Fault detection in ultra-low temperature freezers

Seminar on Digitalisation of Refrigeration and Heat Pump Systems

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Background

Ultra-low temperature freezers / Ultra-sensitive products

- Biological samples
- Vaccine

Temperature-sensitive products

- Maintaining temperatures between -60°C and -86°C is essential for sample integrity.
- Failure to detect faults can lead to sample loss and significant financial and scientific setbacks.

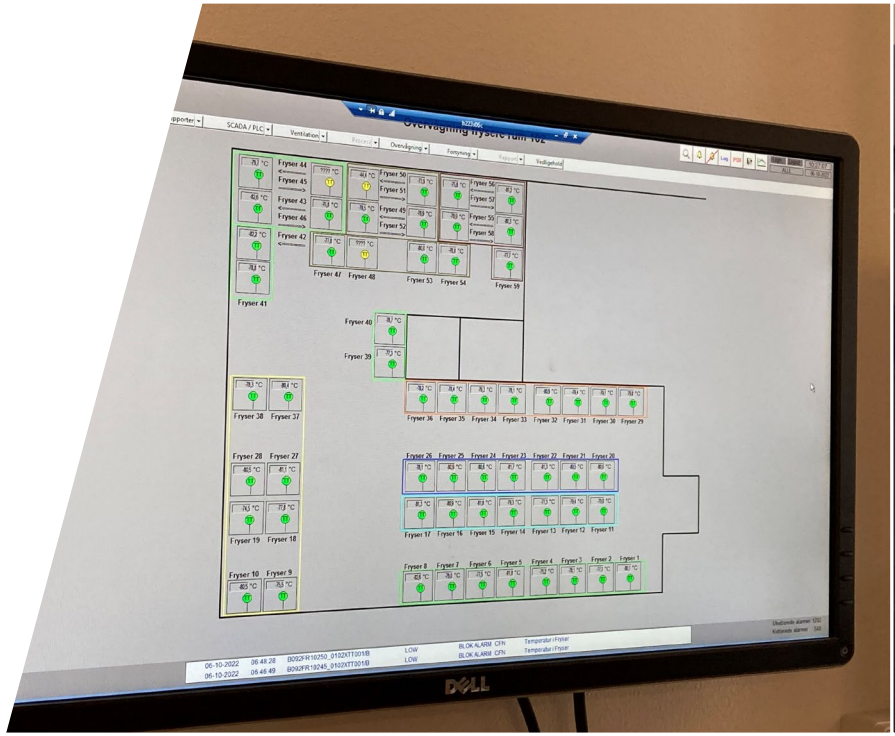
Background

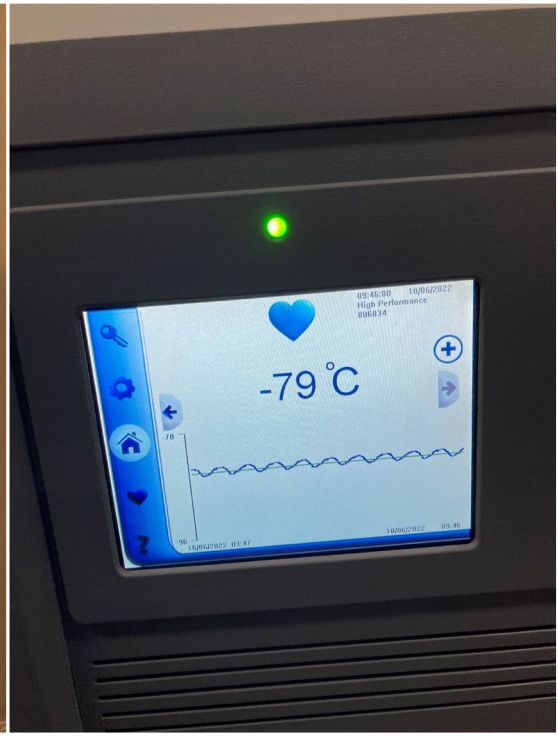
Surveillance systems

- Monitor freezer temperature
- Flag alarms
- Visual inspection of temperature profiles

Untapped potential…

- Most data is not exploited
- Monitoring limited to internal temperatures
- Limited automation

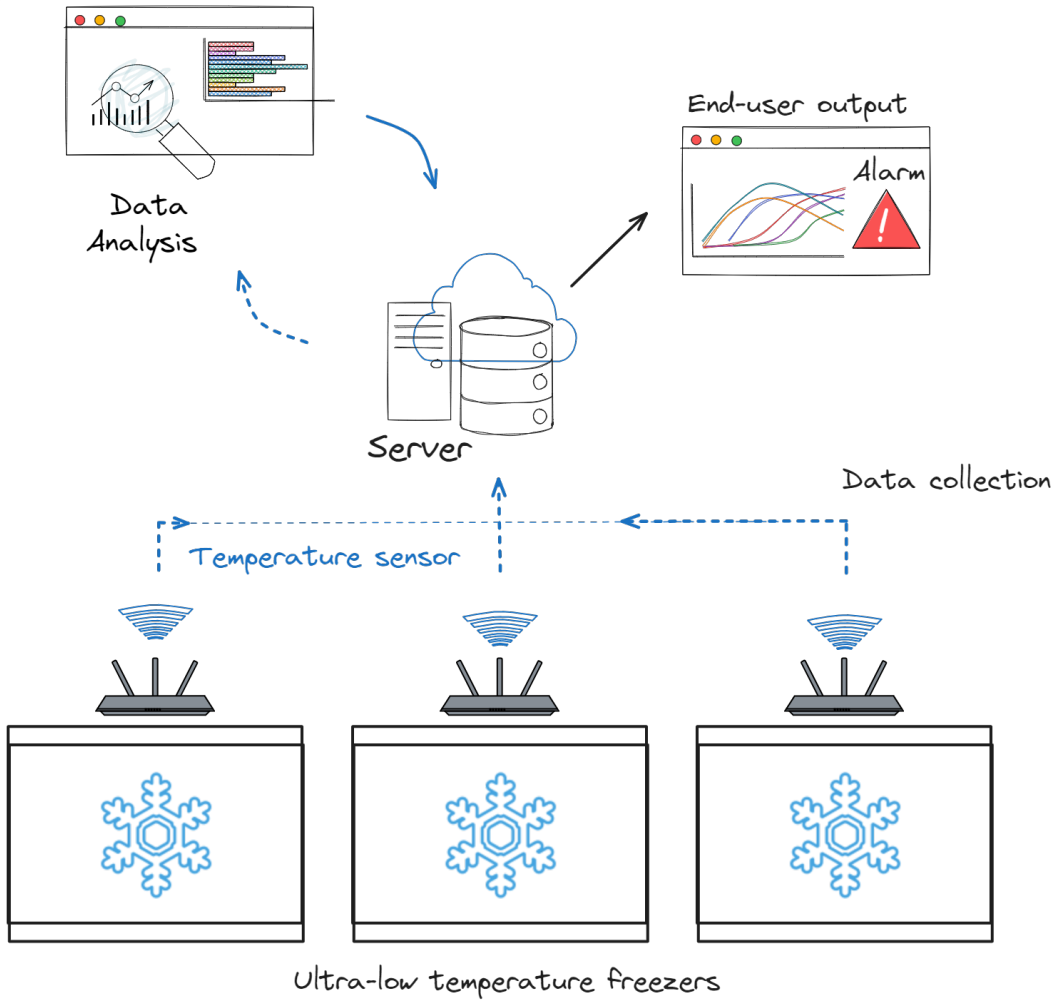




Digital Oracle for ULT freezers- EUDP

Cloud-based surveillance system for ULT freezers (*Digital Oracle*) to transform large amounts of data into simple recommendations to:

- avoid inappropriate use of freezers
- detect the need for maintenance
- save energy



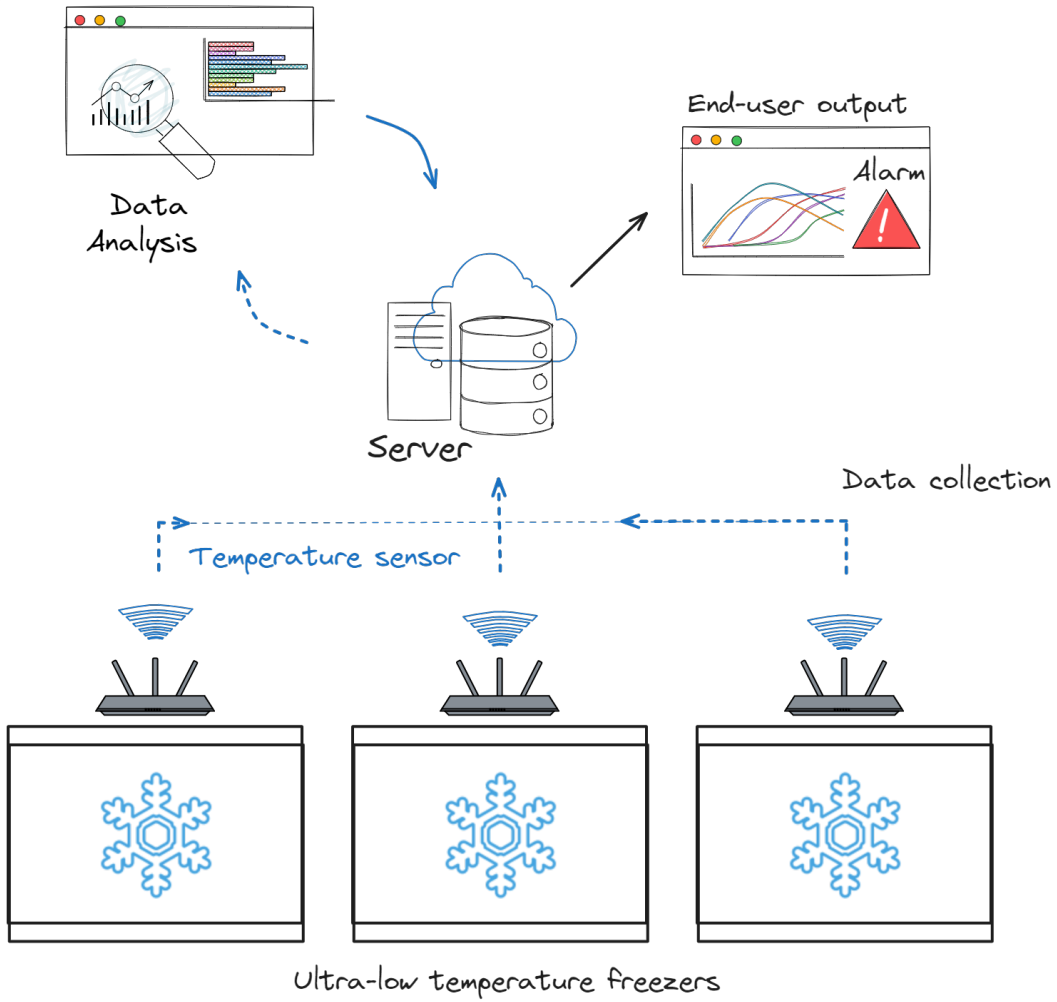
Digital Oracle for ULT freezers- EUDP

Data source
- *Region Sjælland Biobank*
- *Statens Serum Institut*
- *Elcold*

Data collection
Hardware for automatic data collection
- *LH Laboratorie Service*

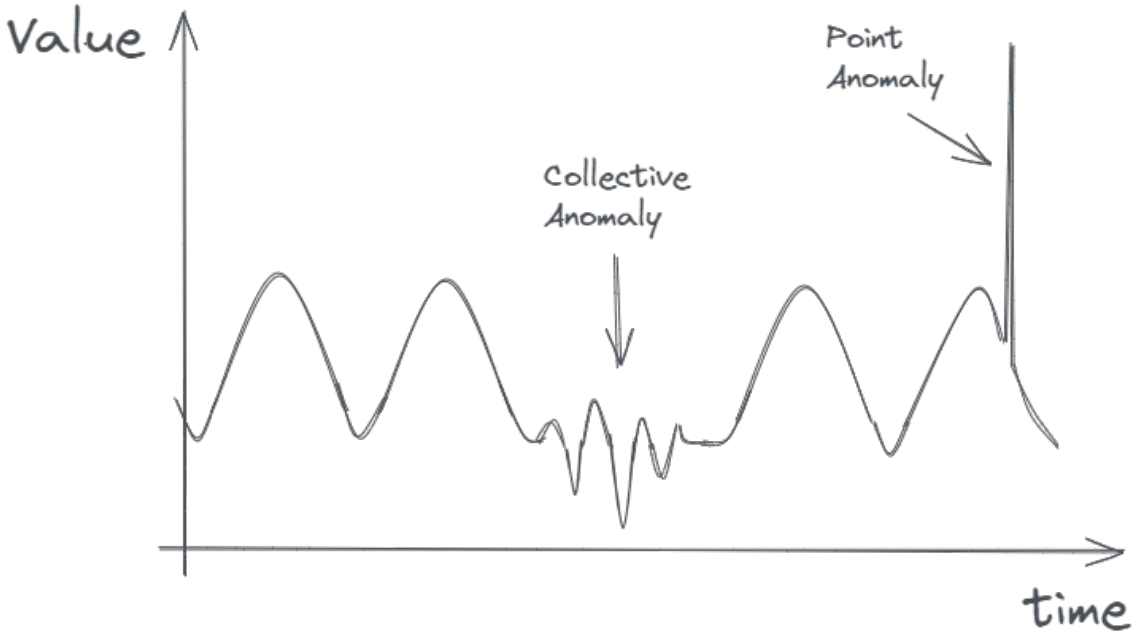
Data storage/sharing
Cloud-based solution for data storage/sharing
- *Schneider Electric*

Data analysis
Data analysis and algorithm development
- *DTU Compute*
- *Danish Technological Institute*



Anomaly detection

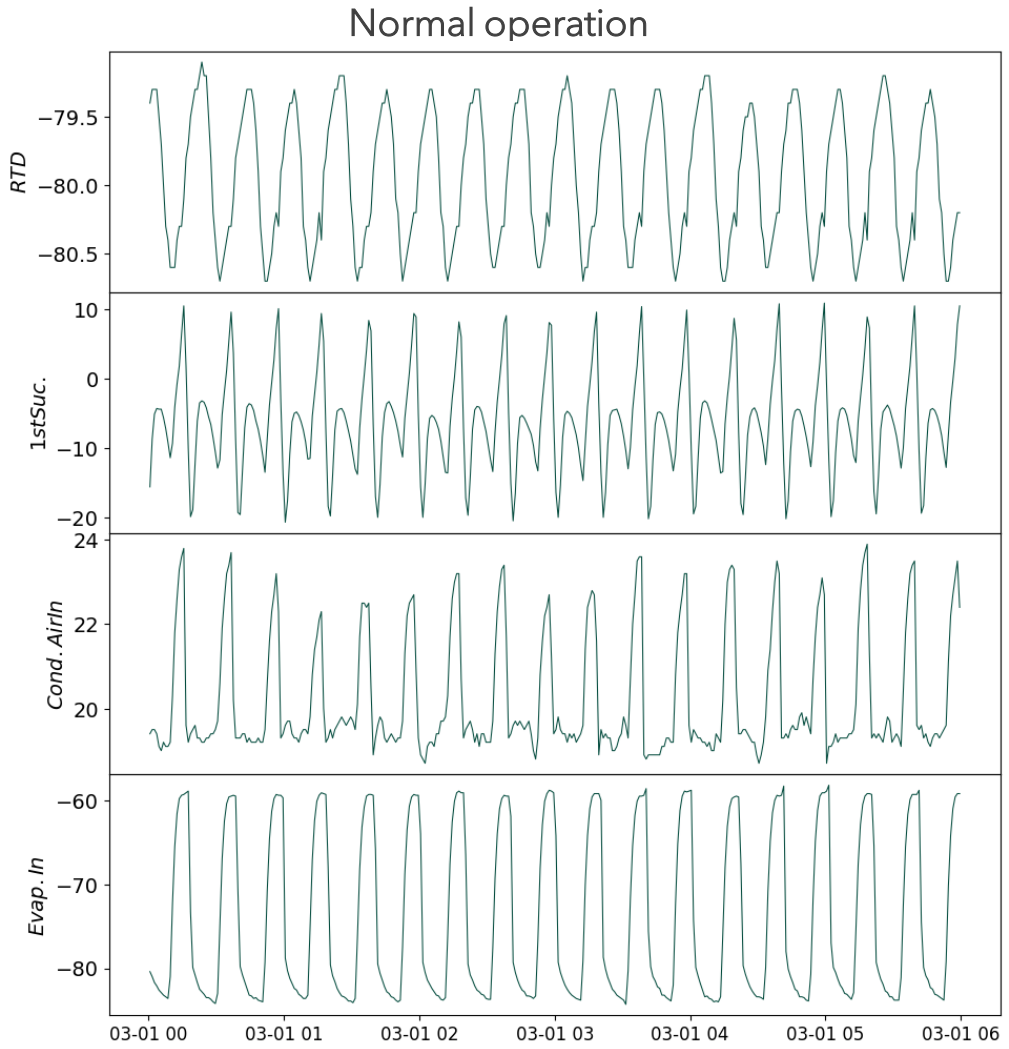
Identification of items, events or observations which do not conform to an expected pattern or other items in a dataset.



Anomaly detection

Identification of items, events or observations which do not conform to an expected pattern or other items in a dataset.

Repeated cyclic patterns under normal operating conditions.



Anomaly detection

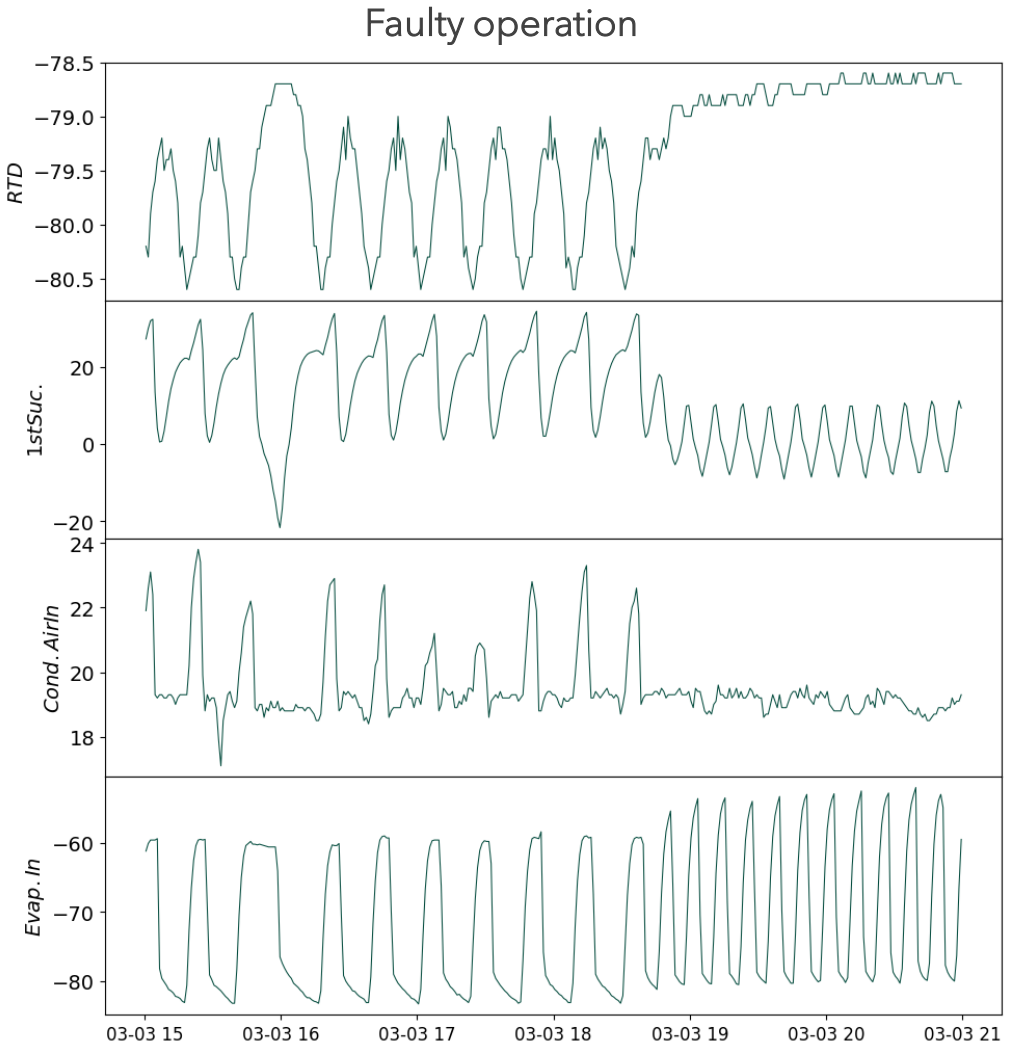
Identification of items, events or observations which do not conform to an expected pattern or other items in a dataset.

Repeated cyclic patterns under normal operating conditions.

Patterns disruption under faulty operating conditions.

Variation in both:

- Trend
- Cyclical component



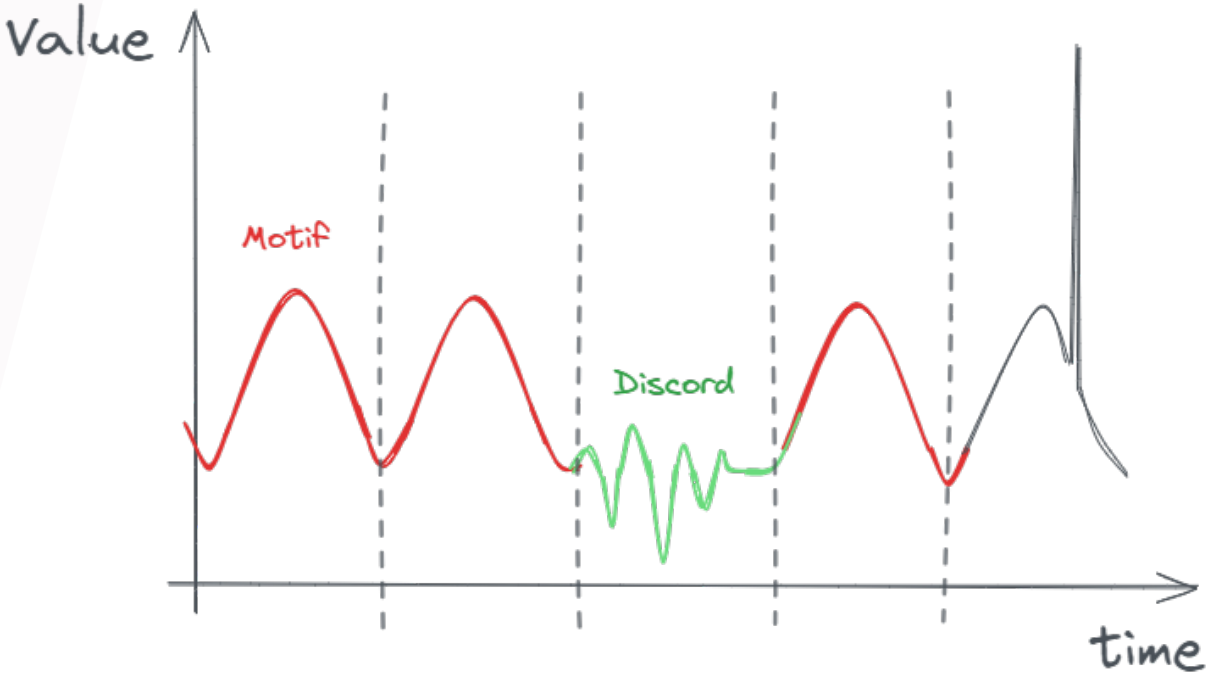
Anomaly detection

Contextual Matrix Profile (CMP)
Pattern recognition algorithm that performs all-similarity-join-search among timeseries.

CMP consists in scanning the entire time series to find:

Motifs: repeated (or very similar) patterns.

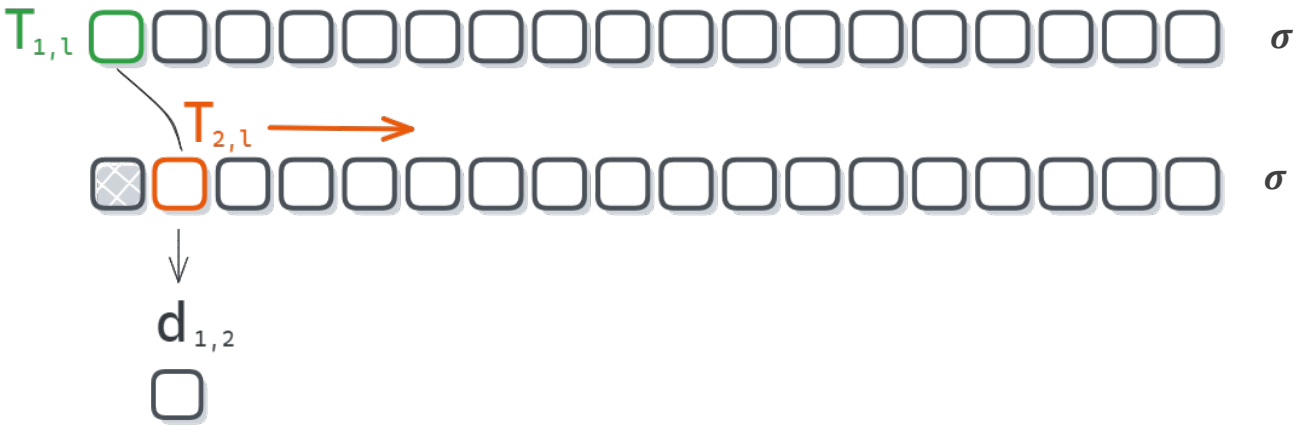
Discords: subsequences that differ from other subsequences in the time series (could be interpreted as a detected anomaly).



Anomaly detection

STEP 1

Given a query subsequence ($T_{1,l}$) and a distance metric (d), we can calculate the distance between the query and each subsequence in the subsequence set $\boldsymbol{\sigma}$.



$$d(i,j) = dist(T_{i,l}, T_{j,l}) = \sqrt{(T_{i,l} - T_{j,l})^2}$$

Anomaly detection

STEP 2

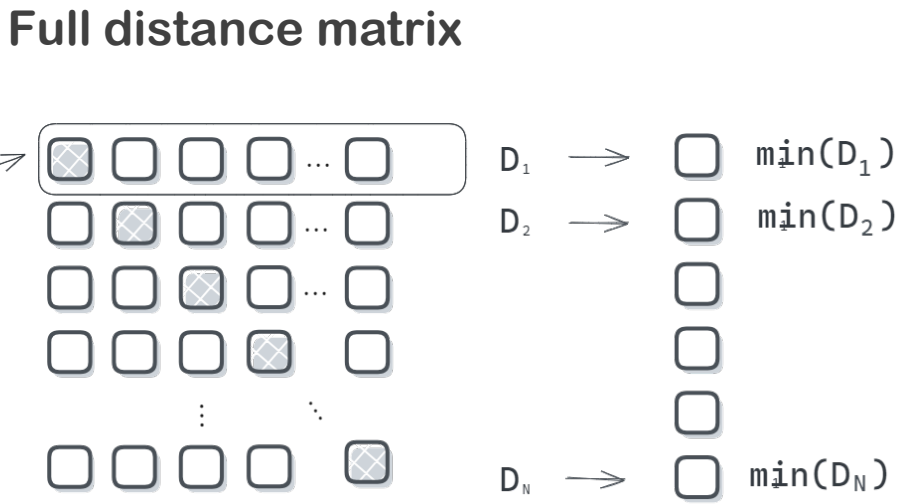
This results in a vector of distances D called Distance Profile.

$$D_i = [d(i,1), \cdots, d(i,j), \cdots, d(i,N)]$$

Anomaly detection

STEP 3

Determining the distance profile for each subsequence in the subsequences-set σ results in the so-called full distance matrix (*DM*).



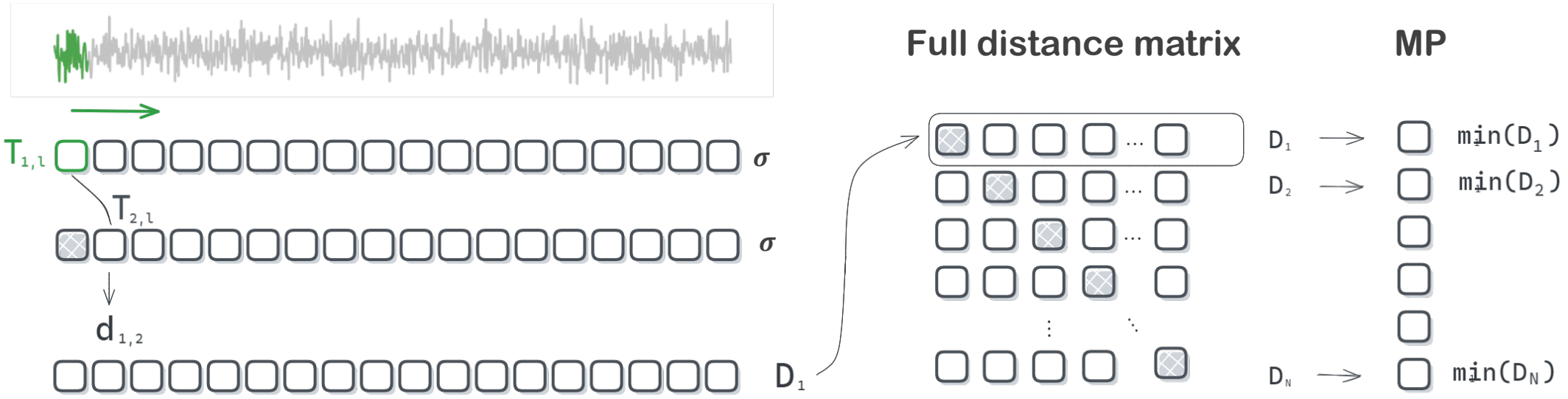
Anomaly detection

STEP 4

Define the matrix profile (MP) as the vector that stores the minimum distances between each subsequence and its nearest neighbour.

The matrix profile value gives a measure of subsequence similarity. If the value is:

- very low at some time index, then it means that somewhere else in the time series the subsequence is very similar.
- if the value is high, it means that the pattern is very atypical and represents a kind of anomaly in the data.



Case study: Biobank data

Statens Serum Institute

Data from 53 ultra-low temperature freezers

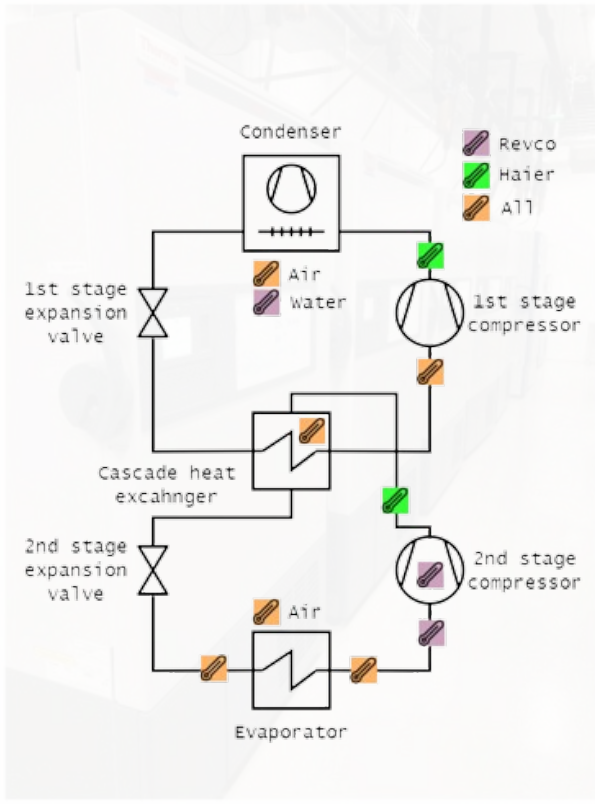
- 10 years 1 minute-wise data
- Temperature data
- Event data
- Service reports

Data publicly available on Nature scientific data:

GitHub

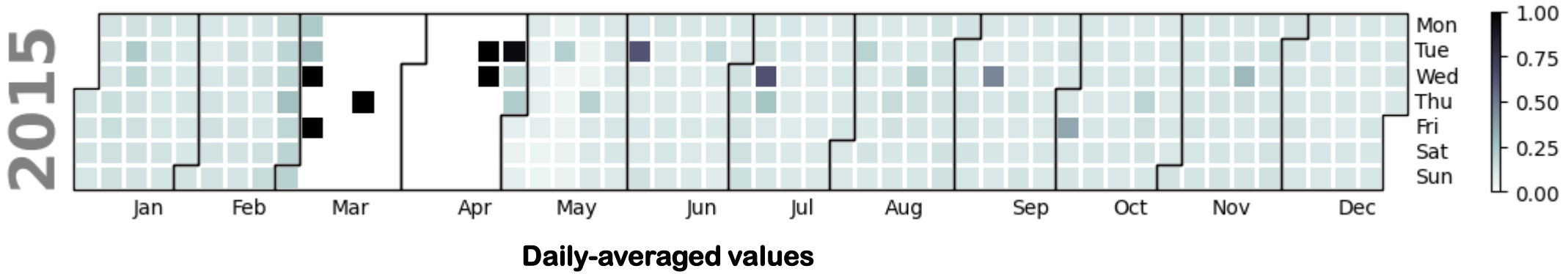
Huang, T. *et al.* *Labelled dataset for Ultra-Low Temperature Freezer to aid dynamic modelling & fault detection and diagnostics*. *Sci Data* **10**, 888 (2023). https://doi.org/10.1038/s41597-023-02808-6

Link to dataset



Case study: Biobank data

Matrix profile applied to internal temperature data (RTD sensor)



Batch processing of one year of historical data

*S*ub-sequence parameters:

- ***Starting index:*** *compressor turn-on*
- **Length:** duty cycle length

Case study: Biobank data

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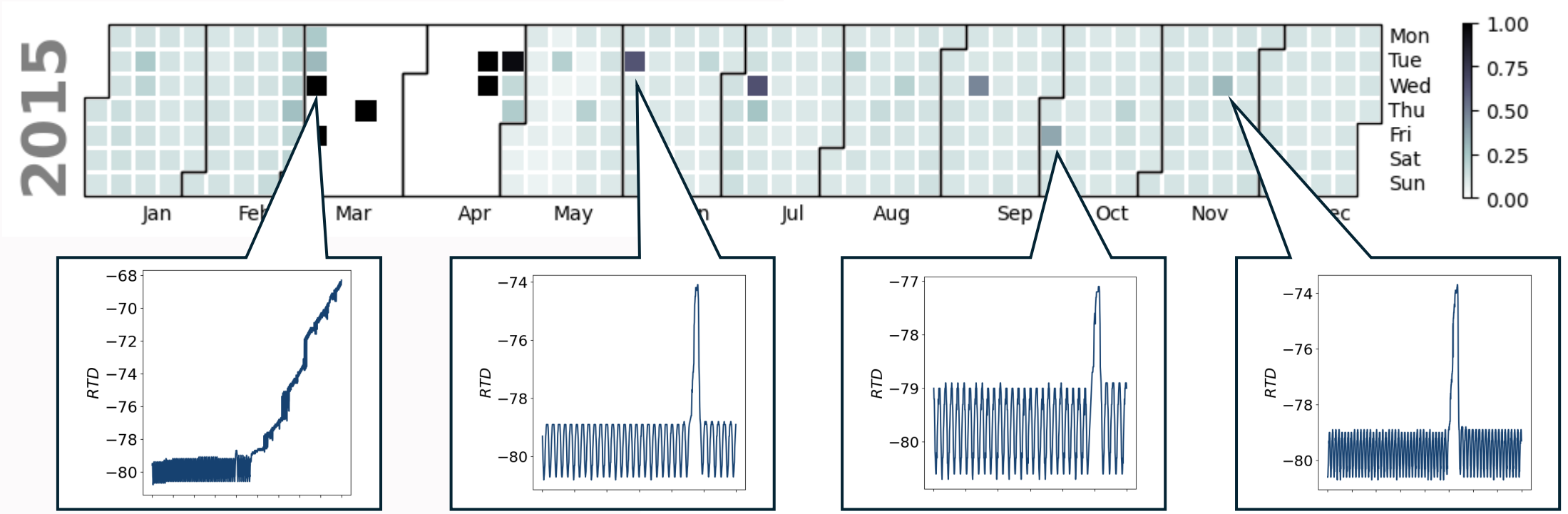

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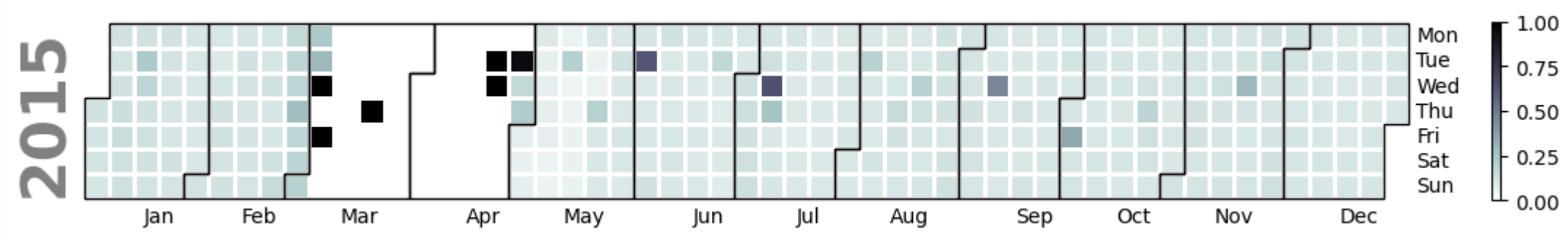


Inter quartile range analysis to define anomalous observations:

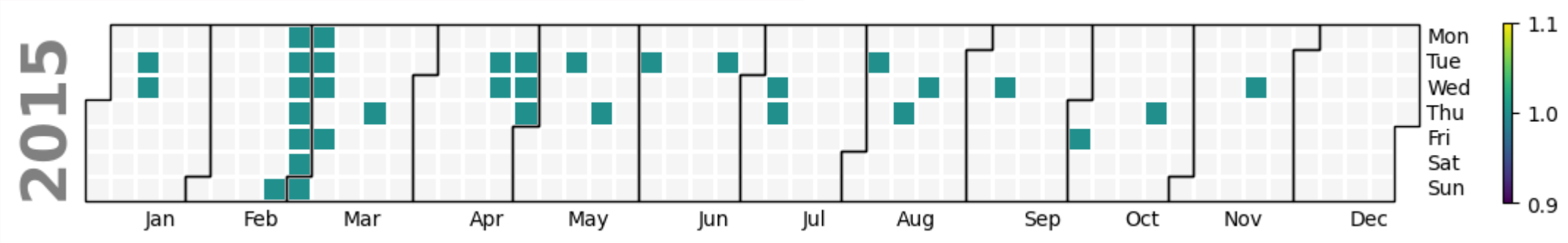
Any value that falls above Y is classified as an anomaly

Threshold = Q_3 + 1.5IQR

Q_1 = 1st quartile
Q_3 = 3rd quartile
IQR = Q_3 – Q_1

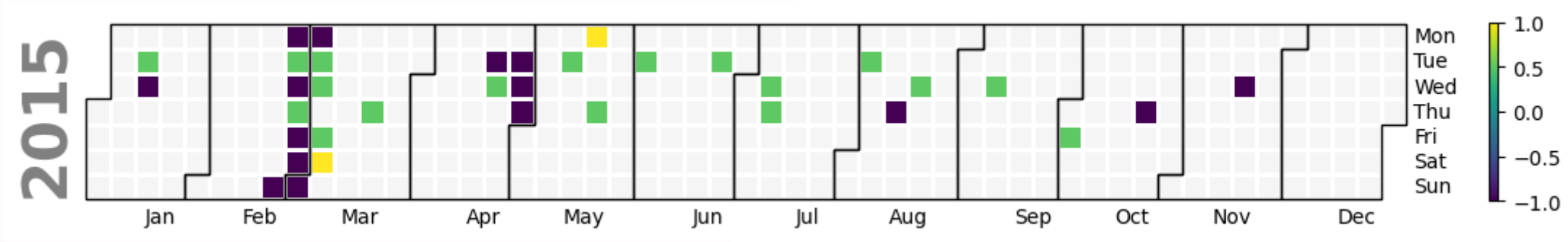
Case study: Biobank data

Anomalies filtered based on the inter quartile range analysis.



Case study: Biobank data

Comparison between predicted anomalies and actual alarm events (event log)´.

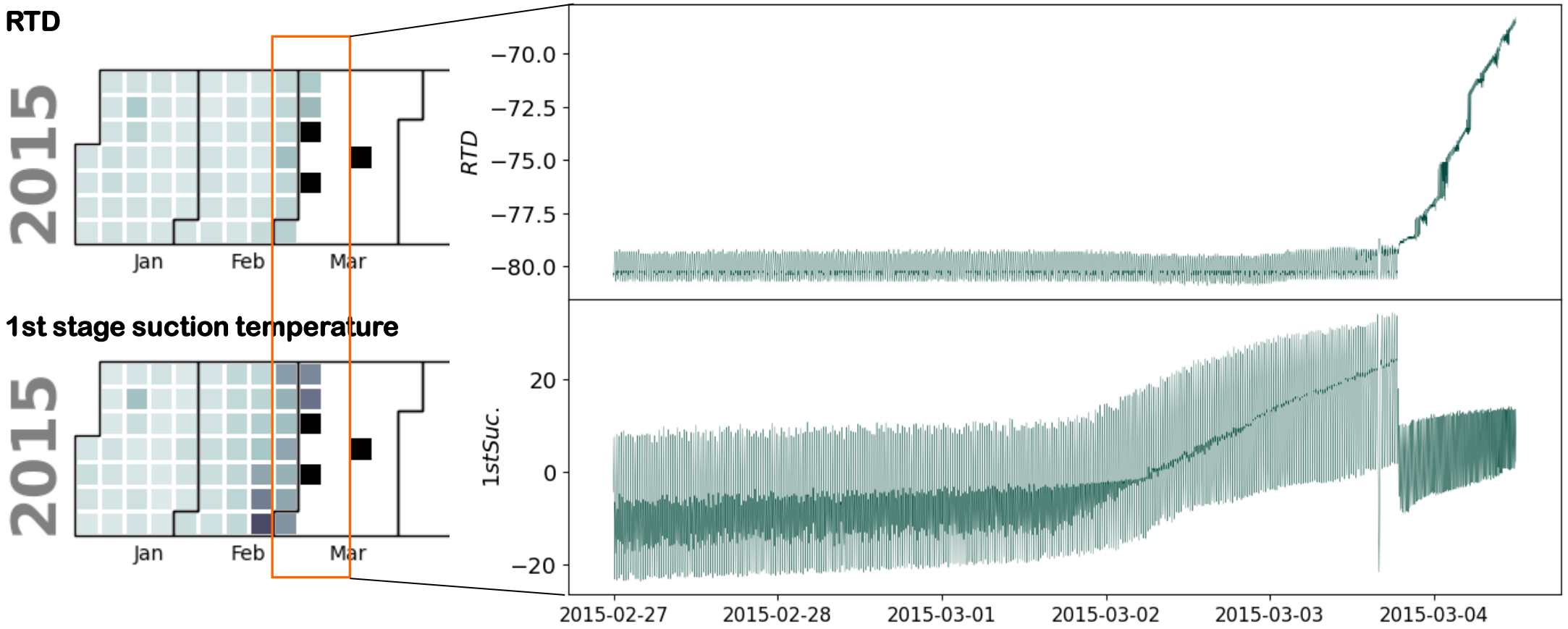


TN 318	FP 15
FN 2	TP 18

Accuracy: 0.95

Precision: 0.55

Case study: Biobank data



Conclusions

- Fault detection algorithm based on the application of the so-called Matrix Profile to identify abnormal patterns in freezer operation.
- MP is an unsupervised learning method that makes no assumption about the data: *simple, intuitive, highly scalable, transferable, and reduce the risk of overfitting ↔ physical interpretability*
- Successfully tested on offline temperature data from different ULT freezers.
- Provide guidelines for simple "rule-based" for system monitoring and predictive maintenance.

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Case study: Controlled failure tests

Elcold ULT freezers

Experimental tests:

- Normal operation
- Loading
- Frequent lid openings
- Lid not properly closed
- Fan damaged/unplagged
- Dirty condenser

Case study: Controlled failure tests

Lid not properly closed