Temporal and Spectral methods for Process and Performance Monitoring

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Progress report on the NSERC Industrial Research Chair (IRC) Program
Partners: U. of Alberta, NSERC, Matrikon, Suncor and iCORE

Credits to the IRC research group

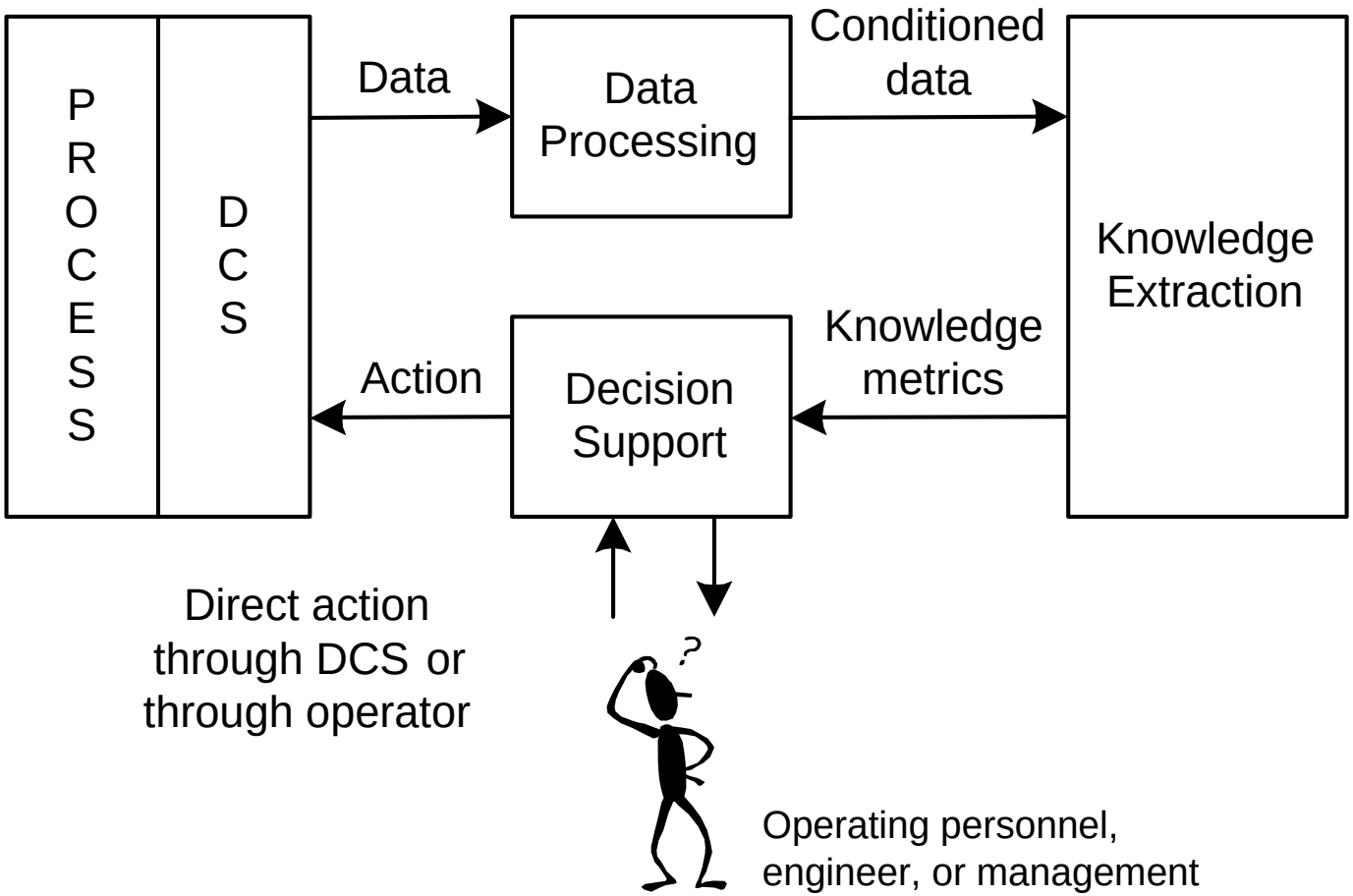
Photo not included in the pdf file due to large file size.

You can see the group photo(s) at:
www.ualberta.ca/~slshah/#photo

Organization

- Background on the program
- Progress report
- Summary

Information-based Decision Support System



Information flow in a real-time information-based decision support system.

Main message

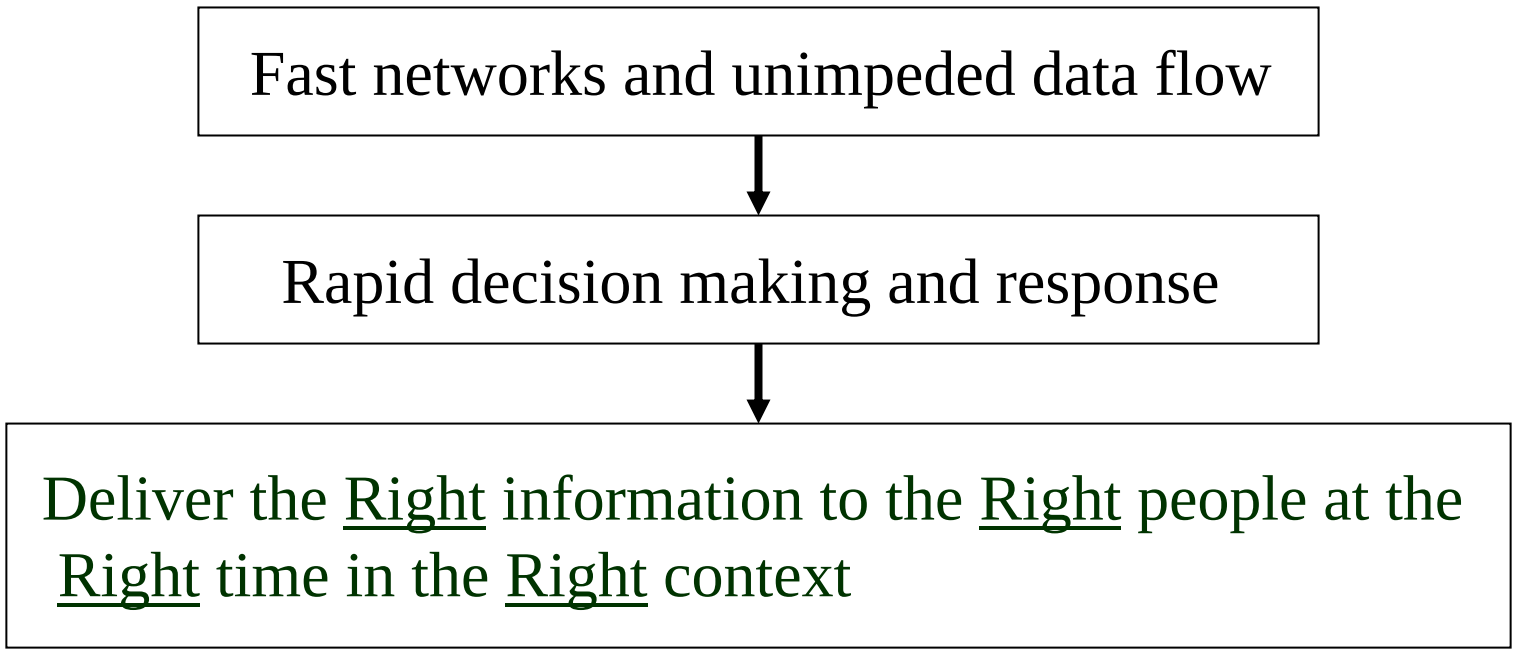
- Maintenance is an important part of the asset life cycle.
- Maintenance costs can constitute anywhere from 3 to 50 percent of production costs.
  - ‘Fail and Fix’ is OUT.
  - ‘Predict and Prevent’ is IN.
- Paradigm shift underway in process operation: ‘Listen’ to your data and use it to monitor the performance of your process.
- Condition based monitoring (CBM) frees people’s time to do things that really matter in managing assets.
- Examine data in a multivariate framework.

Data-fusion/Information-fusion

- Data cleaning/filtering
- Data reconciliation
- Time and event synchronization
- Treatment of missing data

Information flow in an Asset Management System

- Improved asset management results from focused data gathering



Condition based monitoring

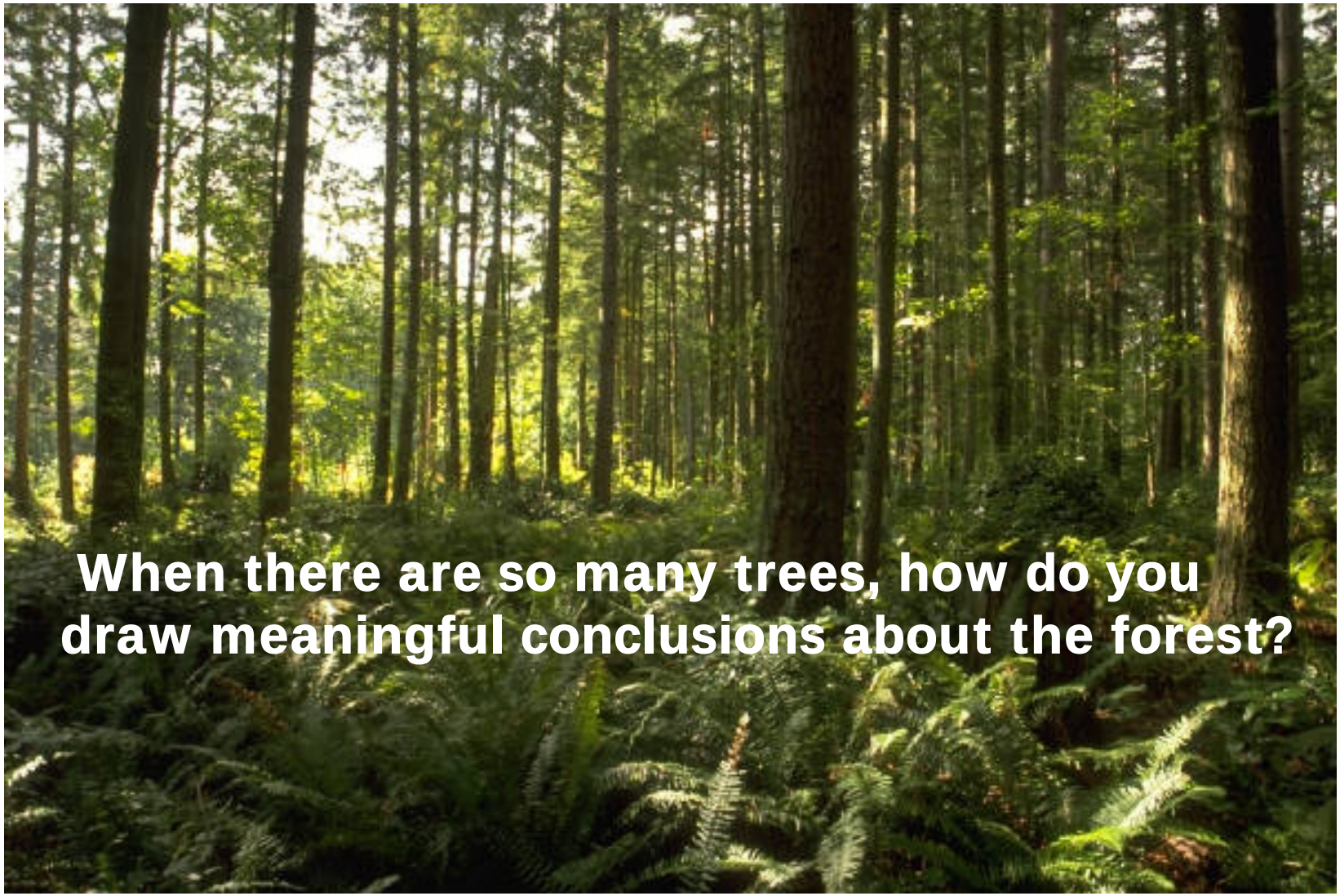
Most valuable CBM technologies do four things:

- Gather data automatically from multiple sources
- Filter data for errors and relevance
- Incorporate logic to identify conditions that require maintenance intervention
- Integrate to other business systems that utilize the same information

Sensor/Information Fusion

- Look at all the data in a cohesive way.
- Data analysis tools should be integrated with the work flow process.
- Examine data in the temporal as well as spectral domains.

Is the overall process safe?



Monitor all sensors ⇨ Information overload??

1	-0.185294206	0.027055773	-0.171819975	0.093276222	-0.027994229	0.098787646	-0.020583535	0.032817213	-0.132101895	0.007443381
-0.185294206	1	0.046731844	0.192725409	0.06221338	-0.121835155	0.007001147	0.072787318	0.256501727	-0.332697412	0.301121428
0.027055773	0.046731844	1	0.497561061	0.097669495	-0.042977998	0.073150009	0.01752308	0.446311963	-0.065613281	0.577804913
-0.171819975	0.192725409	0.497561061	1	0.098720947	0.04428365	0.109814696	0.207062089	0.277424246	0.017018503	0.374057968
0.093276222	0.06221338	0.097669495	0.098720947	1	-0.16665222	0.088320804	0.017838289	0.083761143	0.0118807	0.047680363
-0.027994229	-0.121835155	-0.042977998	0.04428365	-0.16665222	1	-0.083250958	-0.113249872	-0.066049714	0.083771862	-0.024636992
0.098787646	0.007001147	0.073150009	0.109814696	0.088320804	-0.083250958	1	0.11444586	0.18562112	-0.115407265	0.14030574
-0.020583535	0.072787318	0.01752308	0.207062089	0.017838289	-0.113249872	0.11444586	1	0.008346999	-0.031577329	-0.029811791
0.032817213	0.256501727	0.446311963	0.277424246	0.083761143	-0.066049714	0.18562112	0.008346999	1	-0.548843663	0.897175324
-0.132101895	-0.332697412	-0.065613281	0.017018503	0.0118807	0.083771862	-0.115407265	-0.031577329	-0.548843663	1	-0.410961064
0.007443381	0.301121428	0.577804913	0.374057968	0.047680363	-0.024636992	0.14030574	-0.029811791	0.897175324	-0.410961064	1
0.0										890887
-0.1										855722
-0.0										145433
-0.0										586488
-0.0										198421
-0.0										595716
-0.0										375999
0.2										265396
-0.0										686478
-0.0										332399
-0.1										918291
0.0										438833
0.0										413011
-0.0										799394
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0.08599719	0.007025338	0.154179893	0.232546946	0.007835329	-0.086667223	0.156685077	0.023192903	-0.02996409	0.102102098	0.014799742
0.07875747	-0.429241921	-0.344287431	-0.244148911	-0.023116012	-0.027914037	-0.035809918	0.05492866	-0.371758851	0.202342995	-0.500472826
-0.058448605	0.611130166	-0.119253918	0.057550975	0.117777025	-0.183408655	0.082432127	0.10213768	-0.008270005	-0.326478145	-0.006977244
-0.02580405	-0.150816152	0.120793341	0.066957772	0.025269938	0.006378438	-0.075330271	0.07187571	-0.106953812	0.090117193	-0.067876774
0.159960053	-0.46153707	-0.061782981	-0.275932869	0.000719008	0.025290936	0.007663131	-0.053698037	-0.101831356	0.058117208	-0.173365206
0.026409868	-0.563862298	-0.386080423	-0.546002219	-0.101953064	0.031863056	-0.01116078	-0.088594064	-0.187499891	0.05573025	-0.370093034
0.215815744	-0.782048799	-0.133757845	-0.413764596	-0.063567993	0.057507301	0.005673666	-0.045465041	-0.198905102	0.157678121	-0.292768372
0.210107163	-0.762753731	-0.113514688	-0.377067501	-0.080202766	0.058553599	-0.013312535	-0.049311774	-0.178286335	0.116737358	-0.262262234
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0.17932223	-0.707919187	-0.147742155	-0.468437394	-0.086347239	0.046364378	0.023420083	-0.056932385	-0.199912109	0.13527489	-0.320831812
0.149319082	-0.752830887	-0.06056419	-0.348884293	-0.090379995	0.156053854	0.00402923	-0.087617203	-0.010696796	0.026324582	-0.1081197
0.010059676	0.616117603	0.346256652	0.323705183	0.037419038	-0.036121112	0.01731208	0.015883625	0.443358533	-0.280423399	0.559601776

Imagine looking at thousands of numerical values of data!
Without a proper data analysis tool, such an exercise will generate more **heat** than **light!**

Convert process data into a colour coded matrix

A picture is worth a thousand words ..sensors

1	-0.185294206	0.027055773	-0.171819975	0.093276222	-0.027994229	0.098787646	-0.020583535	0.032817213	-0.132101895	0.007443381
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0.027055773	0.046731844	1	0.497561061	0.097669495	-0.042977998	0.073150009	0.01752308	0.446311963	-0.065613281	0.577804913
-0.171819975	0.192725409	0.497561061	1	0.098720947	0.044283695	0.109814686	0.207062089	0.277424246	0.017018503	0.374057968
0.093276222	0.06221338	0.097669495	0.098720947	1	-0.16665222	0.088320804	0.017838289	0.083761143	0.0118807	0.047805363
-0.027994229	-0.121835155	-0.042977998	0.04428365	-0.16665222	1	-0.083250958	-0.113249872	-0.066049714	0.083771862	-0.024636992
0.098787646	0.007001147	0.073150009	0.109814686	0.088320804	-0.083250958	1	0.11444586	0.18562112	-0.115407265	0.14030574
-0.020583535	0.072787318	0.01752308	0.207062089	0.017838289	-0.113249872	0.11444586	1	0.008349999	-0.031577329	-0.029811791
0.032817213	0.256501727	0.446311963	0.277424246	0.083761143	-0.066049714	0.18562112	0.008349999	1	-0.548843663	0.897175324
-0.132101895	-0.332697412	-0.065613281	0.017018503	0.0118807	0.083771862	-0.115407265	-0.031577329	-0.548843663	1	-0.410961064
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-0.004367924	0.415302265	0.212895416	0.422025428	0.121021716	-0.096013616	0.208845673	0.062699756	0.305190719	-0.192434667	0.383145433
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-0.024869432	-0.190808521	0.216974667	0.238447454	0.043845472	0.02495333	-0.005302967	-0.052698509	0.117642296	0.030820275	0.12666478
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0.017414435	-0.037744275	0.109437444	-0.048190722	-0.019413361	0.085313857	-0.03284987	-0.090511989	0.148464685	-0.022750366	0.185438833
0.038764349	-0.713947863	-0.052827235	-0.199718753	-0.077278511	0.145219414	-0.072139066	-0.148773823	-0.170502021	0.300067528	-0.221413011
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0.041199633	-0.557289409	-0.29471802	-0.59961326	-0.110351578	0.076308499	-0.029991342	-0.089972975	-0.114970901	-0.040561871	-0.28198484
0.0859979	0.007025338	0.154179893	0.232546946	0.007835329	0.086967223	0.156685077	0.023192903	-0.02996409	0.102102098	0.014799742
0.07875747	-0.429241921	-0.344287431	-0.244148911	-0.023116012	-0.027914037	-0.035809918	0.05492866	-0.371758851	0.202342995	-0.500472826
-0.058448605	0.611130166	-0.119253918	0.057550975	0.117777025	-0.183408655	0.082432127	0.10213768	-0.008270005	-0.326478145	-0.009977244
-0.02580405	-0.150816152	0.120793341	0.066957772	0.025269938	0.006378438	-0.075330271	0.07187571	-0.106953812	0.090117193	-0.067876774
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0.215815744	-0.782048799	-0.133757845	-0.413764596	-0.063567993	0.057507301	0.005673666	-0.045485041	-0.198905102	0.157678121	-0.292768372
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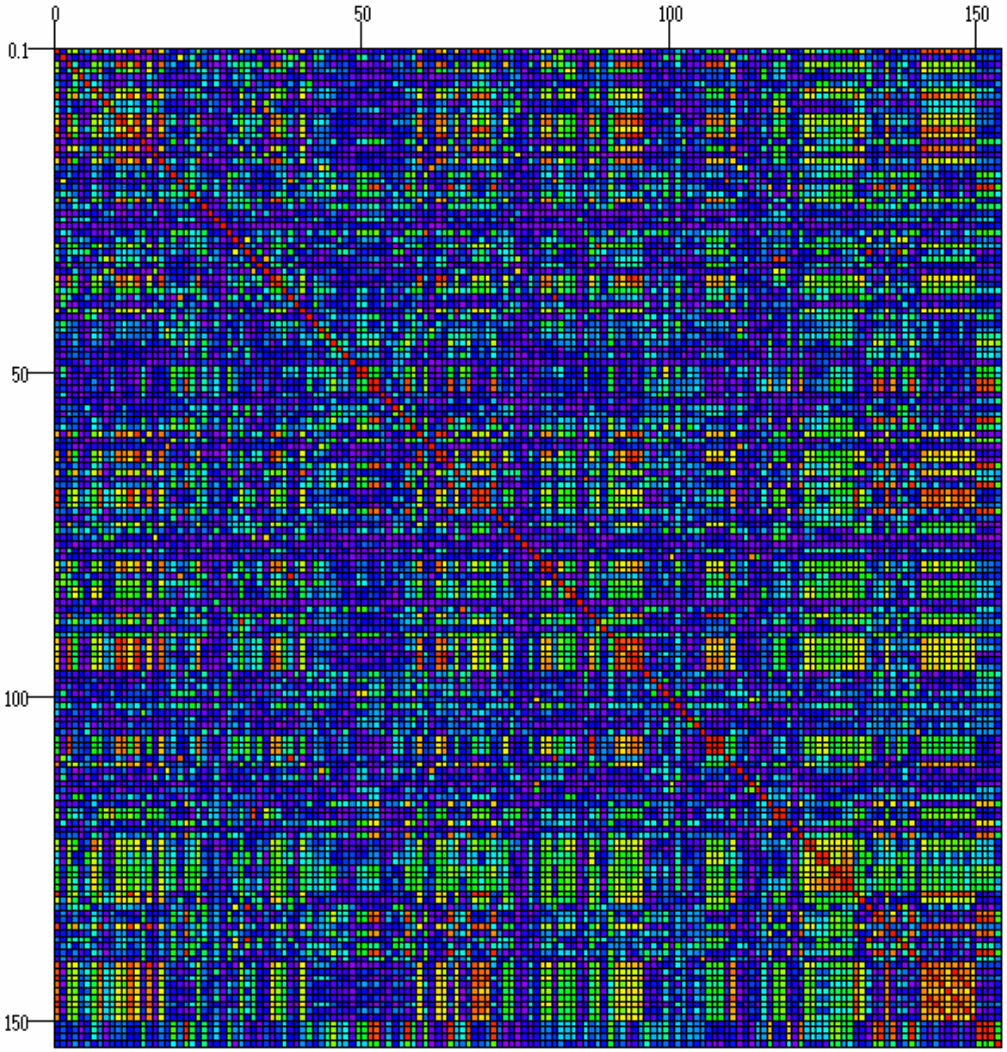
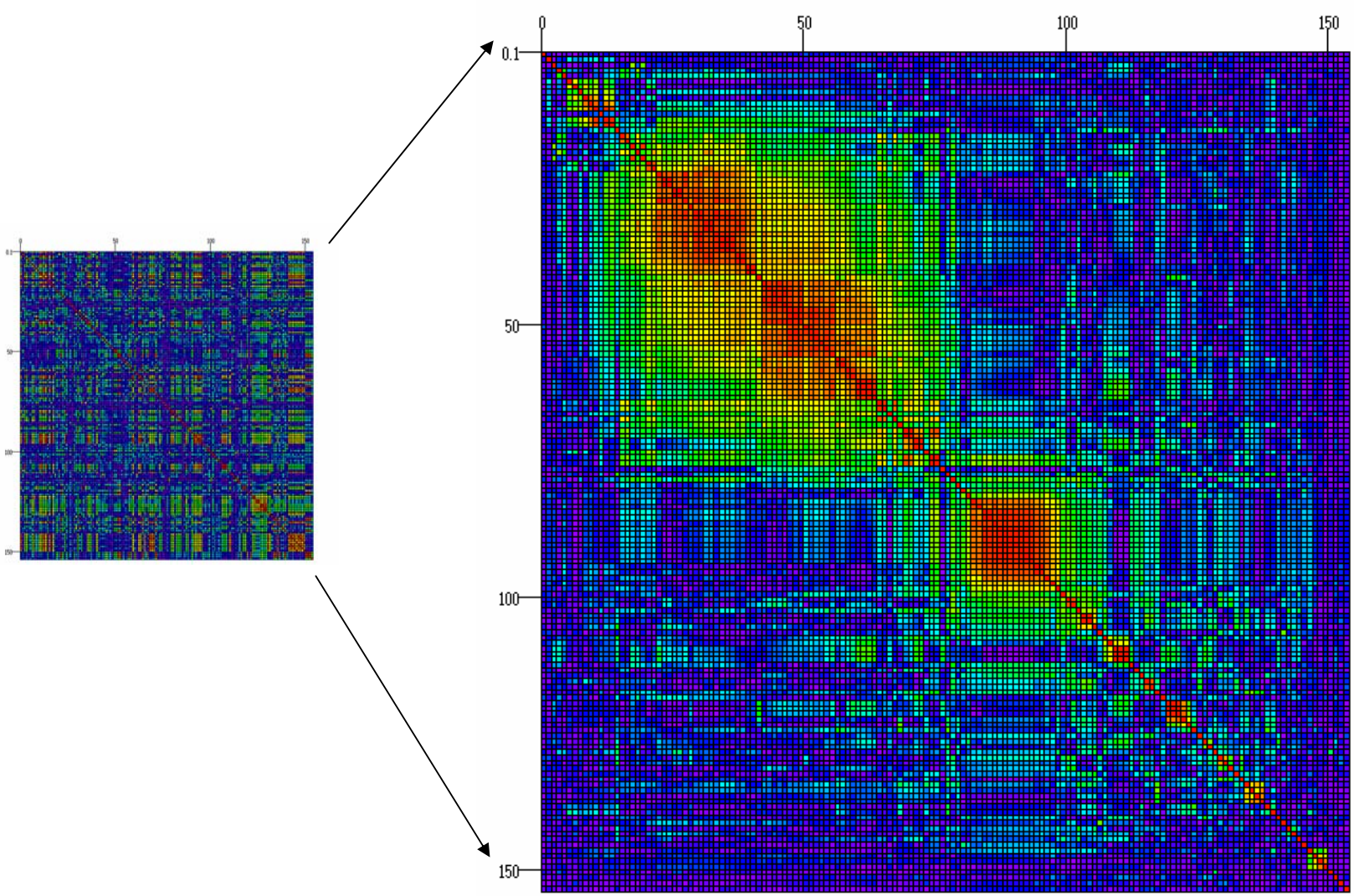
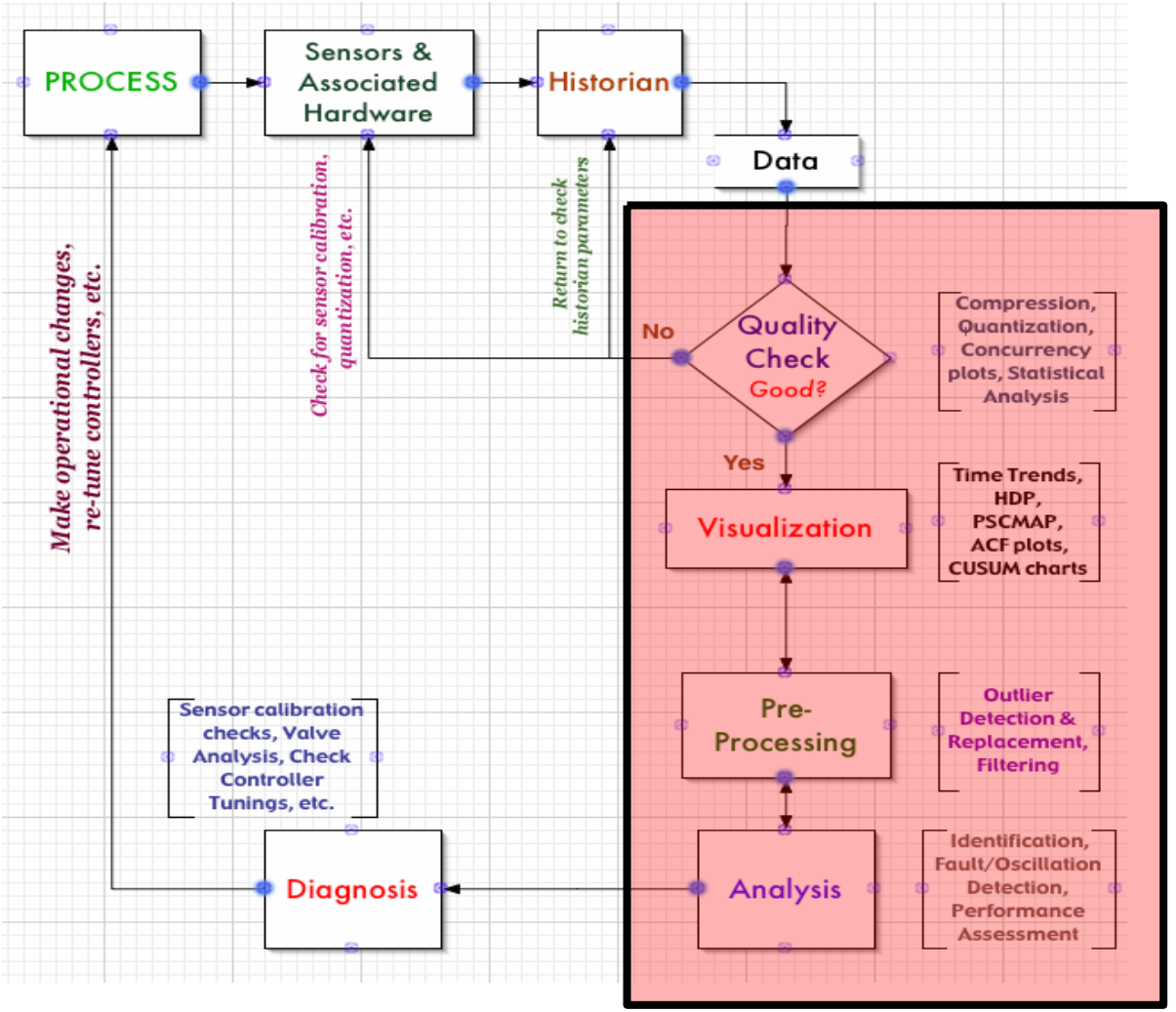
-0.160786539	0.822759906	0.082111296	0.319369724	0.073604799	-0.115269237	0.02934483	-0.005308015	0.179202768	-0.192898469	0.239070492
0.17932223	-0.707919187	-0.147742155	-0.468437394	-0.086347239	0.044364378	0.023420083	-0.056932385	-0.199912109	0.13527488	-0.320631812
0.149319082	-0.752830887	-0.09055419	-0.348884293	-0.093379995	0.156353854	0.00402923	-0.007617203	-0.016967795	0.026324582	-0.1081197
0.010059676	0.616117603	0.346256652	0.323705183	0.037419038	-0.036121112	0.01731208	0.015883925	0.443358533	-0.280423399	0.559801776



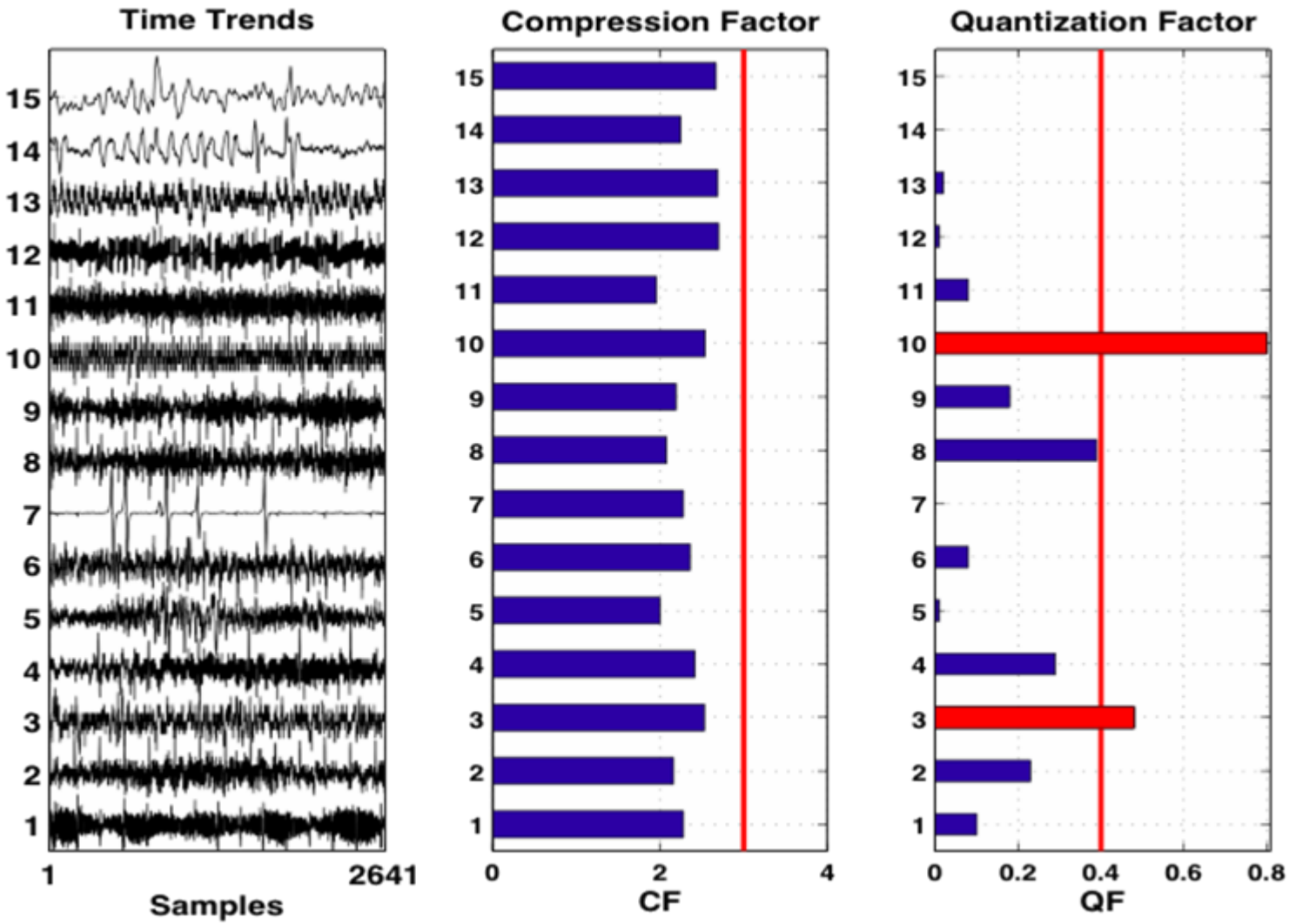
Reorder variables so that inter-relationships are easily seen



A sensor-fusion toolbox?



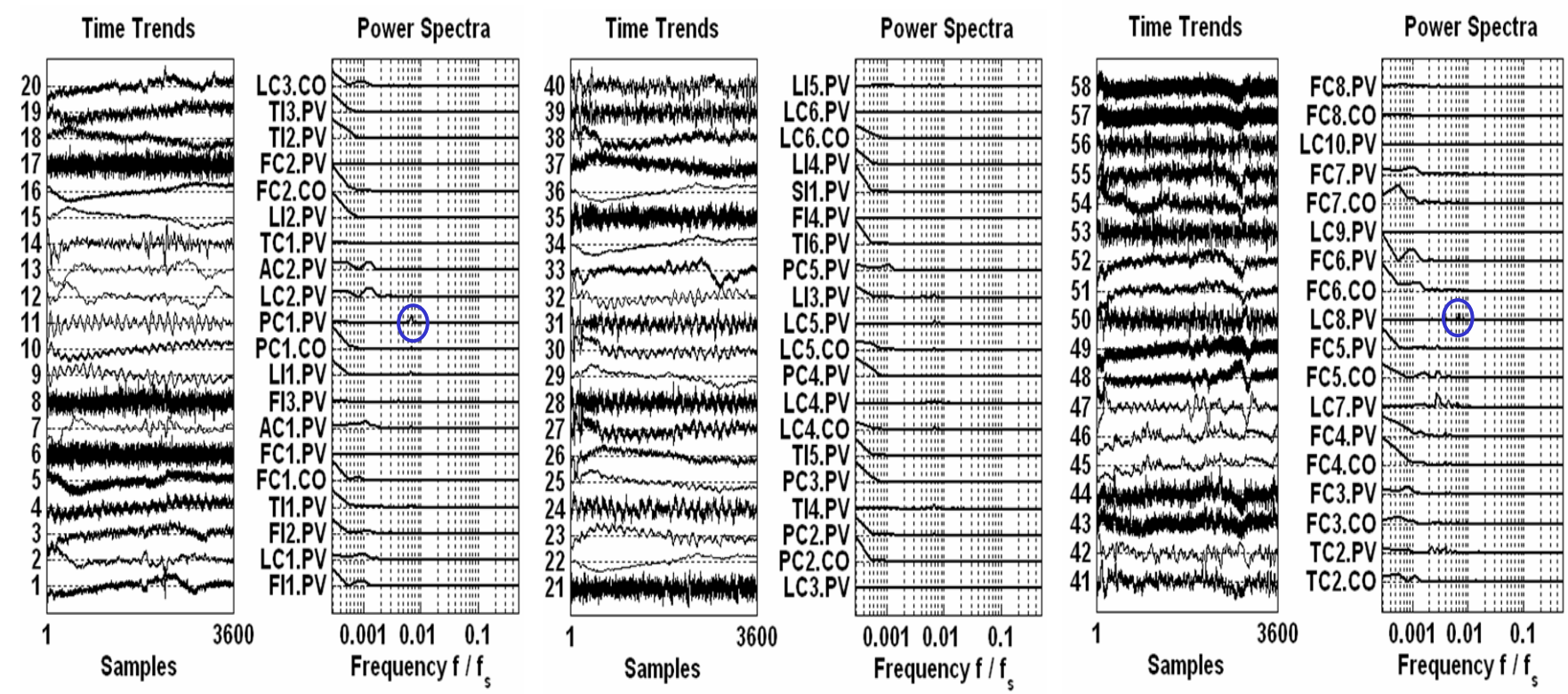
Compression & Quantization Analysis



Overview of the data

Interested in oscillations with period 2.5 hours

(about 150 samples/cycle, or 1/150 = 0.0067)



tag 1- 20

tag 21- 40

tag 41- 58

Demonstration of the DVA Toolbox

Highlights of key results

- Image-based softsensor design for interface level detection in the sep cell
- Detection and quantification of valve stiction
- Controller performance monitoring
  - Diagnosis of univariate loops
  - Assessing the impact of MPM on multivariate performance
- Condition based monitoring using multivariate and machine learning methods
- Data analysis and visualization
- Reconstruction of missing data
- Temporal analysis of process data for plant-wide oscillation detection
- Design of softsensors based on multivariate methods

Overview of 2 recent results

1.How to reconstruct compressed data?

Syed Imtiaz

Process data is often compressed

- If 1000 variables are measured in a process
- 8.75 GB of data is logged each day
- equivalent to
  - 262.5 GB per month
  - 3150 GB a year

- Compression makes data archiving manageable
- Facilitates transfer via Telecommunication

Missing Data in Process Industries

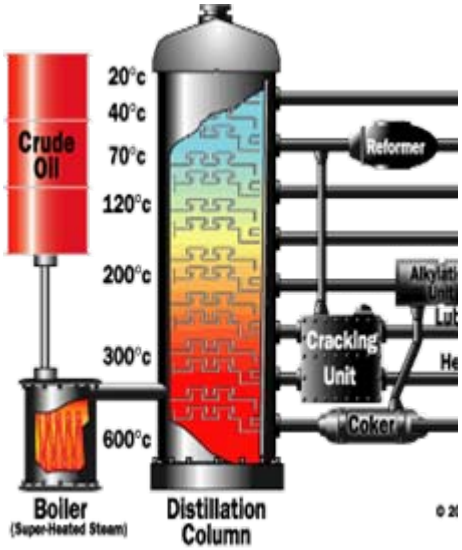
Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
9.99	9.90	19.88	19.88	9.99	9.99
NaN	NaN	NaN	19.58	9.57	9.57
NaN	NaN	NaN	19.09	9.38	9.38
9.71	9.82	19.53	19.53	9.71	9.71
NaN	NaN	NaN	19.92	9.91	9.91
NaN	NaN	NaN	19.61	NaN	9.63
10.18	10.04	20.22	20.22	NaN	10.18
NaN	NaN	NaN	19.77	NaN	9.96
NaN	NaN	NaN	20.18	NaN	9.91
9.96	10.49	20.46	20.46	NaN	9.96
NaN	NaN	NaN	20.60	NaN	10.19
NaN	NaN	NaN	20.05	NaN	9.75
9.72	10.05	19.76	19.76	NaN	9.72
NaN	NaN	NaN	19.67	NaN	9.48
NaN	NaN	NaN	19.44	NaN	9.47
9.41	9.94	19.36	19.36	NaN	9.41
NaN	NaN	NaN	19.51	9.54	9.54
NaN	NaN	NaN	20.07	9.82	9.82
9.76	10.52	20.28	20.28	9.76	9.76
NaN	NaN	NaN	20.35	9.87	9.87
NaN	NaN	NaN	20.00	9.81	9.81
9.86	10.48	20.34	20.34	9.86	9.86
NaN	NaN	NaN	20.29	10.03	10.03
NaN	NaN	NaN	20.28	10.27	10.27
10.37	10.05	20.43	20.43	10.37	10.37

Multi-Rate Data

Sensor Failure

Response Outside Instrument Range

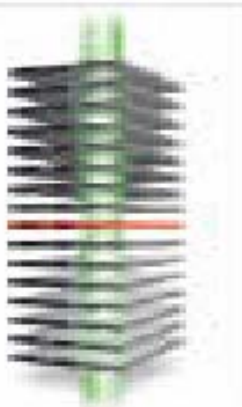
Data Compression in the Process Industry



X_{raw}

Compression

X_{comp}



Data Historian

Decompression

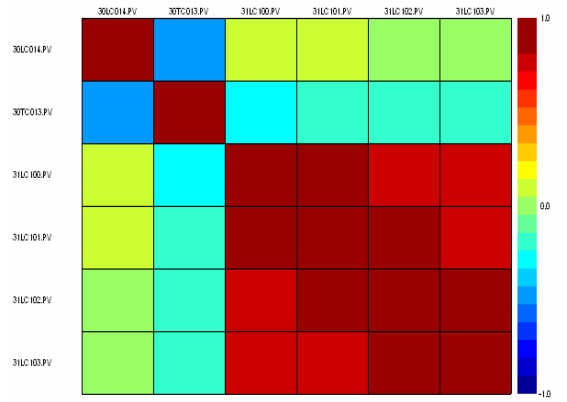
Data Analyst

$X_{reconst}$

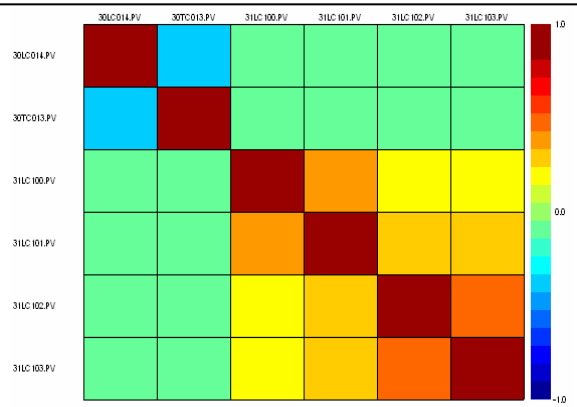
$X_{reconst} \neq X_{raw}$

Effect of Compression on Correlation Structure Refinery Process Data

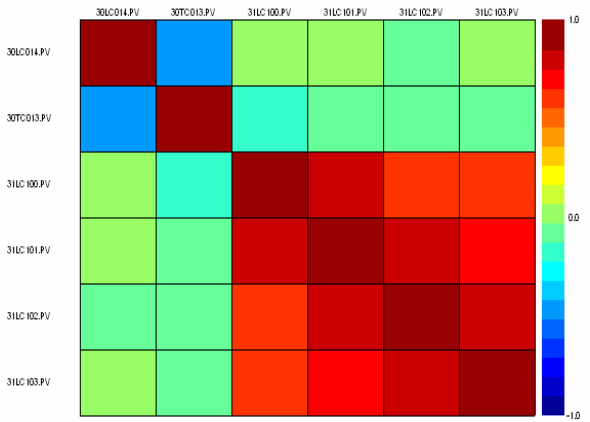
Uncompressed Data Correlation Color Plot



Correlation Color Plot of Reconstructed Data from Swinging Door algorithm



Correlation Color Plot of Reconstructed Data from Wavelet compression algorithm



Correlation Color Plot of Reconstructed Data using PCAIA

2. Oscillation Diagnosis using the Adjacency Matrix

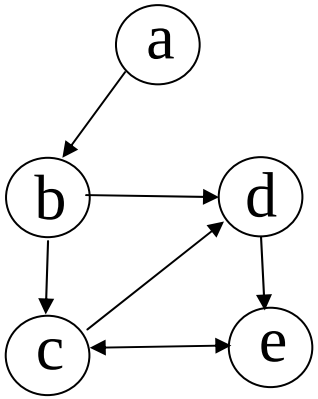
Hailei Jiang*, Rohit Patwardhan#, Sirish Shah*,
Department of Chemical and Materials Engineering
*University of Alberta
#Matrikon Inc.

Challenges in Data and Information fusion

- How to effectively incorporate process knowledge and process flow sheet information for process monitoring?
- How to use this information intelligently for process monitoring?
- New paradigm: Use of the adjacency matrix in variability transfer and model quality monitoring.

Adjacency Matrix

Richard Mah,1989



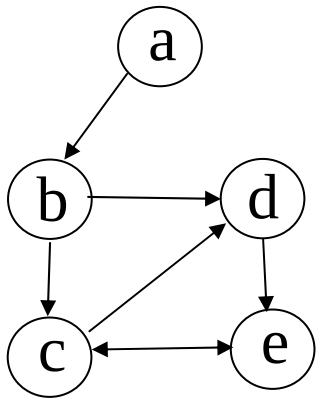
$$\begin{array}{c} \\ a \\ b \\ c \\ d \\ e \end{array}\begin{array}{c} \begin{array}{ccccc} a & b & c & d & e \end{array} \\ \begin{bmatrix} & 1 & & & \\ & & 1 & 1 & \\ & & & 1 & 1 \\ & & & & 1 \\ & & 1 & & \end{bmatrix} \end{array} = \mathbf{x} \qquad \mathbf{x}^2 = \begin{array}{c} \\ a \\ b \\ c \\ d \\ e \end{array}\begin{array}{c} \begin{array}{ccccc} a & b & c & d & e \end{array} \\ \begin{bmatrix} 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 2 \\ 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 \end{bmatrix} \end{array}$$

$$\mathbf{x}^3 = \begin{bmatrix} 0 & 0 & 0 & 1 & 2 \\ 0 & 0 & 2 & 0 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 \end{bmatrix} \qquad \mathbf{x}^4 = \begin{bmatrix} 0 & 0 & 2 & 0 & 1 \\ 0 & 0 & 1 & 2 & 2 \\ 0 & 0 & 1 & 1 & 2 \\ 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 & 1 \end{bmatrix} \qquad \mathbf{x}^5 = \begin{bmatrix} 0 & 0 & 1 & 2 & 2 \\ 0 & 0 & 2 & 1 & 3 \\ 0 & 0 & 2 & 1 & 2 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 2 \end{bmatrix}$$

Reachability Matrix

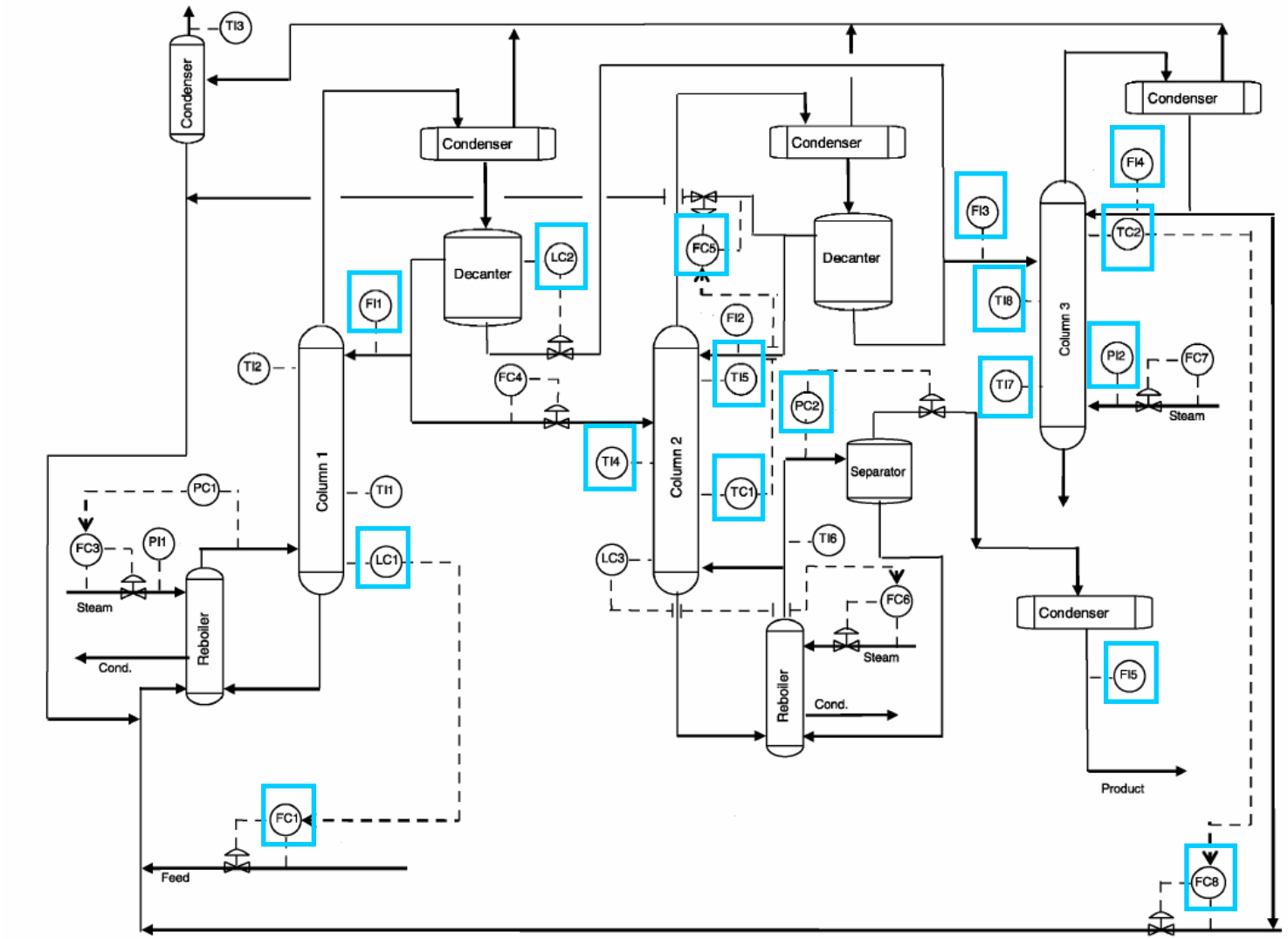
$$\mathbf{A} = \mathbf{X} + \mathbf{X}^2 + \mathbf{X}^3 + \ldots + \mathbf{X}^N$$

$$\mathbf{R} = (\mathbf{A})^{\sharp} \begin{cases} If\ \mathbf{A}(i,j) = 0, \mathbf{R}(i,j) = 0, \\ If\ \mathbf{A}(i,j) \neq 0, \mathbf{R}(i,j) = 1, \end{cases}$$

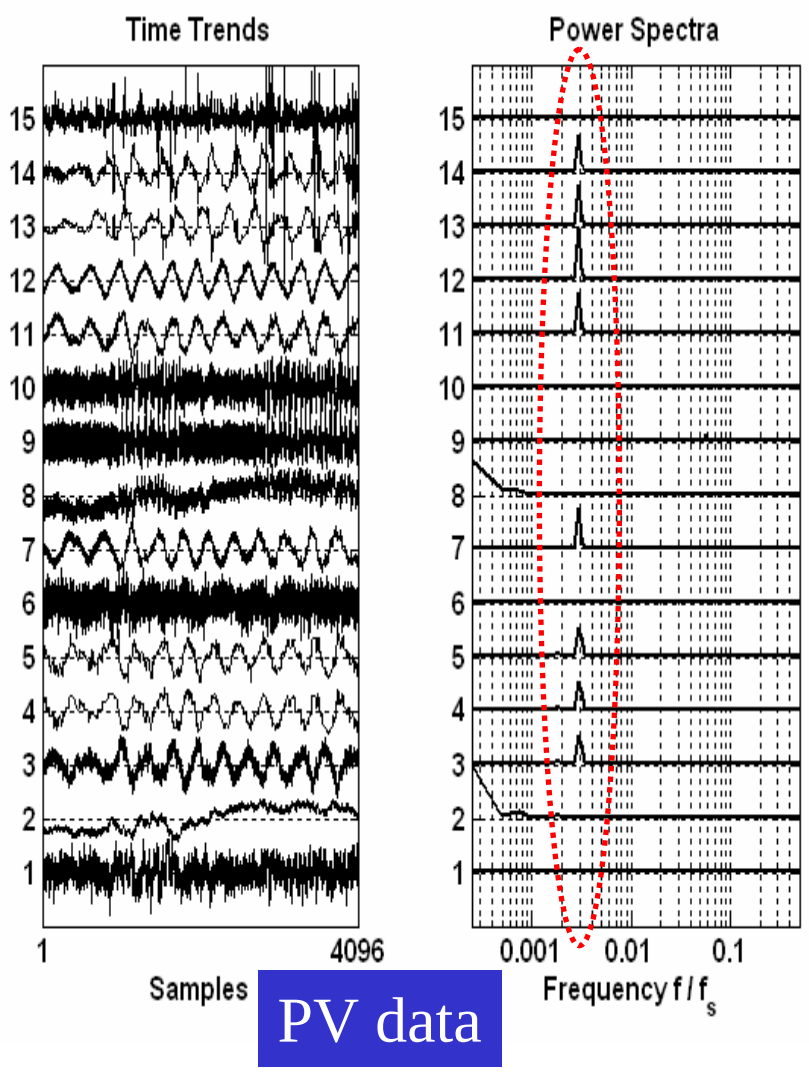


$$\mathbf{R} = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \end{bmatrix}$$

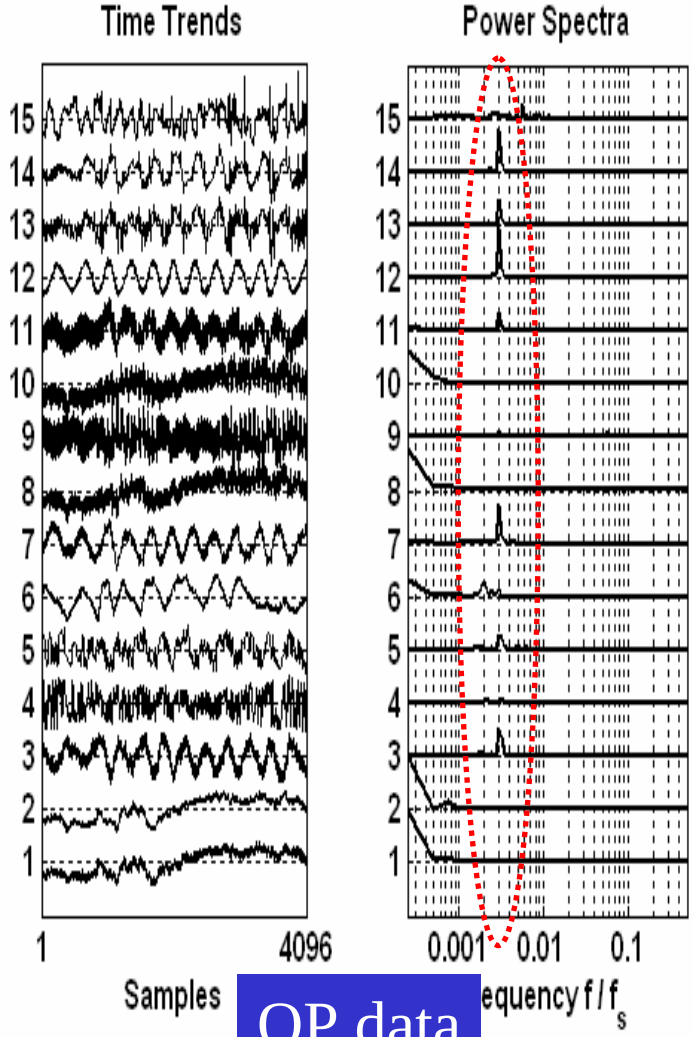
Industrial Application 1 – Eastman Chemicals



PV and OP data

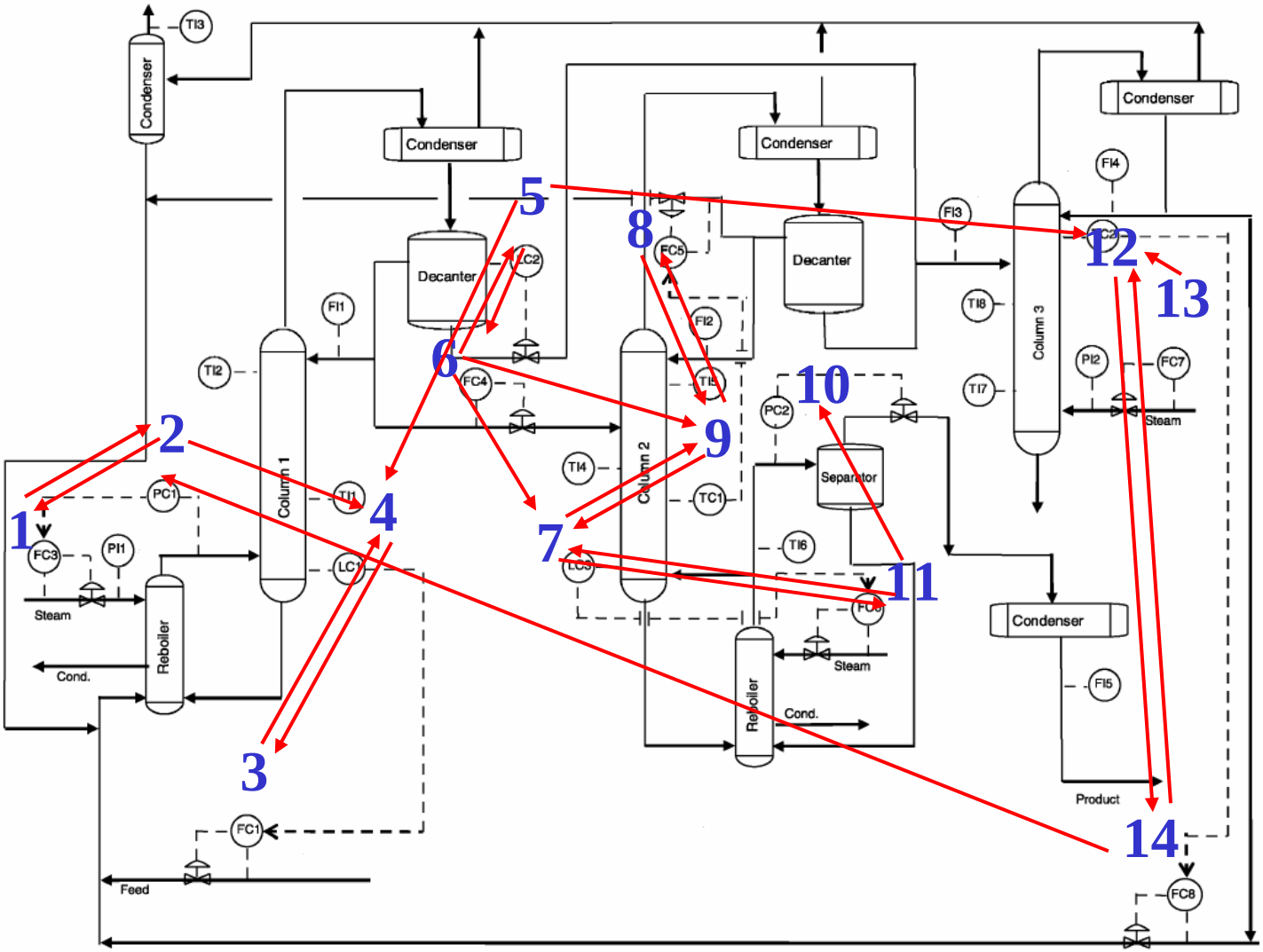


PV data



OP data

Industrial Application 1 – Eastman Chemicals



Adjacency Matrix

		1	2	3	4	5	6	7	8	9	10	11	12	13	14
		FC3	PC1	FC1	LC1	LC2	FC4	LC3	FC5	TC1	PC2	FC6	TC2	FC7	FC8
1	FC3	1	1	0	0	0	0	0	0	0	0	0	0	0	0
2	PC1	1	1	0	1	0	0	0	0	0	0	0	0	0	0
3	FC1	0	0	1	1	0	0	0	0	0	0	0	0	0	0
4	LC1	0	0	1	1	0	0	0	0	0	0	0	0	0	0
5	LC2	0	0	0	1	1	1	0	0	0	0	0	1	0	0
6	FC4	0	0	0	0	1	1	1	0	1	0	0	0	0	0
7	LC3	0	0	0	0	0	0	1	0	1	0	1	0	0	0
8	FC5	0	0	0	0	0	0	0	1	1	0	0	0	0	0
9	TC1	0	0	0	0	0	0	1	1	1	0	0	0	0	0
10	PC2	0	0	0	0	0	0	0	0	0	1	0	0	0	0
11	FC6	0	0	0	0	0	0	1	0	0	1	1	0	0	0
12	TC2	0	0	0	0	0	0	0	0	0	0	0	1	0	1
13	FC7	0	0	0	0	0	0	0	0	0	0	0	1	1	0
14	FC8	0	1	0	0	0	0	0	0	0	0	0	1	0	1

Reachability Matrix

		1	2	3	4	5	6	7	8	9	10	11	12	13	14
		FC3	PC1	FC1	LC1	LC2	FC4	LC3	FC5	TC1	PC2	FC6	TC2	FC7	FC8
1	FC3	1	1	1	1	0	0	0	0	0	0	0	0	0	0
2	PC1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
3	FC1	0	0	1	1	0	0	0	0	0	0	0	0	0	0
4	LC1	0	0	1	1	0	0	0	0	0	0	0	0	0	0
5	LC2	1	1	1	1	1	1	1	1	1	1	1	1	0	1
6	FC4	1	1	1	1	1	1	1	1	1	1	1	1	0	1
7	LC3	0	0	0	0	0	0	1	1	1	1	1	0	0	0
8	FC5	0	0	0	0	0	0	1	1	1	1	1	0	0	0
9	TC1	0	0	0	0	0	0	1	1	1	1	1	0	0	0
10	PC2	0	0	0	0	0	0	0	0	0	1	0	0	0	0
11	FC6	0	0	0	0	0	0	1	1	1	1	1	0	0	0
12	TC2	1	1	1	1	0	0	0	0	0	0	0	1	0	1
13	FC7	1	1	1	1	0	0	0	0	0	0	0	1	1	1
14	FC8	1	1	1	1	0	0	0	0	0	0	0	1	0	1

Oscillation Contribution Index

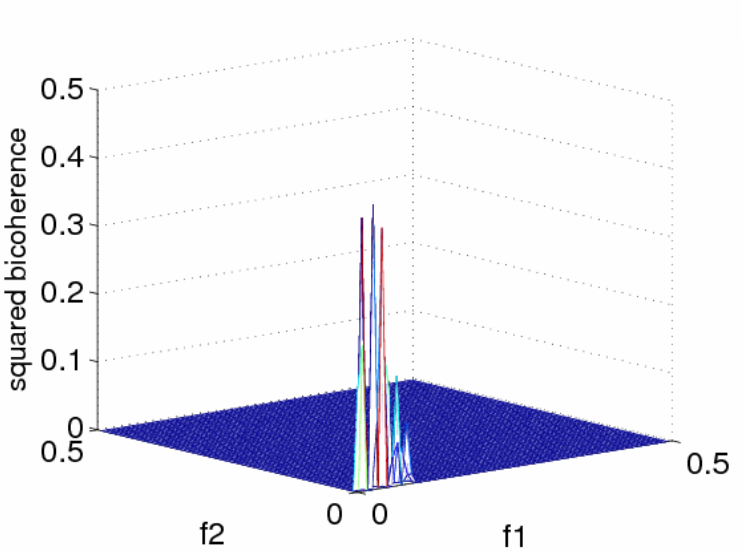
Tag	LC2.pv	LC2.op	TI4.pv	TC1.pv	TC2.pv	TI5.pv
OCI	4.77	3.86	2.56	2.45	2.27	1.53

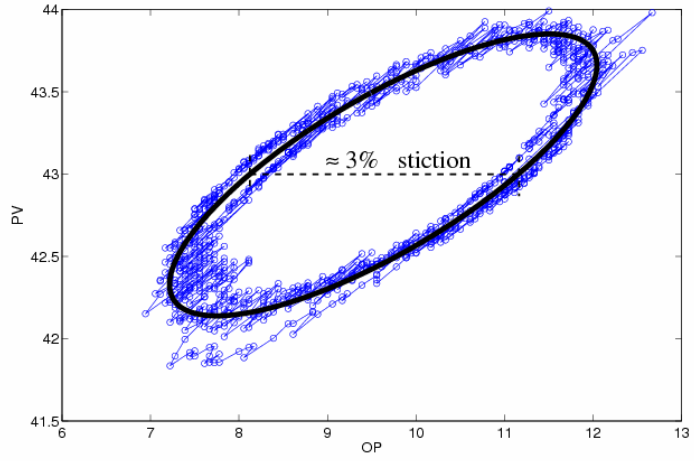
Tag	FC8.pv	TC2.op	FC8.sp	TI8.pv	FI3.pv	PI2.pv
OCI	1.50	1.35	1.35	1.18	1.07	1.04

Hailei Jiang, M.A.A. S. Choudhury and Sirish Shah

Detection and diagnosis of plant-wide oscillation from industrial data using the spectral envelope method, *Journal of Process Control*, *2007*, *2*

Valve Stiction Diagnosis





1. These plots confirm a pattern of valve stiction.

2. Plant test has confirmed that this loop is the root cause.

Concluding Remarks

- Use your data. It is a key resource for quality and productivity gains
- The real world is multivariate and NOT univariate. Data/Sensor fusion and information extraction is important.
- Treat equipment as well as algorithms as ‘assets’;
  - Visit and revisit assets regularly
  - Benchmark process performance
- Process monitoring or CBM needs an advanced set of efficient temporal and spectral data analysis tools

Additional remarks

- CBM for reliable process operation and asset management is a journey and not a destination.
- Start simply…but start

Acknowledgements

- Mitsubishi Chemicals, AT Plastics, Eastman Chemicals
- NSERC-Matrikon-Suncor-iCORE Industrial Research Chair Program for Financial Support

Thank you for listening.

Questions?

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- M. Vidyasagar (India)