



# **ADVANCED CONTROL TECHNIQUES**

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# Advanced Control Techniques Outline



- What is advanced control?
  - Advanced Control now
  - Why Advanced Control?
  - Justification of Advanced Control
- PID Control
- Adaptive PID Control
- Process Models
- Predictive Control (MPC)
- Multivariable Control
- Real Time Process Optimization (RTO)
- Fuzzy Logic
- Neural Networks
- Other Advanced Control Tools



# ADVANCED CONTROL

- The techniques described here have been applied to a wide variety of systems.
- In the process industries, they have been applied to:
  - Oil refining
  - Reactors
  - Separation processes
  - Power generation systems including boilers
  - Pulp & Paper (lime kiln)
  - HVAC
  - And so on.
- Many of these are reported by academics involved in industrial collaborative projects or by consultants.
- There are also many unreported cases of successful advanced control applications, primarily because of commercial confidentiality.
- Nowadays, more and more successful applications are reported by both users and common control systems providers.



# What exactly is advanced control?



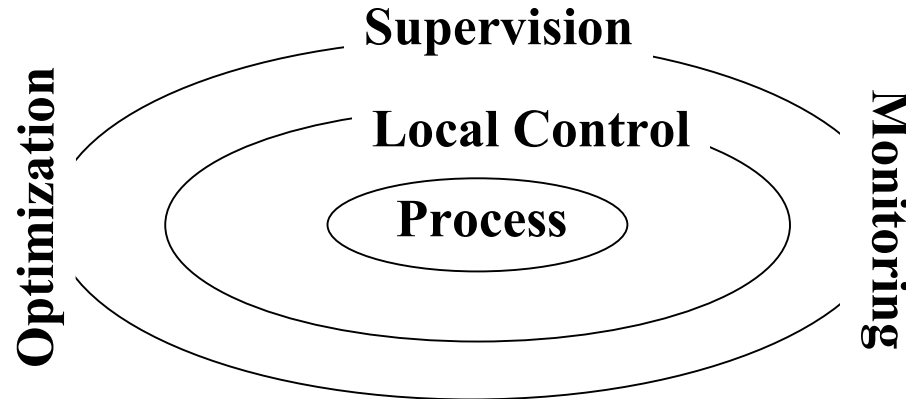
Depending on an individual's background, advanced control may mean different things. It could be the implementation of

- feedforward or cascade control schemes
- time-delay compensators
- self-tuning or adaptive algorithms
- multivariable control algorithms
- model predictive control schemes
- optimization strategies

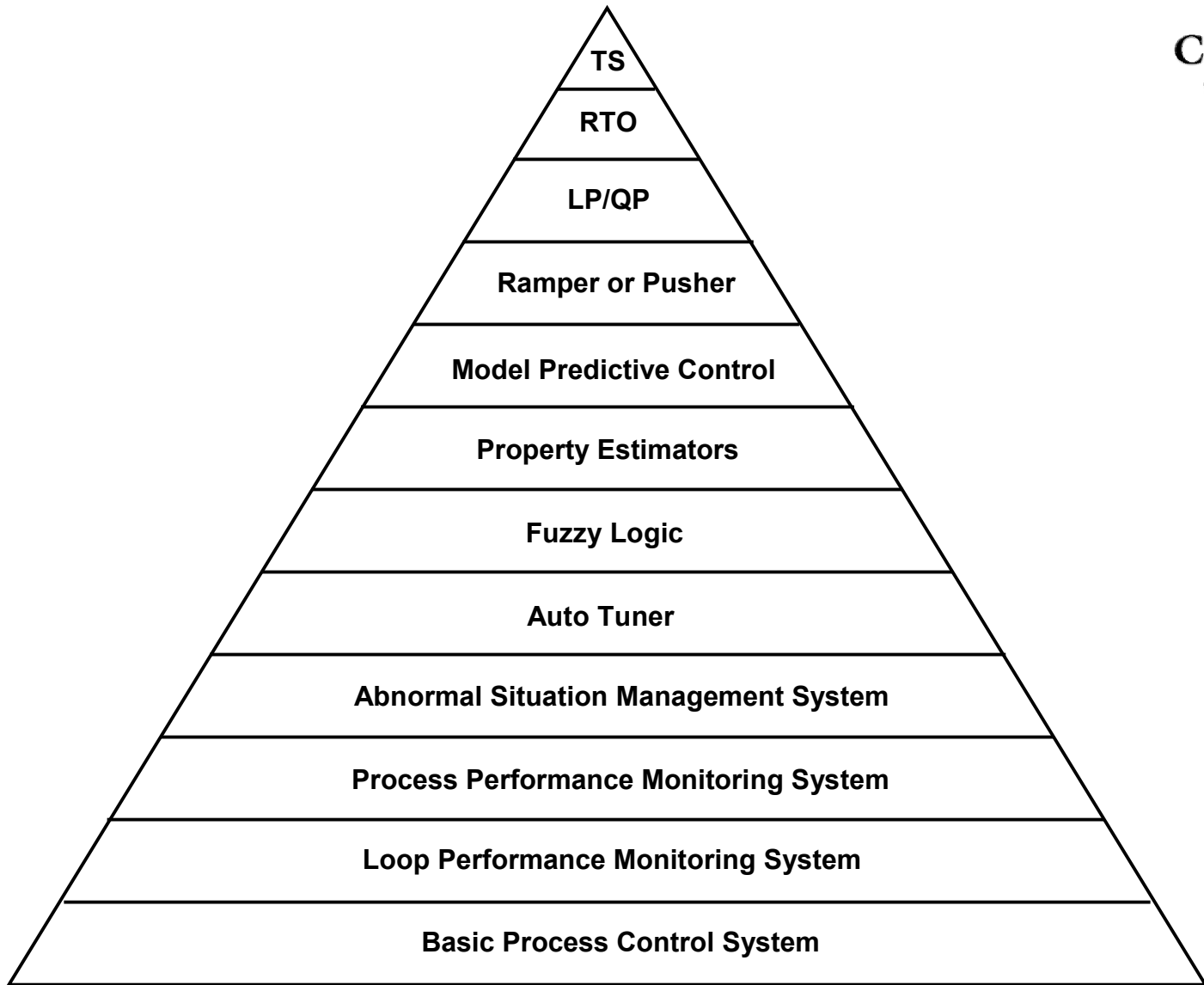
The views of academics and practicing engineers can differ significantly.



# ADVANCED CONTROL



- Hierarchical information and control structure.
  - The flow of information is bi-directional, from management layer to process level and vice versa.
- Integrate the various components in an efficient and manageable fashion.
  - Each component is designed as a modular, yet integrable element.
- The type of local controllers employed depends on the task at hand. The goal is to keep the process operating at desired conditions.
- Although it is easier to tune and maintain simple controllers, some processes do require control by more sophisticated algorithms.
- However, unless such sophisticated controllers are installed and maintained by well trained personnel, they can be prone to failure.



TS is tactical scheduler, RTO is real time optimizer, LP is linear program, QP is quadratic program

## Pyramid of Technologies



# Advanced Control Now



- Until the last decade, the higher level tasks of monitoring, optimization, and supervision were mainly carried out by human beings.
- Due to the advent of modern technology, and advances in the field of Artificial Intelligence, these can now be automated. In particular, the installation, operation and integrity of modern controllers can be supervised by higher level systems.
- The advent of powerful and friendly integrated software has moved advanced process control (APC) from the realm of consultants into the arena of the average process control engineer.
- There is an opportunity for the engineers closest to the process and daily operation to take much more active role in the development and support of APC applications.



# Why Advanced Process Control (I)



- Any improvement in the performance of control strategies will result in:
  - more consistent production
  - facilitating process optimization
  - less re-processing of products
  - less waste
- Process models underpin most modern control approaches. Depending on the model forms, different controllers can be synthesised.
- Even the prevalent Proportional+Integral+Derivative (PID) algorithm can be designed from a model based perspective.
- The performance capabilities of PID algorithms are limited though.
- More sophisticated strategies, such as adaptive algorithms and predictive controllers have been proposed for improved process control.
- Many real processes are nonlinear and adaptive systems may not be able to cope with significant nonlinearities.



## Why Advanced Process Control (II)



- Process plants, designed for flexible production and to maximize recovery of energy and material, are becoming more complex.
- Process units are tightly coupled and the failure of one unit can seriously degrade overall productivity. This situation presents significant control problems.
- The literature on relevant control, monitoring, supervision and optimization techniques is voluminous, each article exhorting a certain solution to a particular problem.
- There is currently not one technique that will solve all the control problems that can manifest in modern plants. Indeed, different plants have different requirements.

*A systematic studied approach to choosing pertinent techniques and their integration into a co-operative management and control system will significantly enhance plant operation and profitability.*

***This is the goal of advanced process control.***



# Justification of Advanced Process Control



It has been constantly reported that advanced control can:

- improve product yield
- reduce energy consumption
- increase capacity
- improve product quality and consistency
- reduce product giveaway
- increase responsiveness
- improve process safety
- reduce environmental emissions

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- By implementing advanced control, benefits ranging from 2% to 6% of operating costs have been quoted.
- These benefits are clearly enormous and are achieved by reducing process variability, hence allowing plants to be operated to their designed capacity.

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# PID Control (I)



- The Proportional+Integral+Derivative (PID) controller accounts for more than 80% of installed automatic feedback control devices in the process industries.
- In the past, these have been tuned using frequency response techniques or empirically derived rules-of-thumb.
- The modern approach is to determine the settings of the PID controller based upon **a model of the process.**
- The settings are chosen so that the controlled response adhere to user specifications.
- A typical criterion is that the controlled response should have a quarter decay ratio
- Alternatively, it may be desired that the controlled response follow a defined trajectory or that the closed loop has certain stability properties (e.g., lambda-tuning method).
- It can be easily shown that a Proportional+Integral controller is optimal for a first order linear process without time-delays.
  - Similarly, the PID controller is optimal for a second order linear process without time-delays.

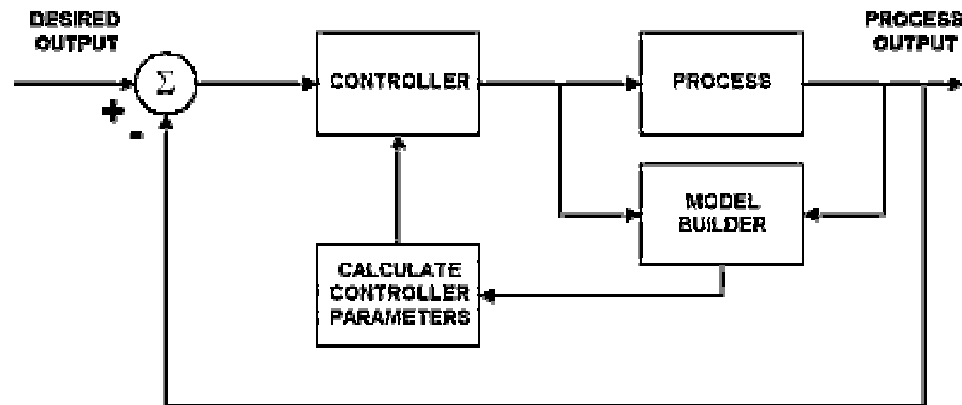


# PID Control (II)



- In practice, process characteristics are nonlinear and can change with time.
- Thus the linear model used for initial controller design may not be applicable when process conditions change or when the process is operated at another region.
- One solution is to have a series of stored controller settings, each pertinent to a specific operating zone.
- Once it is detected that the operating regime has changed, the appropriate settings are switched in.
- This strategy, called parameter- or gain-scheduled control, has found favor in applications to processes where the operating regions are changed according to a preset and constant pattern.
- In applications to continuous systems, however, the technique is not so effective.

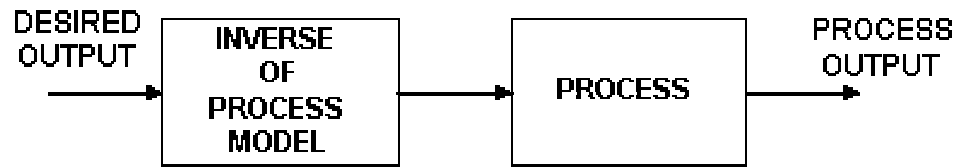
- Here the parameters of a linear model are updated regularly to reflect current process characteristics.
- These parameters are in turn used to calculate the settings of the controller as shown schematically in the Figure below.



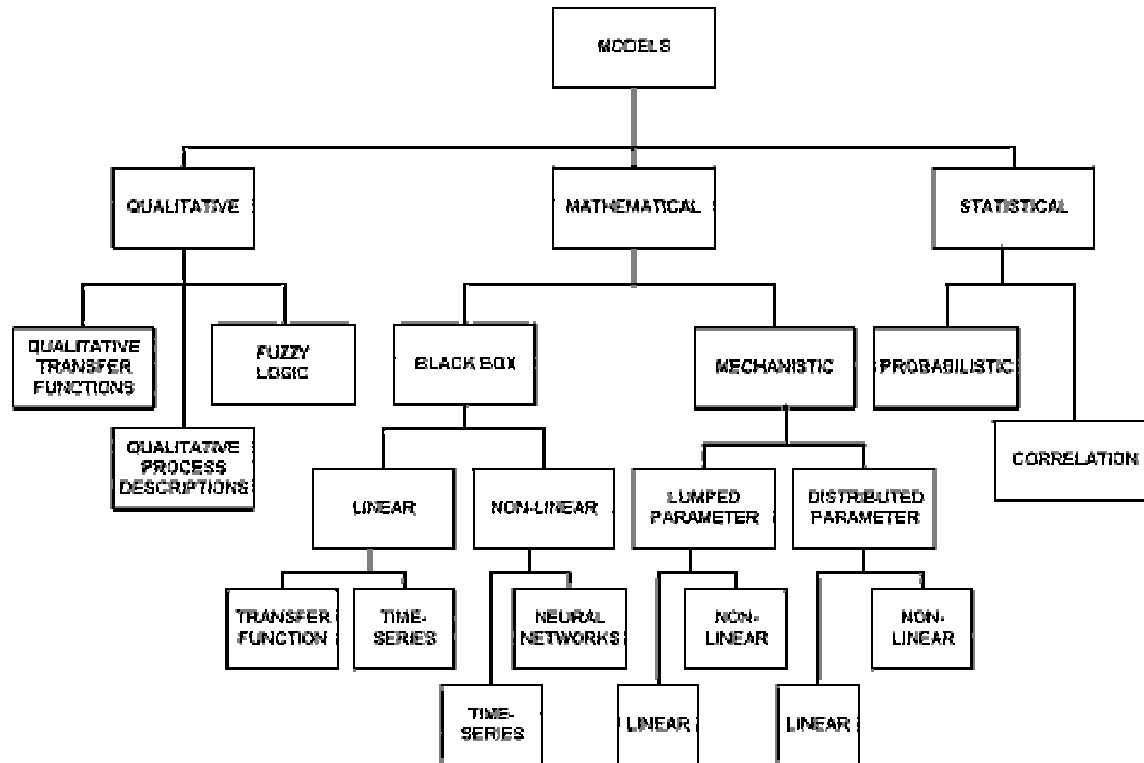
- The settings of the controller can be updated continuously according to changes in process characteristics.
- Such devices are therefore called auto-tuning/adaptive/self-tuning controllers.
- In some formulations, the controller settings are directly identified.
- A faster algorithm results because the model building stage has been avoided.



# Model based (modern) automatic control



# Process Model Types





# Adaptive control and non-linear processes



- Theoretically, all model based controllers can be operated in an adaptive mode.
- There are instances when the adaptive mechanism may not be fast enough to capture changes in process characteristics due to system nonlinearities.
- Under such circumstances, the use of a nonlinear model may be more appropriate for PID controller design.
- Nonlinear time-series, and recently neural networks, have been used in this context.
- A nonlinear PID controller may also be automatically tuned using an appropriate strategy, by posing the problem as an optimization problem. This may be necessary when the nonlinear dynamics of the plant are time-varying.
- Again, the strategy is to make use of controller settings most appropriate to the current characteristics of the controlled process.
- A self-tuning PID controller based on the use of a nonlinear neural net model has been reported.

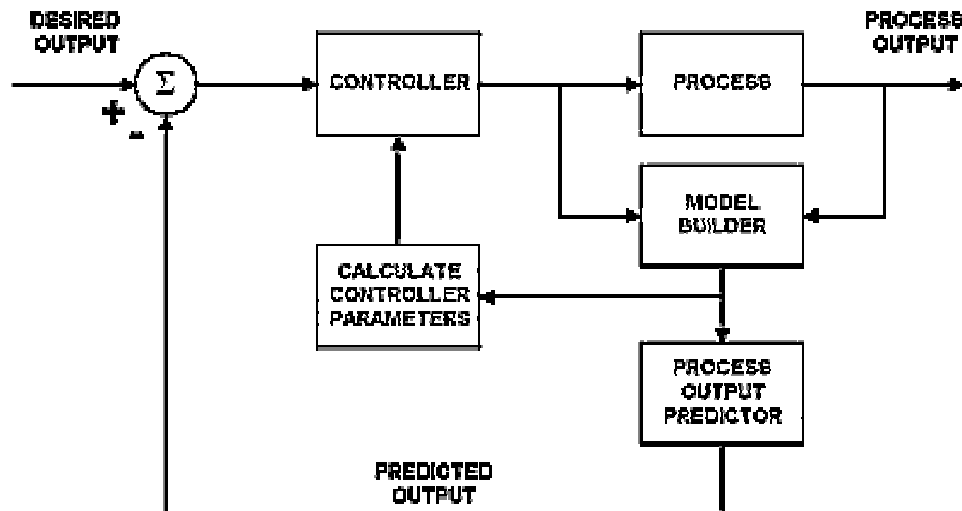


# Predictive Constrained Control

(dead time compensation)



- PID type controllers do not perform well when applied to systems with significant time-delays.
- Perhaps the best known technique for controlling systems with large time-delays is the 'Smith predictor'. It overcomes the debilitating problems of delayed feedback by using predicted future states of the output for control.
- Currently, some commercial controllers have Smith predictors as programmable blocks.
- There are many other model based control strategies that have dead-time compensation properties.
- If there is no time-delay, these algorithms usually collapse to the PID form.
- Predictive controllers can also be embedded within an adaptive framework and a typical adaptive predictive control structure is shown in Figure below.





# Evolution to Predictive Control



- The classical Generalized Minimum Variance (GMV) controller is an example of this philosophy.
- GMV control minimizes the squared weighted difference between the desired value and the predicted output while penalizing excessive control effort.
- The prediction horizon is the time-delay of the system, and this is a fixed parameter.
- GMV control, however, cannot effectively cope with variable time-delays and process constraints.
- This led to the development of long-range predictive controllers, e.g. the **Generalized Predictive Controller (GPC) and Dynamic Matrix Control (DMC)**. Also known as Model Predictive Control (MPC).



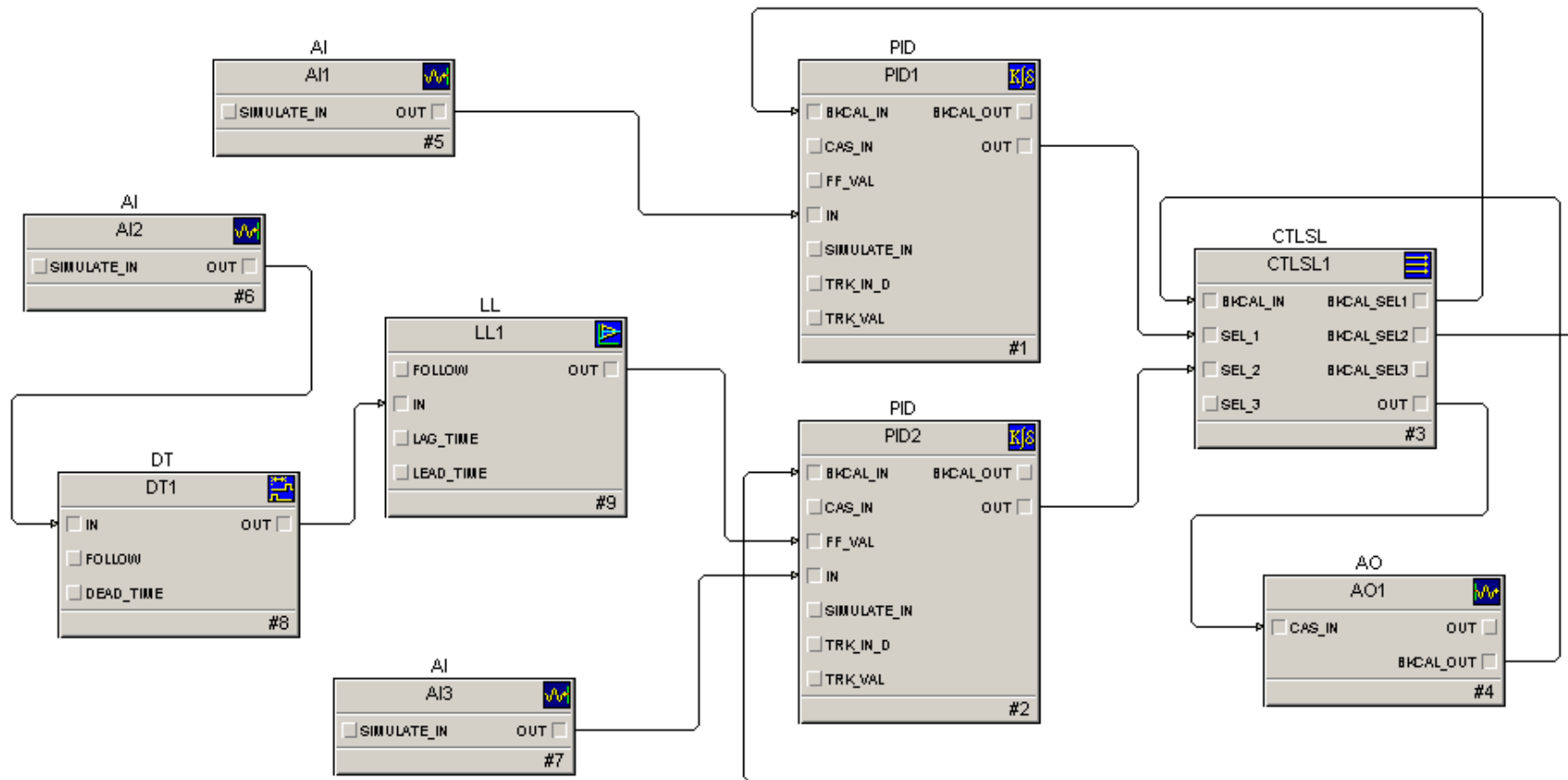
# Model Predictive Control



- Based on **Generalized Predictive Controller (GPC) or Dynamic Matrix Control (DMC)**.
- The control problem is formulated in a manner similar to that adopted in the GMV approach.
- The differences are that the model is used to provide predictions of the output over a range of time-horizons into the future.
- Usually the range is between the smallest and largest expected delays.
- This alleviates the problem of varying time-delays and hence enhances robustness.
- Calculation of the control signal is essentially an optimization problem.
- Economic objectives as well as process constraints can be included in the problem formulation.
- Examples of process constraints are:
  - the limits to liquid flows in fixed sized piping,
  - allowable temperatures and pressures in process units,
  - emissions to atmosphere, etc.
- Nowadays, the phrase 'predictive control' refers to the application of long-range predictive controllers.
- Again, predictive controllers may be designed using linear or nonlinear models.

# Model Predictive Control vs PID

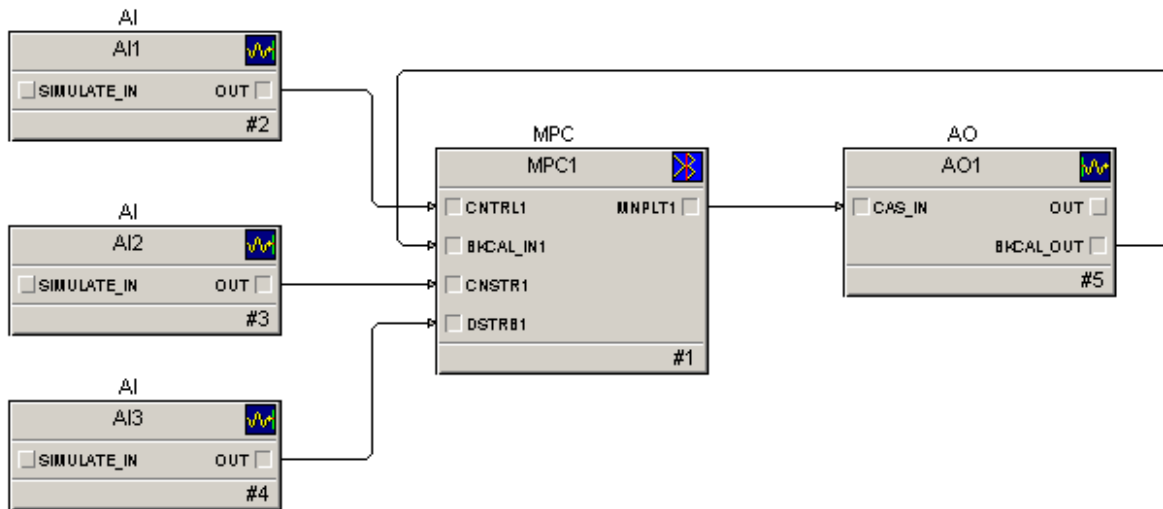
(Example of SISO, one constraint, and one disturbance with typical PID)





# Model Predictive Control

(Example of SISO, one constraint and one disturbance with MPC)





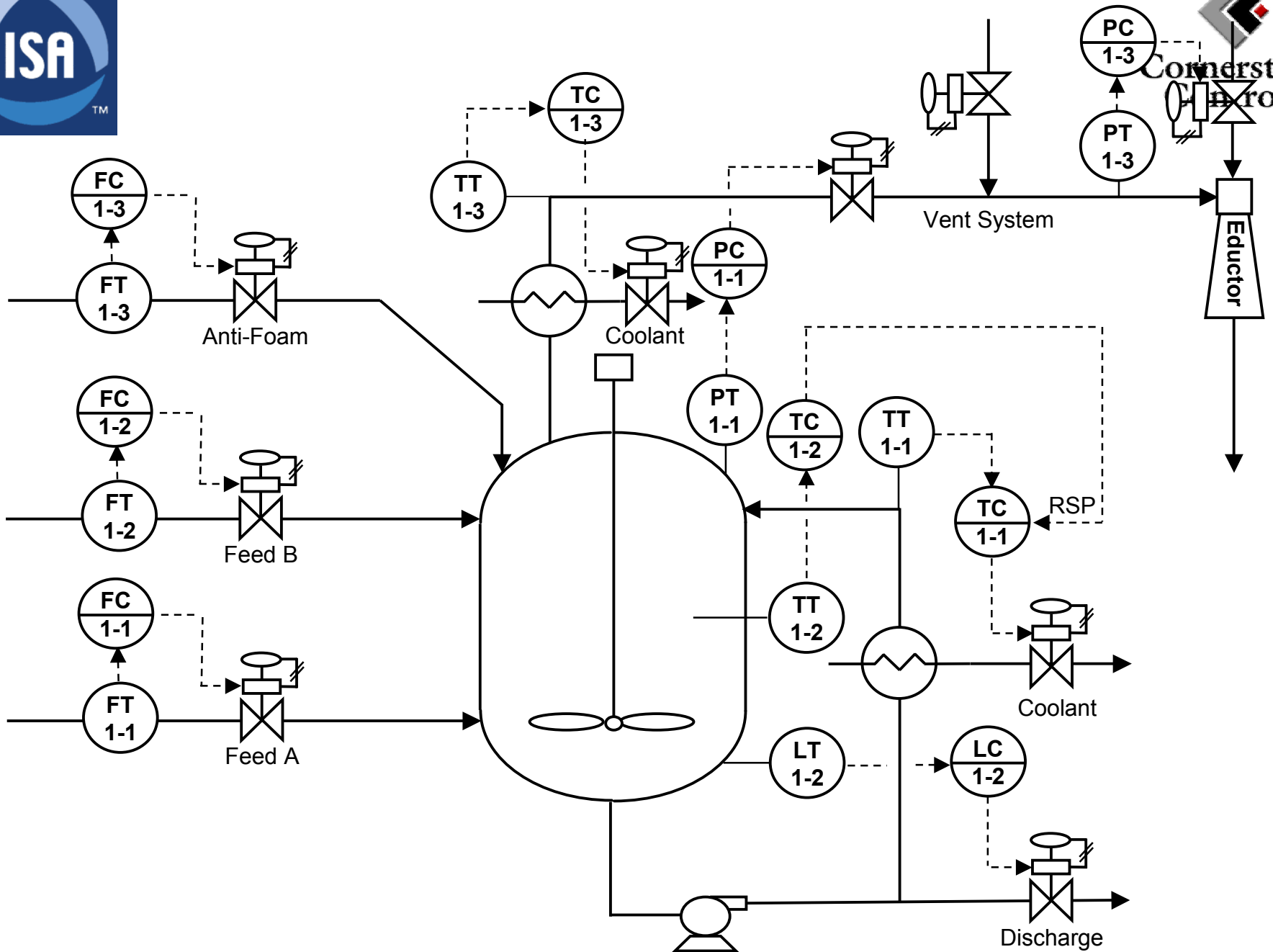
# Multivariable Control (I)



- Thus far, we have only considered the case where there is one manipulated input and one controlled output; single-input single-output (**SISO**) systems.
- With most processes, there are many variables that have to be regulated.
- The chemical reactor is a typical example where level, temperature and pressure have to be kept at design values, that is there are at least three control loops; **a multi-loop system**.
- If the actions of one controller affect other loops in the system, then control-**loop interaction** is said to exist.
- If each controller has been individually tuned to provide maximum performance, then depending on the severity of the interactions system instability may occur when all the loops are closed.
- SISO controllers, whether adaptive, linear or nonlinear strategies, may therefore not be applicable to such processes.



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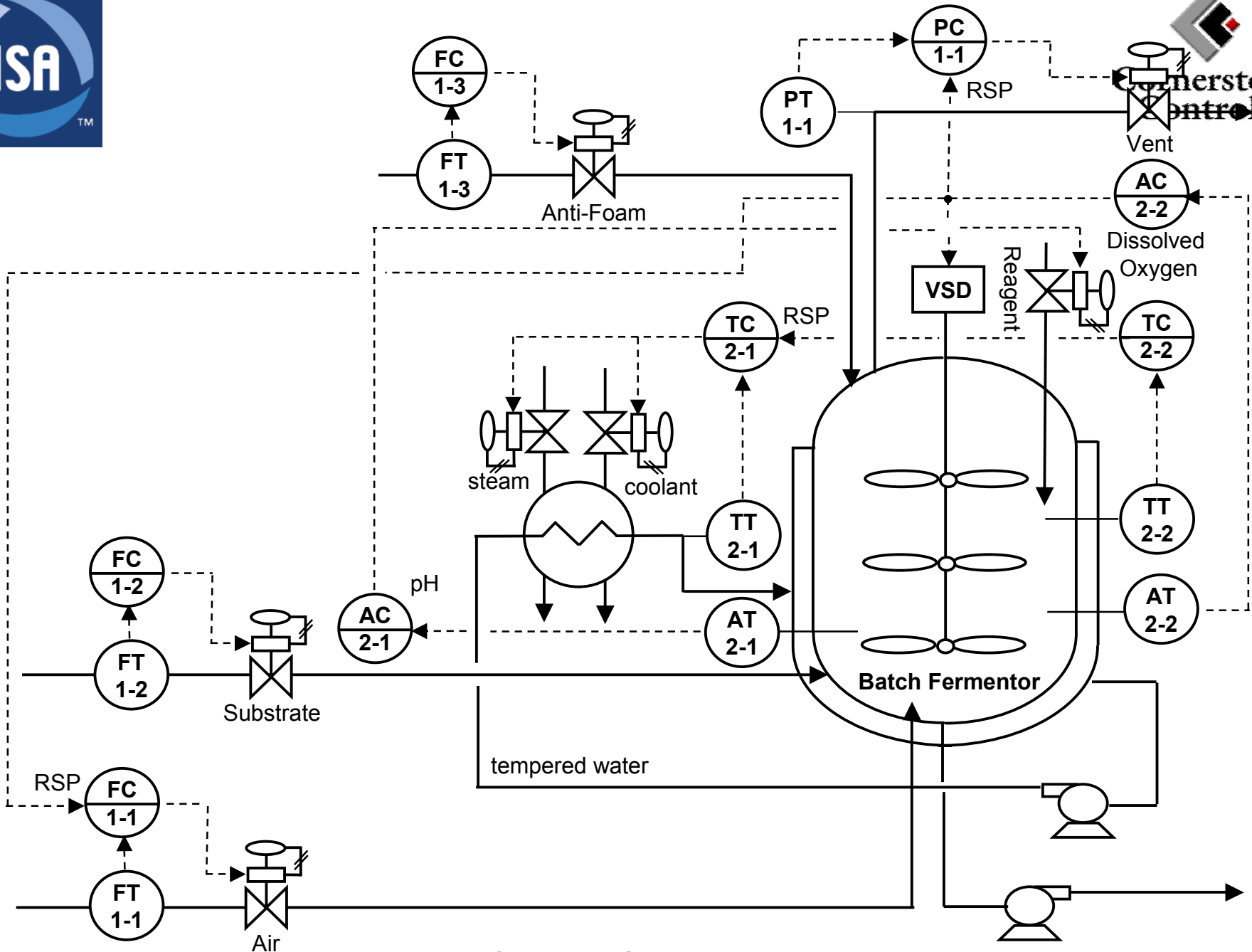
Reactor Control System



## Multivariable Control (II)



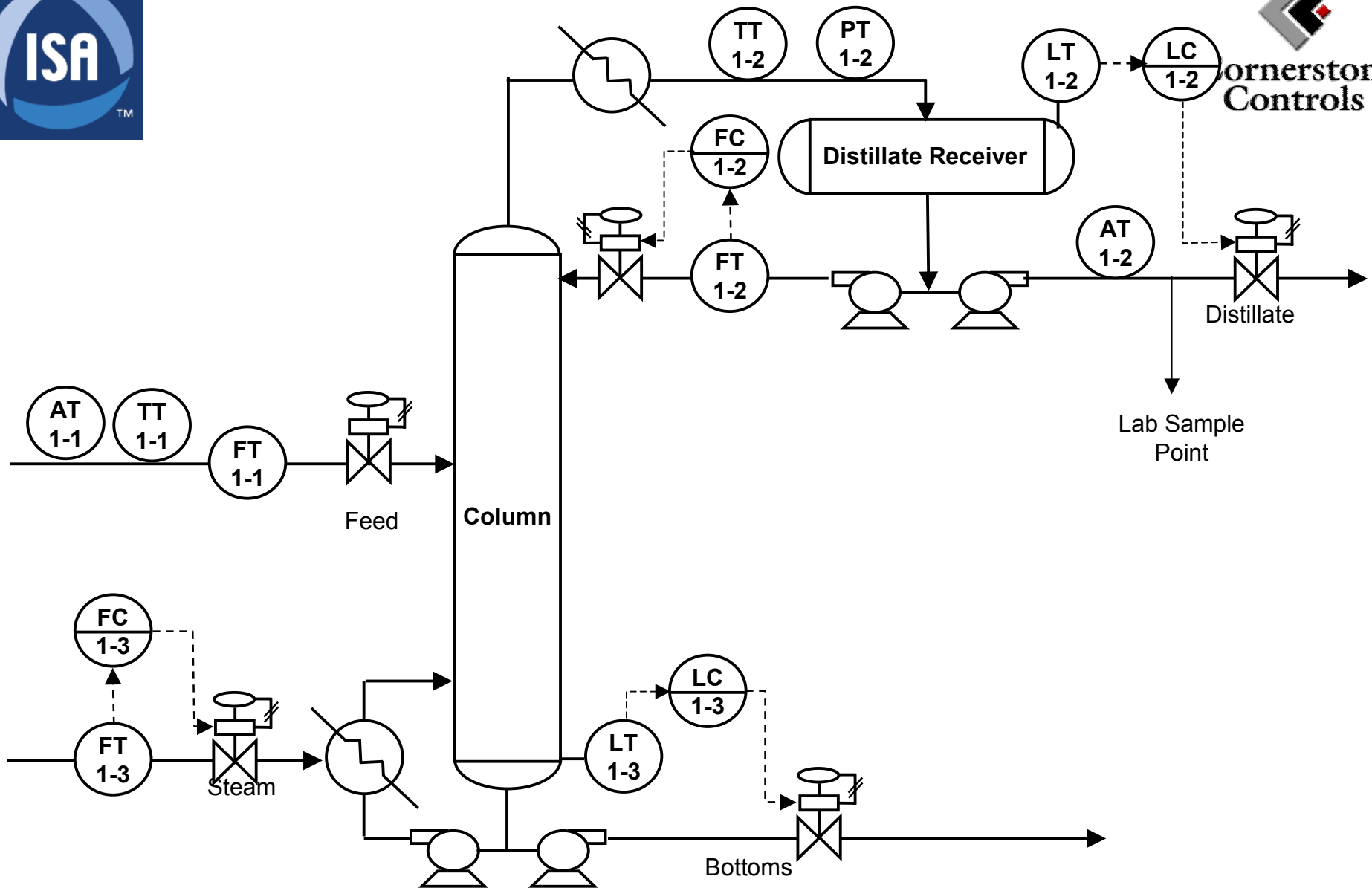
- Models used in the design of SISO controllers do not contain information about the effects of loop interactions. Thus, they cannot be expected to perform well.
- For a multiloop strategy to work, individual SISO controllers are usually detuned (made less sensitive), resulting in sluggish performances for some or all loops.
- Ideally, multivariable controllers should be applied to systems where interactions occur.
- As opposed to multi-loop control, multivariable controllers take into account loop interactions and their de-stabilizing effects.
- Fortunately, it is a relatively trivial task to modify model based controllers to accommodate multivariable systems.
- By regarding loop interactions as feed-forward disturbances, they can be easily included in the model description.
- Following SISO designs, multivariable controllers that can provide time-delay compensation and handle process constraints can also be developed with relative ease.
- By incorporating suitable numerical procedures to build the model on-line, adaptive multivariable control strategies result.



**Fermentor Control System**



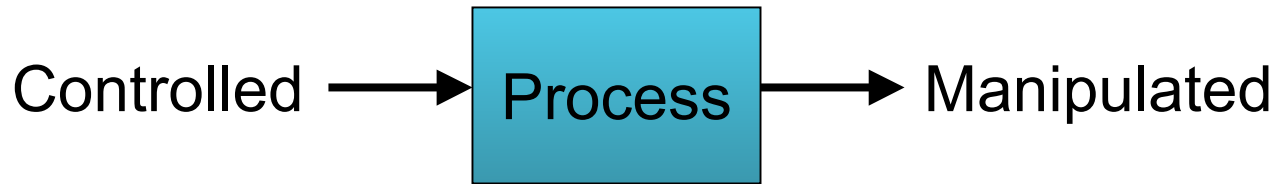
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Typical Distillation Process



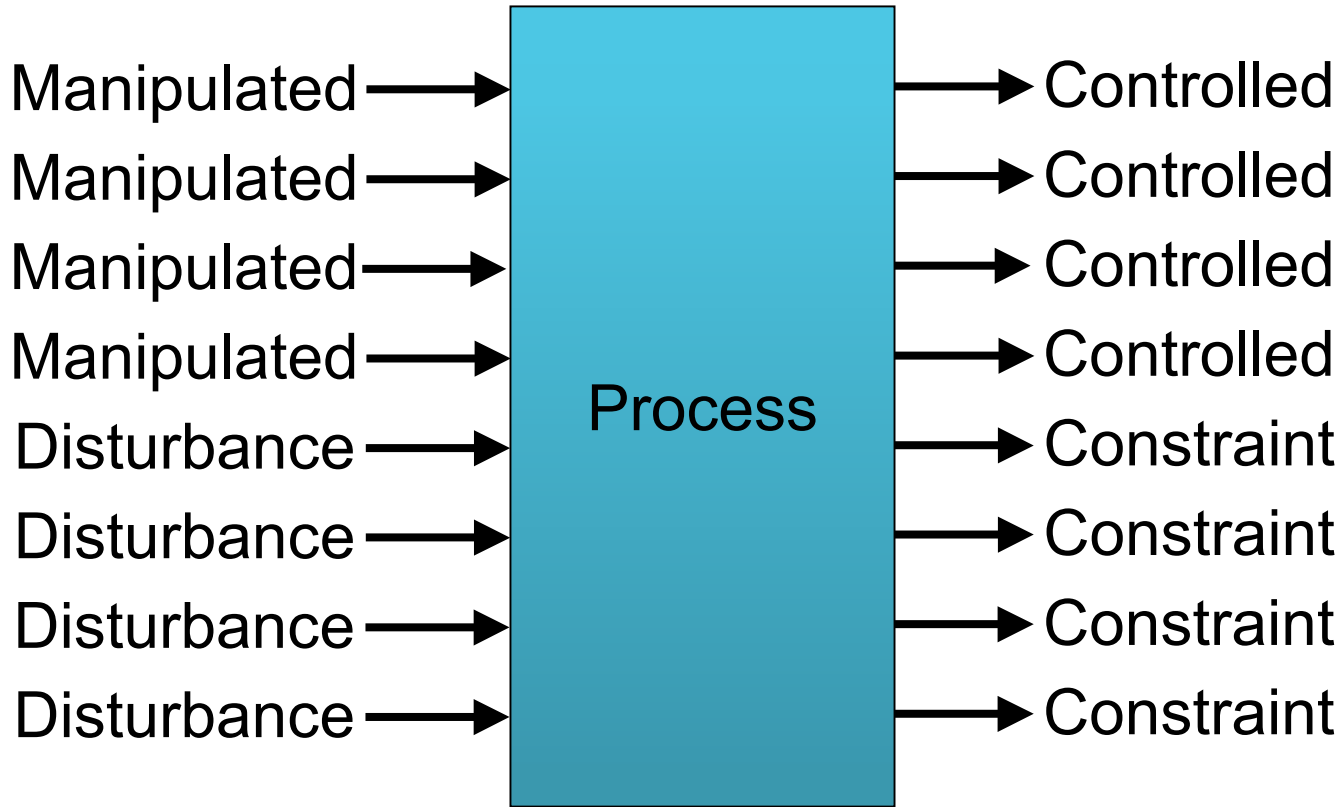
# Model Predictive Control



Very Small  
1x1 Process



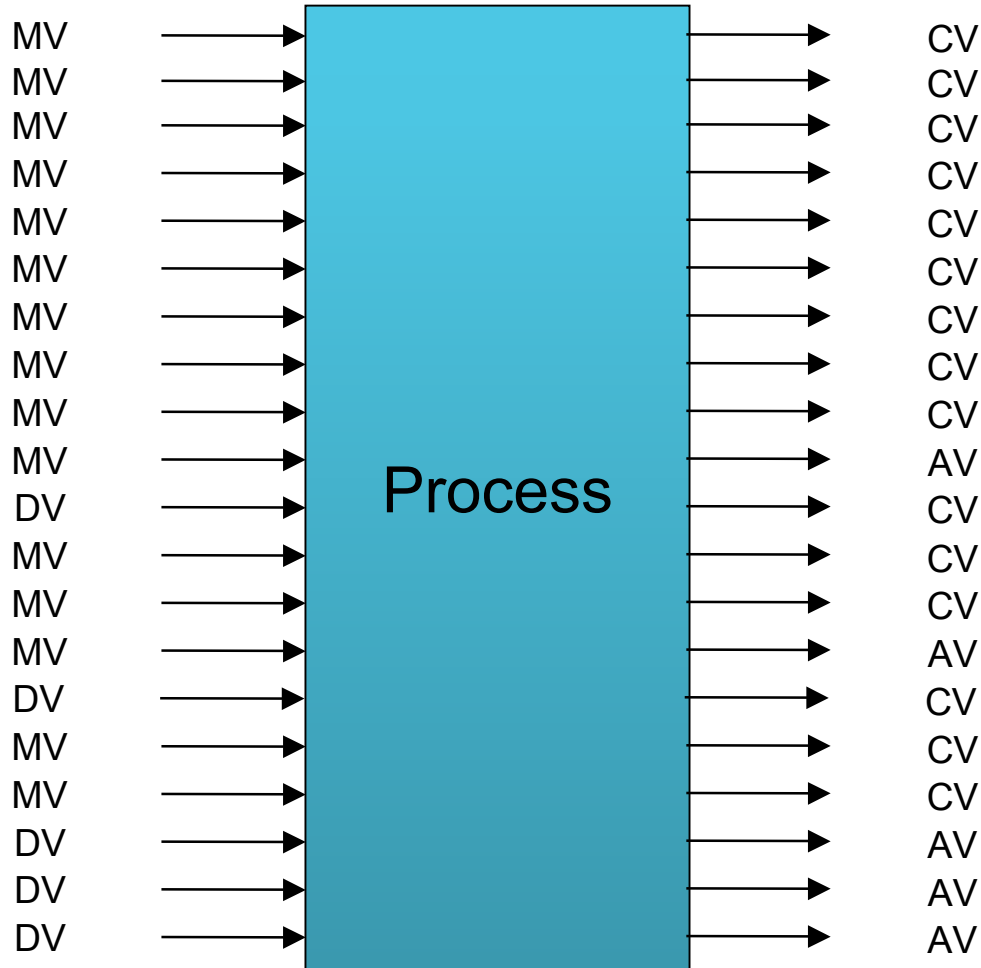
# Model Predictive Control Application Sizes



**Bigger  
8x8 Process**

# Embedded Model Predictive Control Application Sizes

- Up to 20x20



Max 20  
MV's

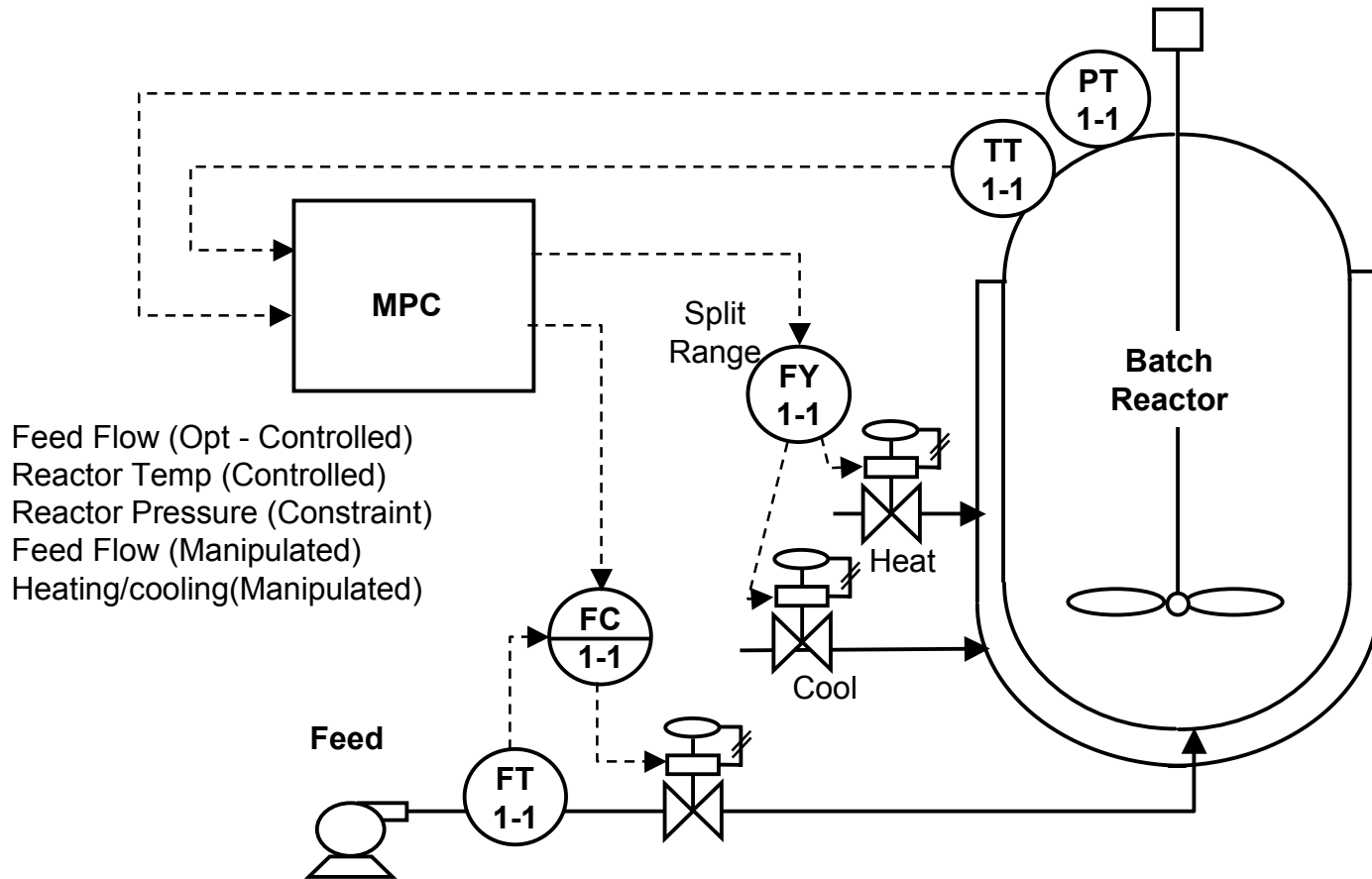
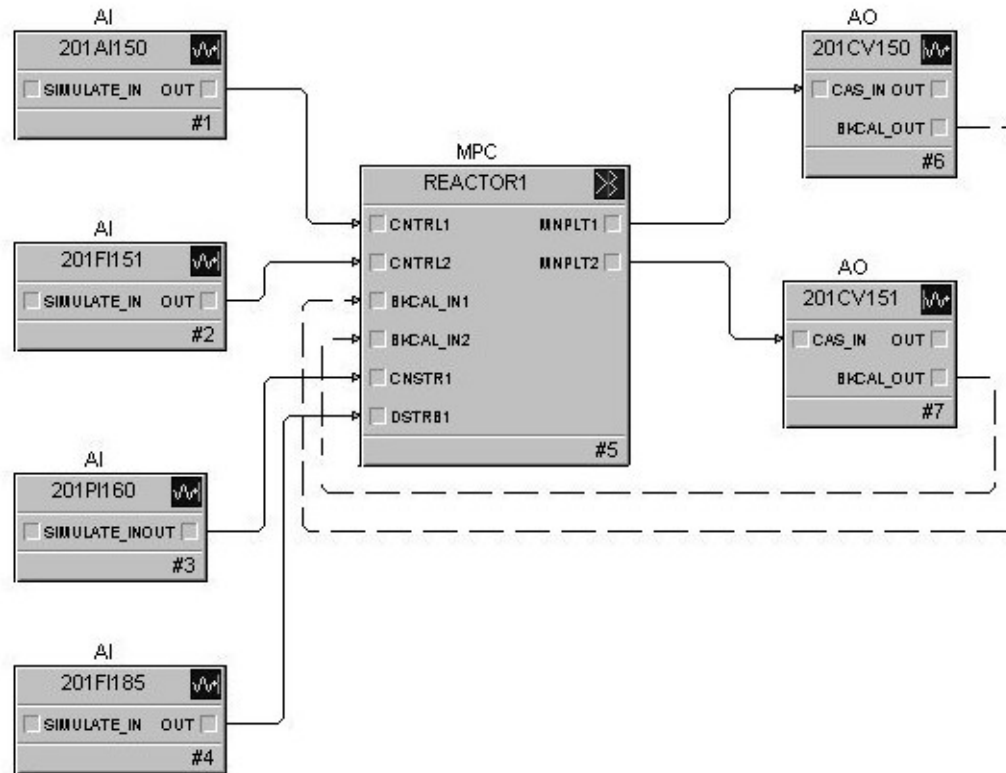


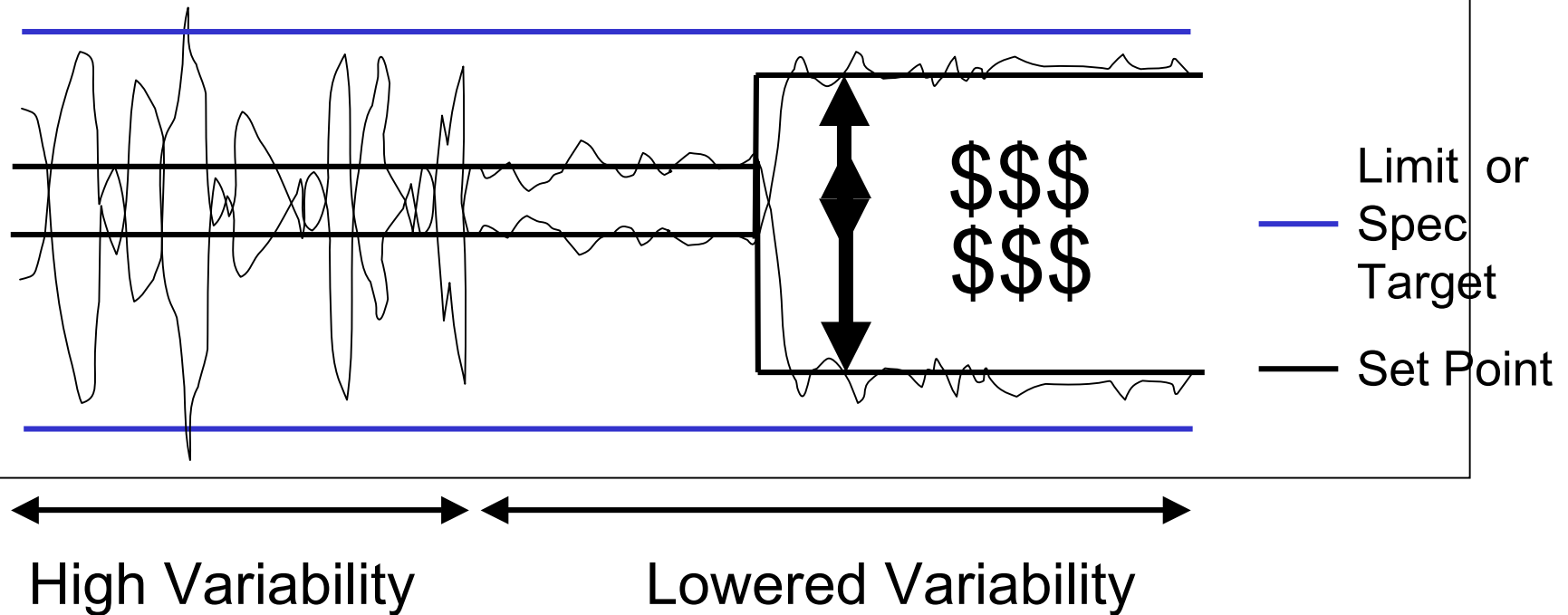
Figure 9.24 MPC Configuration for Batch Reactor Control



Configuration of MPC Strategy

# MPC Embedded Optimization

- MPC can have single variable optimization capability, often referred to as a “pusher”
- It allows MPC to keep one variable very close to a constraint without actually violating it.

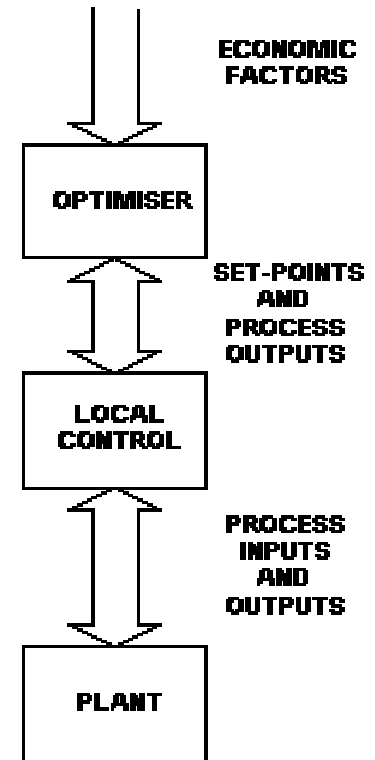


# Embedded Optimization

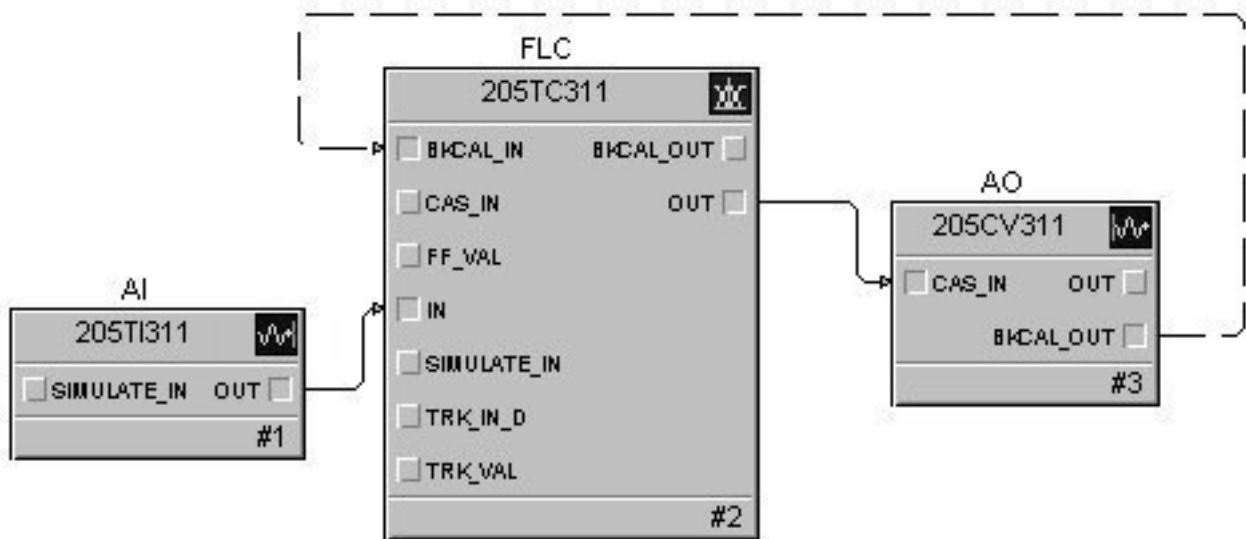
- MPC can have an embedded LP (linear program) that allows it to find the best combination of multiple set points to satisfy a particular operating goal.
- Operating modes could include:
  - Operate at maximum throughput
  - Operate at minimum energy consumption
  - Operate at maximum profit
  - Operate at minimum cost

# Real Time Process Optimization (RTO)

- The application of optimization techniques is not restricted to the design of predictive constrained controllers.
- Process optimization is a task in its own right.
- Unlike local controllers, which seek to maintain unit operating conditions at desired levels, the plant optimizer utilizes a model of the plant to adjust operating conditions of the process so as to:
  - minimize raw material usage
  - maximize profits.
- The outputs of the optimizer therefore set the targets for the local controllers, taking into consideration the operational limits of the plant.
- This effectively bridges the gap between the plant's true business objectives and its actual operations.
- Due to the complexity and the scale of this type of optimization problem, the model used is normally a steady-state description to enable a tractable solution.
- As with control algorithms, adaptive on-line optimization is also feasible.

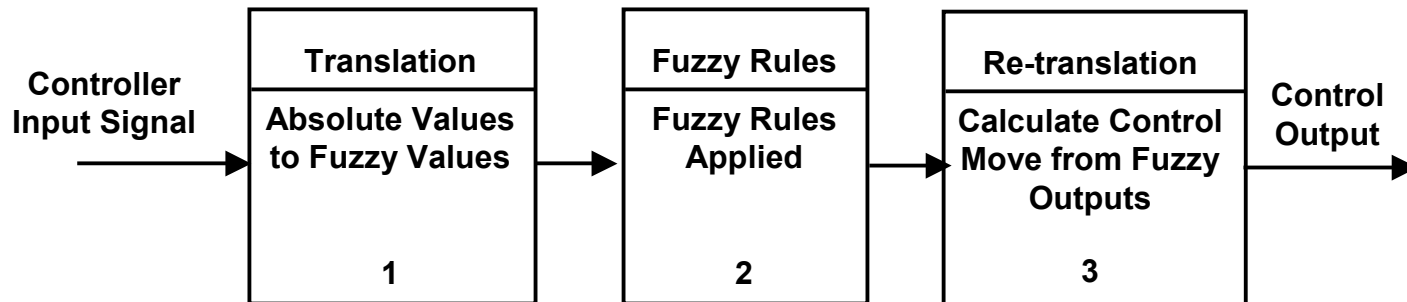


# Fuzzy Logic



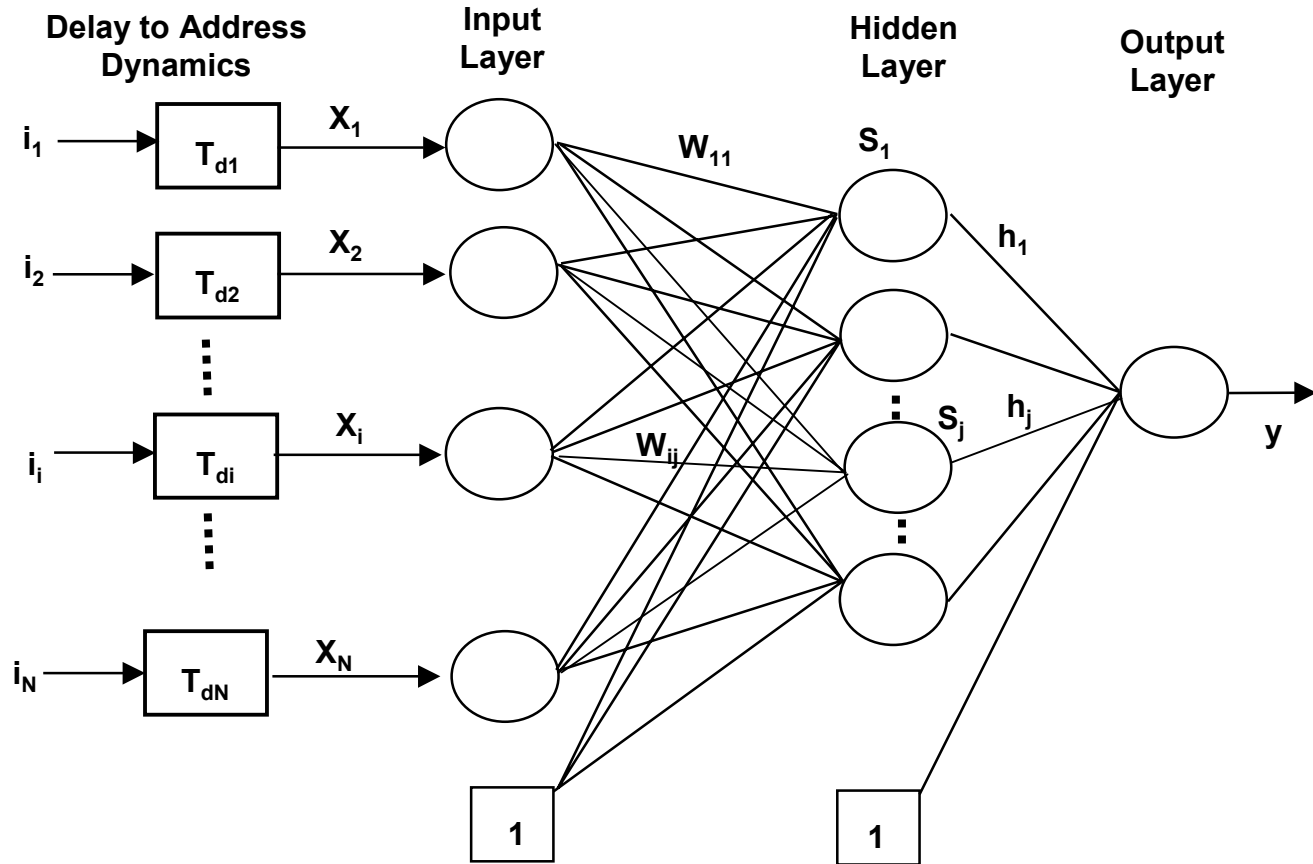
Fuzzy Logic Control Designed as a Function Block

## Fuzzy Logic (II)



A typical fuzzy logic controller diagram

# Neural Networks



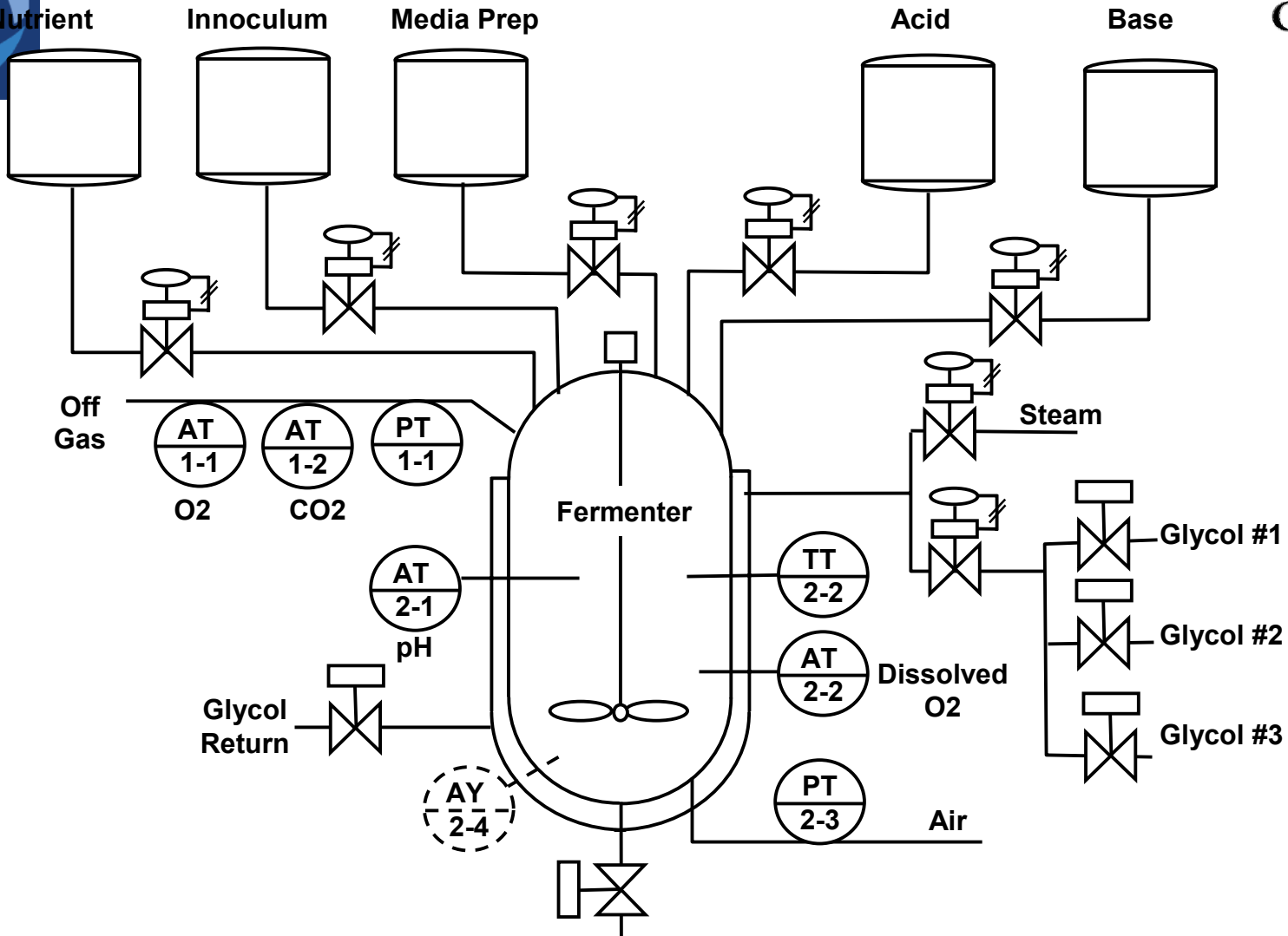
Three layer feed-forward Neural Network



# Neural Networks (II)

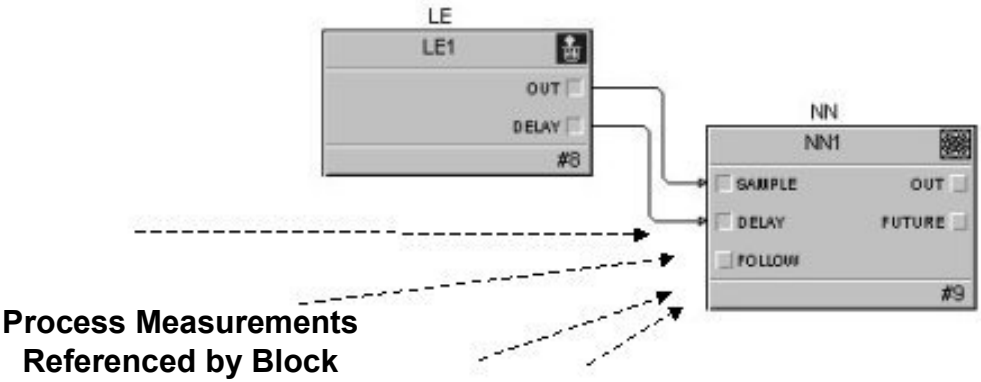


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**Fermentation Process for which end of batch was predicted using a neural network**

# Neural Networks (III)



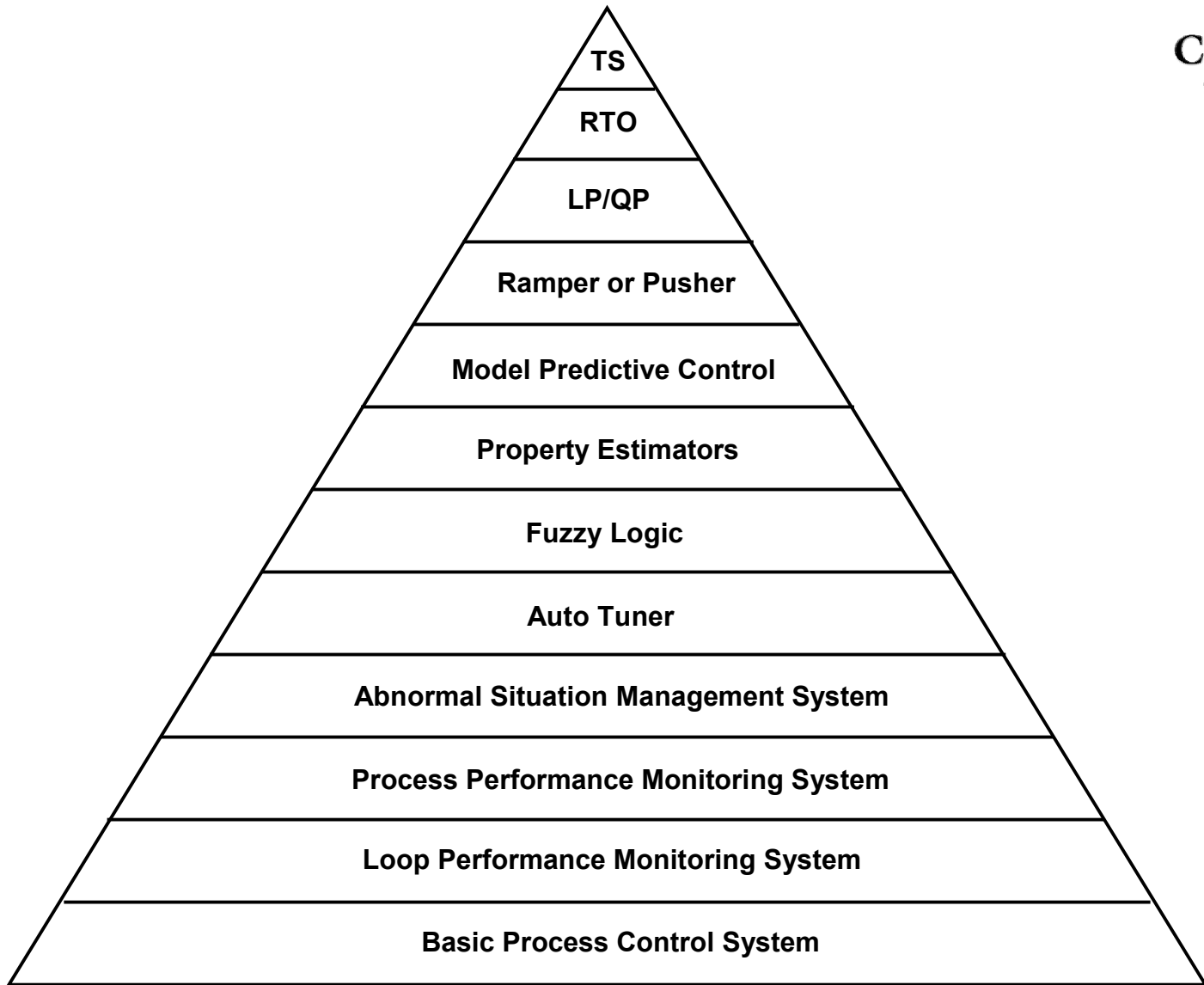
Soft Sensor uses upstream measurements to predict process output values.



## Other Advanced Control Tools



- Digital Plant
- Process Monitoring: Yield Monitoring, Alarm Alerts, Alarm Management, etc.
- Fault Detection, Location and Diagnosis
- Expert systems
- Robust Control
- Performance Monitoring
  - Variability
  - Control mode
  - Equipment usage



TS is tactical scheduler, RTO is real time optimizer, LP is linear program, QP is quadratic program

## Pyramid of Technologies



**END**