Challenges for Industrial Control Systems

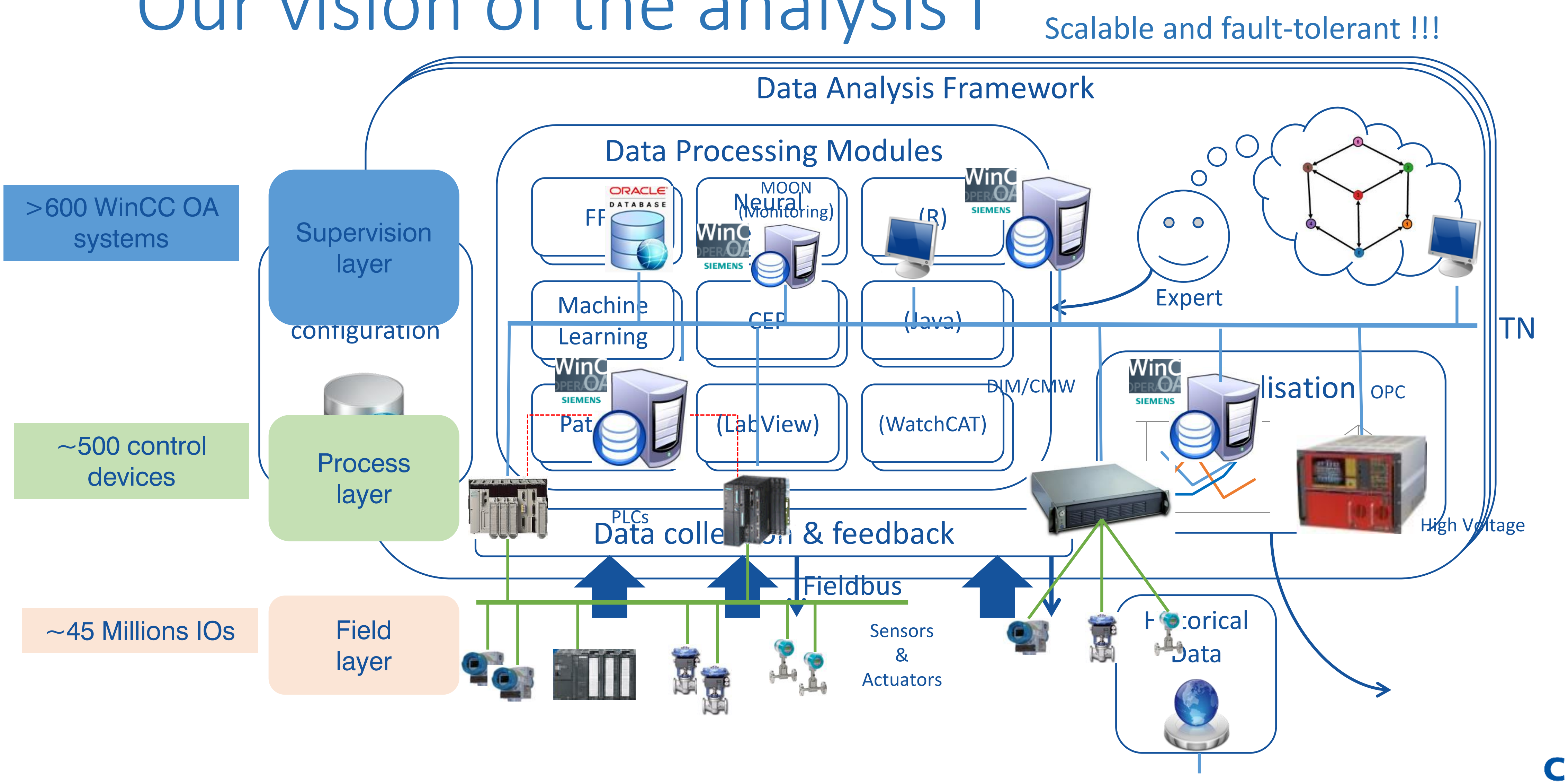
CERN openlab Machine Learning and Data Analytics workshop

29 April 2016

Axel Voitier
Filippo Tilaro
Manuel Gonzalez Berges

With input from many CERN colleagues

Our vision of the analysis framework



Main expected features

- **Integration with CERN control system**
- **Scalability**
  - Scale the computation load across several hosts (OpenStack VMs)
  - Distributed storage for temporary results
- **Merging events and numerical data analysis**
  - Predictive trending
  - Temporal reasoning (CEP)
  - Statistical Analysis
- **Possibility to prototype additional plug-ins and algorithms**
  - Agree on a general API for new algorithm definition and integration
  - Integration with ‘R’
  - Data analysis flow definition in building blocks
- **Reporting**
  - Graphical visualization of huge list of signals/results
  - Interface to provide feedback to external systems (i.e.: WinCC OA)
- **Conversion into a Service**
  - On-line mode for continuous control system monitoring over custom time-windows
  - Support for historical analysis
- **Data management**
  - Different sampling rates / gap
  - Custom data model (i.e.: temperature in K/C)
  - Custom data access (i.e.: vector vs sequence)

CERN control system use-cases

Based on real examples

Use-cases classification

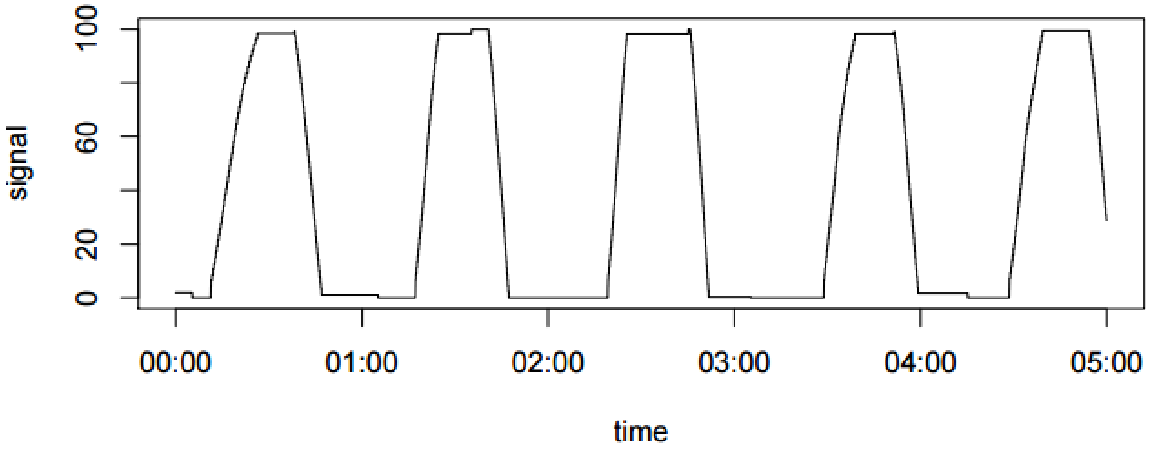
- **Online monitoring**
  - Continuous service to analyse the system status and inform operators in case of fault detection
- **Fault diagnosis**
  - "Forensics" analysis of system faults that have already happened in the past. In some cases root-cause analysis
- **Engineering design**
  - Analysis of historical data to draw conclusions about system behaviours which could be helpful to improve / optimize the system under analysis

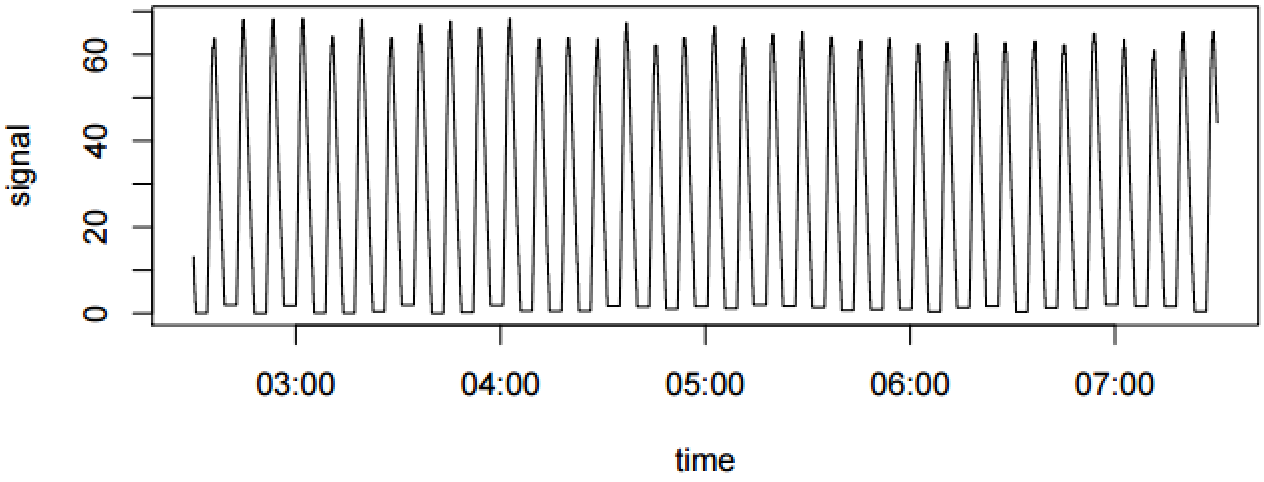
Online monitoring

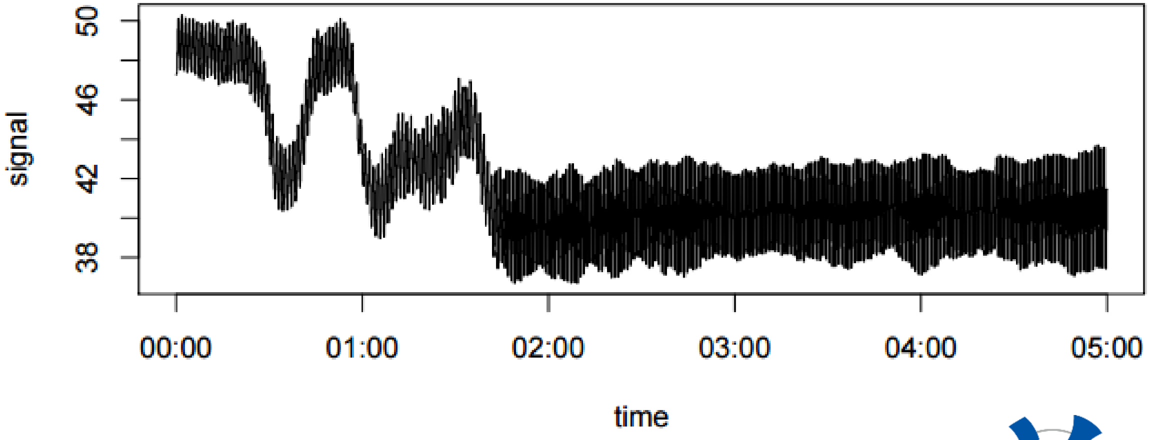
- Oscillation analysis in cryogenics valves (CRYO, CV)
- Online analysis of control alarms (MOON)
- LHC dashboard (CRYO)

Oscillation analysis for cryogenics valves

- Goal: detect whenever a signal is oscillating in any anomalous way. Impact on:
  - Control system stability
  - Increased communication load
  - Maintenance (use of actuators)
  - Safety
  - Performances (Physic time)

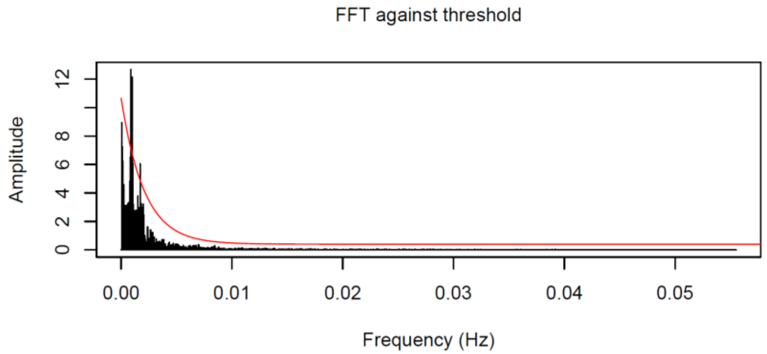


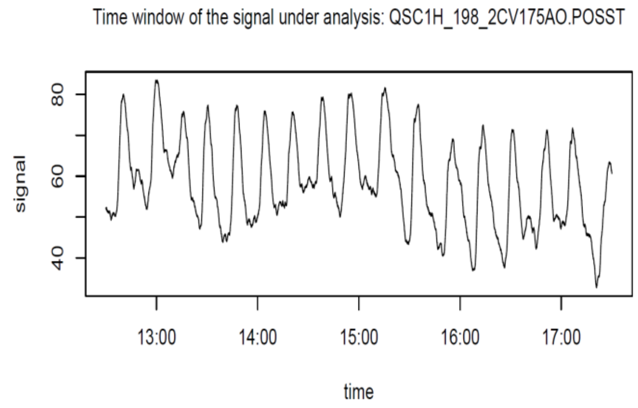


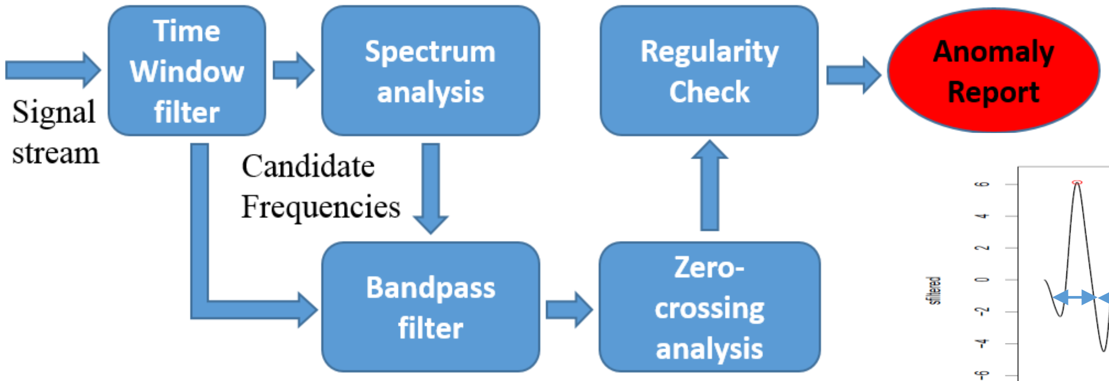


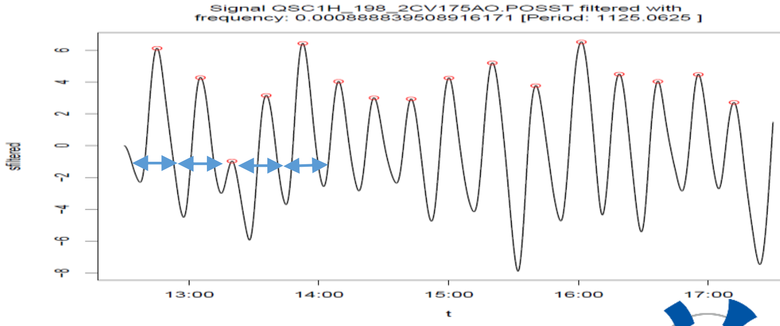
Oscillation analysis flow

- Use of machine learning:
  - Threshold learning model
  - Dynamic learning
  - Associate the oscillation with system status conditions
- On-line analysis:
  - > 3000 sensors
  - Continuous analysis

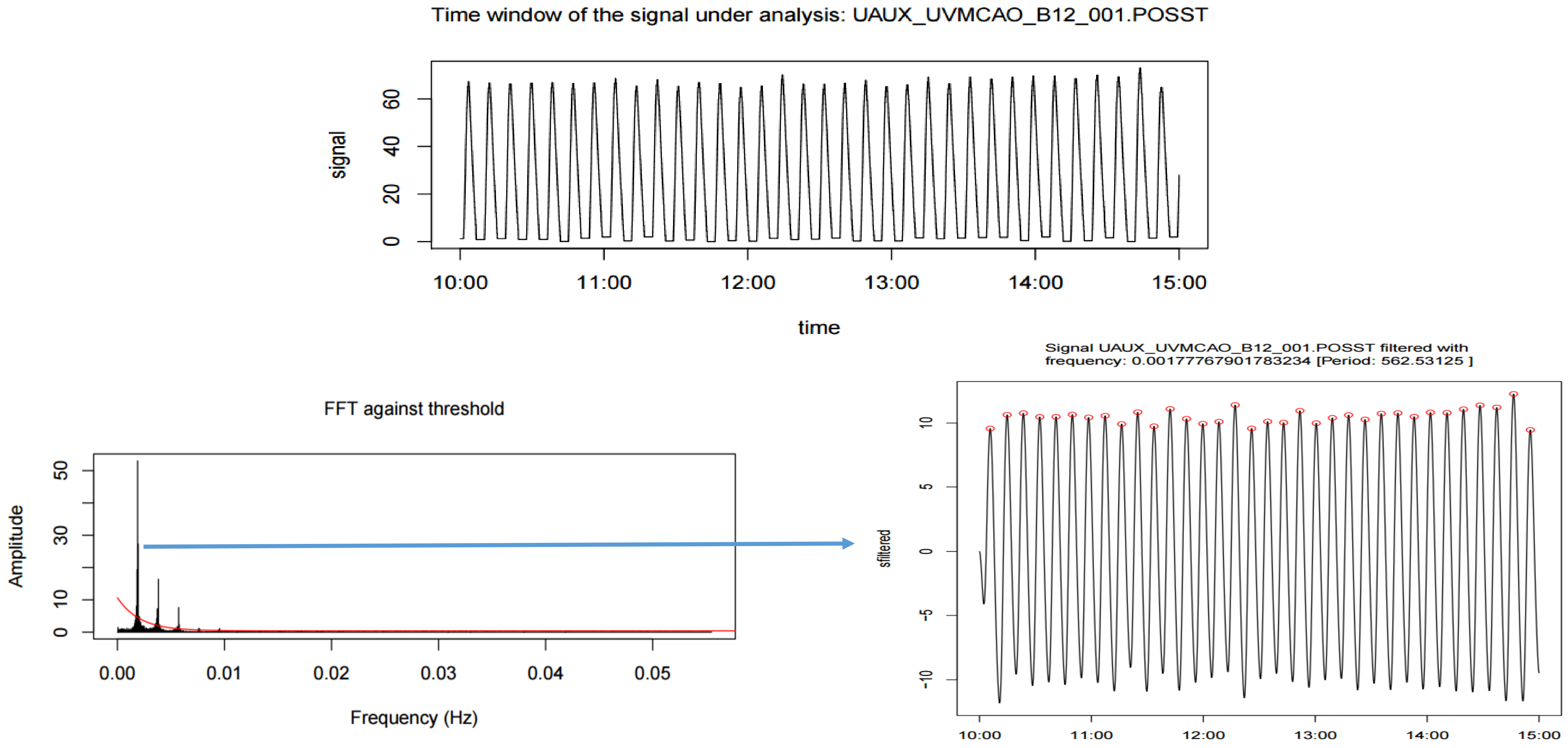




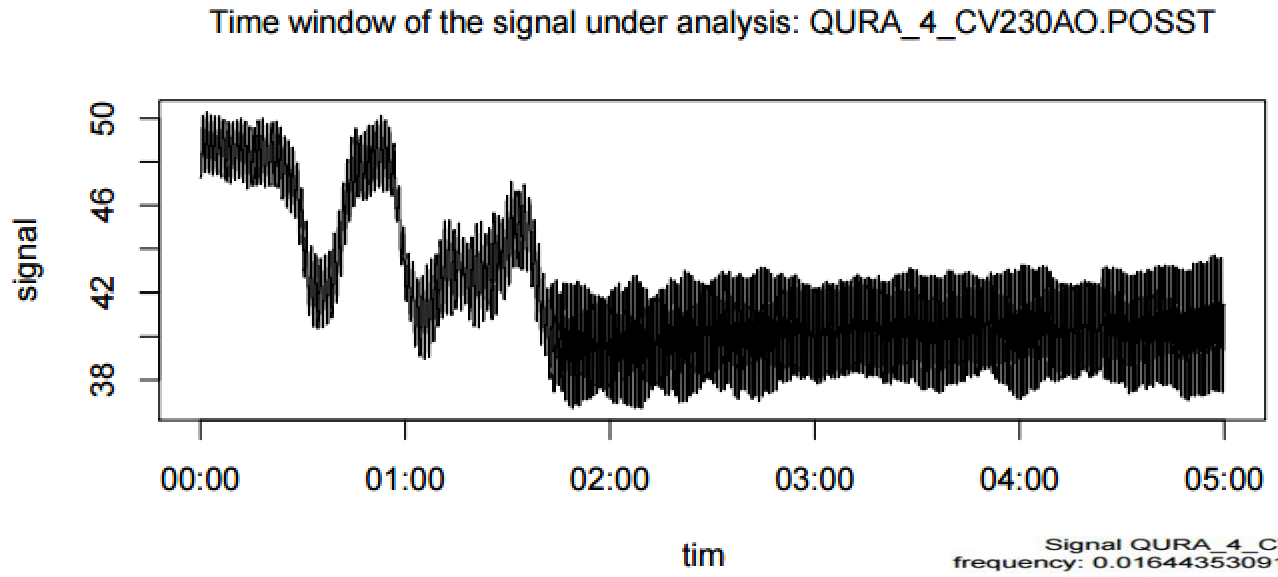


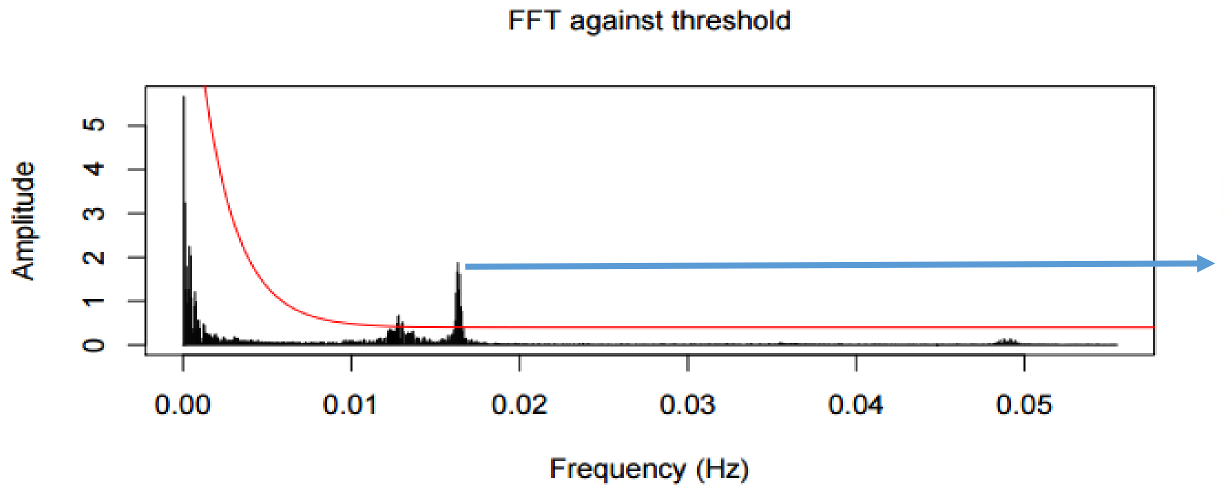


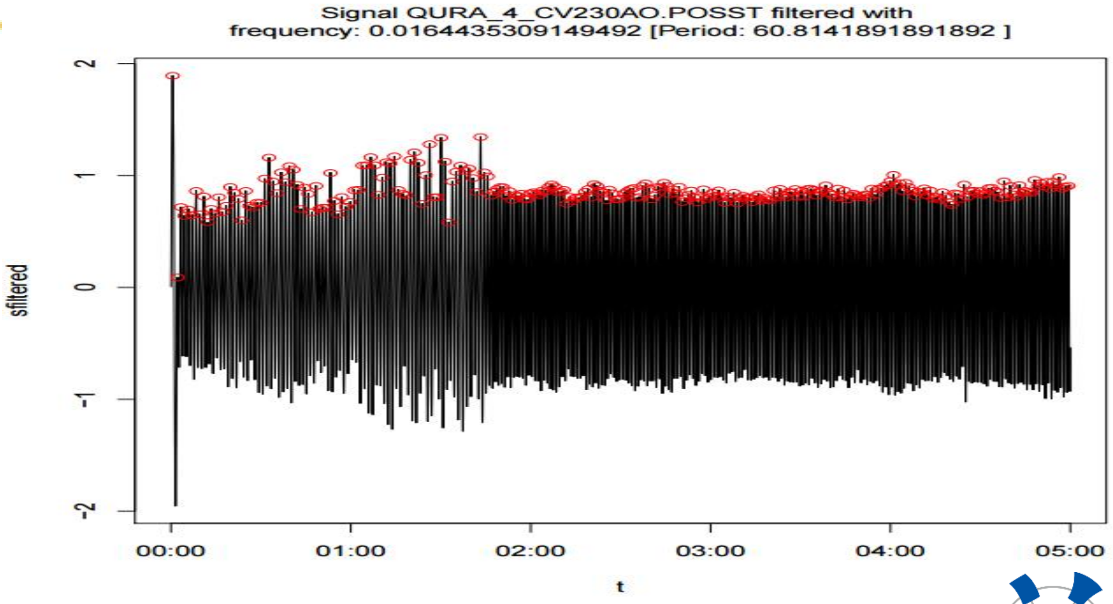
Oscillation detection Ex#1



Oscillation detection Ex#2

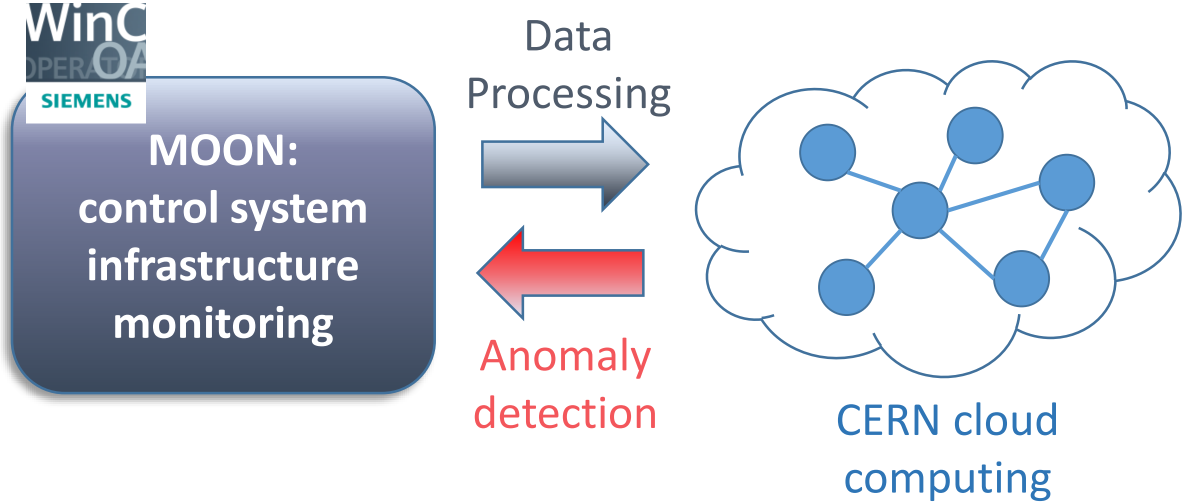




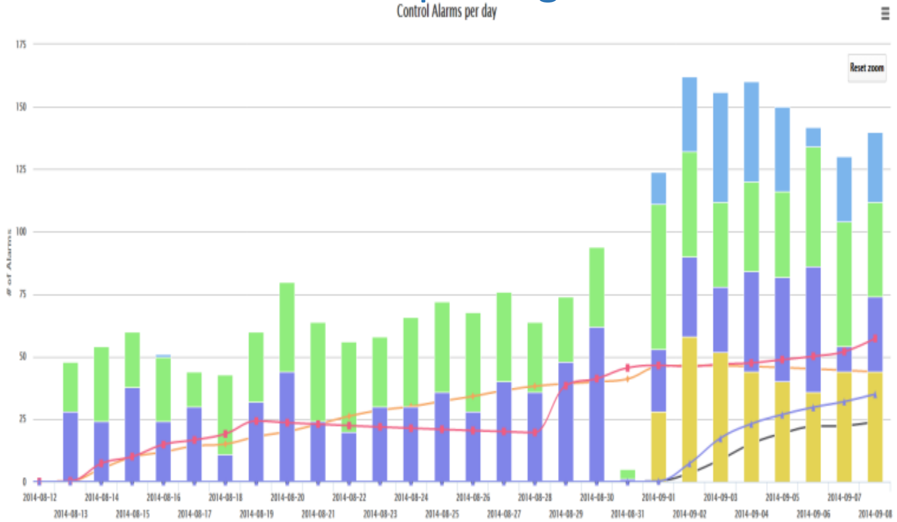


Online analysis of control alarms

- Alarms analysis to detect anomalies or abnormal behaviors for thousands of devices
- Events sequence mining
  - to understand the alarms’ dependencies
  - for short term forecast
- Threshold learning algorithm and outliers detection techniques
  - Based on alarms’ distribution
  - Parallelization using the CERN OpenStack cluster
- Graphical visualization of the anomalies/outliers



Web Reporting

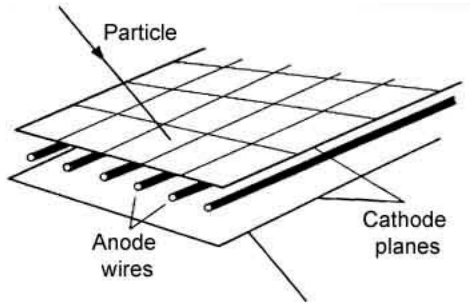


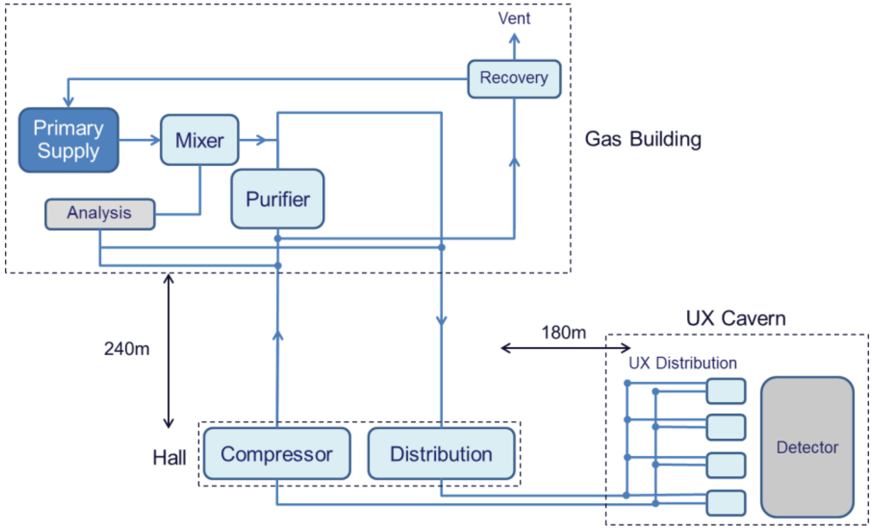
Fault diagnosis (off-line)

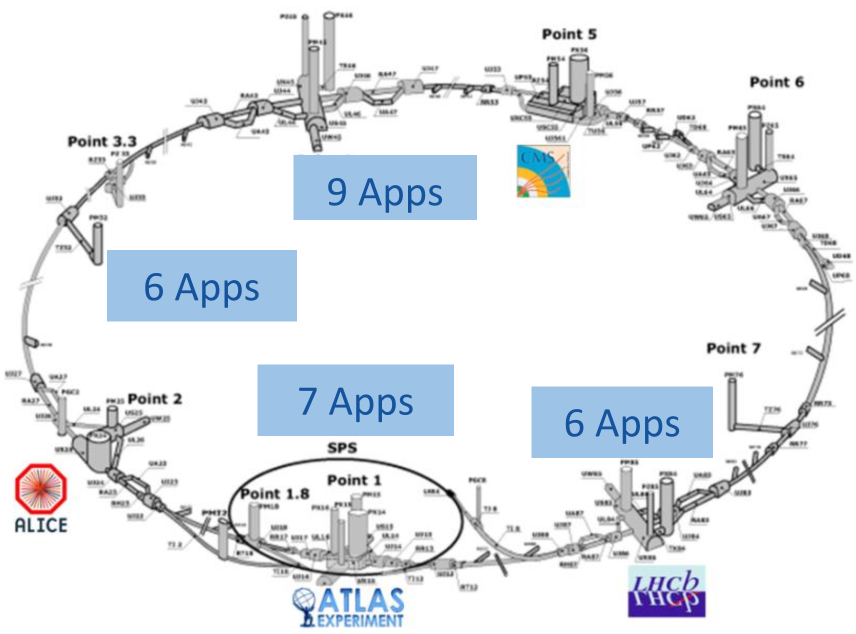
- Root cause analysis for control alarms avalanches (GAS system)
- Anomaly detection by sensors data mining

An example:

Gas control system @CERN



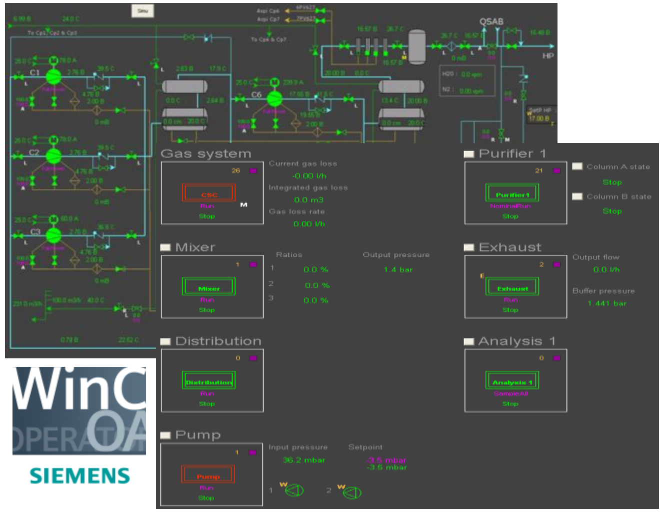




- 28 gas systems deployed around LHC
- 4 Data Server, 51 PLCs (29 for process control, 22 for flow-cells handling)
- Essential for particle detection
- Reliability and stability are critical
  - Any variation in the gas composition can affect the accuracy of the acquired data
- ~18 000 physical sensors / actuators

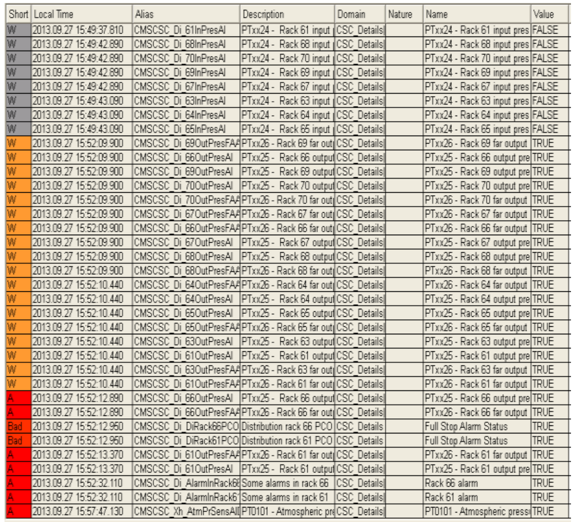
CERN openlab

Alarm flooding problem



Fault in the distribution system

Domino effect



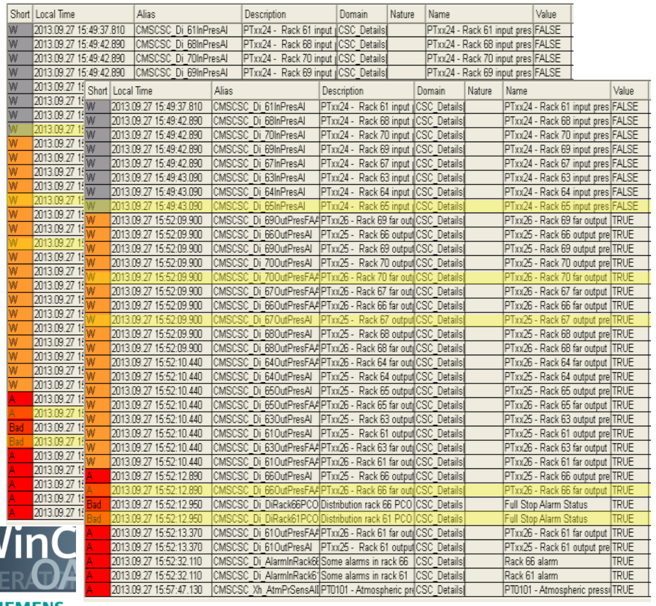
Short	Local Time	Alias	Description	Domain	Nature	Name	Value
W	2013.09.27 15:49:37.810	CMSCSC_Di_61InPresAl	PTxx24 - Rack 61 input	CSC_Details		PTxx24 - Rack 61 input pres	FALSE
W	2013.09.27 15:49:42.890	CMSCSC_Di_68InPresAl	PTxx24 - Rack 68 input	CSC_Details		PTxx24 - Rack 68 input pres	FALSE
W	2013.09.27 15:49:42.890	CMSCSC_Di_70InPresAl	PTxx24 - Rack 70 input	CSC_Details		PTxx24 - Rack 70 input pres	FALSE
W	2013.09.27 15:49:42.890	CMSCSC_Di_69InPresAl	PTxx24 - Rack 69 input	CSC_Details		PTxx24 - Rack 69 input pres	FALSE
W	2013.09.27 15:49:42.890	CMSCSC_Di_67InPresAl	PTxx24 - Rack 67 input	CSC_Details		PTxx24 - Rack 67 input pres	FALSE
W	2013.09.27 15:49:43.090	CMSCSC_Di_63InPresAl	PTxx24 - Rack 63 input	CSC_Details		PTxx24 - Rack 63 input pres	FALSE
W	2013.09.27 15:49:43.090	CMSCSC_Di_64InPresAl	PTxx24 - Rack 64 input	CSC_Details		PTxx24 - Rack 64 input pres	FALSE
W	2013.09.27 15:49:43.090	CMSCSC_Di_65InPresAl	PTxx24 - Rack 65 input	CSC_Details		PTxx24 - Rack 65 input pres	FALSE
W	2013.09.27 15:52:09.900	CMSCSC_Di_69OutPresFA	PTxx26 - Rack 69 far out	CSC_Details		PTxx26 - Rack 69 far output	TRUE
W	2013.09.27 15:52:09.900	CMSCSC_Di_66OutPresAl	PTxx25 - Rack 66 output	CSC_Details		PTxx25 - Rack 66 output pre	TRUE
W	2013.09.27 15:52:09.900	CMSCSC_Di_69OutPresAl	PTxx25 - Rack 69 output	CSC_Details		PTxx25 - Rack 69 output pre	TRUE
W	2013.09.27 15:52:09.900	CMSCSC_Di_70OutPresAl	PTxx25 - Rack 70 output	CSC_Details		PTxx25 - Rack 70 output pre	TRUE
W	2013.09.27 15:52:09.900	CMSCSC_Di_70OutPresFA	PTxx26 - Rack 70 far out	CSC_Details		PTxx26 - Rack 70 far output	TRUE
W	2013.09.27 15:52:09.900	CMSCSC_Di_67OutPresFA	PTxx26 - Rack 67 far out	CSC_Details		PTxx26 - Rack 67 far output	TRUE
W	2013.09.27 15:52:09.900	CMSCSC_Di_66OutPresFA	PTxx26 - Rack 66 far out	CSC_Details		PTxx26 - Rack 66 far output	TRUE
W	2013.09.27 15:52:09.900	CMSCSC_Di_67OutPresAl	PTxx25 - Rack 67 output	CSC_Details		PTxx25 - Rack 67 output pre	TRUE
W	2013.09.27 15:52:09.900	CMSCSC_Di_68OutPresAl	PTxx25 - Rack 68 output	CSC_Details		PTxx25 - Rack 68 output pre	TRUE
W	2013.09.27 15:52:09.900	CMSCSC_Di_68OutPresFA	PTxx26 - Rack 68 far out	CSC_Details		PTxx26 - Rack 68 far output	TRUE
W	2013.09.27 15:52:10.440	CMSCSC_Di_64OutPresFA	PTxx26 - Rack 64 far out	CSC_Details		PTxx26 - Rack 64 far output	TRUE
W	2013.09.27 15:52:10.440	CMSCSC_Di_64OutPresAl	PTxx25 - Rack 64 output	CSC_Details		PTxx25 - Rack 64 output pre	TRUE
W	2013.09.27 15:52:10.440	CMSCSC_Di_65OutPresAl	PTxx25 - Rack 65 output	CSC_Details		PTxx25 - Rack 65 output pre	TRUE
W	2013.09.27 15:52:10.440	CMSCSC_Di_65OutPresFA	PTxx26 - Rack 65 far out	CSC_Details		PTxx26 - Rack 65 far output	TRUE
W	2013.09.27 15:52:10.440	CMSCSC_Di_63OutPresAl	PTxx25 - Rack 63 output	CSC_Details		PTxx25 - Rack 63 output pre	TRUE
W	2013.09.27 15:52:10.440	CMSCSC_Di_61OutPresAl	PTxx25 - Rack 61 output	CSC_Details		PTxx25 - Rack 61 output pre	TRUE
W	2013.09.27 15:52:10.440	CMSCSC_Di_63OutPresFA	PTxx26 - Rack 63 far out	CSC_Details		PTxx26 - Rack 63 far output	TRUE
W	2013.09.27 15:52:10.440	CMSCSC_Di_61OutPresFA	PTxx26 - Rack 61 far out	CSC_Details		PTxx26 - Rack 61 far output	TRUE
A	2013.09.27 15:52:12.890	CMSCSC_Di_66OutPresAl	PTxx25 - Rack 66 output	CSC_Details		PTxx25 - Rack 66 output pre	TRUE
A	2013.09.27 15:52:12.890	CMSCSC_Di_66OutPresFA	PTxx26 - Rack 66 far out	CSC_Details		PTxx26 - Rack 66 far output	TRUE
Bad	2013.09.27 15:52:12.950	CMSCSC_Di_DiRack66PCO	Distribution rack 66 PCO	CSC_Details		Full Stop Alarm Status	TRUE
Bad	2013.09.27 15:52:12.950	CMSCSC_Di_DiRack61PCO	Distribution rack 61 PCO	CSC_Details		Full Stop Alarm Status	TRUE
A	2013.09.27 15:52:13.370	CMSCSC_Di_61OutPresFA	PTxx26 - Rack 61 far out	CSC_Details		PTxx26 - Rack 61 far output	TRUE
A	2013.09.27 15:52:13.370	CMSCSC_Di_61OutPresAl	PTxx25 - Rack 61 output	CSC_Details		PTxx25 - Rack 61 output pre	TRUE
A	2013.09.27 15:52:32.110	CMSCSC_Di_AlarmInRack66	Some alarms in rack 66	CSC_Details		Rack 66 alarm	TRUE
A	2013.09.27 15:52:32.110	CMSCSC_Di_AlarmInRack61	Some alarms in rack 61	CSC_Details		Rack 61 alarm	TRUE
A	2013.09.27 15:57:47.130	CMSCSC_Xh_AtmPrSensAl	PT0101 - Atmospheric pre	CSC_Details		PT0101 - Atmospheric press	TRUE

Alarms flooding

- **Diagnosing a fault is complex:** it may take weeks!
  - Alarms flooding: a single fault can generate up to a thousand of events
  - Number of different sequences:

    ~$6x10^{297}$ from: n!/(n-k)! , n=max seq. length, k=n/10
  - A single fault can stop the whole control process
  - The 1st alarm is not necessarily the most relevant for the diagnosis
  - Alarm generation depends on the system status

Events stream analysis



WinCC OA
SIEMENS

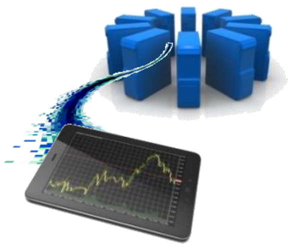
Event lists generated
by the same fault

Data

Analyze

Identify and detect fault / abnormal pattern for Diagnosis and Prognostics based on domain knowledge

Learn



Provide experts with Root-cause and Gap Analysis using Rules and Patterns Mining

Diagnose

Forecasts, Trends and Early-Warnings to increase Operating Hours

Sequence: Confidence: 83.3 % / Appearance count: 5
CMSCSC_Di_62PRegAI | Alarm Unacknowledged | Rising
CMSC
CMSC
CMSC
CMSC
CMSC
CMSC
CMSC
CMSC
CMSC

Sequence: Confidence: 100.0 % / Appearance count: 6
CMSCSC_Di_62PRegAI | Alarm Unacknowledged | Rising
CMSCSC_Di_62PRegAI | Position Status (HH-LL) | Rising
CMSCSC_Di_YC60995 | Auto Off/Close Request Status | Falling
CMSCSC_Di_YC60995 | Auto On/Open Request Status | Rising
CMSCSC_Di_YC60995 | Off/Closed Status | Falling
CMSCSC_Di_YC60995 | On/Opened Status | Rising
CMSCSC_Di_YC60995 | Output Order Value Status | Rising

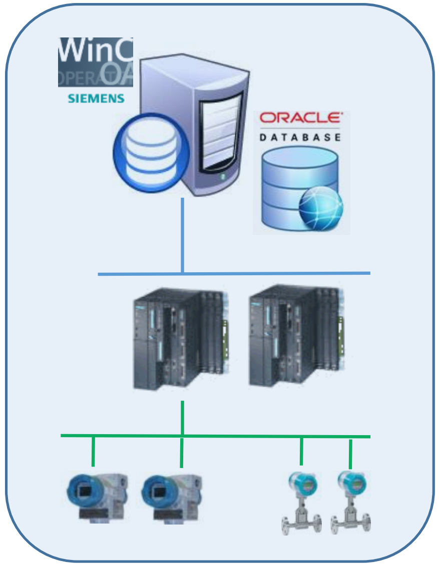
Pattern AA B A A B → **Alarm**

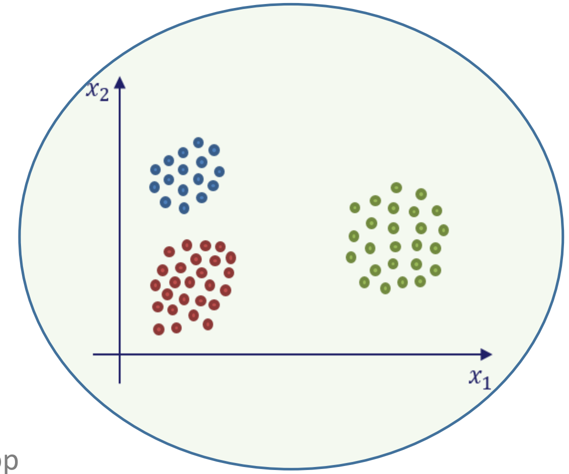
X T C D F A A E D N D B K D F A A B K D

CERN openlab

Anomaly detection by sensors data mining

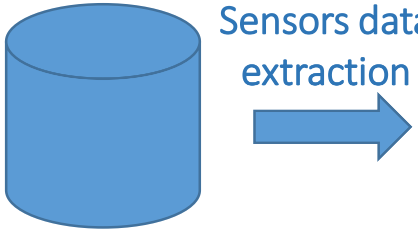
- Goal: Detect abnormal or unforeseen system behaviours
- Possible issues:
  - Sensors faults/glitches
  - Hardware failures/degradations
  - False measurements
  - Wrong tuning/structure
  - …
- Sensors mining to learning:
  - Logical relations
  - Physical relations
- Challenges:
  - Normal/anomalous boundaries are not precise
  - Different application domains/systems
  - Mostly unsupervised training
  - Dynamic system => dynamic model
  - Different types of anomaly
  - Noise and duration of an anomaly





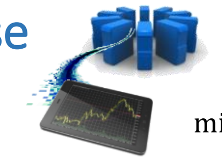
Machine learning algorithms for anomaly detection in Cryo

LHC Logging Service



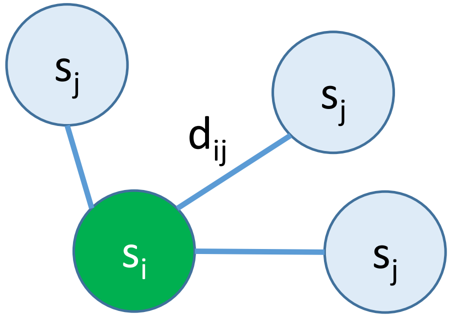
Sensors data extraction

Learning phase

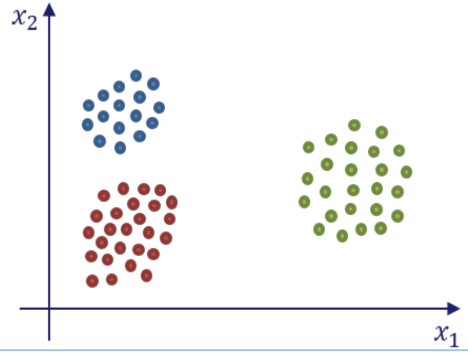


- Building a model based on historical data
- 3 different algorithms
  - Correlation index and KNN-graph
  - K-Mean clustering and probability model
  - Statistics expert-based model

$$E(d_i) = \sum_{j=1}^{k} d_{ij} * P(j|i)$$

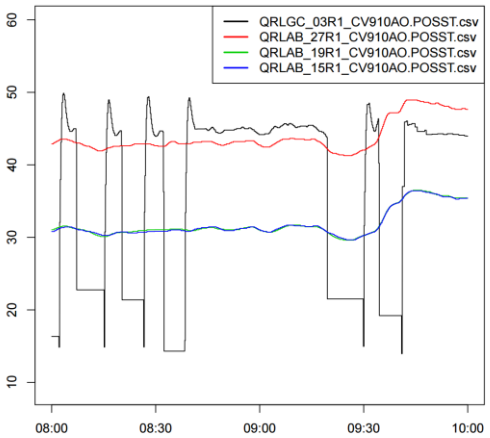


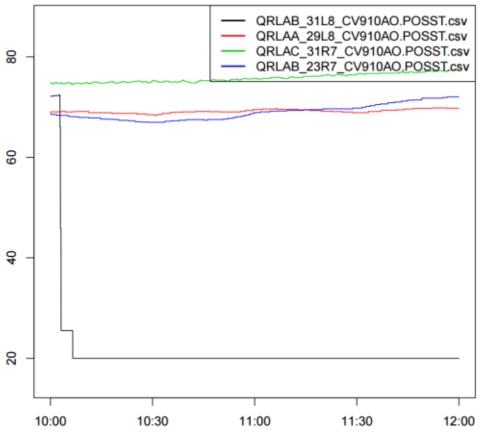
$$\min \frac{1}{C} \sum_{k=1}^{C} \max_{l \neq k} \left\{ \frac{\frac{\sum_i \| x_i - c_k \|}{N_k} + \frac{\sum_i \| x_i - c_l \|}{N_l}}{\| c_k - c_l \|} \right\}$$



Anomaly detection

- Use the previous model to detect anomalies
- On-line analysis over a time window of 1 day
- Continuous analysis against thousands of sensors



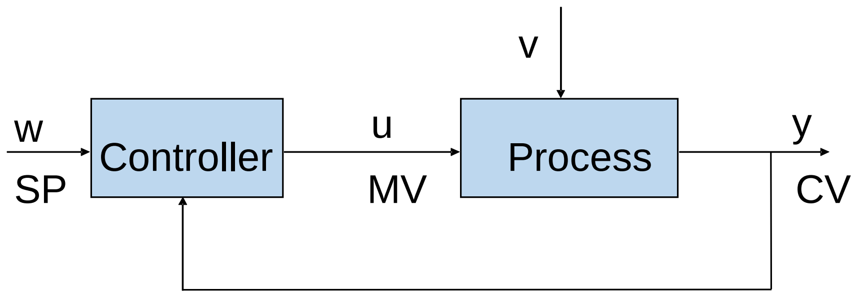


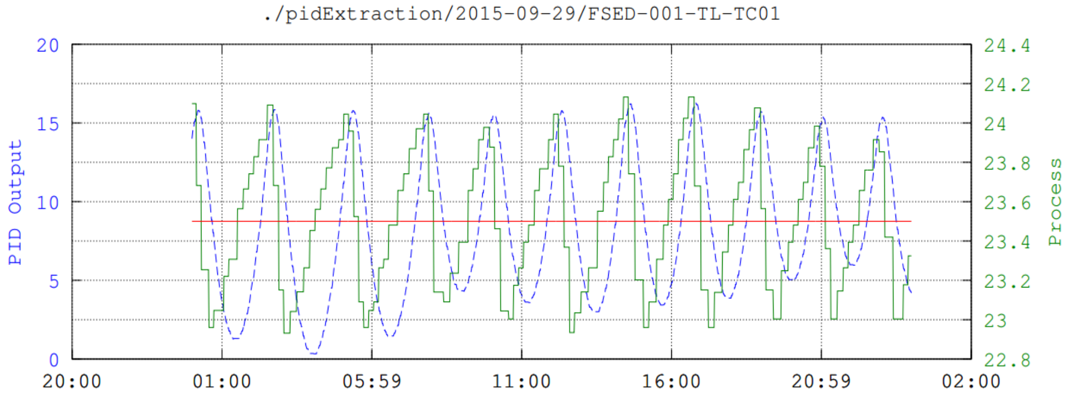
Engineering design

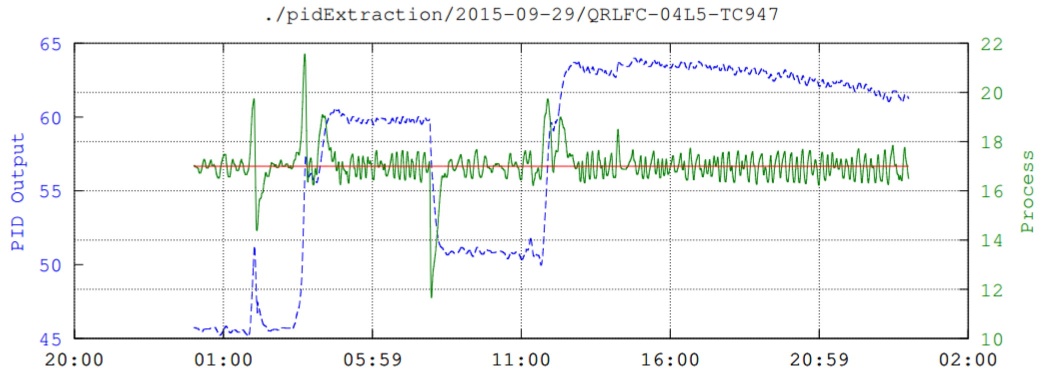
- PID supervision (CRYO, CV)
- Recommendation system for WinCC OA users (PSEN)

Evaluation of PID supervision

- PID performance has an impact on:
  - Process security
  - Quality of physics
  - Maintenance (stress on the equipment)
- Issues:
  - Many sources of faults/malfunctions
  - System status dependency
  - External disturbances/factors
  - Bad tuning
  - Wrong controller type/structure
  - Slow degradation







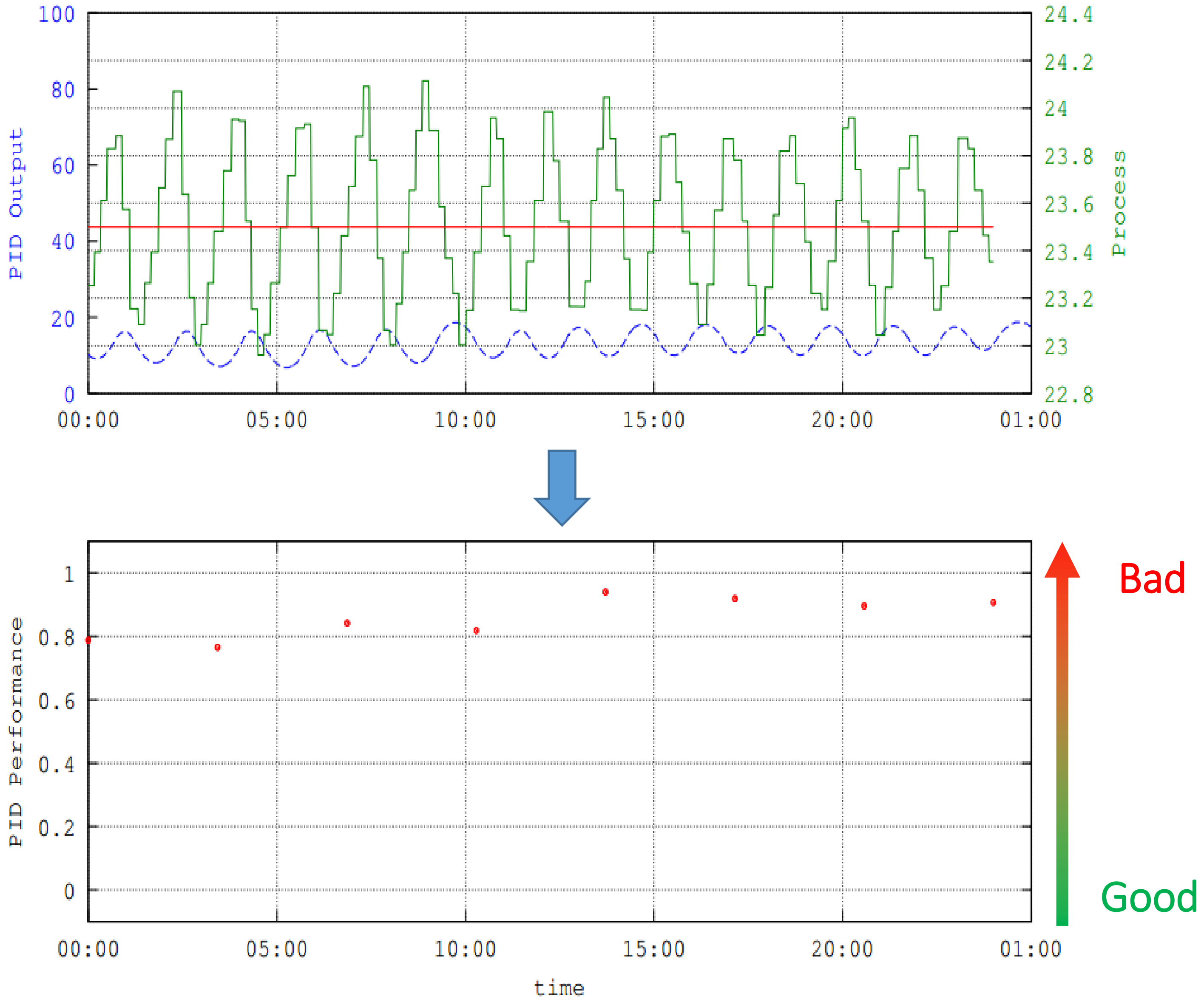
PID supervision Ex#1

- **PID anomaly detection:**
  - Learning each PID model from the historical data
  - Extraction of similar PID models
  - Comparison of PID behaviours:
    - on the single PID level
    - similar PID

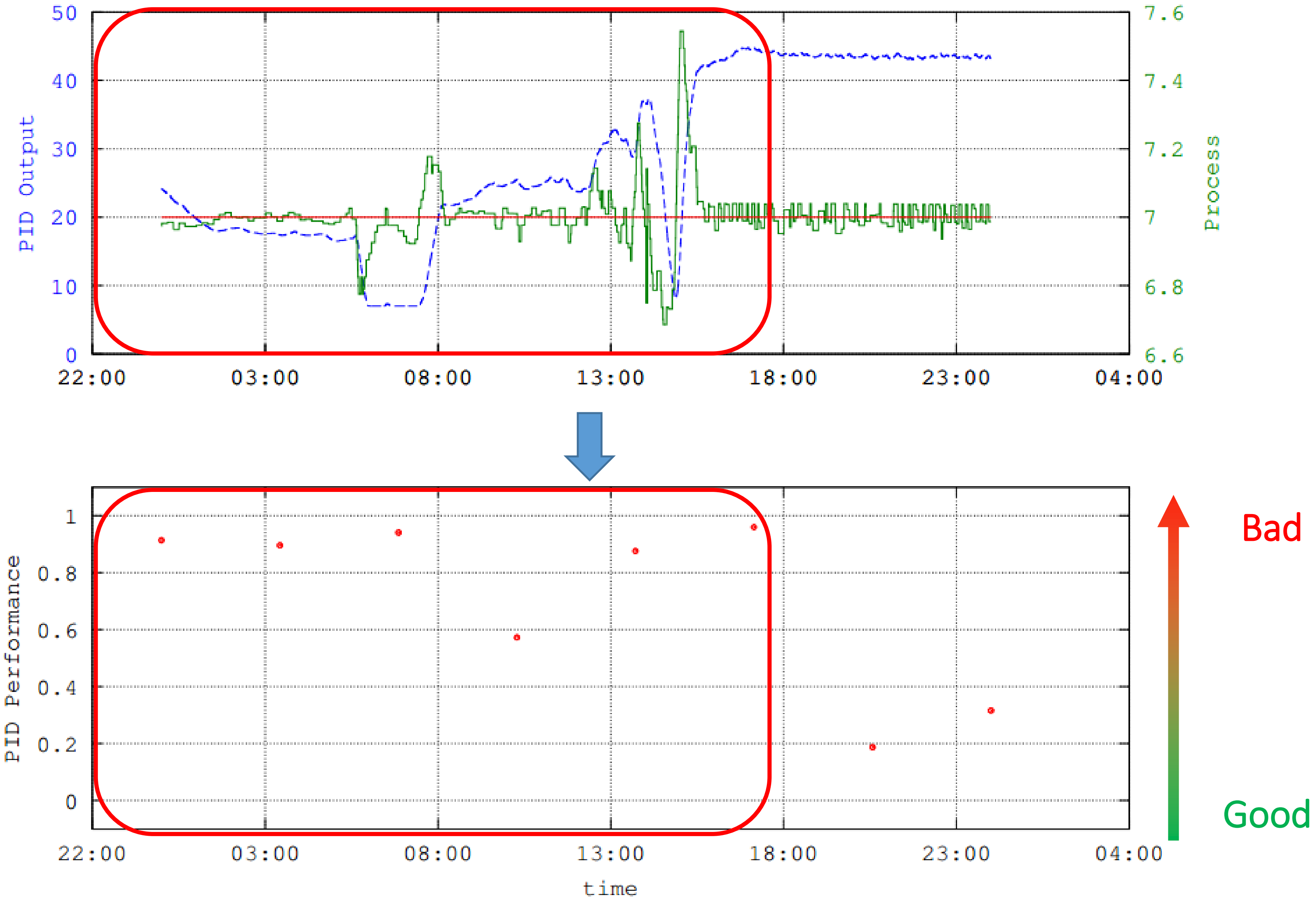
- **Efficiency of control process:**
  - Comparison of PID performances
  - Time/actions taken/energy consumed to reach steady points
  - Stability of the controlled variable

- **In collaboration with the University of Valladolid**

Based on: "Performance monitoring of industrial controllers based on the predictability of controller behaviour", R. Ghraizi, E. Martinez, C. de Prada



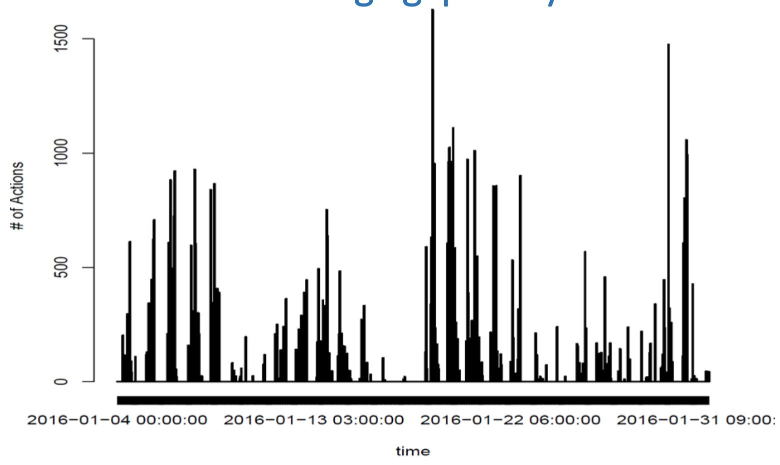
PID supervision Ex#2



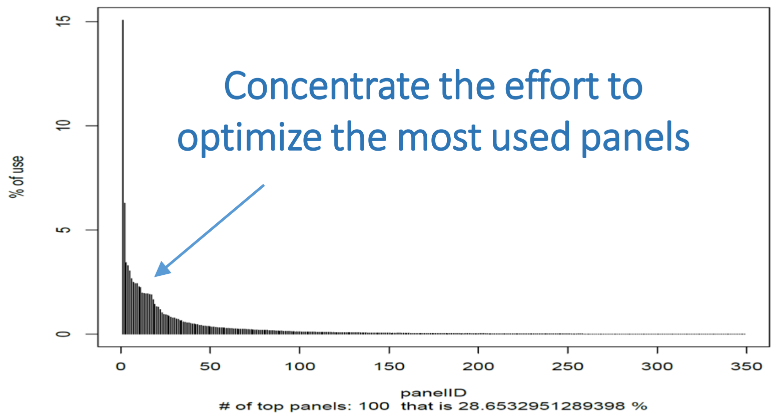
Recommendation system for WinCC OA users

Users' actions extraction

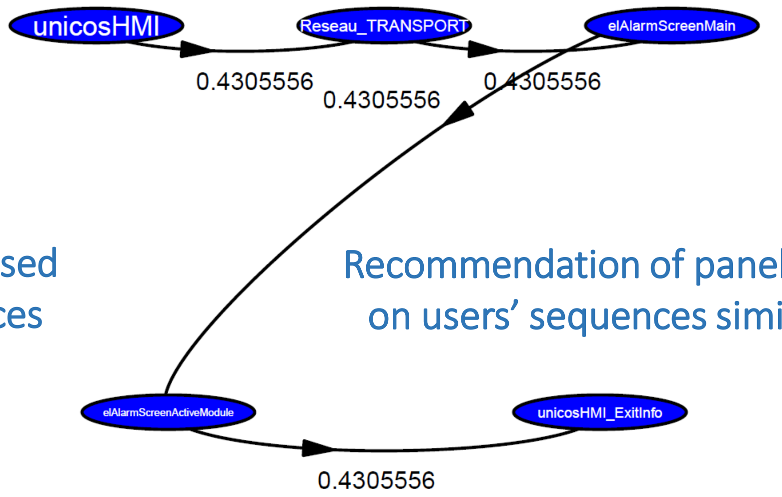
Users' usage gap analysis



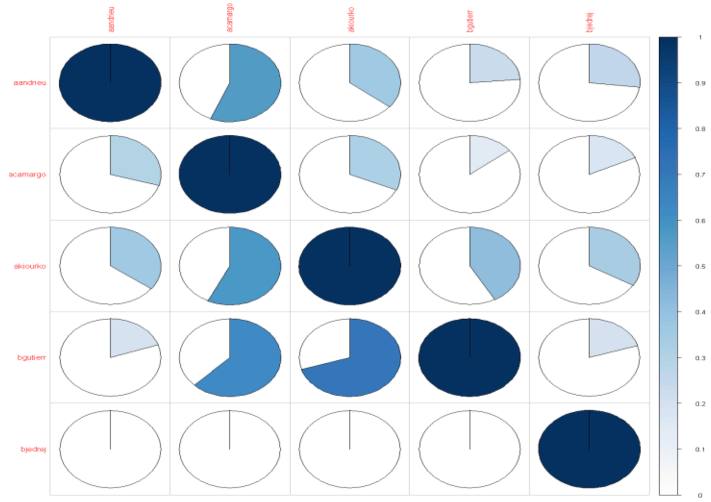
Normalized distribution of panels usage



Users' frequent sequences



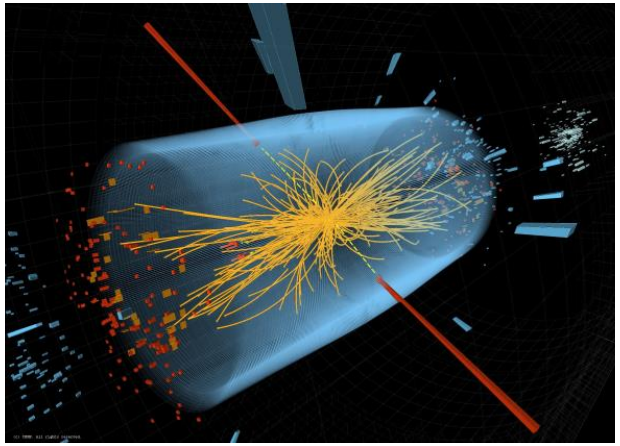
Jaccard Sequences Similarity



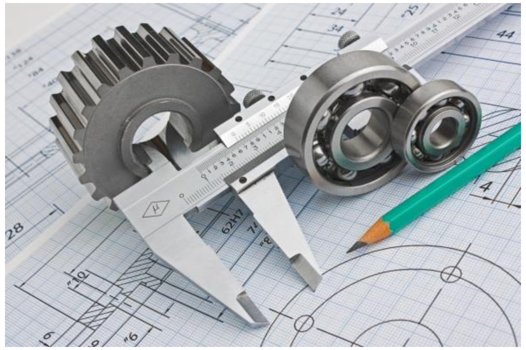
Recommendation of panels based on the specific users' sequences

Recommendation of panels based on users' sequences similarities

Data Analytics Benefits



- **Increased System Reliability**
  - Minimized forced outages
- **Complete data analysis**
  - Reduced service effort: weeks → hours
- **24/7 Expert Knowledge Availability**
  - One central knowledge base



Operation support

- Big data visualization
- Forecast system status and take proper actions in time
- Prevent possible faults and system downtime

Diagnosis support

- Identify root causes
- More accurate analysis
- Accelerate analysis From weeks to hours
- Identify hidden patterns

Engineering support

- Evaluate and improve operational performance
- Increase reliability and efficiency by design
- Lead control system decisions

Use-cases: a partial list

- **Online monitoring**
  - Control System Health
  - Electrical power quality of service
  - Looking for heat in superconducting magnets
  - Oscillation in cryogenics valves
  - Discharge of superconducting magnets heaters
  - Trending and forecast of the control process behavior
- **Faults diagnosis**
  - Anomalies in the process regulation
  - PLC anomalies
  - Data loss detection
  - Root-cause analysis for complex WinCC OA installations
  - Analysis of sensors functioning and data quality
  - Analysis of OPC-CAN middleware
  - Analysis of electrical power cuts
  - Cryogenic system breakdowns
- **Engineering design**
  - Electrical consumption forecast
  - Efficiency of electric network
  - Predictive maintenance of control systems elements
  - Predictive maintenance for control disks storage
  - Vibration analysis
  - Efficiency of control process
  - …