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# Non-parametric trend analysis of condition monitoring indicators

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**WESC**  
25<sup>th</sup> May 2023



Adrien MARSICK

# Non-parametric trend analysis of condition monitoring indicators

A. Marsick<sup>1,2</sup>, H. Andre<sup>3</sup>, I. Khelf<sup>2</sup>, Q. Leclere<sup>1</sup>, J. Antoni<sup>1</sup>



# Context on condition-based maintenance

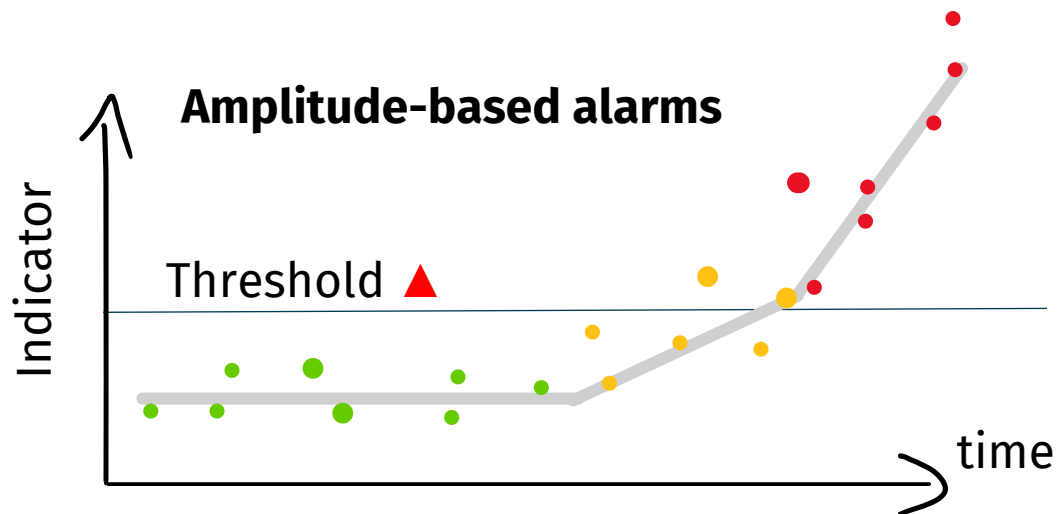


Monitoring workflow

Physical signals

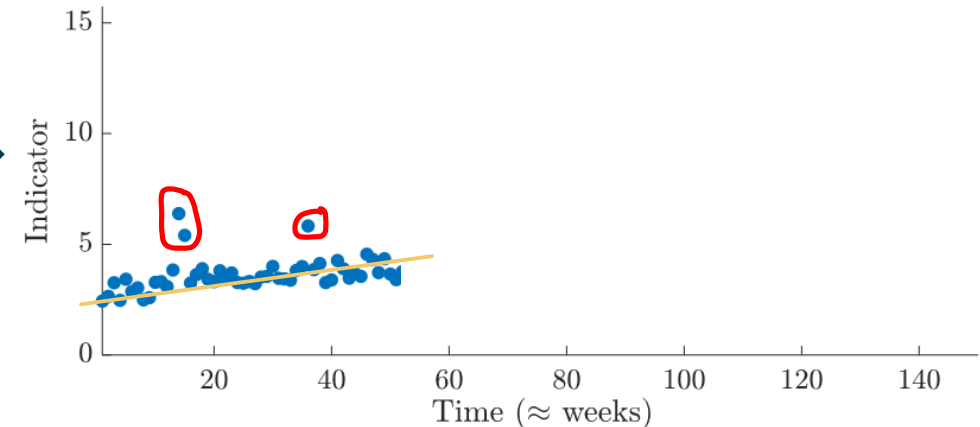
Health indicators

Alarms



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

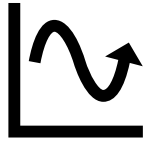
## Challenges



- 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

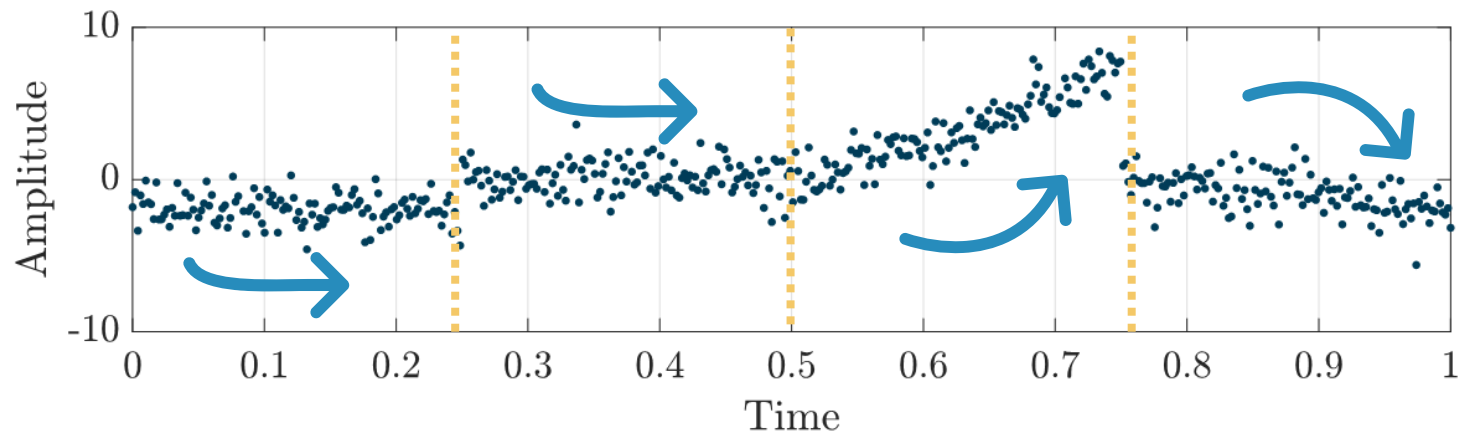
What is a trend ?



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**

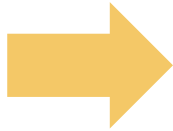
Tasks

1. Segment episodes
2. Characterise

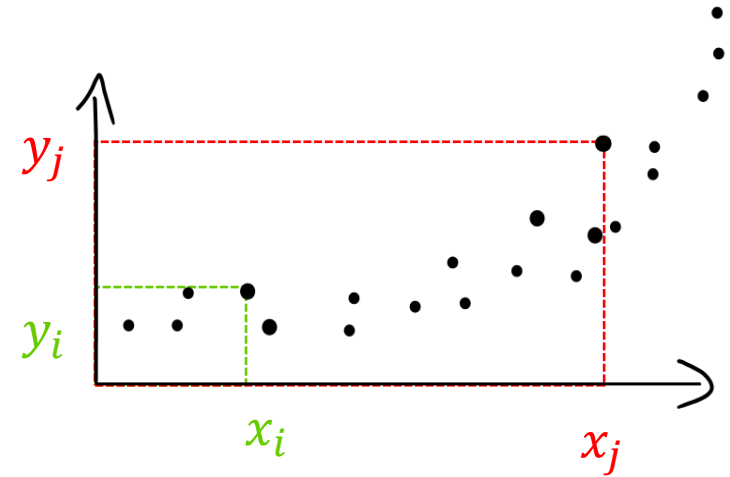


# Rank-based statistics

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

$y_j > y_i$  ?

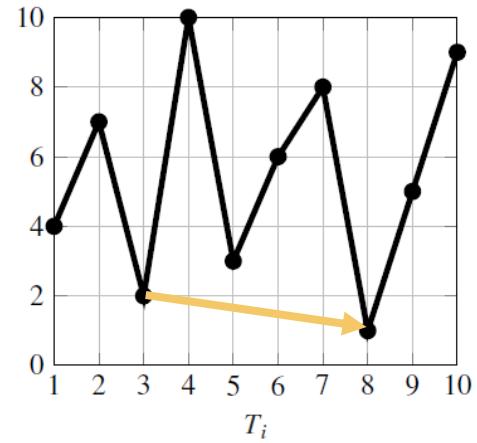
Concordant pair

$y_j < y_i$  ?

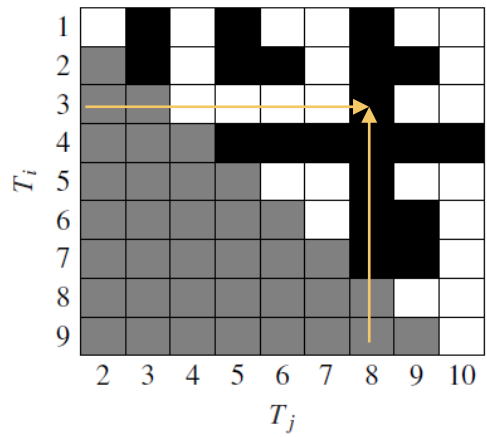
Discordant pair



Pair to pair comparison



Rank Matrix



# A view on two rank tests

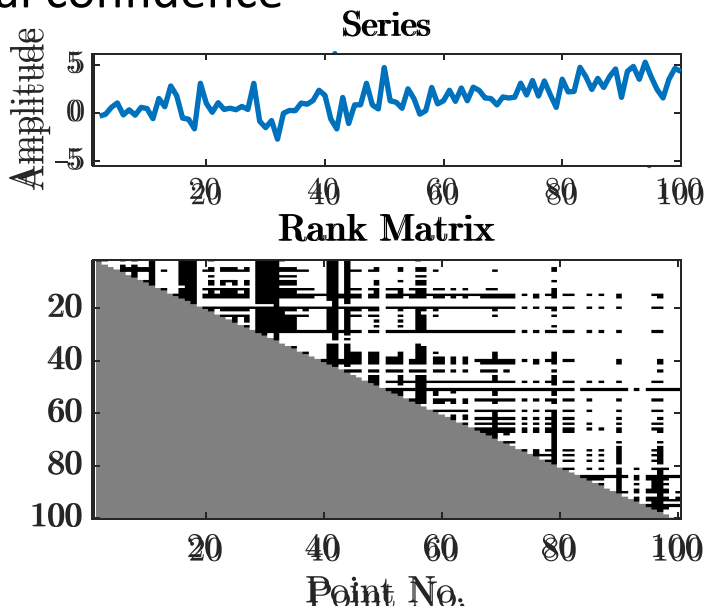
## Stationarity: Mann-Kendall test

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

Concordant



Discordant

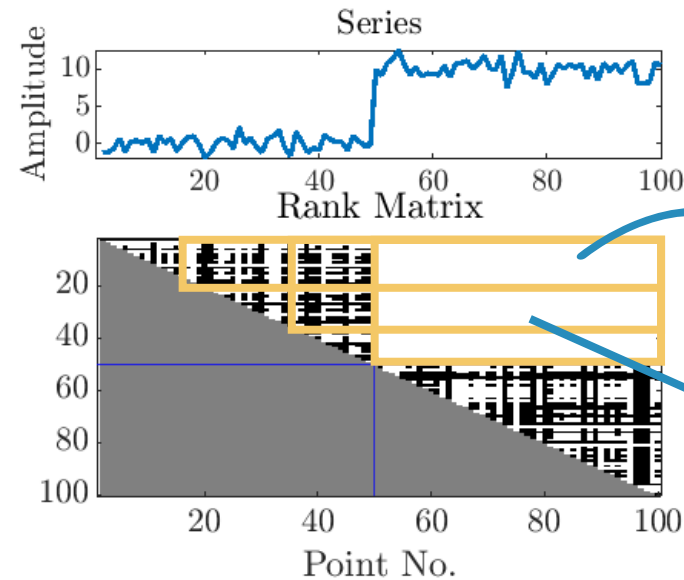


Equal pairs on average

Non parametric, independent of amplitude, robust to outliers

## Change-point: Pettitt test

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

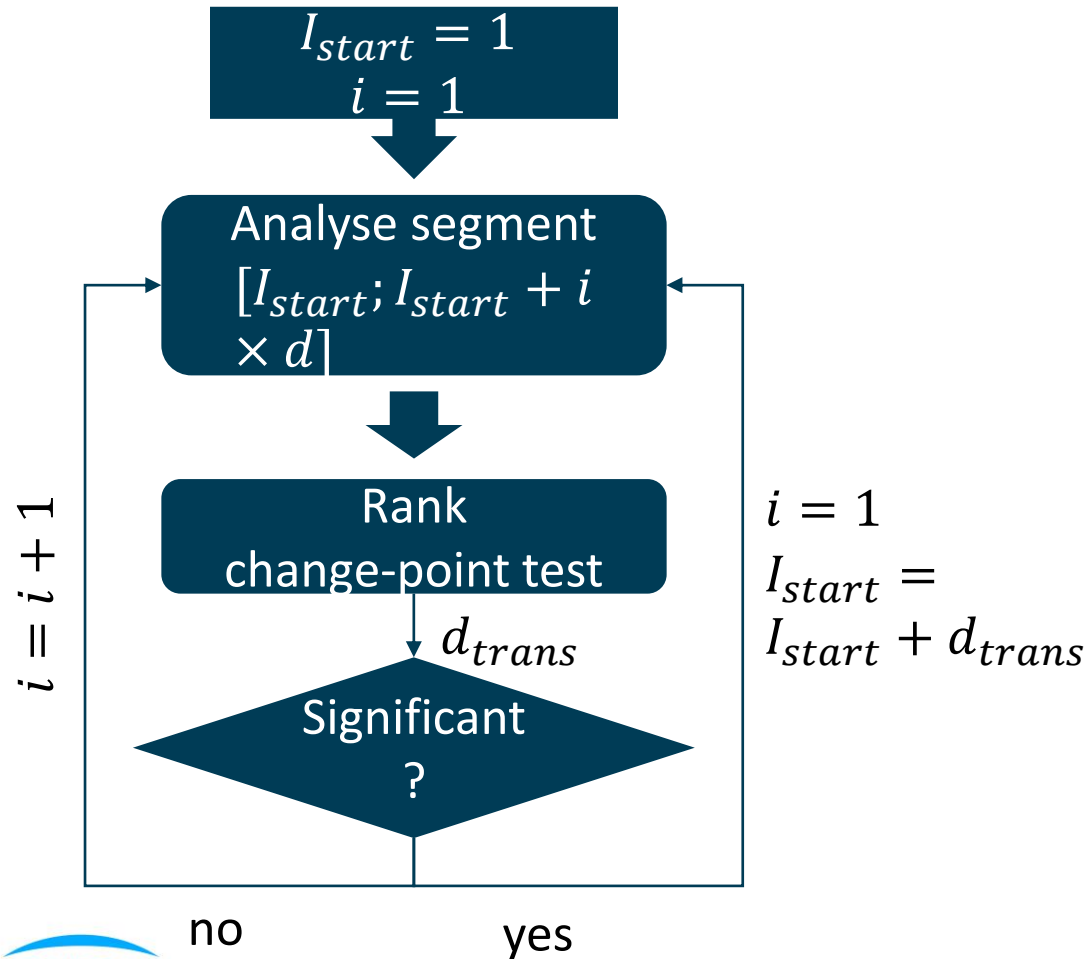


Sum of rectangle

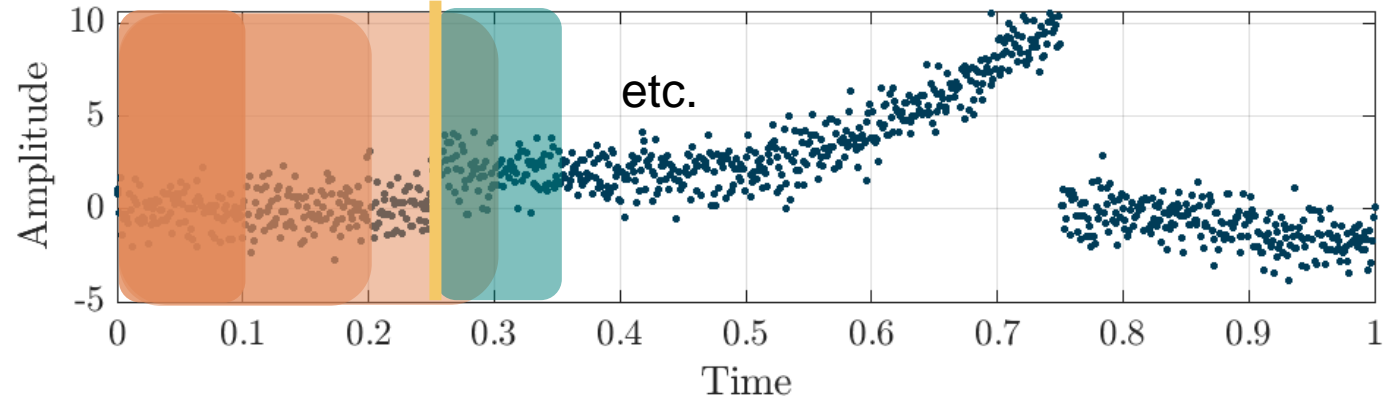
Maximum at transition

# Segmentation algorithm

## Sliding window with Pettitt change point test



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

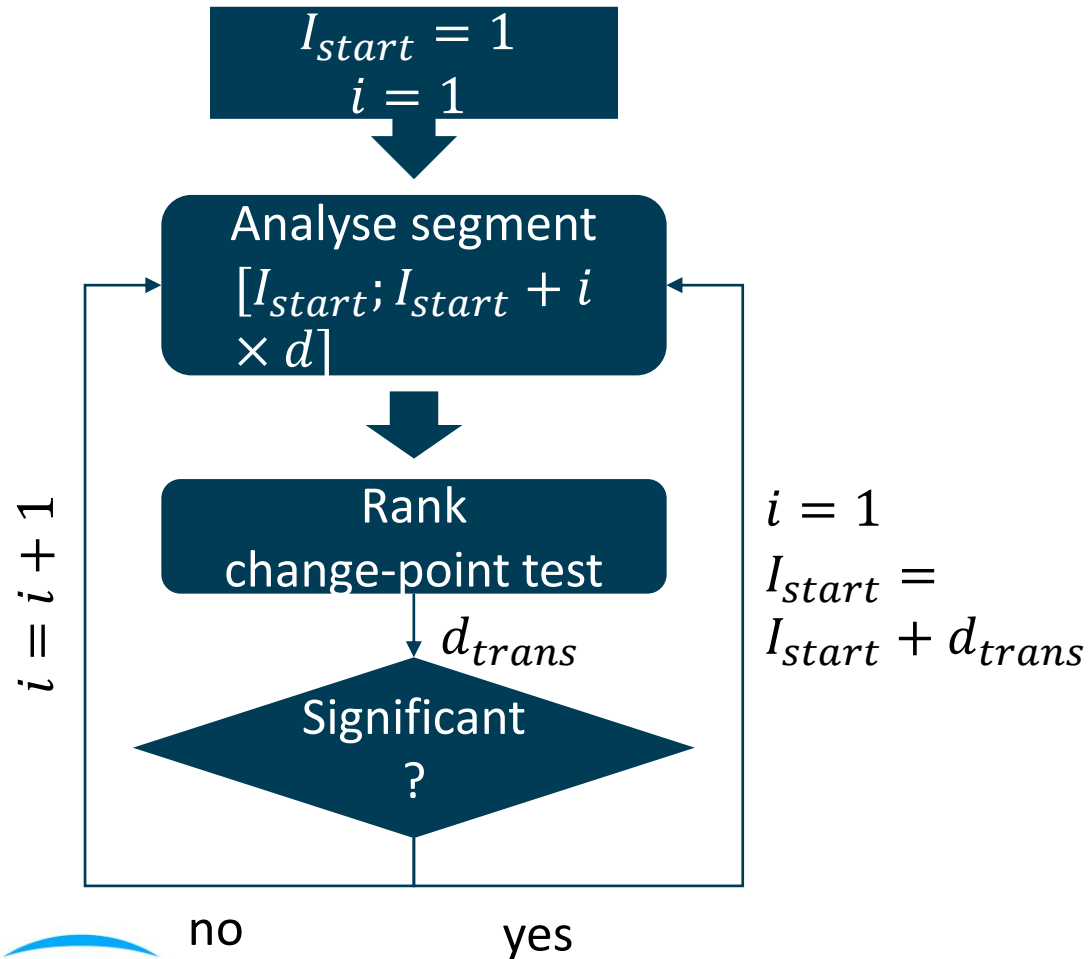


### Algorithm

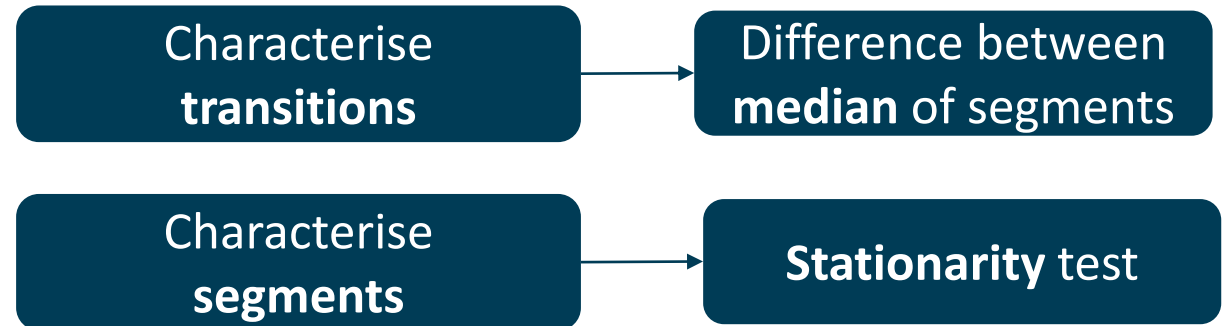
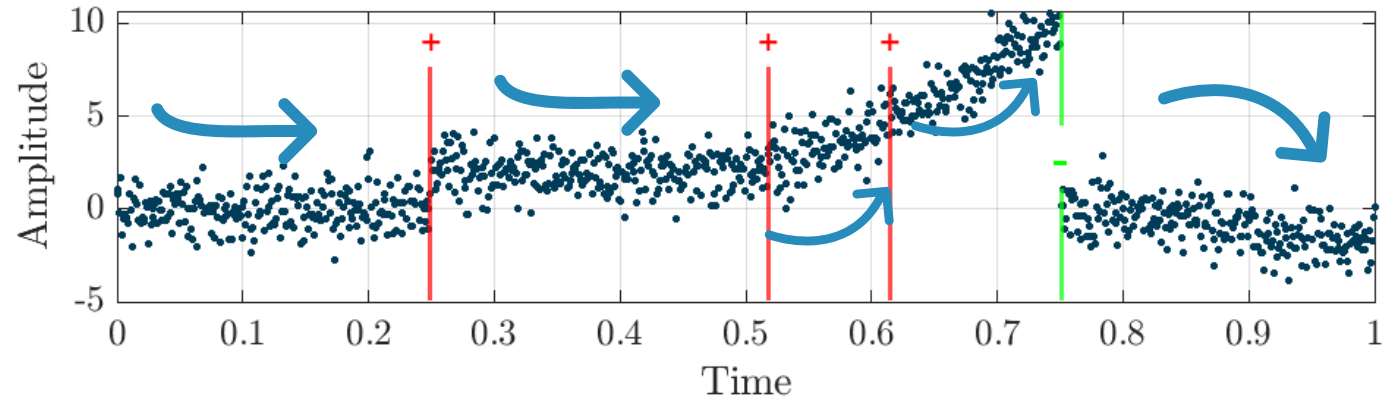
Segment $\rightarrow [0; 0.1]$ $i = 1$ $d = 0.1$ Change point $\rightarrow$ NO	Segment $\rightarrow [0; 0.2]$ $i = 2$ $d = 0.1$ Change point $\rightarrow$ NO	Segment $\rightarrow [0; 0.3]$ $i = 3$ $d = 0.1$ Change point $\rightarrow$ YES $I_{start} = 0.25$
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#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

## Sliding window with Pettitt change point test



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

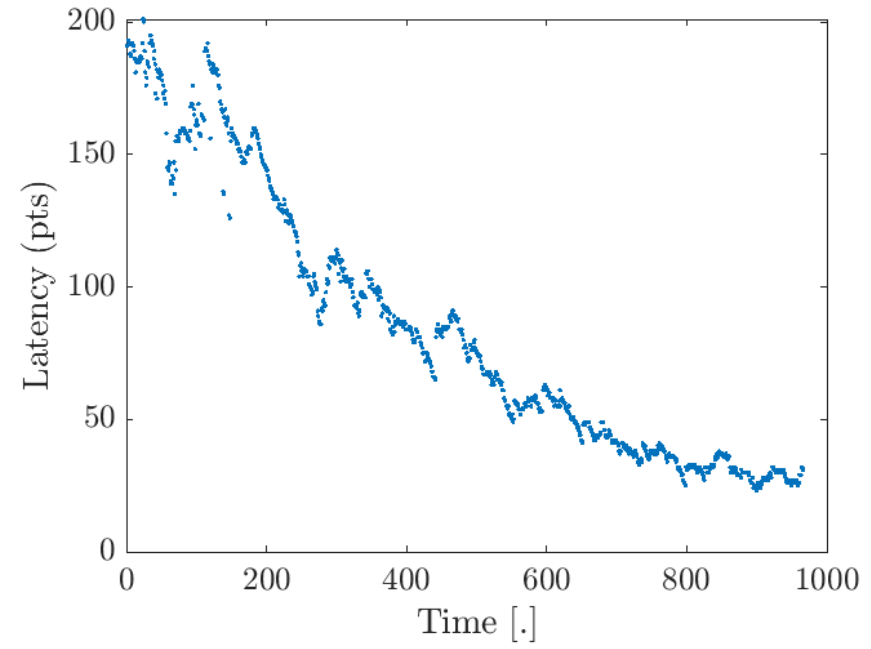
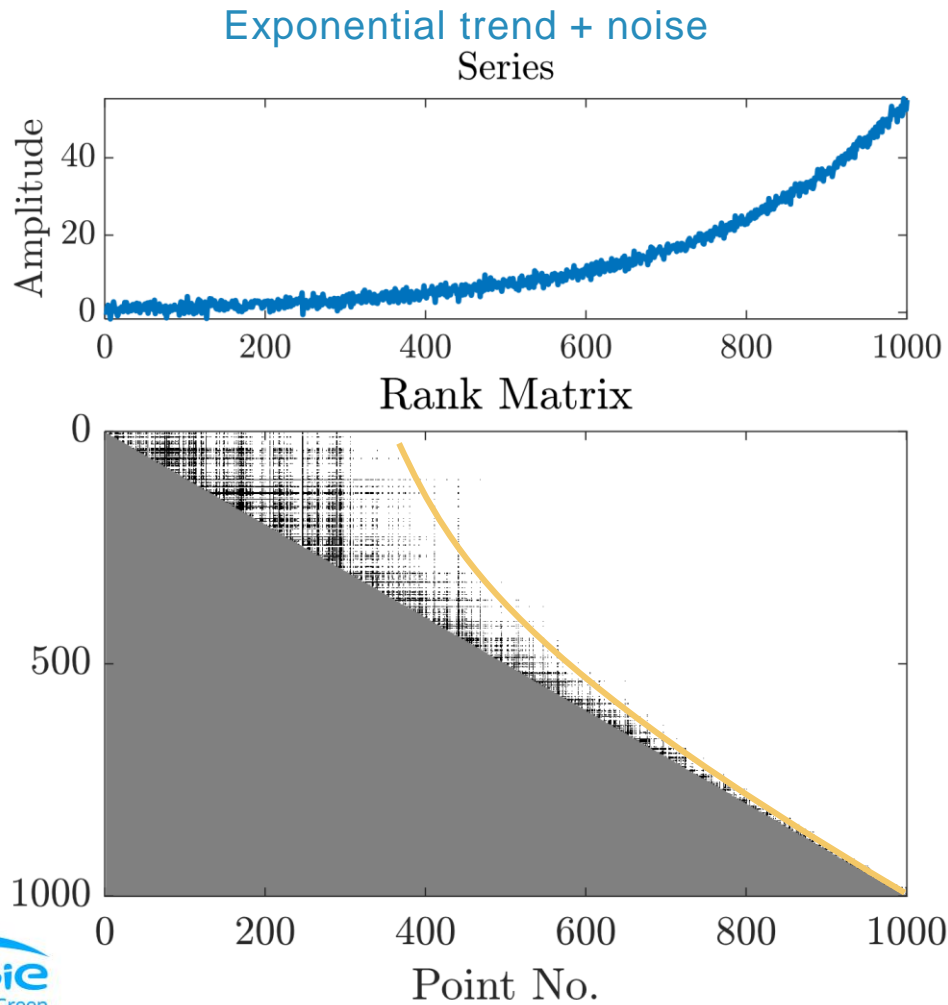




# A rank-based evaluation of the slope

## 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



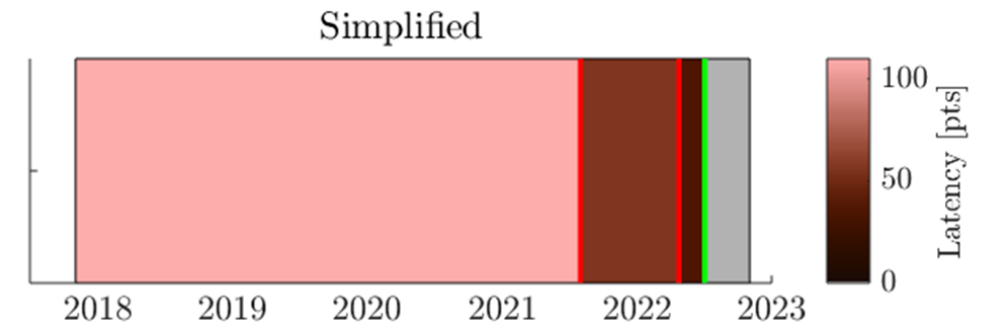
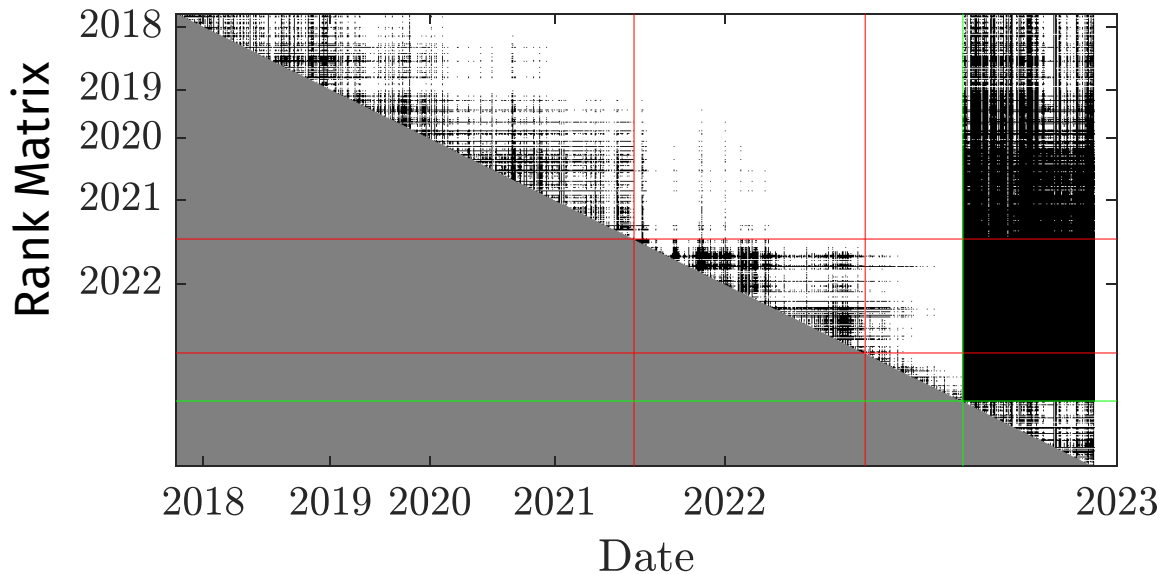
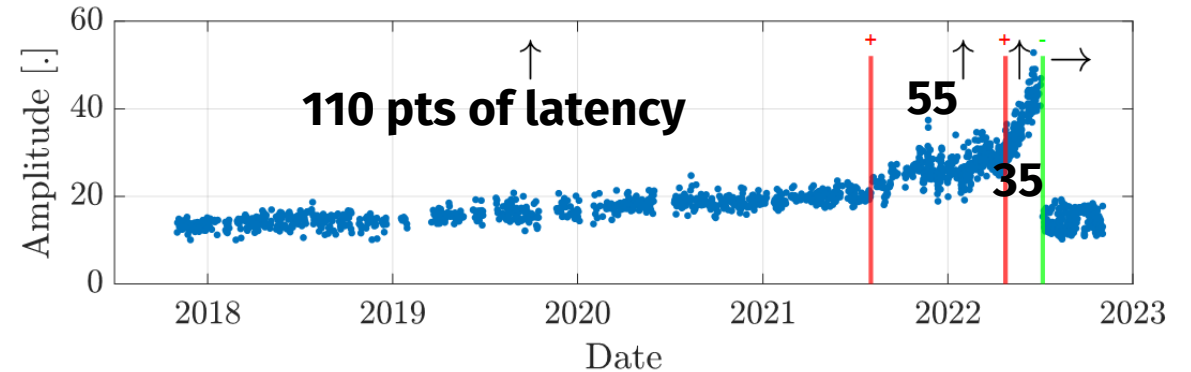
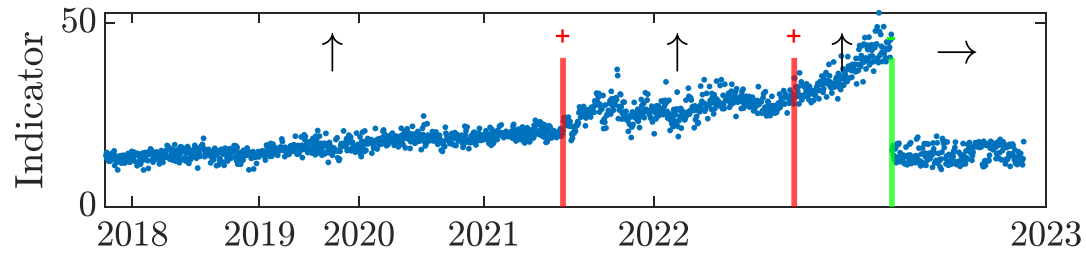
## Non-parametric measure of Slope to Noise Ratio

# Example vibration-based indicator



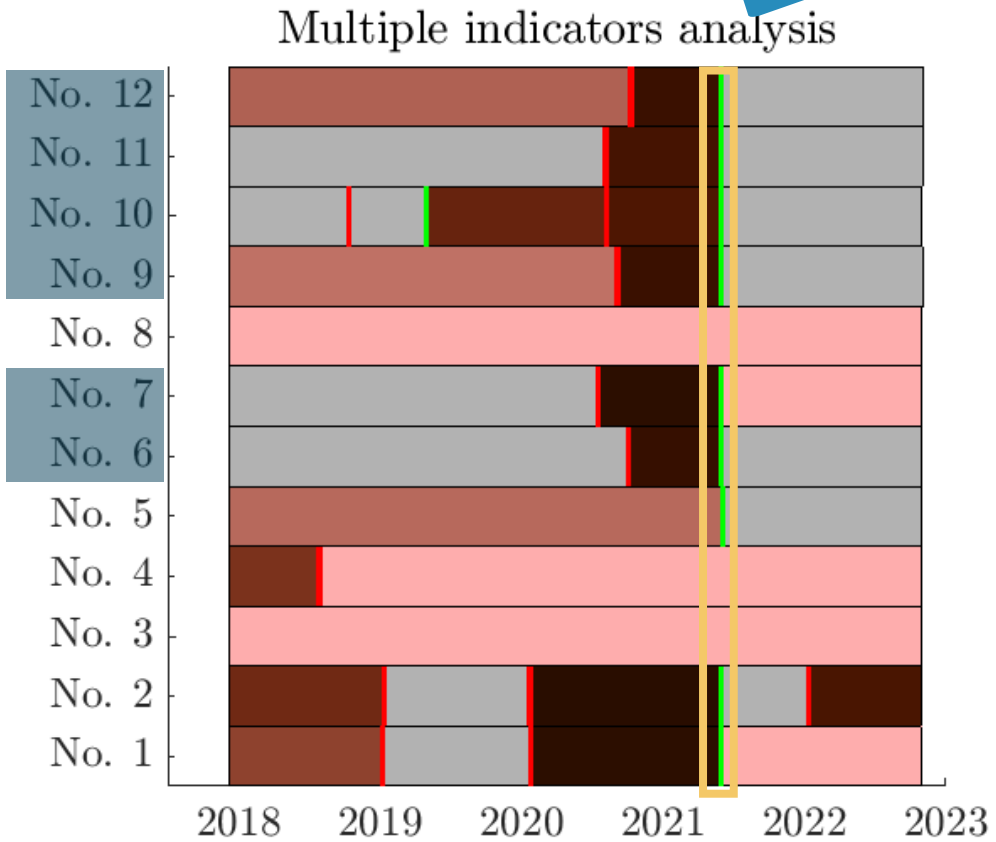
Damaged bearing

Condition indicator



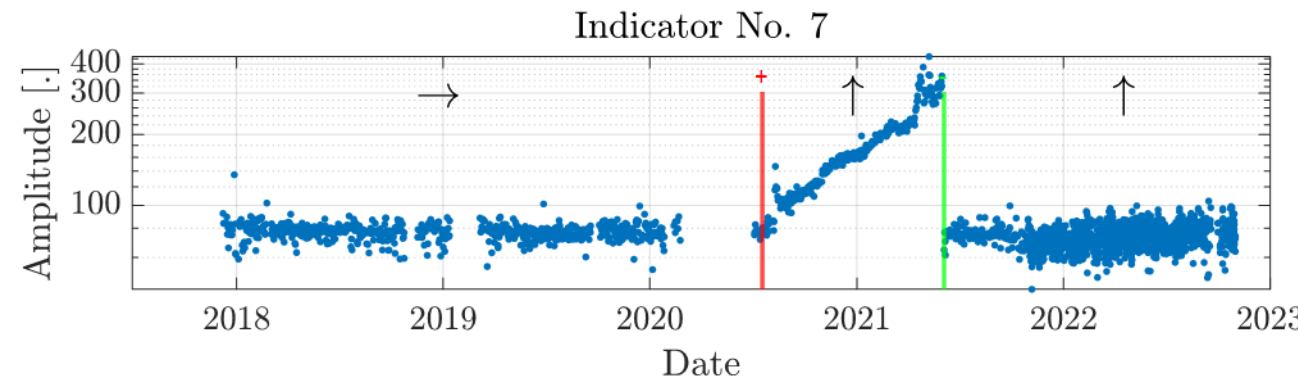
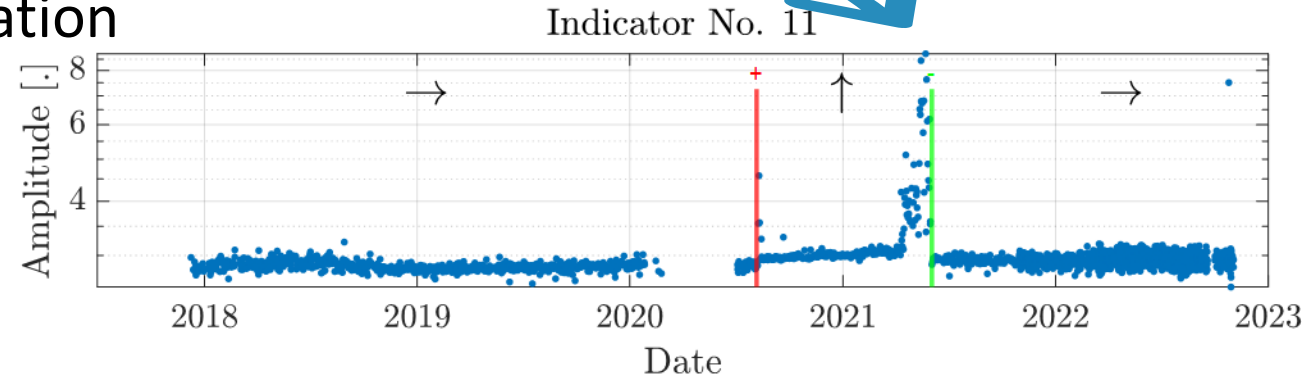
- Robust segmentation
- Qualitative characterisation of episodes
- Information on latency

# Multi-indicators monitoring



- | Decreasing median
- | Increasing median

Maintenance operation

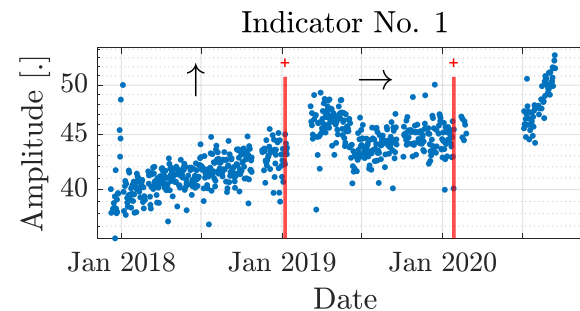
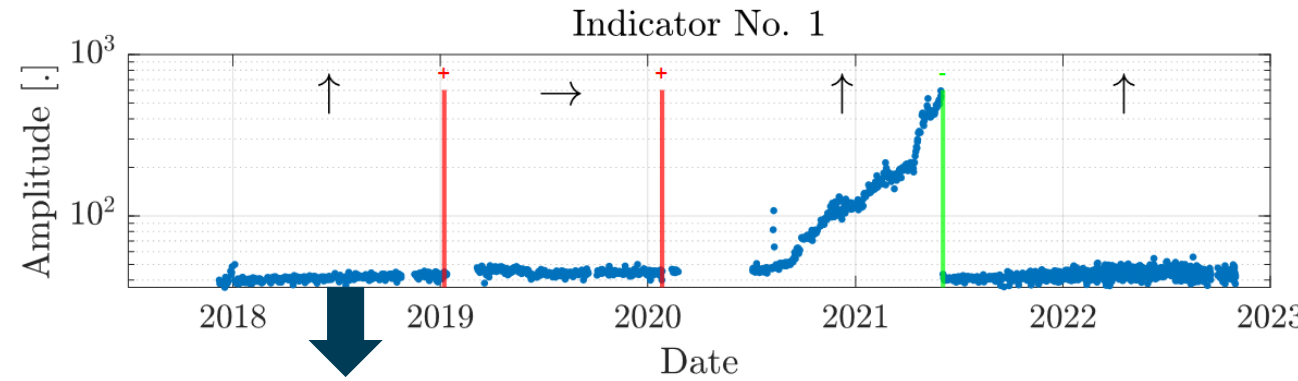
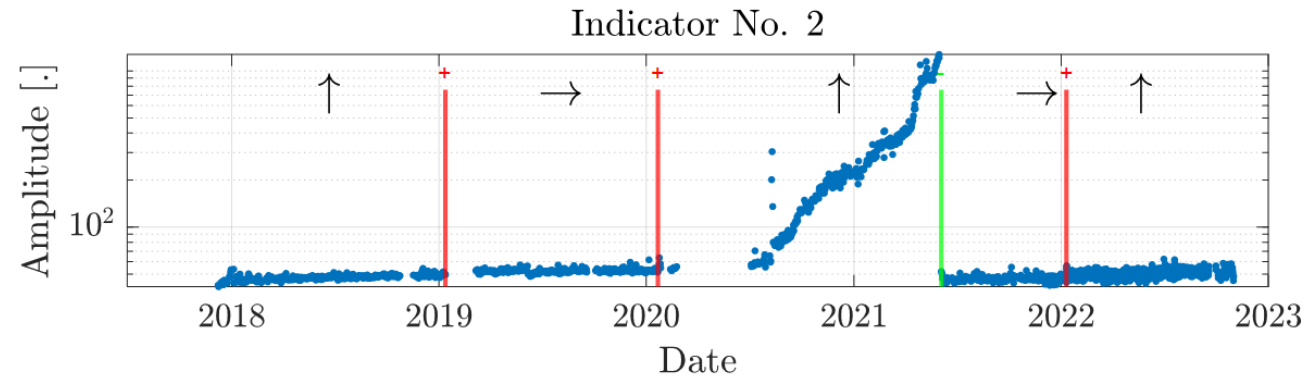
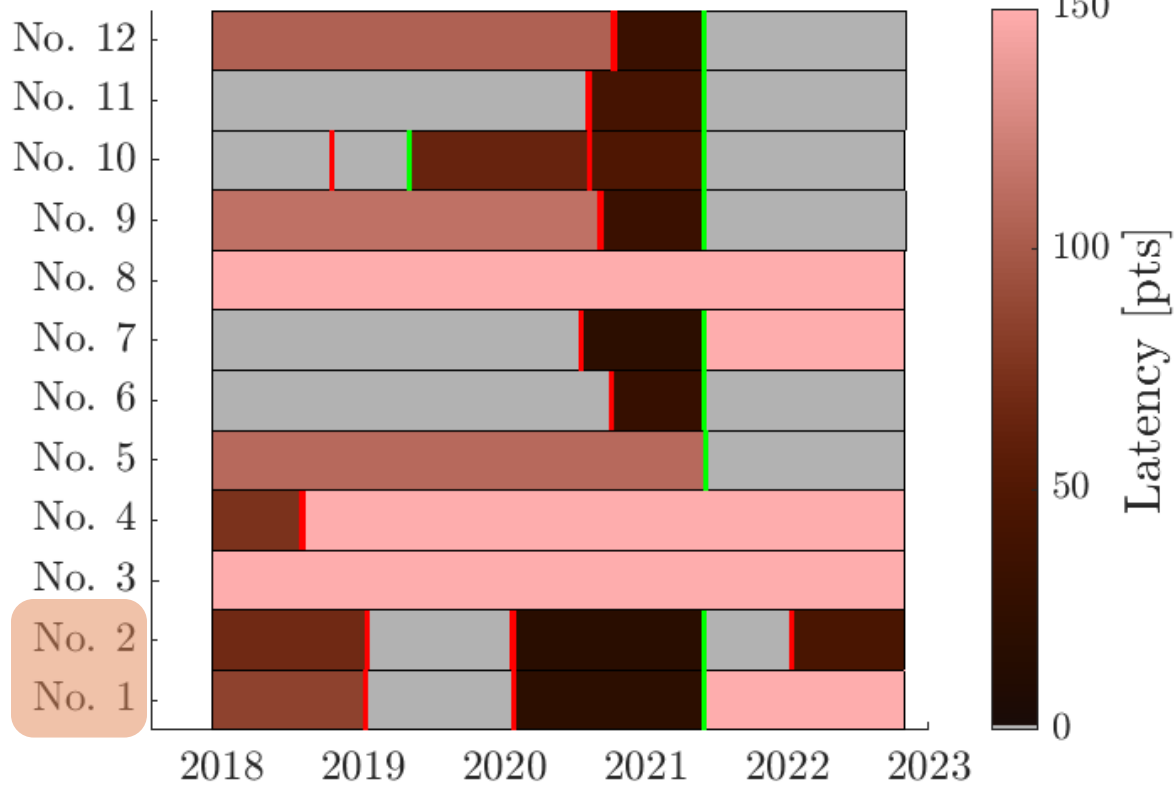


Similar dynamic

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

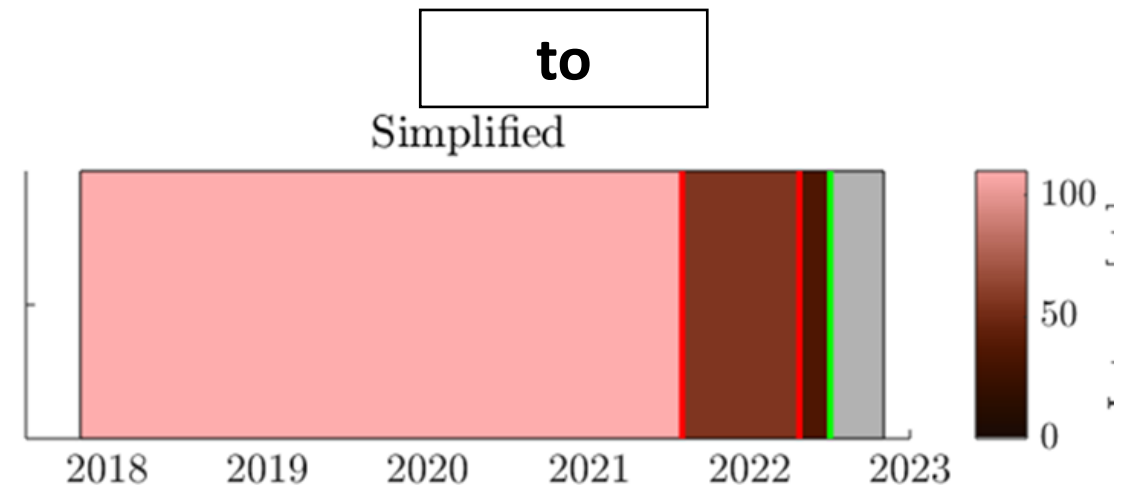
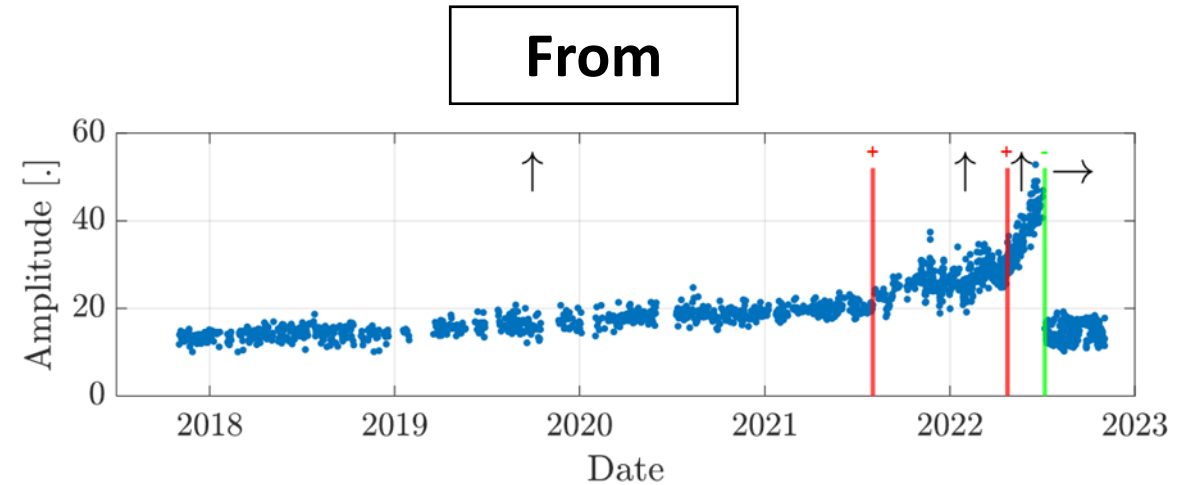
## Gains of the method:



- 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

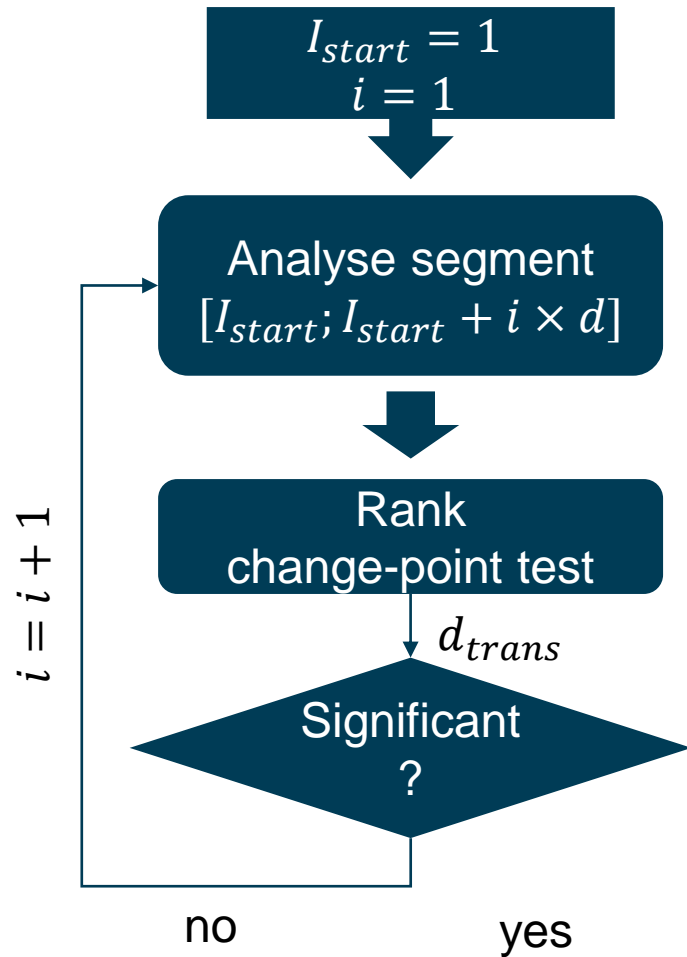
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[1] A.N. Pettitt, A Non-Parametric Approach to the Change-Point Problem, *Journal of the Royal Statistical Society. Series C (Applied Statistics)*. 28 (1979) 126–135. <https://doi.org/10.2307/2346729>.

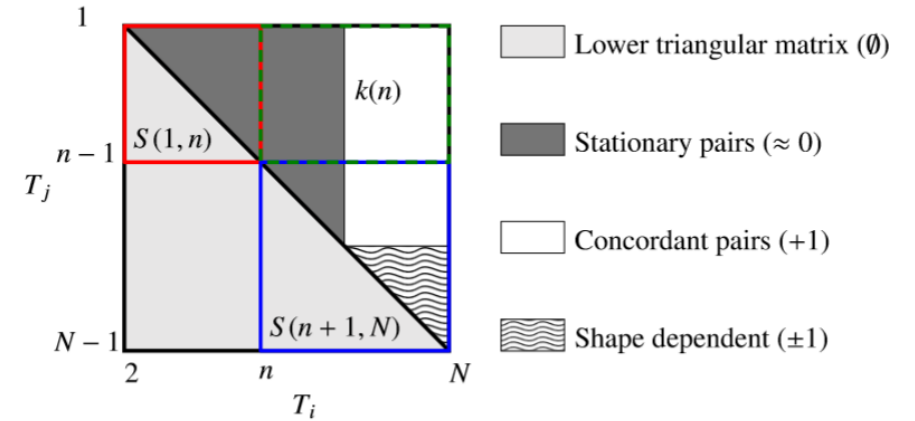
[2] H.B. Mann, Nonparametric Tests Against Trend, *Econometrica*. 13 (1945) 245–259. <https://doi.org/10.2307/1907187>.



# 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

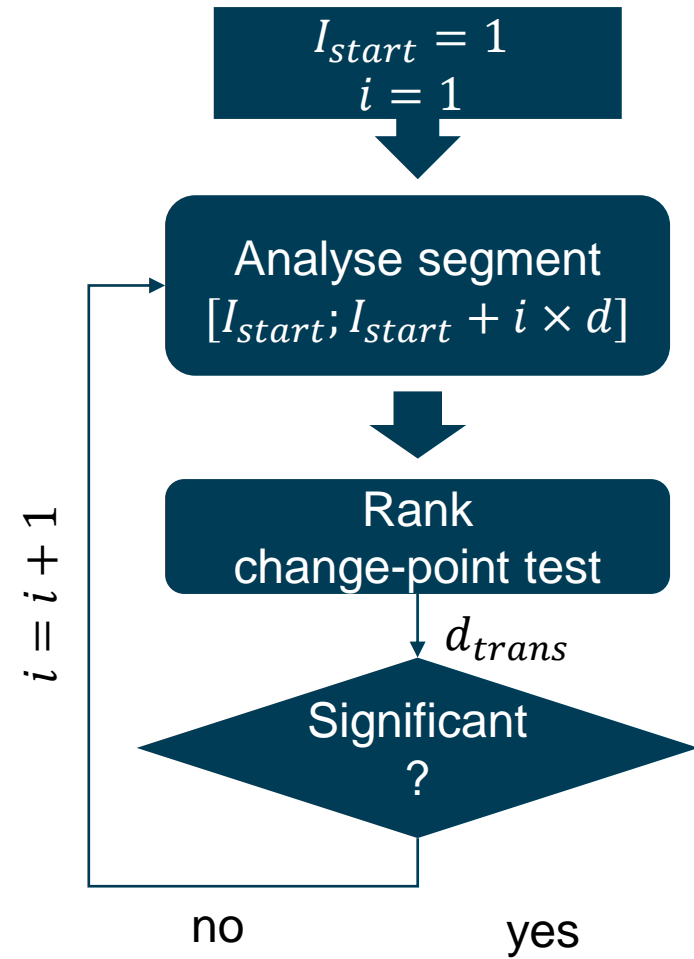
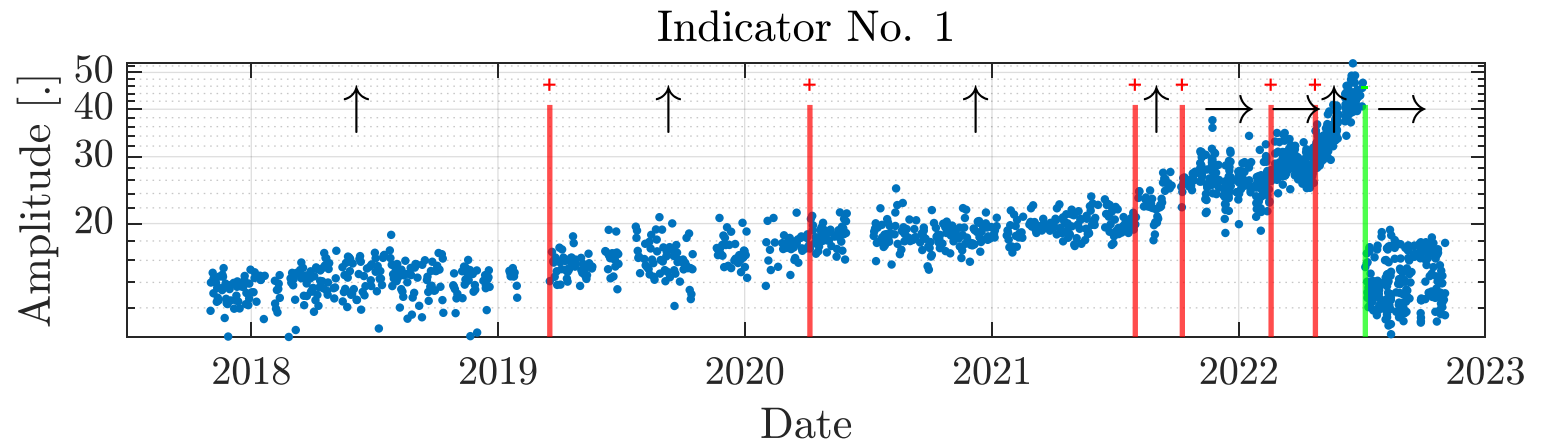
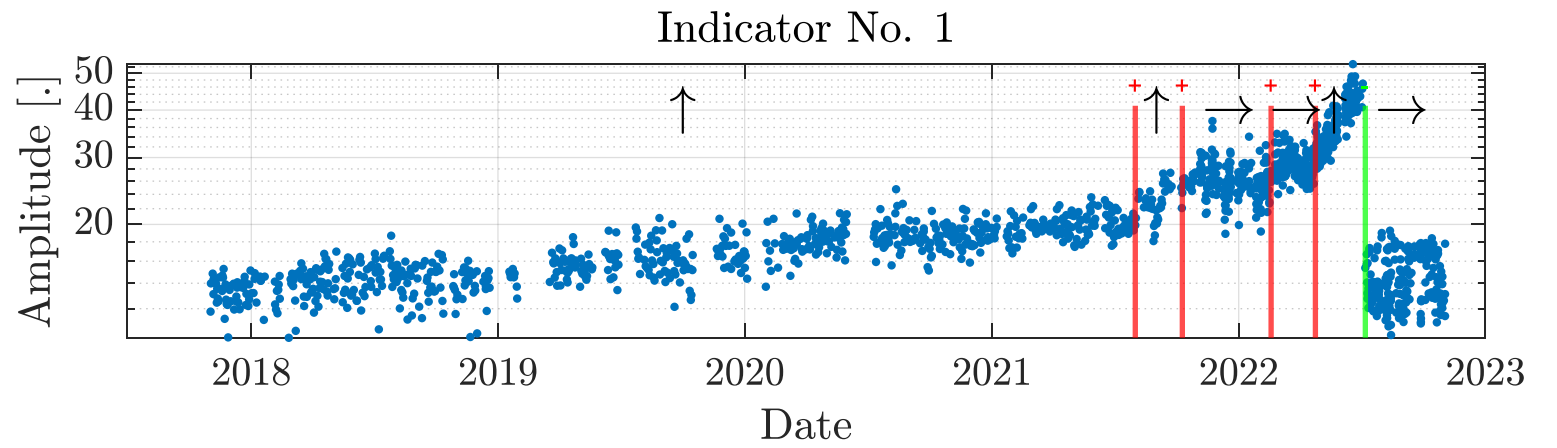
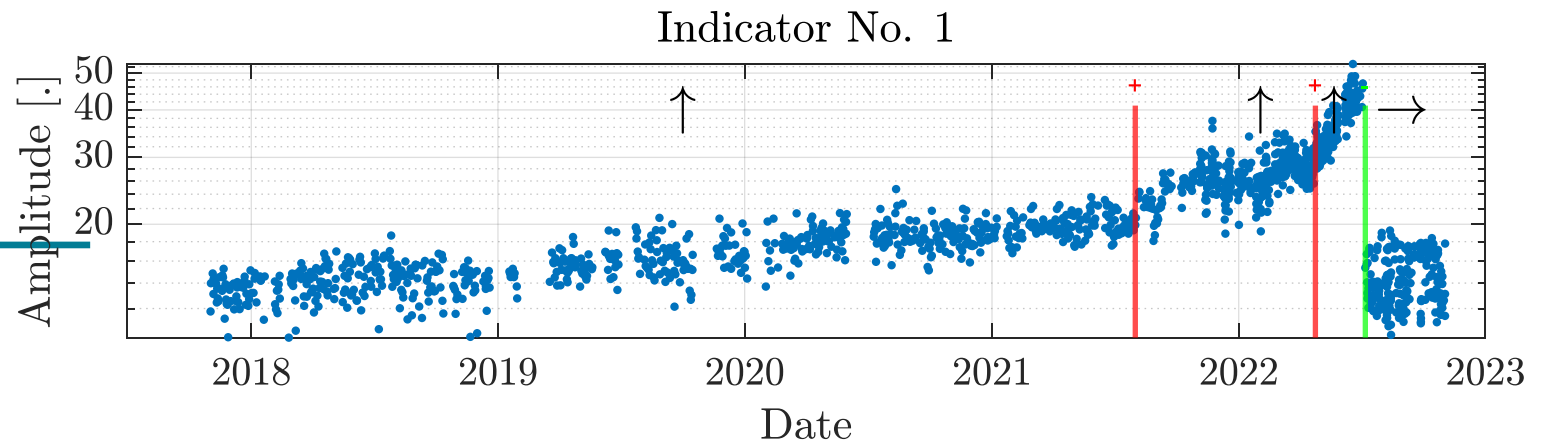
$$K = \max_{1 \leq n \leq N} (|k(n)|), \quad (7)$$

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

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

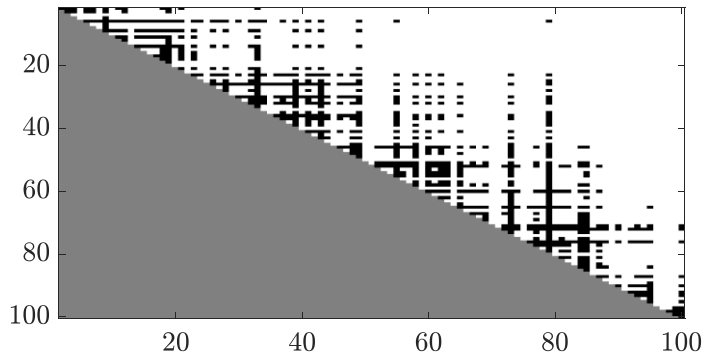
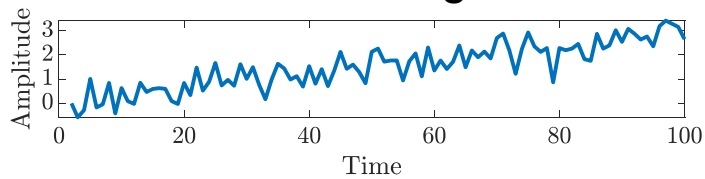
Variance of the sum is

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

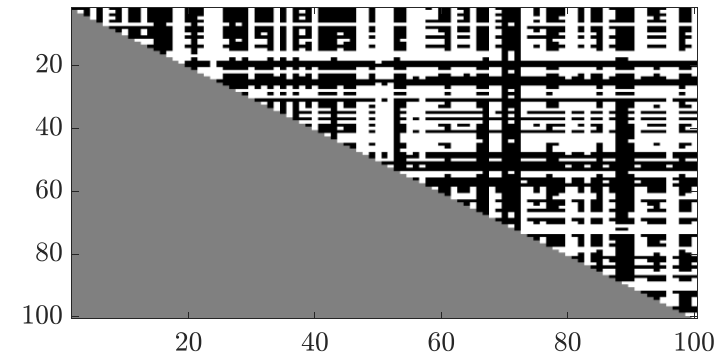
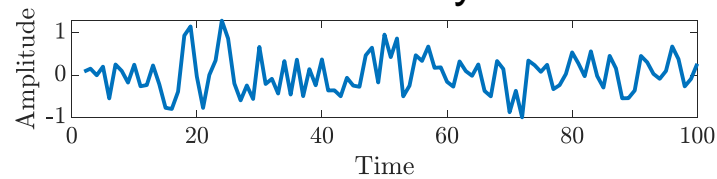
With null mathematical expectation

Deviation from gaussian

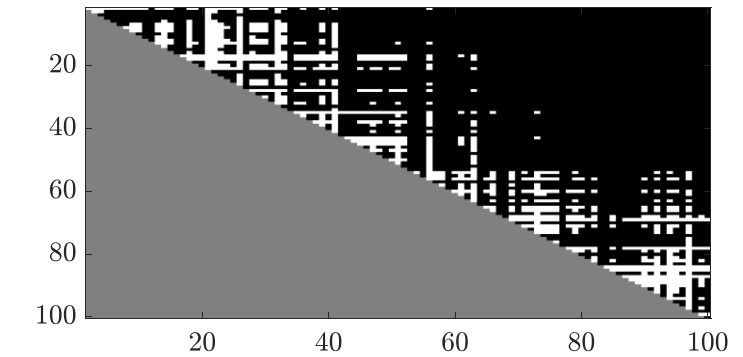
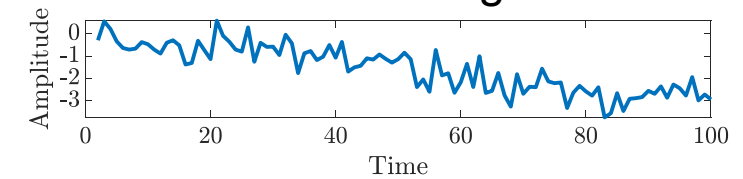
Increasing



Stationary



Decreasing



Statistically more +1 pairs

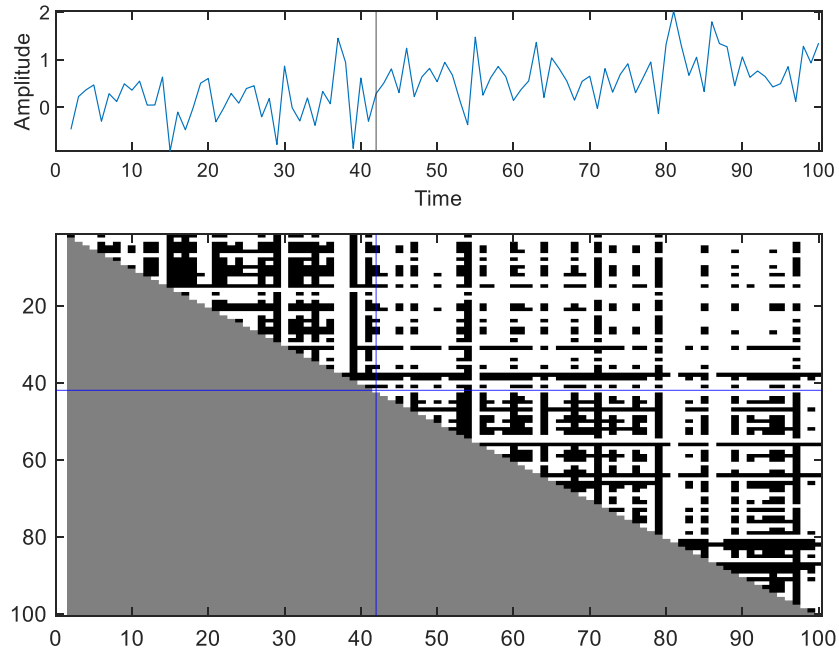
Statistically equal +/-1 pairs

Statistically more -1 pairs

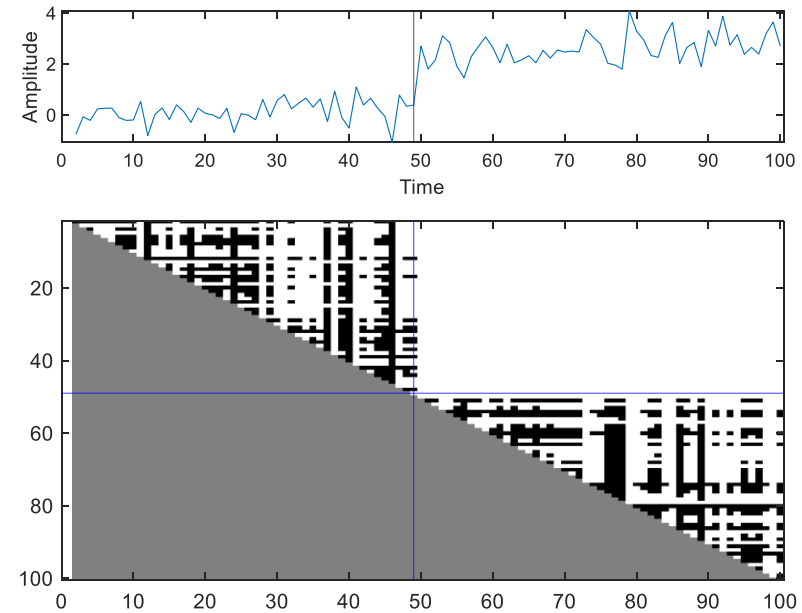
# The issue of increasing trends

- Pettitt test : detection of change in median

Linear increase + noise



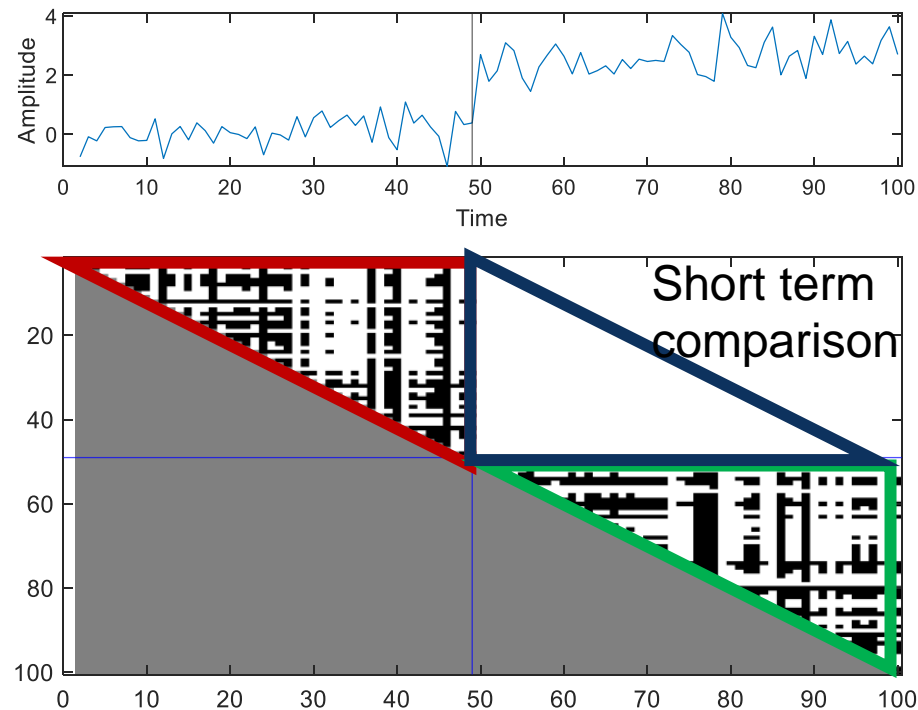
Linear increase + step



How to differentiate the two ?

# The issue of increasing trends

- Pettitt test : detection of change in median

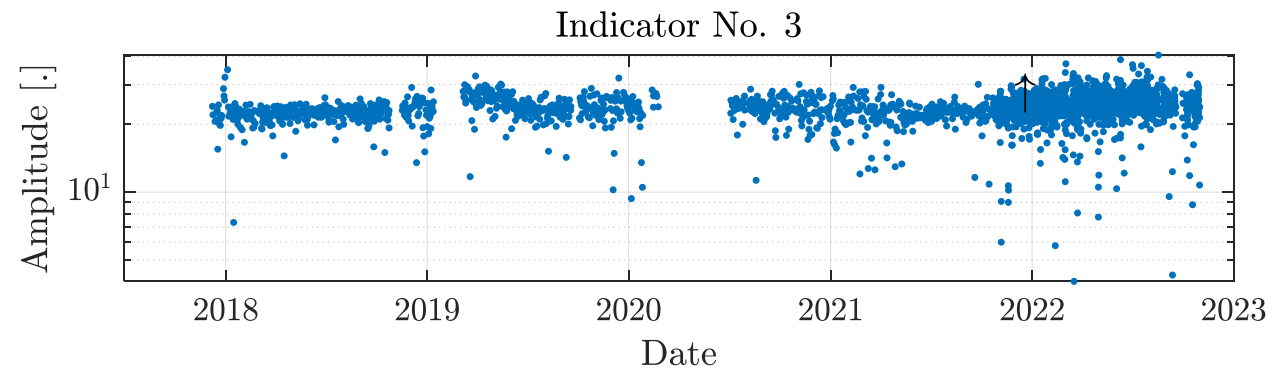
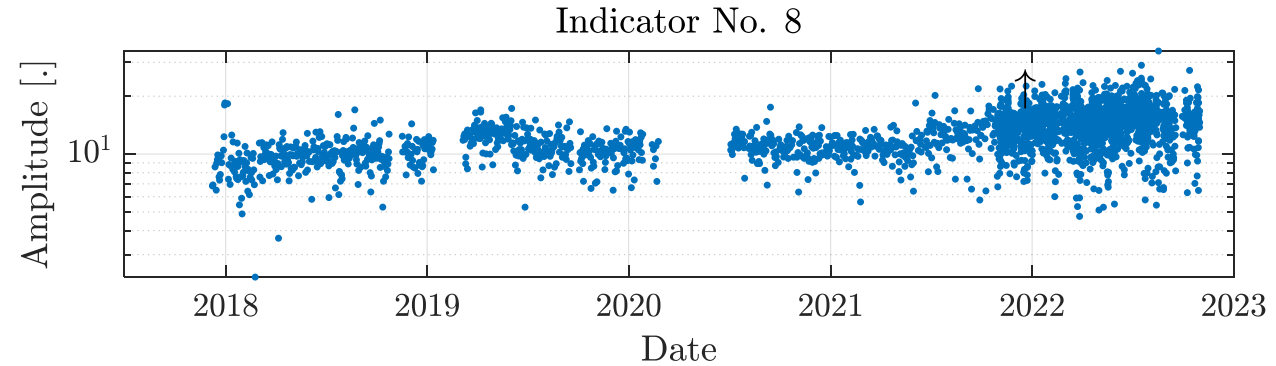
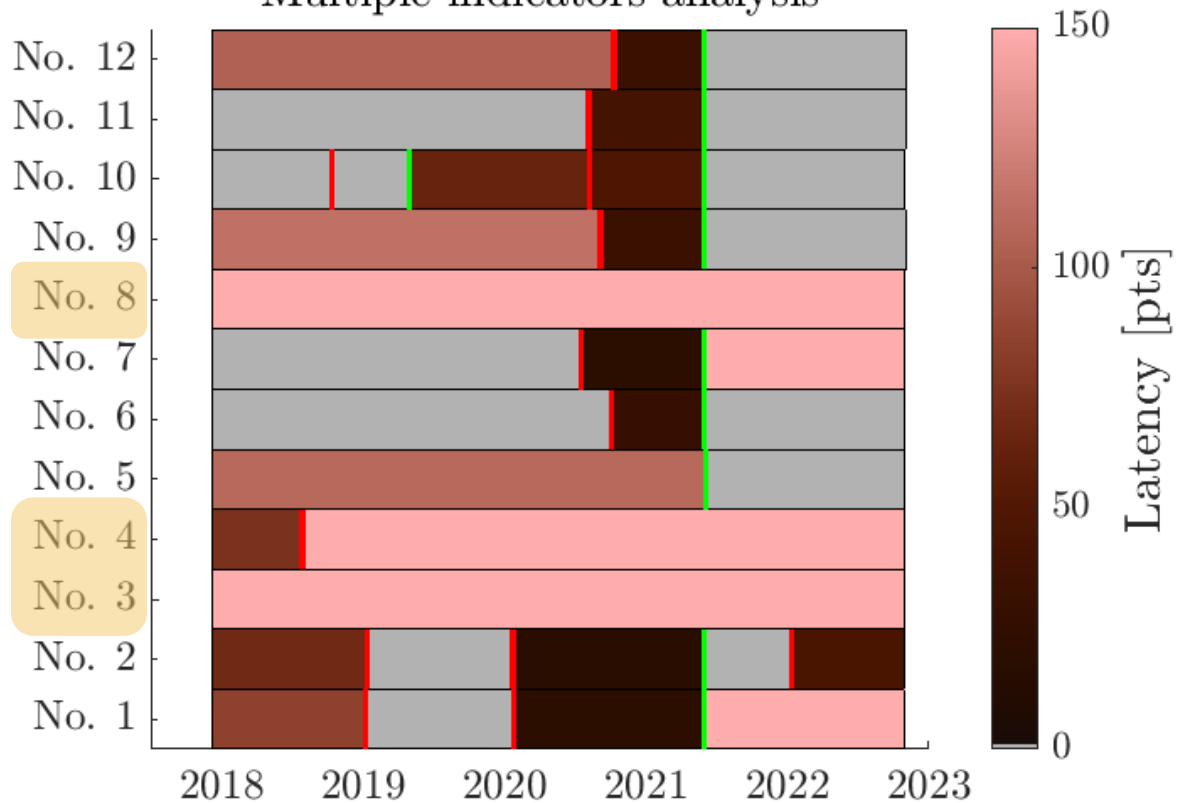


Criteria on rank correlation

# Global surveillance and industrial application

## Segmentation on multiple indicators

Multiple indicators analysis

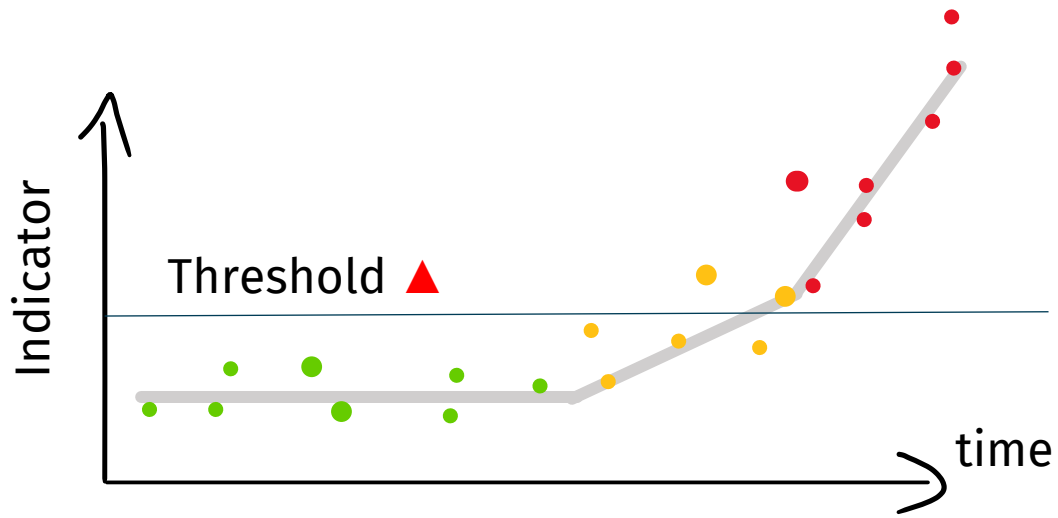


Non significant episodes

High latency

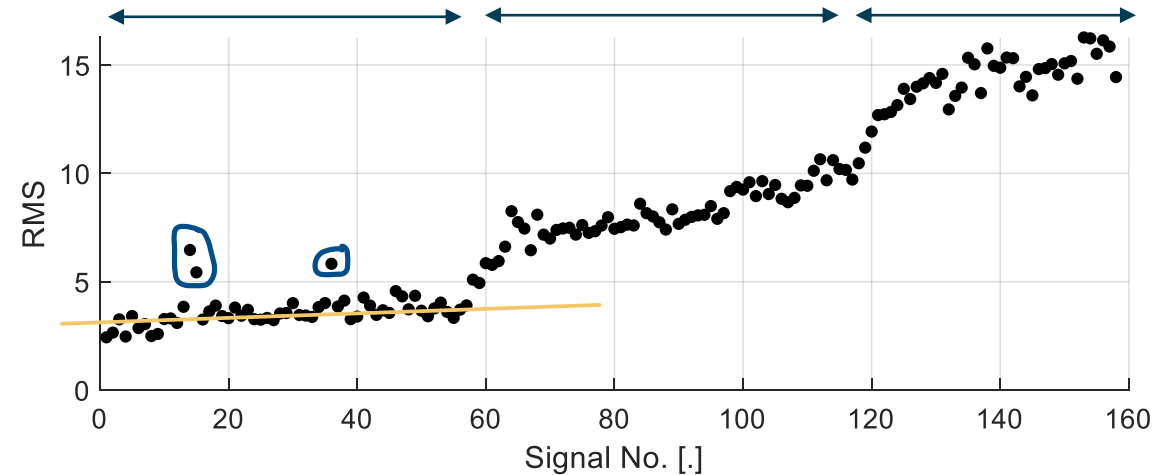
# Context on condition-based maintenance

## 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