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Fifth Framework Programme

PAM

Controller Benchmarking: from Single Loops to Plant-Wide Economic Assessment

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Talk Outline

- Motivation for Benchmarking control loops
- Intuitive introduction to Benchmarking techniques
- Real-Life Examples
- Extensions to address limitations of current algorithms
- Ongoing developments:
  - On-line Benchmarking
  - linking with Process Economics and Multivariable Benchmarking

Benchmarking: The Concept

- Defined as:

…. the process of continuously measuring and comparing one's business process against comparable processes in leading organisations to obtain information that will help the organisation identify and implement improvements

- Often employed at business level
- Metrics:
  - profitability, on-time on-spec delivery, complaints, absenteeism, staff turnover, product quality, plant availability

Benchmarking: For Control

- Comparing current performance with theoretical best
- Identify underperforming loops for improvement
  - requires link to process economics
  - needs to be done regularly
- Metrics:
  - % time in auto, loop rise time, ISE, disturbance rejection, valve stiction measures, variability

Identifying Underperforming Loops

- Requires *human skills/experience*
- Root cause *not always established*
- Diagnostic tools often *need ‘expert’ users*
- Can we benchmark loops <u>without</u> relying on “experts” ?

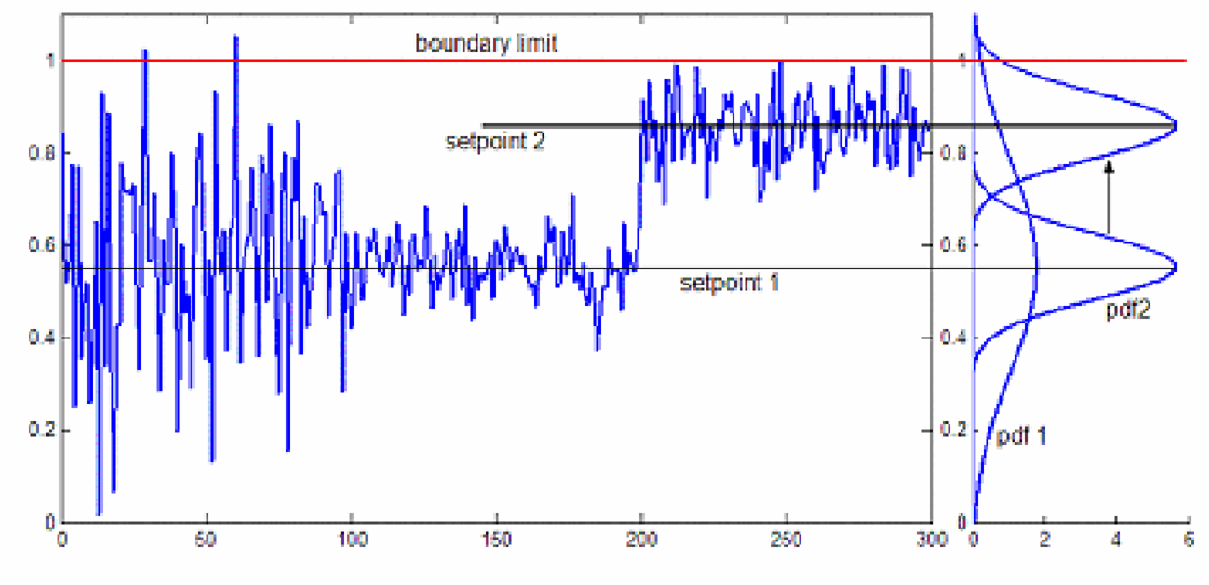
Minimum Variance Benchmarking

- Comparing current performance with theoretical best

Minimum Variance Controller

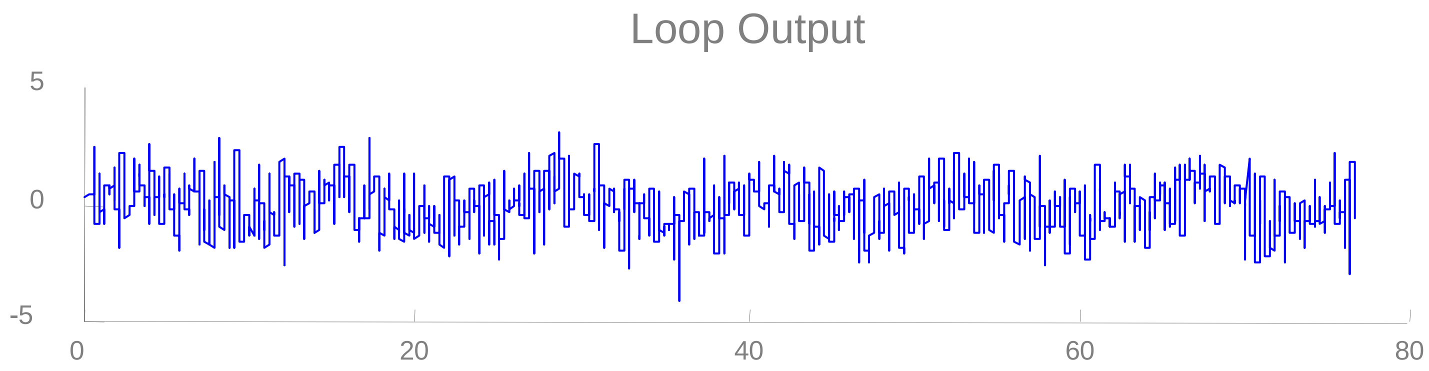
- Uses standard plant operating data

- Process variability is linked to process economics



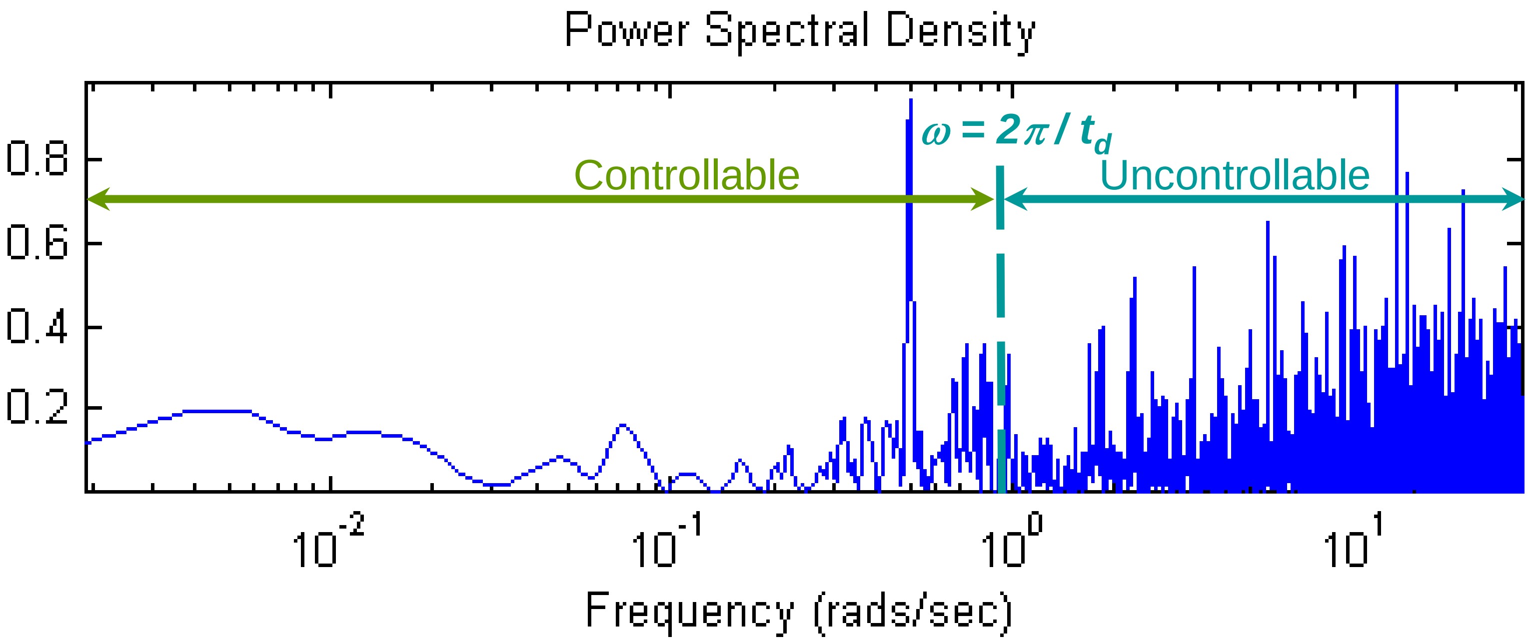
MV Benchmark - How it is Derived

Take loop output or error time trend data….



...together with knowledge of the loop delay t_d (= 7 sec.)

MV Benchmark - How it is Derived

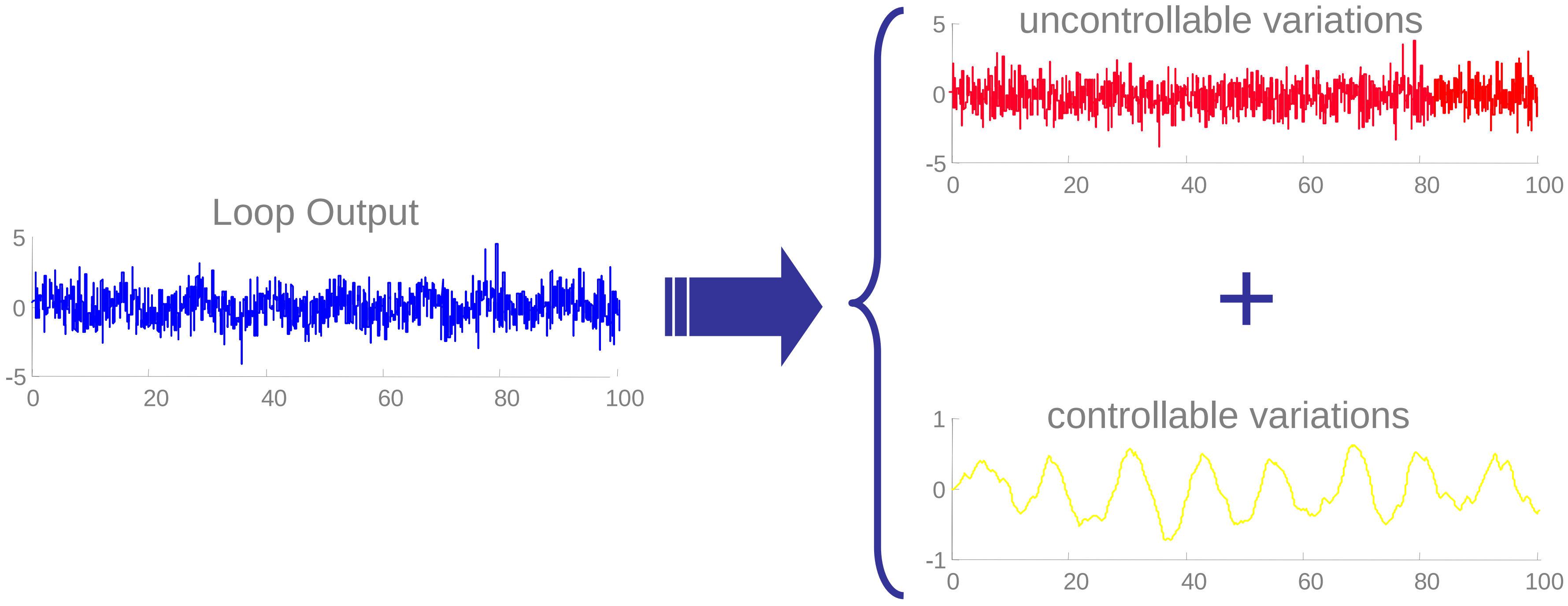


….then partition the data by frequency:

$\Rightarrow \ \omega < 2\pi / t_d$ (controllable)

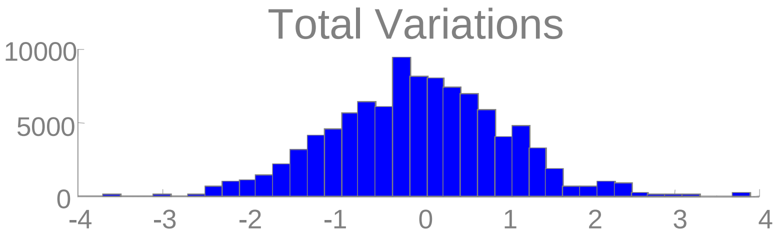
$\Rightarrow \ \omega > 2\pi / t_d$ (uncontrollable)

Partitioning Effect in the Time Domain



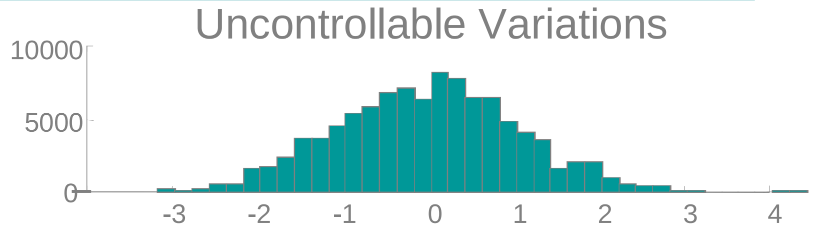
Partition into uncontrollable & controllable variations
(using loop delay)

Effect of Partitioning on Variance



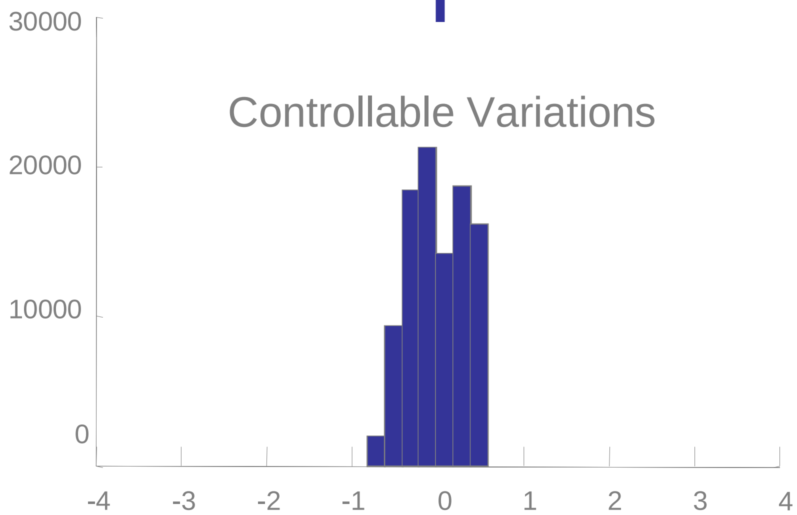
$\sigma^2_{total} = 1.15$

=



$\sigma^2_{uctrlble} = 1.02$

+



$\sigma^2_{ctrlble} = 0.13$

$$benchmark \quad , \eta = \frac{\sigma^2_{uctrlble}}{\sigma^2_{total}}$$

$$\eta = \frac{1.02}{1.15} = 0.887 = 88.7\%$$

MV Benchmark Computation Steps

- Output data representation

  time series model + coloured white noise

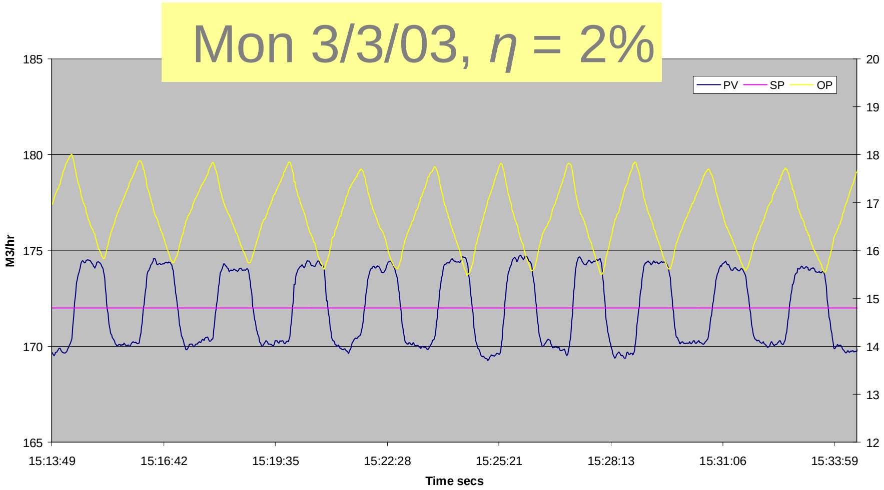
- Model coefficients determined by regression
- Estimate of Minimum Variance

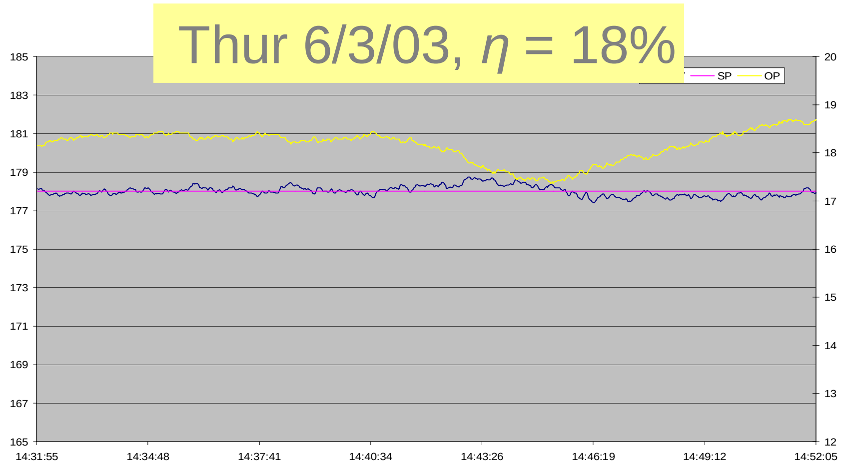
  error data variance - model data variance

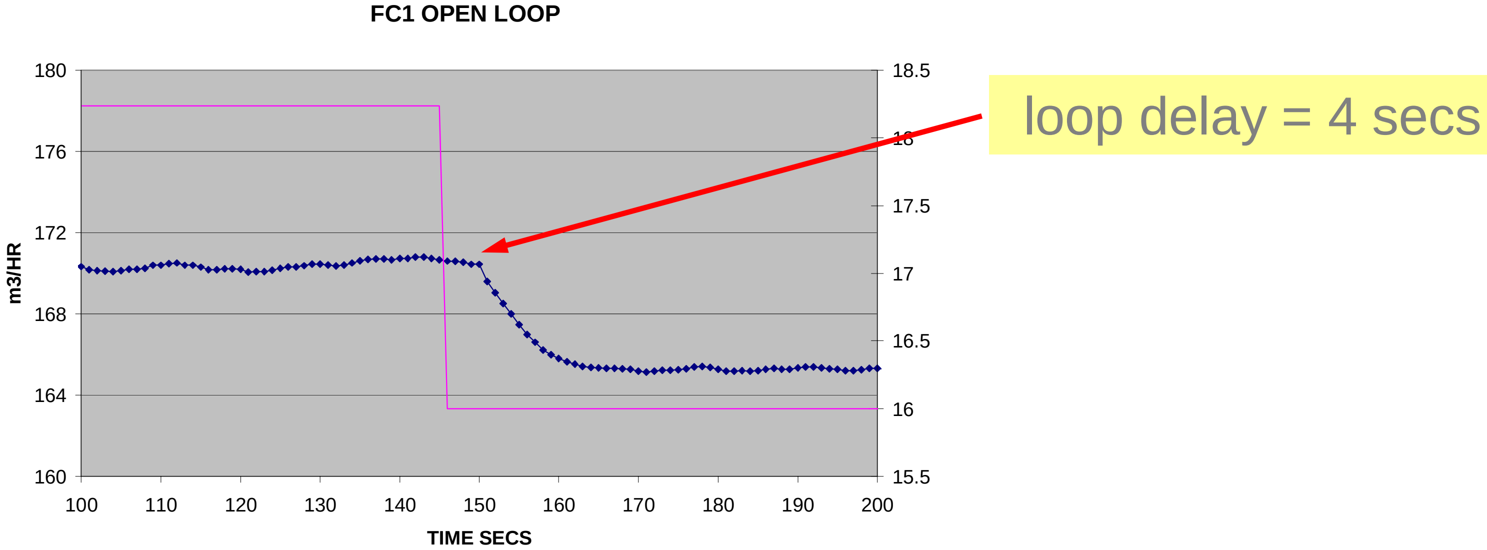
- Benchmark

  ratio of MV & error data variance

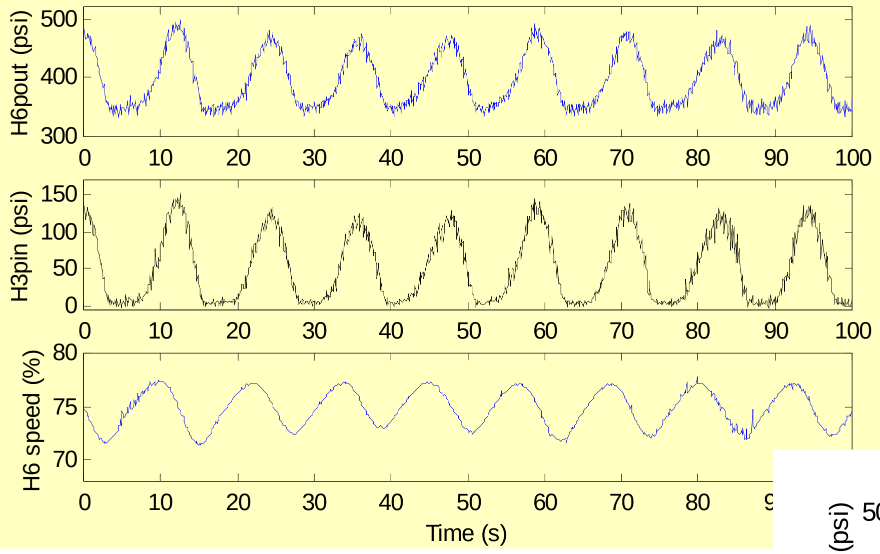
Refinery Flow Loop – MV Example







Food Homogenisation – MV Example

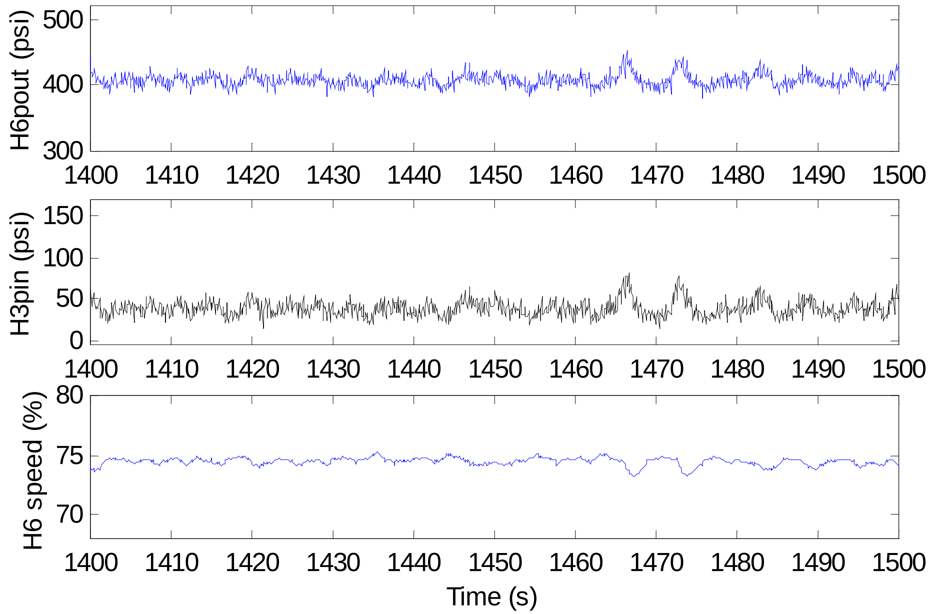


$\eta = 10.9\%$

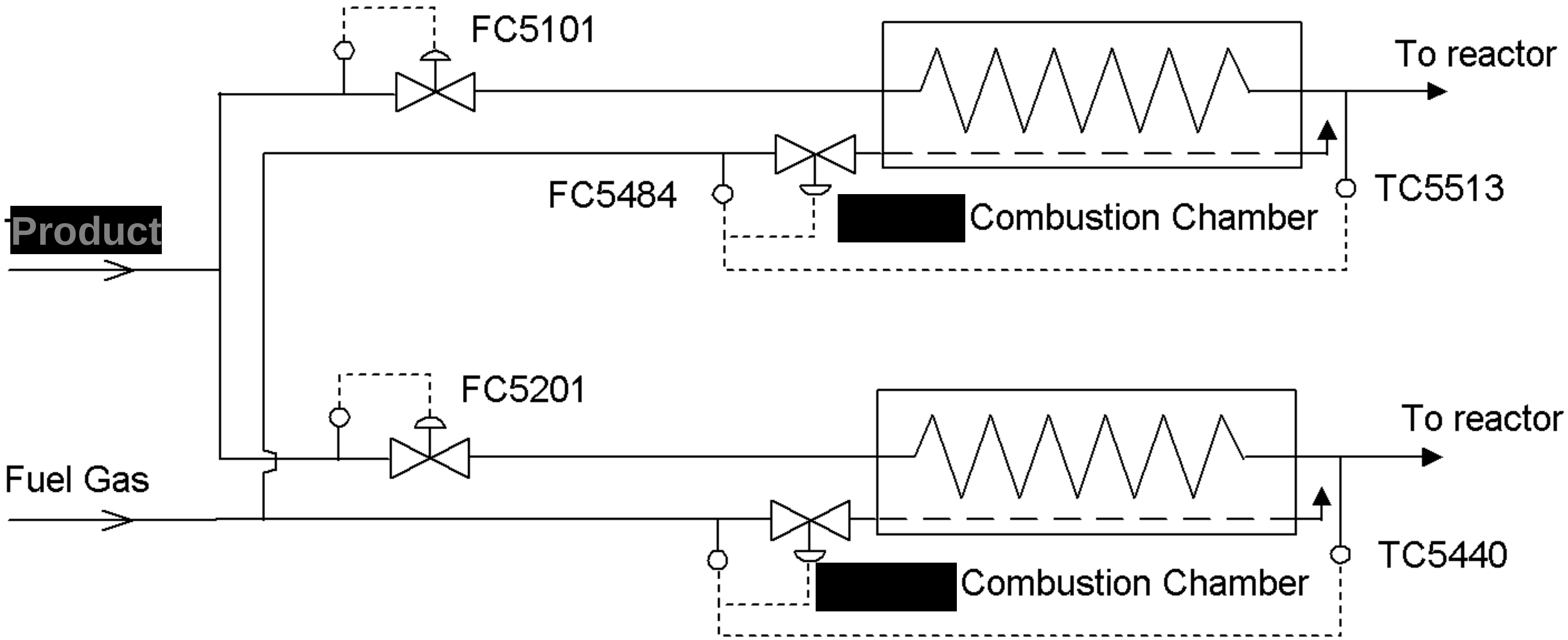
Original System Responses causing excessive wear

Improved System Responses following ISC investigation

$\eta = 79.6\%$



Furnace – MV Example

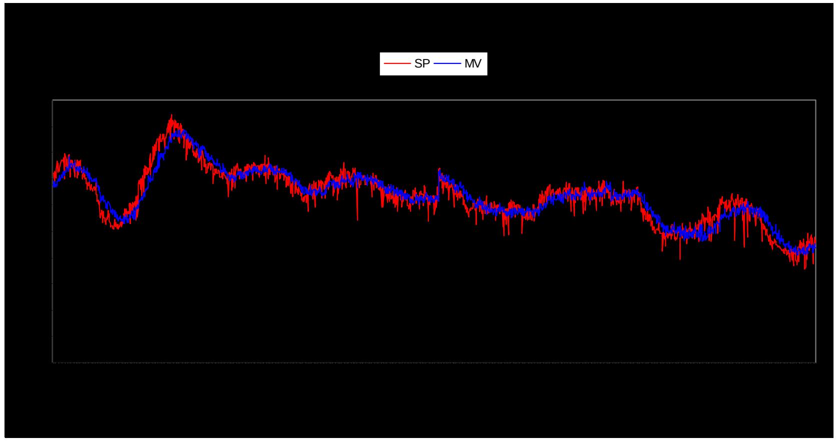


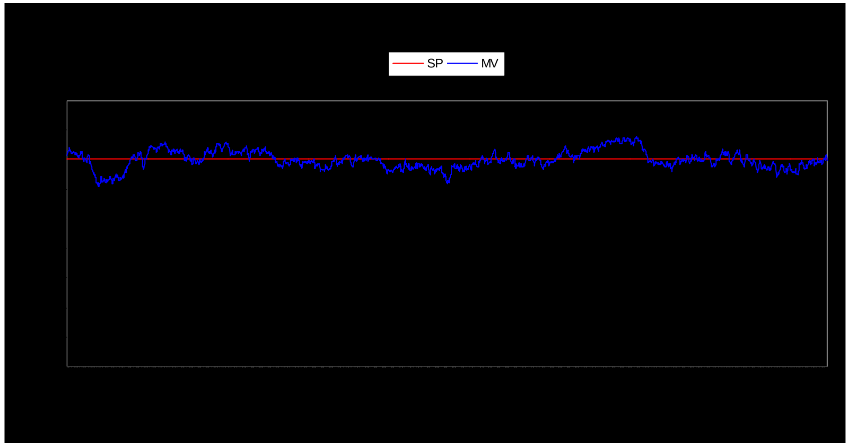
- Furnace exit temperature is critical:
  - product quality, re-work and energy consumption
- Depends on good control

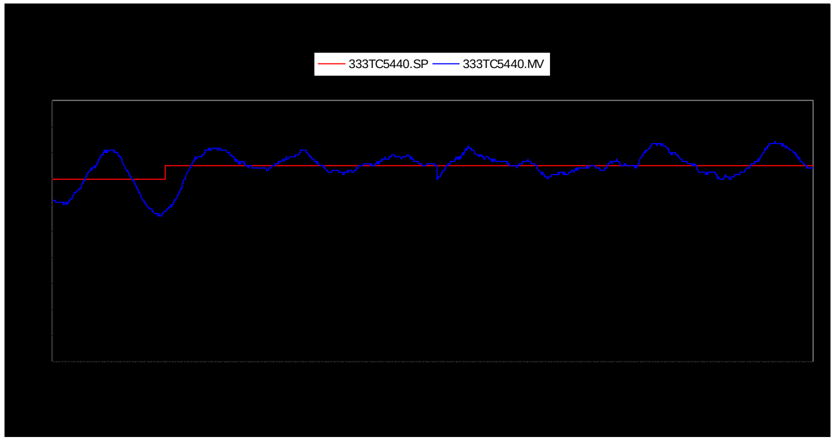
… but which loops are underperforming ?

Furnace – MV Example

- Normal operating data:





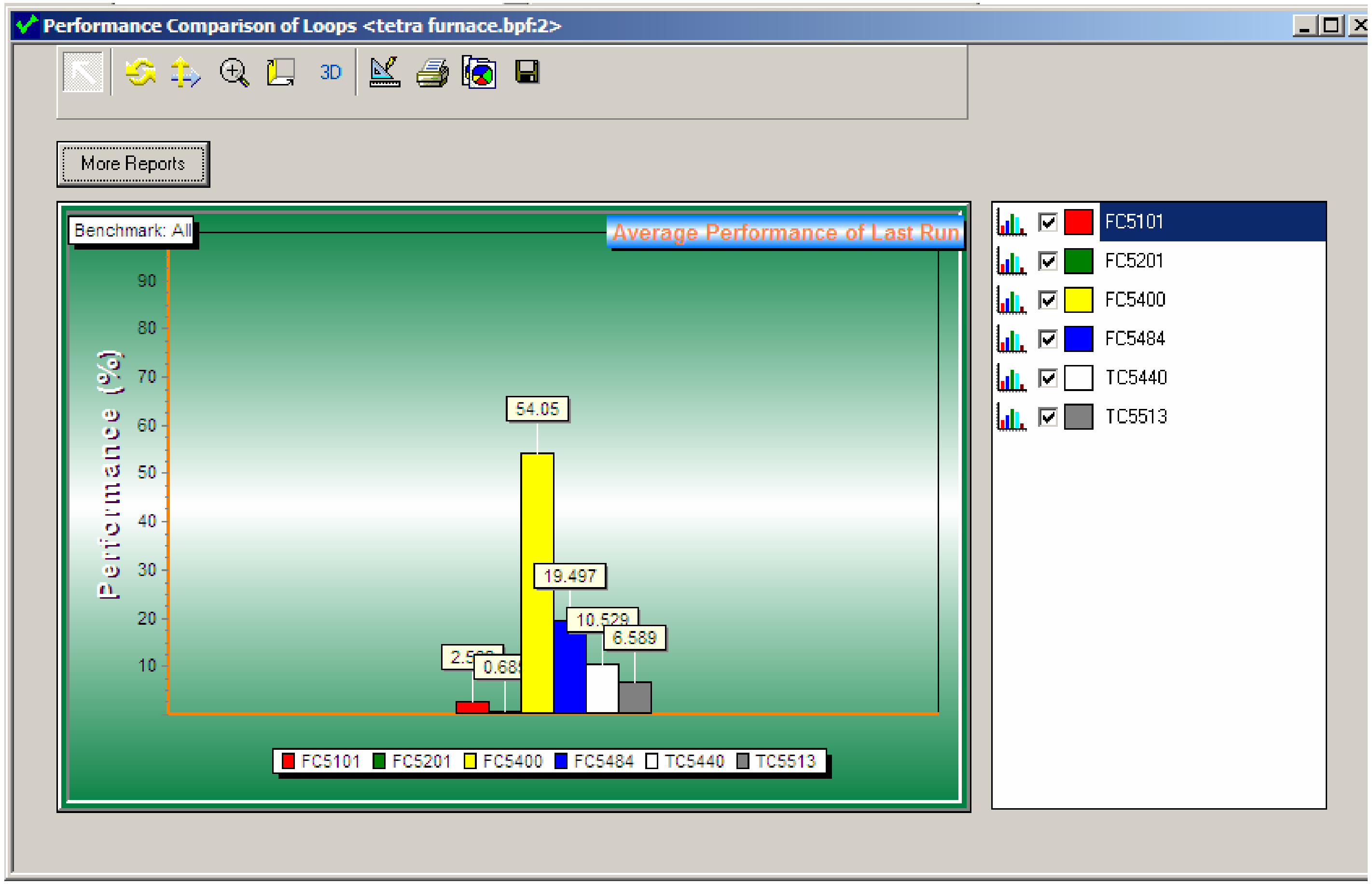


… also need knowledge of loop delays

Furnace – MV Example

- Results from MV Benchmark:
  - Fuel Gas Flow Loop = 50%
  - Temperature Loop = 15%
  - Product Flow Loop = 2%
- Poor product flow control!!
- Agreed with a formal investigation of the process

Furnace – MV Example



MV Benchmark Limitations

Minimum variance analysis highlights deficiencies,

however…..there are some drawbacks :

- Actuator *movement is not penalised*
- Assumes *unlimited controller order*
- Noise tends to be amplified

…which results in a *pessimistic* benchmark

MV Benchmark Limitations

Also need:

- Raw data required – ***not*** archived/compressed data
- Loop delay
- Formal link to economics
- Only works on a loop by loop basis

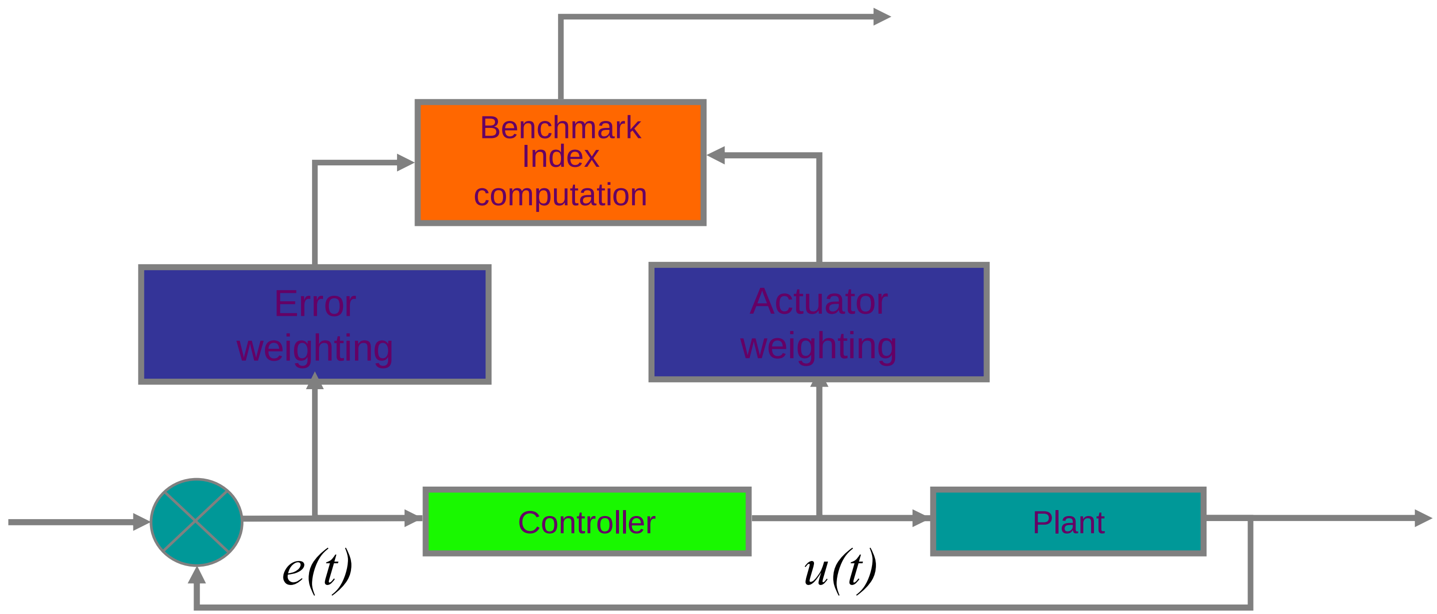
New Developments in Benchmarking

- New algorithms to address MV limitations
  - Generalised Minimum Variance - GMV Benchmarking
  - Restricted Structure Controller - RS Benchmarking
- On-line Benchmarking
- Incorporating Process Economics
- Multivariable Benchmarking

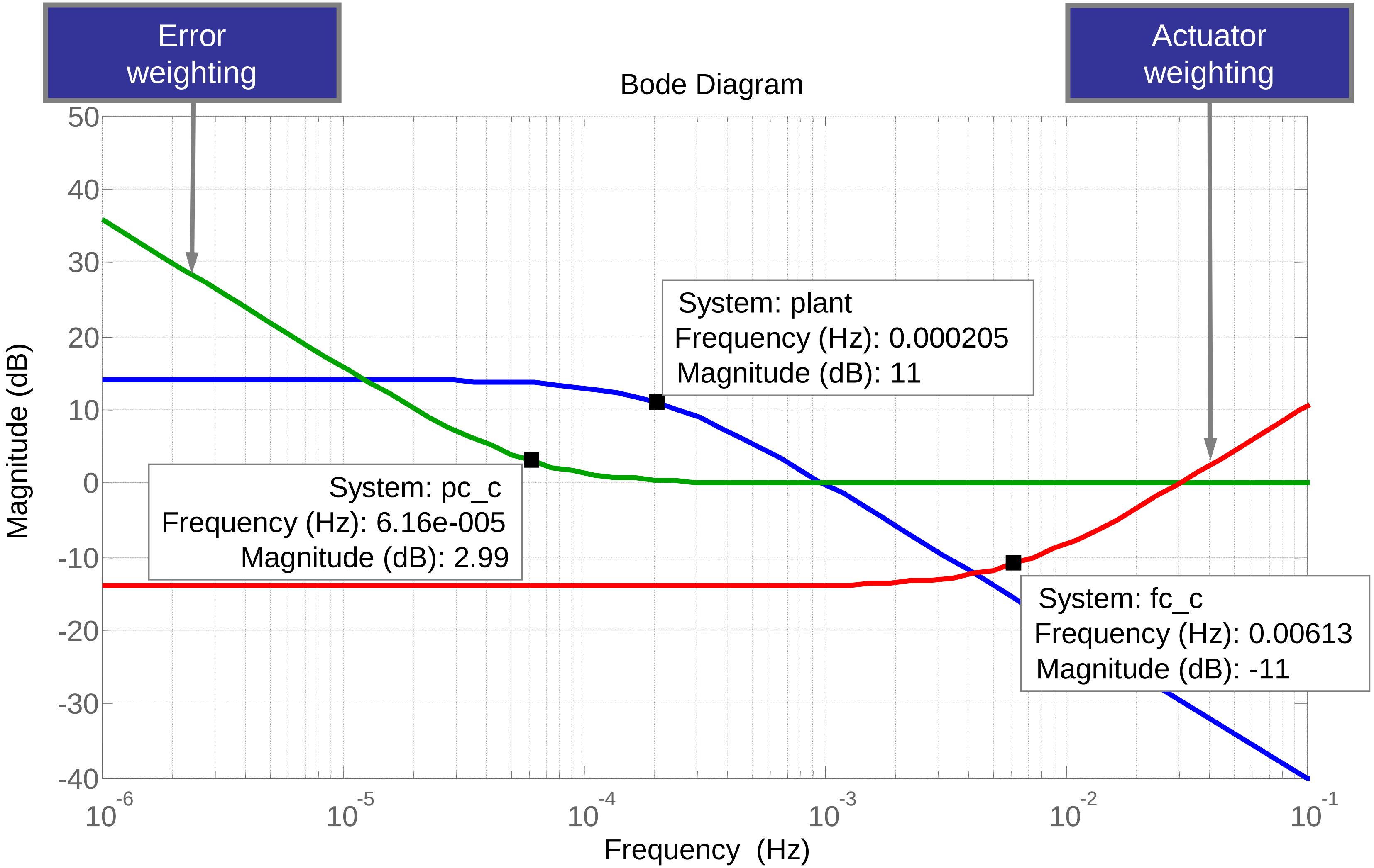
Improved Control Benchmark (GMV)

Using a calculation based on *Generalised Minimum Variance*

Actuator movement can be penalised



GMV Weighting Function Selection



GMV Benchmark Limitations

Generalised Minimum variance penalises control activity and allows some controller action to be included,

…giving a more realistic benchmark

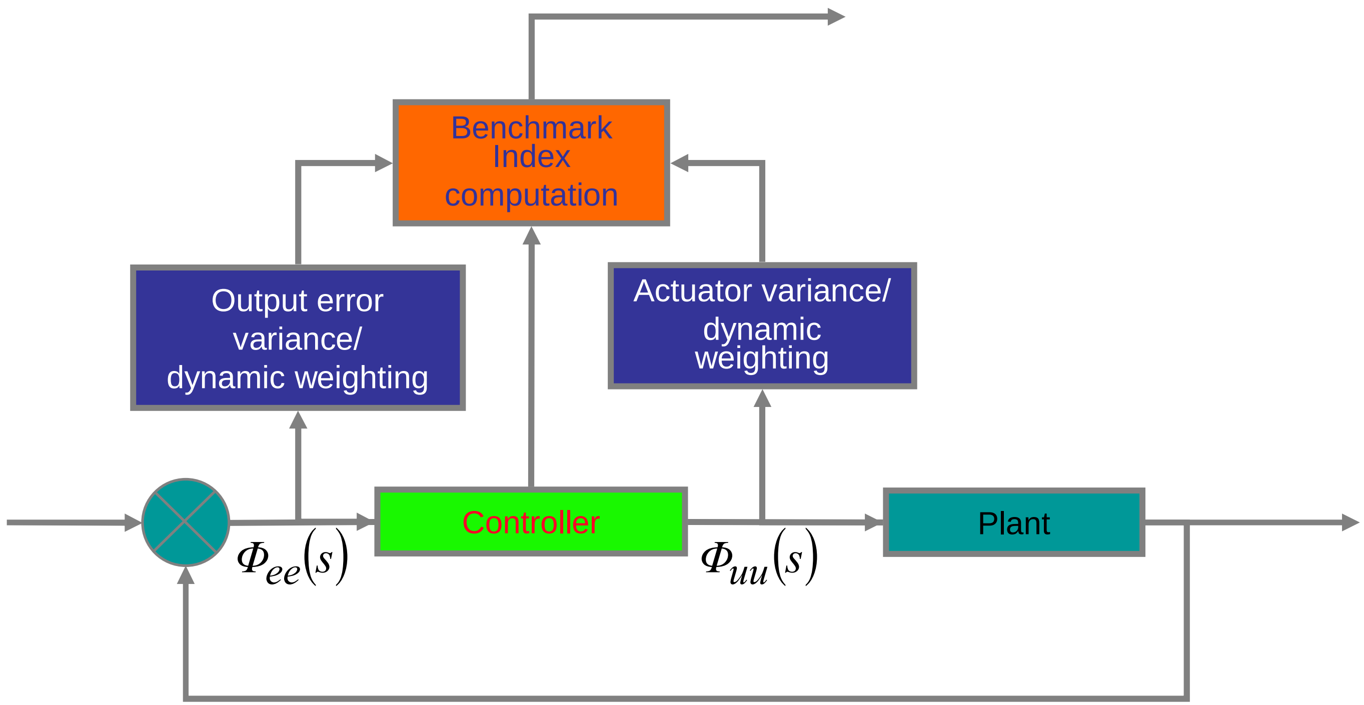
however…..it still :

- Assumes unlimited controller order

Improved control benchmark (RS)

Include *Controller Order* (i.e. compare against best possible PID)

Uses a numerical optimisation and requires full plant model



Summary of Benchmarking Algorithms

Method	MV	GMV	RS-LQG
Data Required			
Loop Delay	☯	☯	☯
Loop O/P Error data	☯	☯	
Actuator I/P data		☯	
System model			☯
Controller structure			☯
Benefits			
Control benchmark	☯	☯	☯
Limits actuator energy		☯	☯
Reflects controller structure			☯
Provides controller parameters			☯

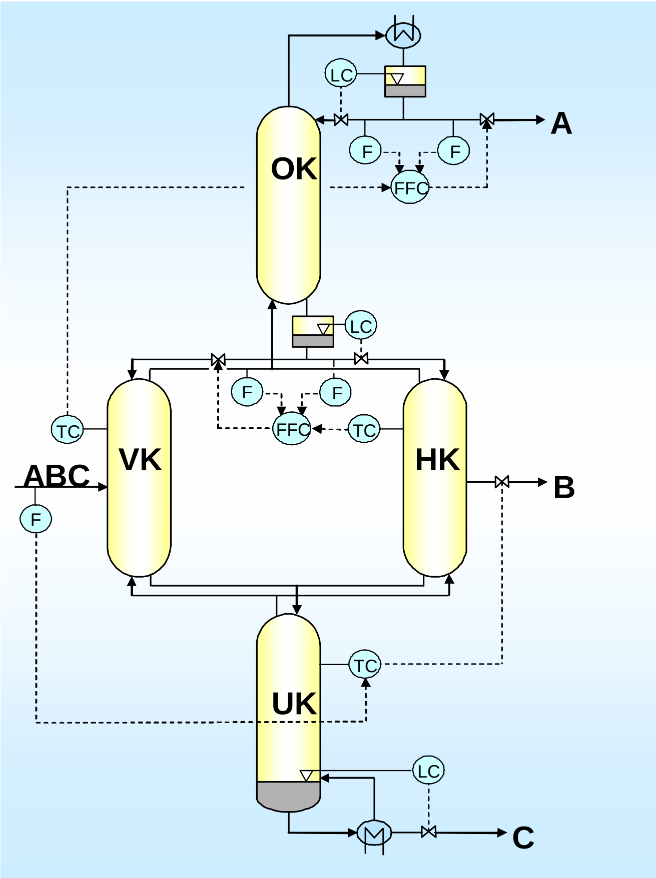
On-line Benchmarking

- Current tools - main difficulty is gathering the data
- Developing an on-line tool :
  - automatic data gathering via OPC, SQL, serial comms, etc.
  - recursive algorithms to simplify storage and computation
  - E-mail alert of poorly performing loops
  - Web-based interface - showing “traffic-lights” for loops

Multivariable Benchmarking

- For SISO benchmarking - interactions not included
  - If one loop is “improved” in isolation, it may degrade neighbouring loops
- MV benchmark extended to MIMO case:
  - Compares performance to Theoretical Best ⇒ **MIMO MV Controller**
    - i.e. one that minimises a combination of variances of all outputs
    - gives a measure of performance of the whole process
    - “Interactor Matrix” contains time delays between the inputs and outputs

MIMO Benchmarking of Divided Wall Column



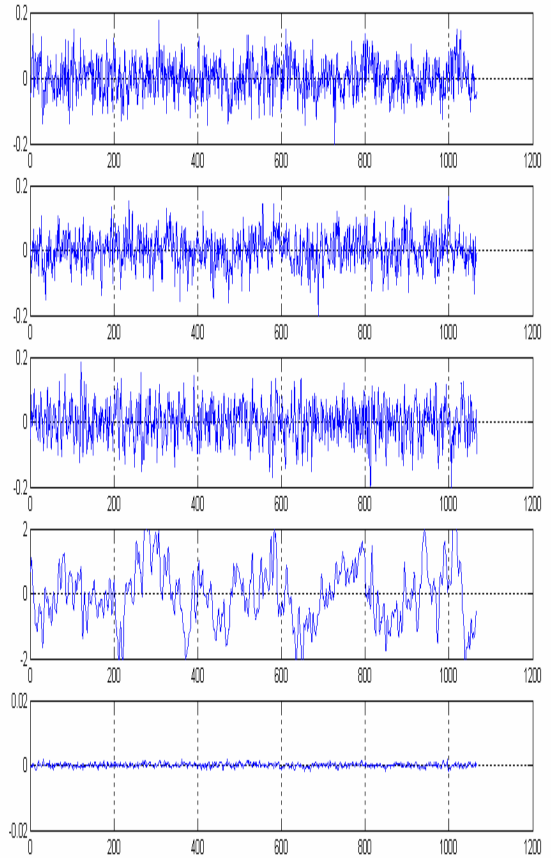
- Ultimate control objective is the purity of A, B, C
- No on-line measurements for purity
- Three temperatures are controlled as a substitute

Outputs	Inputs
Y1 : Temperature in VK	U1 : Split ratio between columns VK and HK
Y2 : Temperature in HK	U2 : Flow of component B
Y3 : Temperature in UK	U3 : Heating energy for component C
Y4 : Pressure in OK	U4 : Cooling energy in the condenser
Y5 : Level in the column sump	U5 : Reflux ratio of component A
	U6 : Flow of component C

Currently applied pairing between MV's and CV's:

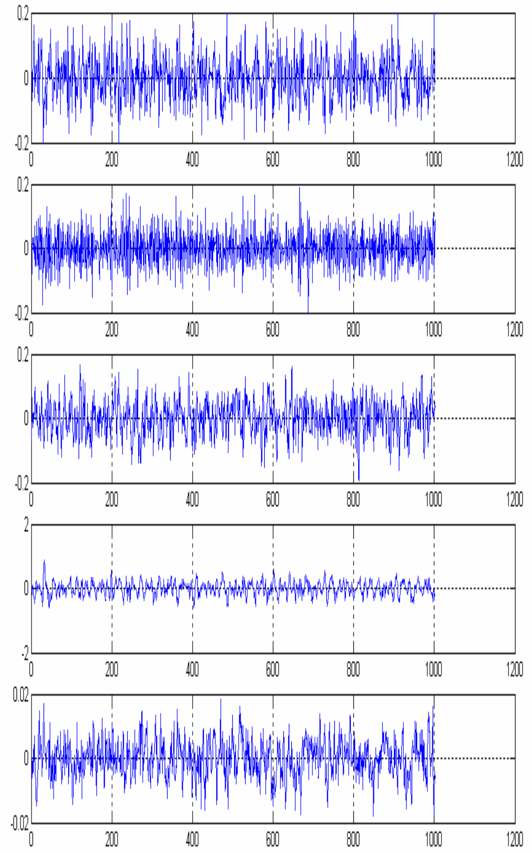
T_{VK} – reflux ratio of A	Y1(U5)
T_{HK} – split ratio	Y2 (U1)
T_{UK} – flow of component B	Y3(U2)
P_{OK} – cooling energy in reflux of A	Y4(U4)
Luk – flow of component C,	Y5(U6).

MIMO Benchmarking of Divided Wall Column



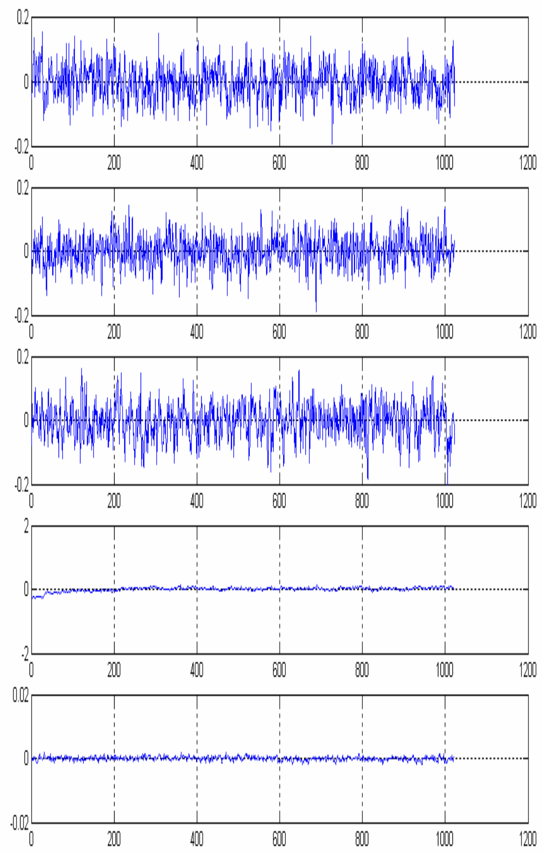
η = 0.5%

Retuned #1



η = 20%

Retuned #2



η = 45%

Incorporating Process Economics

- Ideally – identify those loops that effect process economics
  - simple way - use engineering judgement to assign "Loop Criticality"
- Improvements in variance can be linked to £££'s by :
  - shifting SP closer to a constraint
  - smaller "Irreversible Loss"
- Even in SISO case, assigning £££'s to these opportunities is difficult
- Need to formalise how each loop influences overall process

Incorporating Process Economics # 2

- Including full economics of operation is non-trivial
  - does not (usually) fit into a quadratic cost function
- Theoretical Best Controller is one that operates at constraints
  - e.g. at limit of throughput, temperature, energy costs, etc.
  - Soft constraints - defined as those that depend upon loop tuning
- Benchmarking determines how much these constraints can be pushed
  - problem becomes a constrained optimisation
- This is an ongoing area of research

A Typical Plant-Wide Control Structure

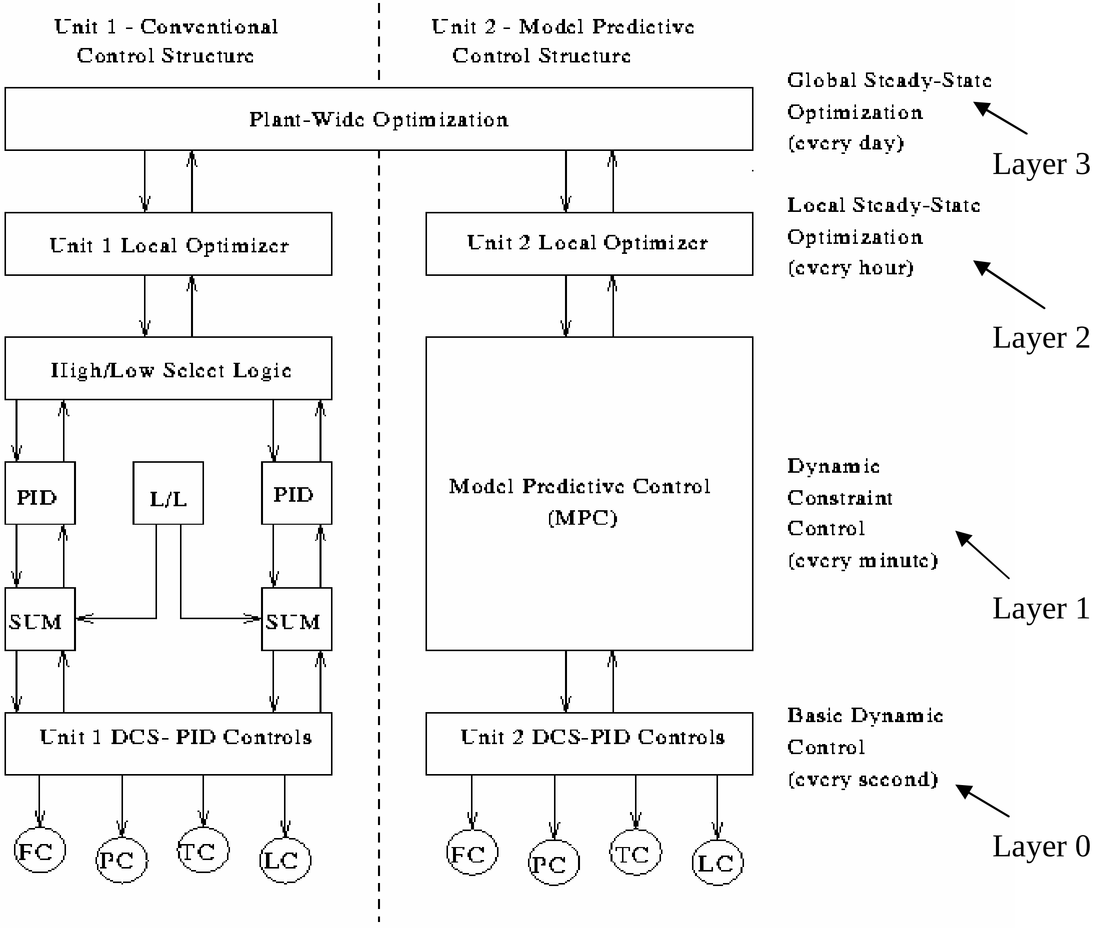


Fig.1 A typical layered plant-wide control structure.

Observations:

1. The plant is controlled in a hierarchical manner.
2. The commands flow from the top to the bottom.
3. The upper layer provides setpoints for the lower layer.
4. The steady state optimisation is performed to optimise profits and the whole operation should follow this objective.
5. The information from the lower layer is used as constraints in the upper level optimisation.

Some Thoughts on Static Optimisation

1. Problem formulation:

$$\min_{y_s,u} J^*(y_s,u)$$
$$s.t. \quad y = f_s(u), u_{min} \le u \le u_{max}$$
$$y_{min} \le y_s \le y_{max}, \quad g(y_s,u) \le 0$$

2. What is involved in the optimisation?

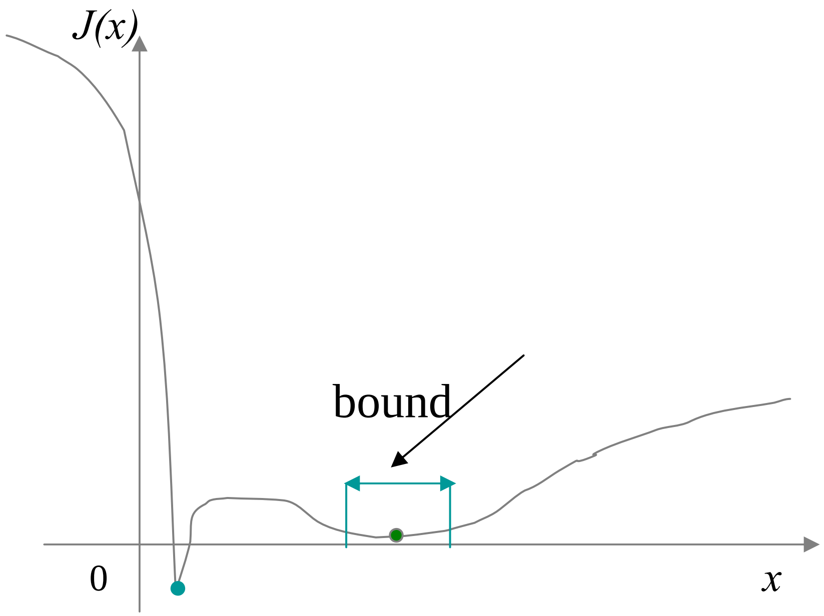
1. Economic cost function .
2. The cause/effect relationship between input/output
3. The constraints.

3.The central piece of the above optimisation problem is the static plant model:

1. It is time-varying, nonlinear.
2. It only includes the most important factors.
3. It represents the static relationships between input/output, *i.e.* many dynamical properties are omitted during the modelling.
4. Identifying the most important factors requires a sound understanding of the process.
5. The quality of this model decides the economic performance of the plant.

The Desirable Output From Static Optimisation

Ideally, the optimisation should not only decide the value of set-points but also decide the tolerable bounds around the set-points such that the cost function will not change much within the bounds.



An Alternative Control Structure

Model Predictive Control Structure.

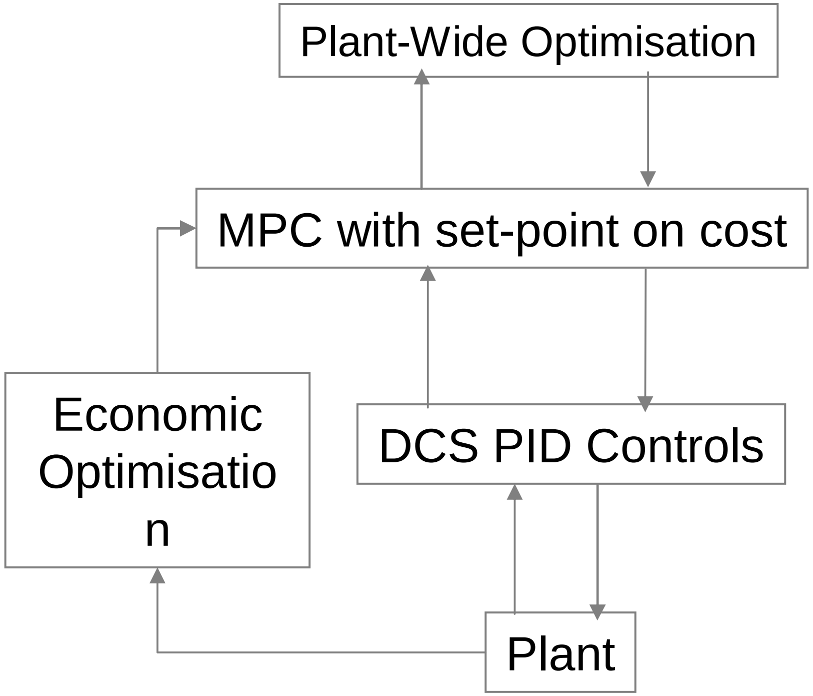


Fig 2. MPC with dynamic optimisation.

Optimisation formulation:

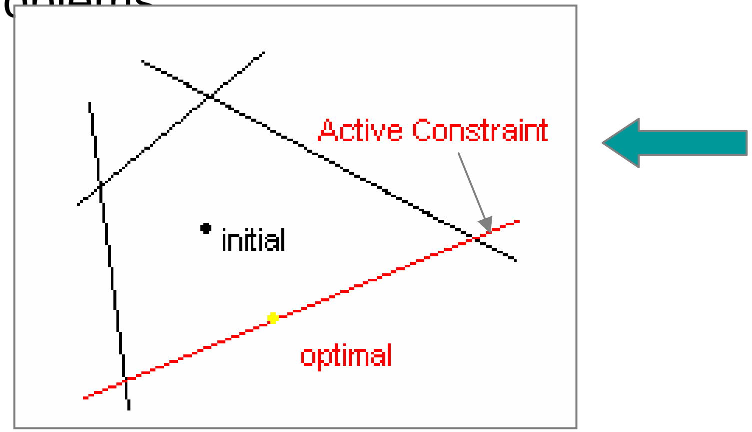
$$
\begin{aligned}
&\min_{y,u} J^*(y,u)\\
&subject\ \ to:\\
&J^*(y,u) := f_r(y,u) + \lambda f_e(y,u)\\
&y(k+1) = f(y(k), y(k-1), \ldots, u(k), u(k-1), \ldots)\\
&u_{min} \leq u \leq u_{max}, y_{min} \leq y \leq y_{max},\\
&g(y,u) \leq 0
\end{aligned}
$$

Remarks:

Since economic benefit is an integrated part of the criterion, this function may not be in the quadratic form, it may even include non-linear or discrete terms.

Soft/Hard Constraints

The optimisation problems formulated before are **constrained** optimisation problems.



In many cases, the optimal solutions are obtained with some constraints active.

Two types of constraints:

- Hard constraints: the one can not be changed by re-tuning controller.
- Soft constraints: the one can be changed by controller tuning.

Question 1: Can we push these constraints further?

By controller benchmarking, this question can be answered.

Controller Benchmarking for Profit Optimisation

Question 2: Do we need to retune the controller?

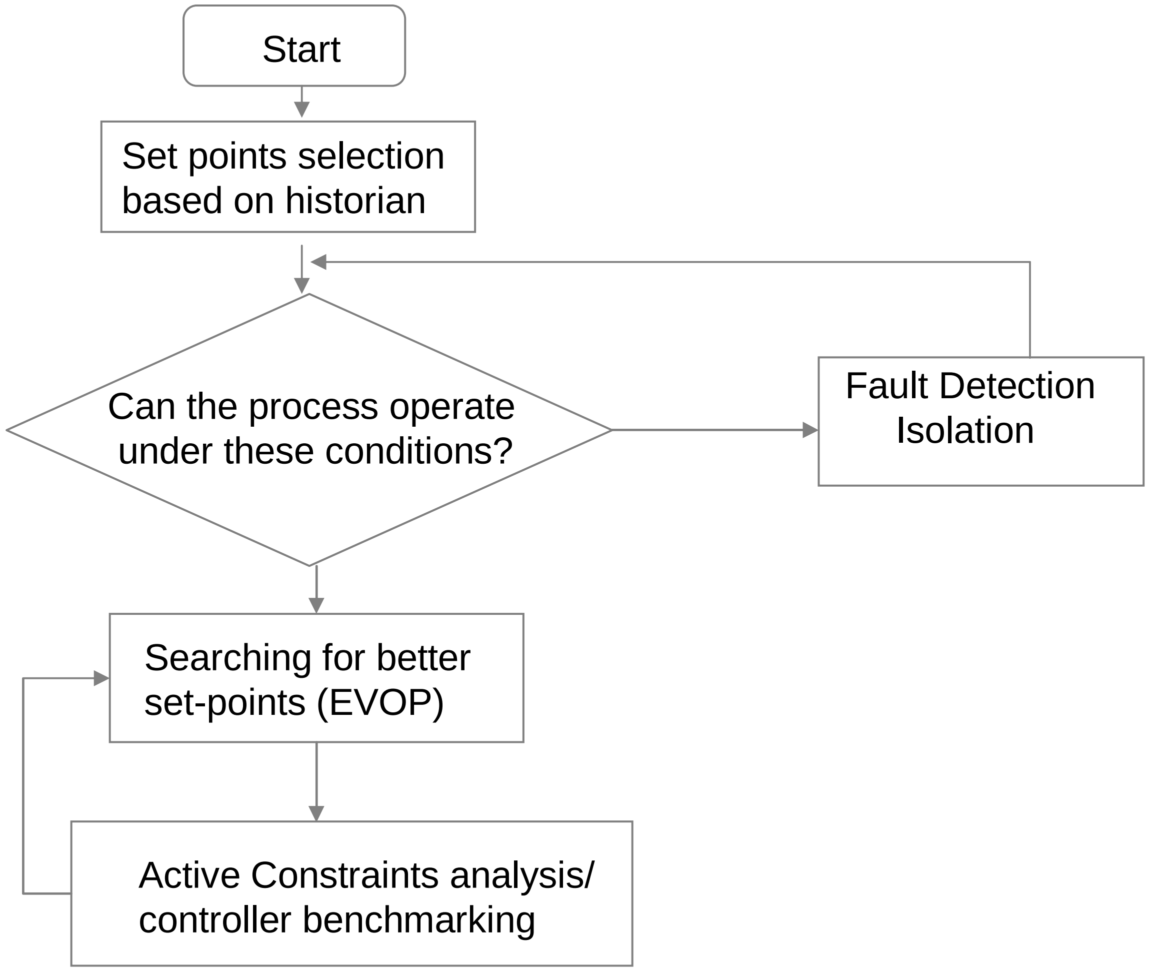
The prioritisation of re-tuning control loop(s) can be formulated as another optimisation problem:

$$
\begin{aligned}
&\max_C \Delta J^*(y,u) - J_c(y) \\
&s.t.\ \ \Delta J^*(y,u) - J_c(y) \geq 0 \\
&y(k+1) = f(y(k), y(k-1), \ldots, u(k), u(k-1), \ldots) \\
&u_{min} \leq u \leq u_{max}, y'_{min} \leq y \leq y'_{max}, \\
&g(y,u) \leq 0
\end{aligned}
$$

Remarks:

1. $J_c(y)$ should be defined by discussing with the industrial partners.
2. By focusing on the active constraints, we can identify the critical control loops or subsystems which have the biggest impacts on the plants' economic performance.
3. We only need to benchmark the subsystem related with the active constraints. The benchmarking problem becomes manageable.

Proposed Procedure of Optimisation



Useful References

M.Paulonis, J.Cox, “A Practical Approach for Large-Scale Controller Performance Assessment, Diagnosis and Improvement”, Journal of Process Control, Vol. 13, pp.155-168, 2003

IEE Seminar “Control Loop Performance Assessment”, 26th Nov 2002

IEEE Conference on Control Applications Workshop on “Controller Benchmarking”, Sep 2002

G.Dumont, “Tools for Monitoring and Tuning Advanced Process Control Systems”, ECC Workshop, Portugal, Sep 2001

B.Huang, S.Shah, “Performance Assessment of Control Loops: Theory and Application”, Springer Verlag, Oct 1999, ISBN 1-85233-639-0

N.Thornhill, M Oettinger, P.Fedenczuck, “Refinery-wide Control Loop Performance Assessment” , Journal of Process Control, Vol. 9, pp.109-124, 1999

N.Thornhill and T Hagglund, “Detection and Diagnosis or Oscillation in Control Loops”, Journal of Control Engineering Practice, Vol. 5, pp. 1343-1354, 1997

Products:

Honeywell - Loop Scout

Matrikon – Process Doctor

Invensys – Performance Watch

Emerson Process – EnTech Toolkit, DeltaV Inspect

ABB – Loop Optimizer

Control Arts Inc – Control Assessment Tool