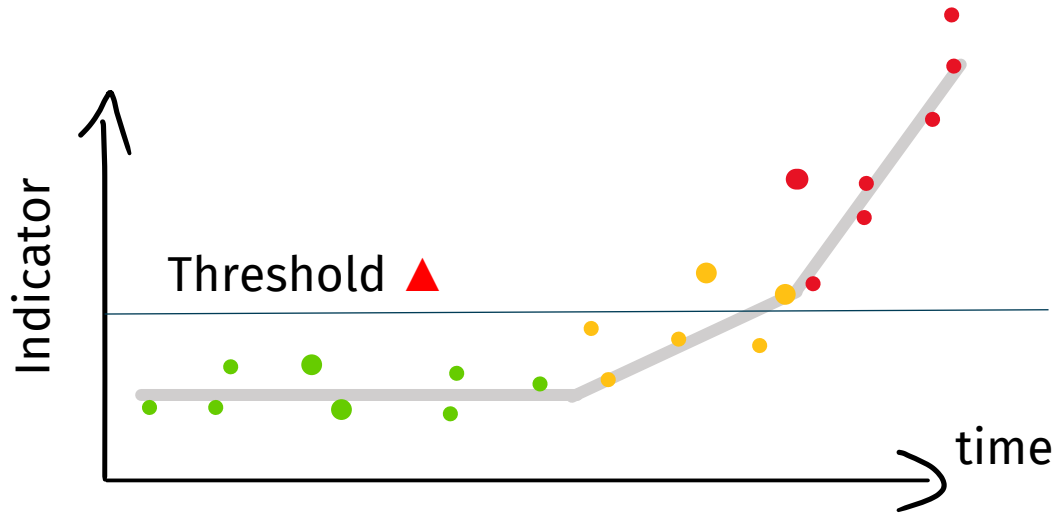


Non significant episodes

High latency

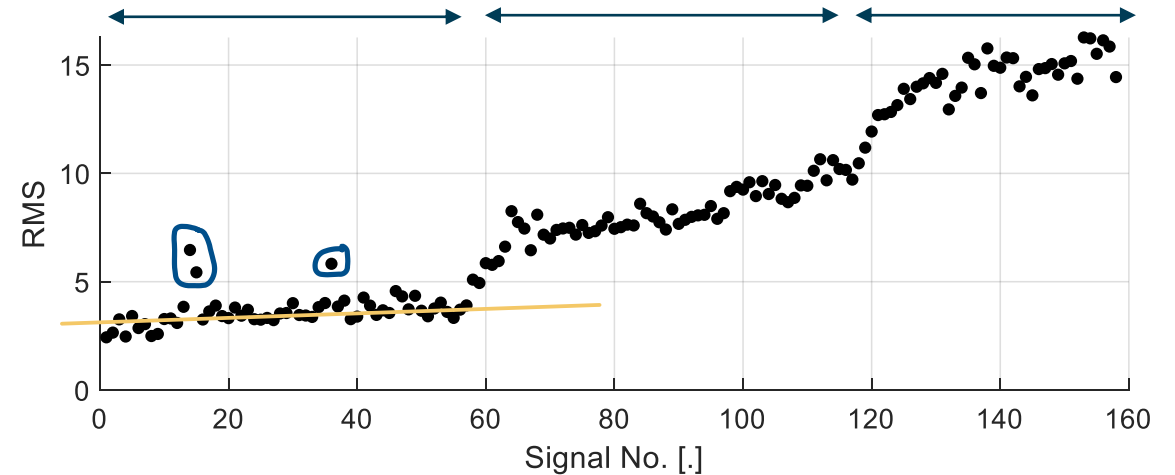
Context on condition-based maintenance

Threshold on the amplitude



- Canonical trend (stationary, initiation, catastrophic increase)
- Usual monitoring
 - Statistical threshold
 - Learnt from “healthy” state

Challenges



- Outliers and unknown noise distribution
- Hidden trends
- Different episodes
- Versatile shapes



Need