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Plant-wide Root Cause Identification of Transient Disturbances with Application to a Board Machine

PAPYRUS
Project set-up

**Project type**
- Collaborative project
- Co-funded by the EU
- 7 partners

**Timing**
- Kick off Sep 2010
- 30 months duration

**Budget**
- >3 M€ (ABB 50%)
- 1.75 M€ EU funding

**Methodology**
- Aalto University
- Universität Duisburg-Essen
- Universite Henri Poincare

**Technology**
- ABB Corporate Research
- ABB CPM Technology
- Predict

**Application**
- EFORA
- Stora Enso
Outline

- Plant-wide disturbance root cause analysis is a large scale problem
- An intuitive **top-down approach** for decomposing this problem
- Extension of the method for root cause analysis of **transient** disturbances
- Case study: Board Machine 4
  Stora Enso, Imatra, Finland
Plant Asset Management
Traditional Approach

- Traditional Approach
  - Buttom-up approach
  - Identified critical assets

asset monitors

1 2 3 4 5 6 7 ...

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Plant Asset Management
Traditional Approach

- Traditional Approach
  - Bottom-up approach
  - Identified critical assets → maintenance prioritisation

WORKFLOW

Maintenance, service, inspections, etc.

asset monitors

product

quality

quantity

efficiency

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Plant Asset Management
Novel Approach

product
quality
category

PPI
Plant Performance Indicator

Root cause analysis

Maintenance, service, inspections, etc.

asset monitors

WORKFLOW

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Top down approach

- Section isolation ➔ Disturbance source isolation ➔ Diagnosis

Step 1
- Monitor process performance indicator, e.g. Moisture
- Detect process performance indicator degradation

Step 2
- $T^2$ contribution plot analysis for different types of measurements
- Isolate section containing disturbance source

Step 3
- Measurements clustering and root cause analysis of isolated section
- Isolate disturbance root cause

Step 4
- Evaluate asset performance indicator
- Diagnosis
Detect process performance indicator degradation

- One of the three end product quality ("Moisture content") exhibits oscillations
Detect process performance indicator degradation

Detection of Moisture Oscillation

- Oscillation index SP-PV...... = 0.42 [-1...1], good < 0.0
- Oscillation index SP......... = -1 [-1...1], good < 0.0
- Oscillation period .......... = 5250 (0...inf] seconds, good = n.a.
- Oscillation amplitude ....... = 1.77 [0...inf] % of operating range, good = n.a.

- Detection of critical PPI variation:
  Oscillation with a period 5250 seconds
- System triggers root cause analysis
A Principal Component Analysis (PCA) Model is built using the collected process data.

The PCA model is able to evaluate the contribution of each tag to the detected abnormal situation.

In order to deal with oscillations, the PCA model uses spectral data (FFT transform of process measurements).

Find process section containing disturbance source

- Contribution Plot using **Pressure** measurements
Find process section containing disturbance source

- Contribution Plot using **Pressure** measurements

![Diagram showing T^2 contribution and contribution plot using Pressure measurements.](image)

- Most contributing tags to Caliper/Moisture variations
- Stock prep/Short circ
- Wire
- Press
- Calender
- Quality control system

Dryer Section contains the root cause

Caliper

Moisture

PPI

X = 220

Y = 13.7

T^2 Contribution

**T^2 contribution**

- Stock prep/Short circ
- Wire
- Press
- Calender
- Quality control system

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Find Process Section containing disturbance source

- Contribution Plot using **Flow** measurements
Isolate disturbance source

- Data Preprocessing: Band pass filtering of process measurements around the detected oscillation frequency
Isolate disturbance source

- Clustering of process measurements belonging to the isolated process section
Isolate disturbance source

• Root cause analysis using non-linearity index (*)

Isolate Disturbance Source

- Root cause analysis using non linearity index

- **Causality Chain**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>KA4_PC0668</td>
<td>1.0 MPa steam pressure control</td>
</tr>
<tr>
<td>KA4_PV0654_1</td>
<td>Steam group 4 pressure valve 1</td>
</tr>
<tr>
<td>KA4_PV0659_1</td>
<td>Steam group 7 pressure valve 2</td>
</tr>
<tr>
<td>KA4_XM1003</td>
<td>Production rate</td>
</tr>
<tr>
<td>KA4_M10451_2</td>
<td>Frontal dry section exhaust air humidity 2</td>
</tr>
<tr>
<td>KA4_FI0658</td>
<td>Steam 1.0 MPa flow</td>
</tr>
<tr>
<td>KA4_PV0660_1</td>
<td>Steam group 8 pressure valve 1</td>
</tr>
<tr>
<td>KA4_PC0659</td>
<td>Condensate flow</td>
</tr>
<tr>
<td>KA4_PC0660</td>
<td>Steam group 8 pressure</td>
</tr>
<tr>
<td>KA4_PC0673_2</td>
<td>Steam group 7 pressure difference valve 2</td>
</tr>
<tr>
<td>KA4_XM1009</td>
<td>Moisture measurement</td>
</tr>
</tbody>
</table>

- **Control loop** to be further diagnosed: **KA4_PC0668** (Steam Pressure)
Diagnose isolated root cause asset

- Steam pressure control loop diagnosis

  - Diagnosis of the isolated faulty asset causing the process performance degradation

**Process value**

- Oscillation index SP-PV...... = 0.87 [-1...1], good < 0.0
- Oscillation index SP........... = -1 [-1...1], good < 0.0
- Oscillation period .......... = 5230 (0...inf] seconds, good = n.a.

**analysis**

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**Diagnosis**

- H5: periodic external disturbance? 0 [%]
- H7: valve stiction? ................. : 100 [%]
- H8: valve leakage? .................. : -1 [%]
- H9: valve size incorrect? .......... : -1 [%]
- ...

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Transient disturbances

- For **periodic signals**, the $T^2$ contribution is evaluated at the **frequency of oscillation** of the KPI.
- To extend the method to **non periodic disturbances**
  - Find the **frequency band** containing most of the signal energy (e.g. use two first peaks of the power spectrum)
  - Compute a **weighted contribution to $T^2$ averaged over this frequency band**. Weights are the values of the KPI normalized power spectrum.
Top down approach

- Section isolation → Disturbance source isolation → Diagnosis

**Step 1**
- Monitor process performance indicator, e.g. Moisture
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**Step 4**
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- Diagnosis
Detect process performance indicator degradation

Transient disturbance

One of the three end product quality (“moisture content”) exhibits variance increase
Detect process performance indicator degradation
Detector of Moisture variance increase

Continuous monitoring using of an observation window of length k

Decision function

Accept $H_0$: $\sum_{i=1}^{k} e_i^2 \geq 2 \frac{\sigma_1^2 \sigma_0^2}{\sigma_0^2 - \sigma_1^2} (\log \eta_1 - k \log \frac{\sigma_0}{\sigma_1})$

Accept $H_1$: $\sum_{i=1}^{k} e_i^2 \geq 2 \frac{\sigma_1^2 \sigma_0^2}{\sigma_0^2 - \sigma_1^2} (\log \eta_0 - k \log \frac{\sigma_0}{\sigma_1})$

$\eta_0 = \frac{\beta}{1-\alpha}$, $\eta_1 = \frac{1-\beta}{\alpha}$

$\alpha$ probability of false alarms
$\beta$ probability of missed detection.
Find process section containing disturbance source

- Contribution Plot using **Pressure** measurements

Most contributing tags to Moisture variations

Dryer Section contains the root cause
Find Process Section containing disturbance source

- Contribution Plot using **Flow** measurements

Most contributing tags to Moisture variations

о = PPI

Tag index

- Stock
- Wire
- Dryer
- Quality

Dryer Section contains the root cause
Isolate disturbance source

- Root cause analysis using Transfer Entropy (*)

Isolate disturbance source
Diagnosis of the deviation in pressure loop

Pressure Setpoint Manually moved
Conclusion
Benefits & impact

- Top-down approach for plant-wide performance management
  - Identification of the root cause of plant performance degradations
  - Limited expert knowledge required
  - Targeted maintenance
  - Optimization of plant performance
Power and productivity for a better world™
Industrial Process Analytics (*)

Industrial Process Analytics has to deal with:

- **Presentation** of data as meaningful information;
- Transforming a flood of data into **insights** about the plant operation.

(*) Courtesy of Prof. Nina Thornhill, ABB/RAEng Research Chair of Process Automation, Imperial College, London.
Case study: Three layer board machine

- Produced board quality is a performance indicator of the board machine

Basis weight defect in cross direction
The large scale challenge

• How to find the root cause faulty asset among 7,000+ tags?
Detect process performance indicator degradation

Transient Disturbance

One of the three end product quality ("moisture content") exhibits variance increase
Detect process performance indicator degradation

Transient Disturbance

1st two peaks of the Moisture spectrum

Power Spectrum - Moisture

Trend Moisture

Moisture (%) vs. Samples (Ts = 10s)
Find Process Section containing disturbance source

Spectral Data

$x$ data matrix of $M$ process variables containing $N$ equally spaced observations

$$x = \begin{bmatrix} x_1(t_1) & \cdots & x_1(t_N) \\ \vdots & \ddots & \vdots \\ x_M(t_1) & \cdots & x_M(t_N) \end{bmatrix}$$

Fourier transform of the data matrix $x \rightarrow$ Frequency matrix
Take the absolute value $\rightarrow$ Power Spectrum.

$X$ matrix where the rows are the single-sided power spectra $X_m$ at frequency $f_n$

$$X = \begin{bmatrix} X_1(f_1) & \cdots & X_1(f_N) \\ \vdots & \ddots & \vdots \\ X_M(f_1) & \cdots & X_M(f_N) \end{bmatrix}$$

As many frequency channels $N$ as there are time samples
Find Process Section containing disturbance source
Principal Components Analysis (PCA)

PCA decomposition approximates the X matrix to reduce the complexity of the data.

Only $R$ principal components (PC’s) that explain most of the variability in the original data set are kept.

$$X = T_R W_R^T + E$$

$T_R$: Loadings matrix

$W_R$: Scores matrix

$E$: Errors not captured by the principal components.
Hotelling’s $T^2$ statistic using the score column vector $w_n$ at frequency $n$:

$$T^2_n = w_n^T D^{-1} w_n = \sum_{r=1}^{R} \frac{w_{r,n}^2}{d_m}$$

$D$ diagonal (eigenvalues $d_m$ of matrix $X^TX$)

$d_m$ expresses the variance of the $r$th score vector $w_m$
Contribution of variable m at frequency channel n to the total $T^2$ at the same frequency channel n

$$C_{m,n}^{[T^2]} = \sum_{r=1}^{R} t_{r,m} X_m(f_n) \frac{w_{r,n}}{d_r}$$

Focus is on a specific frequency $n_1$ (frequency dominating the spectrum of the KPI)

$$C_{m,n=n_1}^{[T^2]} = \sum_{r=1}^{R} t_{r,m} X_m(f_{n_1}) \frac{w_{r,n_1}}{d_r}$$
Find Process Section containing disturbance source

Weighted Spectral Contribution Plot

Contribution of variable m at frequency channel n to the total $T^2$ at the same frequency channel n

$$C_{m,n}^{[T^2]} = \sum_{r=1}^{R} t_{r,m} X_m(f_n) \frac{w_{r,n}}{d_r}$$

Focus is on a **frequency band** $[n_1,n_2]$ (frequency band dominating the spectrum of the KPI)

$$C_{m,n=n_1->n_2}^{[T^2]} = \frac{1}{n_1 - n_2} \sum_{k=n_1}^{n_2} \hat{\chi}_{KPI,k} C_{m,k}^{[T^2]}$$

$\hat{\chi}_{KPI,k}$ normalized power spectrum of the KPI at frequency channel k

The contribution of the power spectrum of the $m$th process variable $X_m$ over the frequency band $[n_1,n_2]$ is weighted by the normalized power spectrum of the KPI at the corresponding frequencies