“Process Operations: When Does Controllability Equal Profitability?”

Thomas F. Edgar
Department of Chemical Engineering
University of Texas
Austin, TX 78712

AIChE WebCAST

March 17, 2008

Justification of Process Control

- Increased product throughput
- Increased yield of higher valued products
- Decreased energy consumption
- Decreased pollution
- Decreased off-spec product
- Safety
- Extend life of equipment
- Improved operability
- Decreased production labor

21^{st} Century Business Drivers for Process Control

BD1. Deliver a product that meets customer specifications consistently

BD2. Maximize the cost benefits of implementing and supporting control and information systems.

BD3. Minimize product variability.

BD4. Meet safety and regulatory (environmental) requirements.

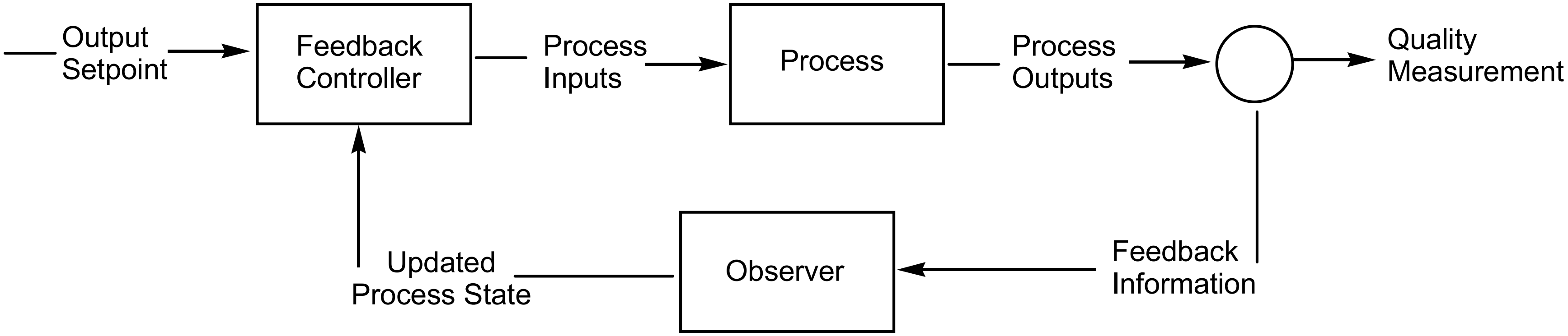
BD5. Maximize asset utilization and operate the plant flexibly.

BD6. Improve the operating range and reliability of control and information systems and increase the operator’s span of control.

Major Control Epochs

1. The early days (1950-70)
2. The energy crisis and digital control (1970-80)
3. Quality, safety, and environment (1980-90)
4. The enterprise view (1990 – present)

Feedback Control Is Basic Building Block (Since 1950s)



Output Setpoint

Feedback Controller

Process Inputs

Process

Process Outputs

Quality Measurement

Feedback Information

Observer

Updated Process State

Desirable Closed Loop Performance

- Tight control about a set point
- Fast, smooth set point changes
- Insensitivity to model errors
- Insensitivity to plant changes
- Ease of on-line tuning

Beginnings of Advanced Process Control (APC)

- First usage of APC was in guidance and control of aircraft/satellites.
- Due to complexity of these systems, PID control was inadequate.
- Digital computer control was required for analysis of the differential equations.

  1957 – Sputnik launching

  USSR/USA competition in control technology

  (Maximum vs. Minimum Principle)

General Nonlinear Optimal Control Problem

$$\min_{u(t),t_f} J = \phi(x(t_f)) + \int_{t_0}^{t_f} L(x,u,t)dt$$

$s.t.$

$$\dot{x} = f(x,u,t)$$

$$g(x,u,t) \le 0$$

$$h_0(x(t_0),u(t_0)) \le 0$$

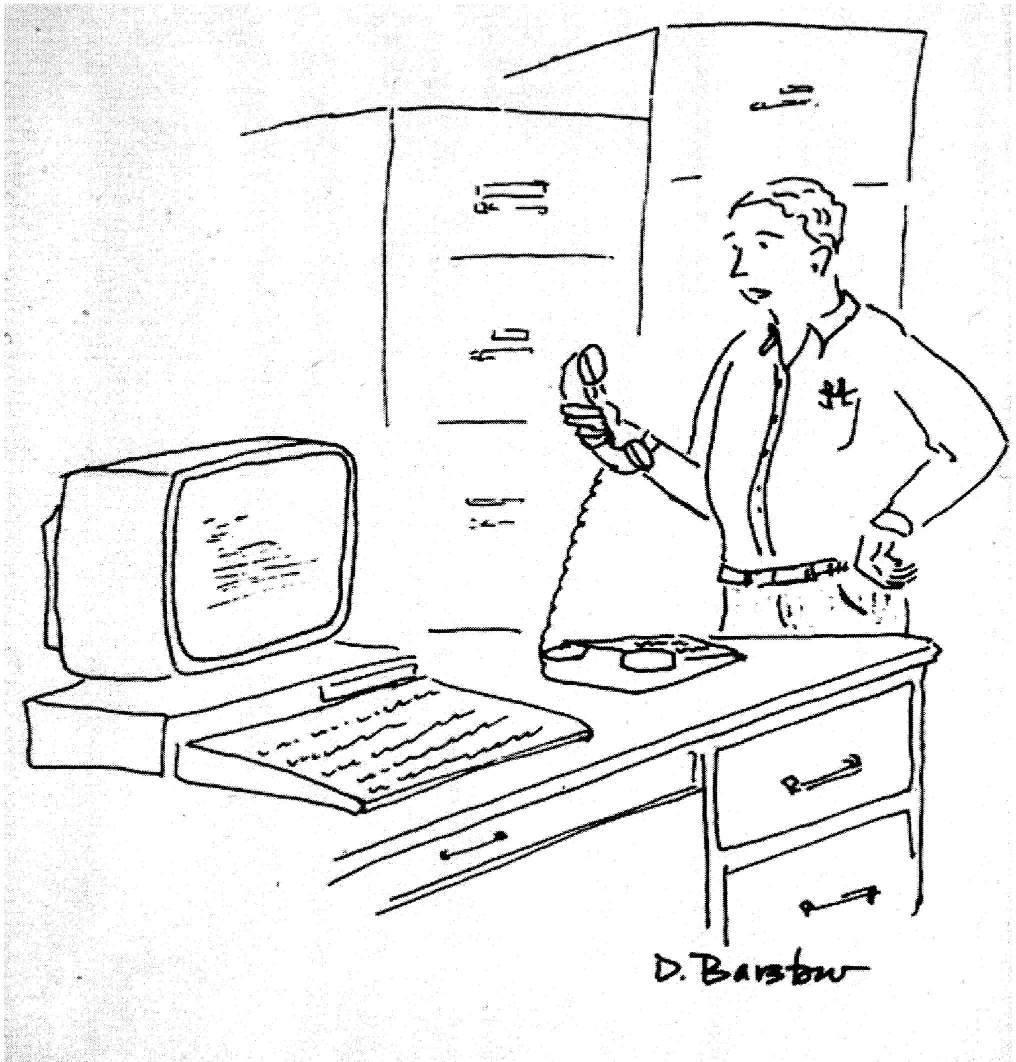
$$h_f(x(t_f),t_f) \le 0$$

Nonlinear Optimal Control in 1960s

- Minimum time problem (nonlinear CSTR)
- Maximize yield in tubular reactor (A→B)
  - Siebenthal and Aris (1964)
  - Rosenbrock and Storry (1964)
  - Lapidus and Luus (1967)

Hierarchical (Multi-level) Control (1960s)

- Applied by Mobil Oil in thermal cat cracking (1967)
- Supervisory level using optimization
- Regulatory loops at lowest level



THE CHRONICLE OF HIGHER EDUCATION DONNA BARSTOW

"It's for you."

1960s/1970s – Conflict Between “Modern” and “Classical” Control Camps

- Time domain vs. frequency domain
- Optimization vs. PID tuning
- PID control was still dominant in process industries.

LQG Problem

$$J = \int_0^{t_f} \left[x^T Q x + u^T R u \right] dt$$

$$\dot{x} = Ax + Bu$$

$$u^{opt} = -Kx(t) \quad \text{Feedback control}$$

Modifications in Quadratic Performance Index

- Only weight output variables (no control weighting), but controller saturates
- Add quadratic terms involving du/dt (effectively adds integral action)
- Do positive deviations cost more (or less) than negative deviations (product specs, energy use)?

Why APC Was Not Used (1960-80)

- There were very few pilot installations for testing control algorithms.
- Proprietary processes and great variety of processes prevented technology transfer.
- Engineers design safe self-regulatory processes – then use large inventories and blend products.

- You can’t make any money with APC.
- Inter-disciplinary problem – knowledge required includes control theory, engineering, advanced math, statistics.
- Small yield for effort – plants have other problems to solve that will give more significant increase in production, yield, quality, etc.
- Math model of process required in process control – not easy to get for some processes.

Computers (as of 1960)

	Average Monthly Rental (1960 $)	Maximum Core Storage Capacity (in 1000 bits)	Add Time (Micro-sec)	Read Cards Per Min
IBM-7090	55,000	160	0.004	250
CDC-1604	34,000	32	0.005	1300
DEC-PDP1	2,200	4	0.010	(Tape Input)

Major Developments Influencing Acceptance of APC in Late 1970s and 1980s

- Energy crisis
- Distributed control hardware
- Environmental restrictions
- Quality control (international competition)
- Computing speed

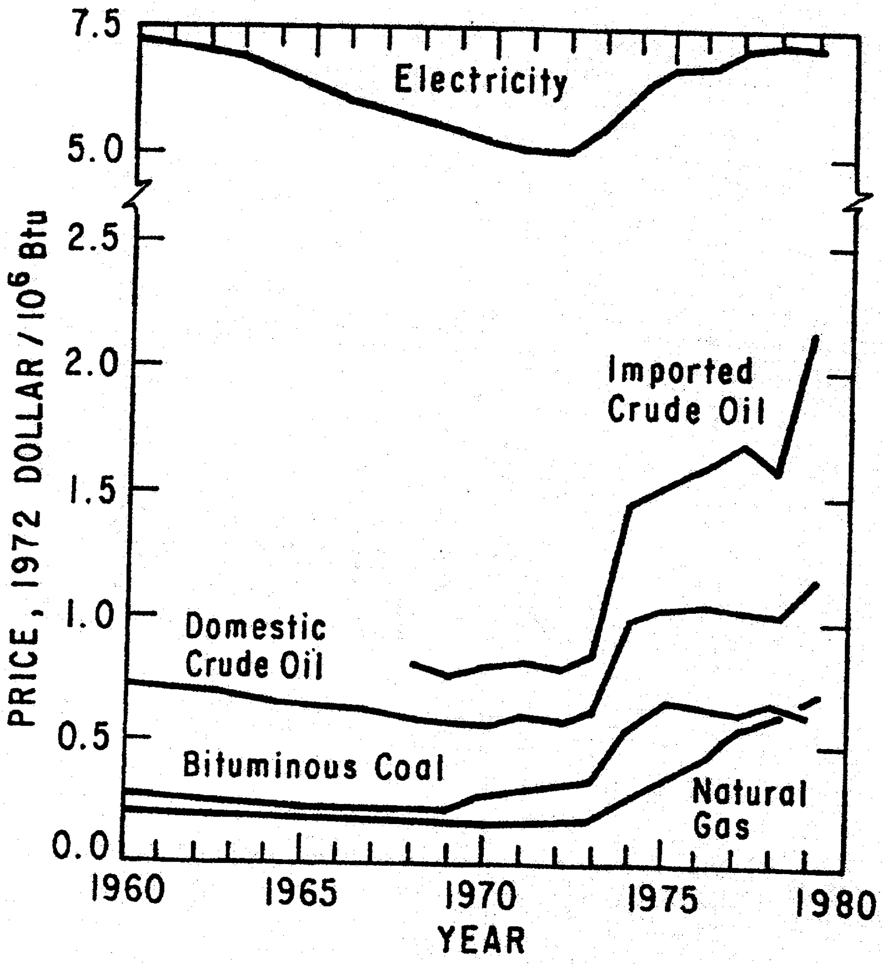
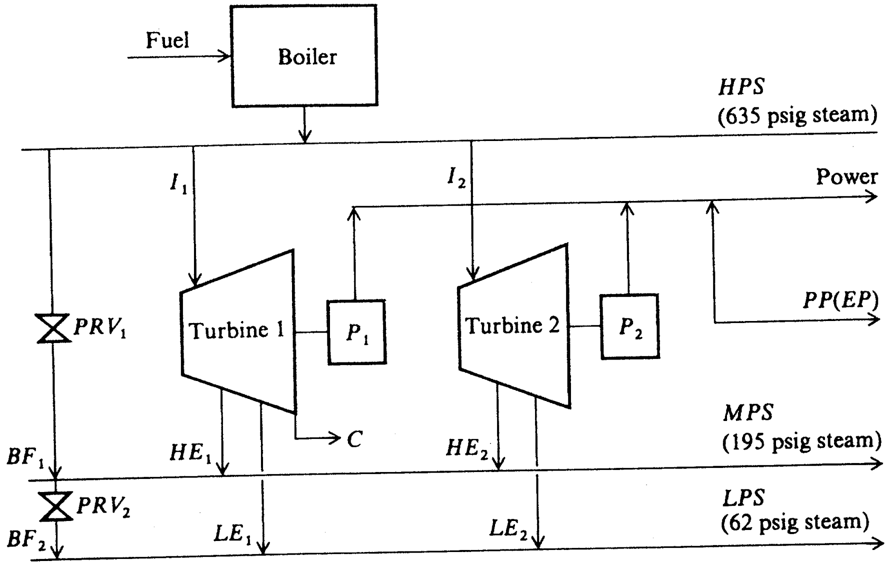
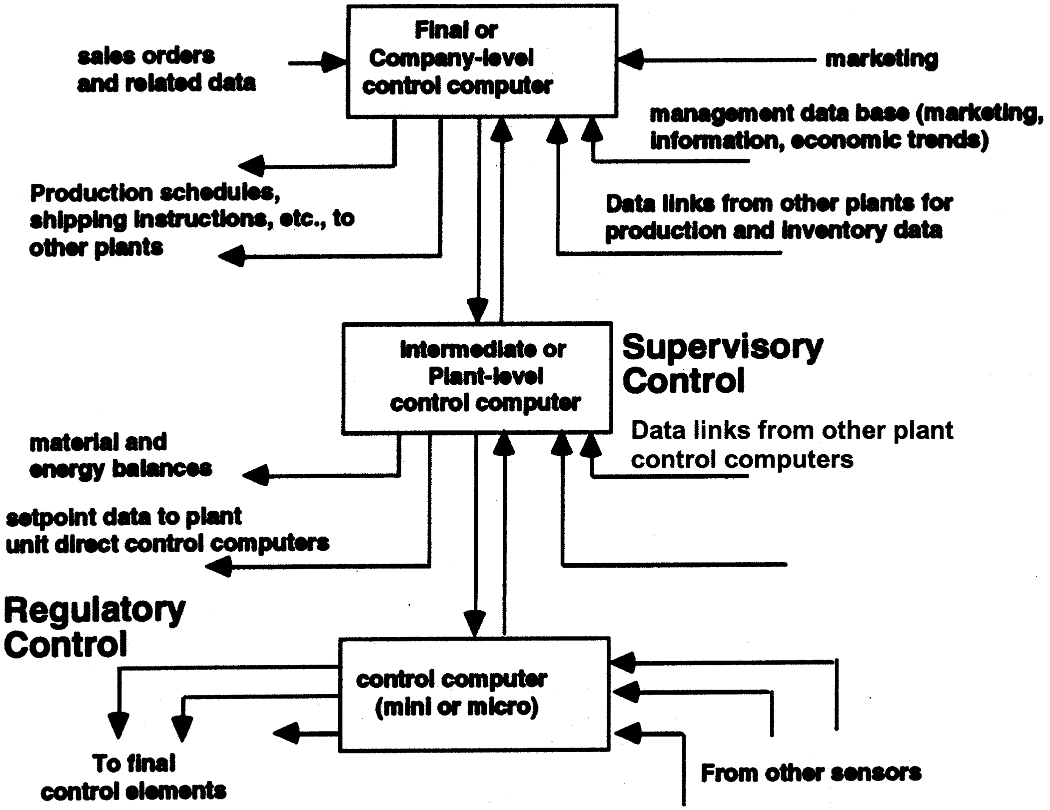


Figure 1-3. How U.S. fossil fuel and electricity prices have varied.[2]



Notation: I_i = inlet flowrate for turbine *i* [lb_m/h]
HE_i = exit flowrate from turbine *i* to 195 psig header [lb_m/h]
LE_i = exit flowrate from turbine *i* to 62 psig header [lb_m/h]
C = condensate flowrate from turbine 1 [lb_m/h]
P_i = power generated by turbine *i* [kW]
BF_1 = bypass flowrate from 635 psig to 195 psig header [lb_m/h]
BF_2 = bypass flowrate from 195 psig to 62 psig header [lb_m/h]
HPS = flowrate through 635 psig header [lb_m/h]
MPS = flowrate through 195 psig header [lb_m/h]
LPS = flowrate through 62 psig header [lb_m/h]
PP = purchased power [kW]
EP = excess power [kW] (difference of purchased power from base power)
PRV = pressure-reducing valve

Figure 10.6 Boiler/turbogenerator system.



Hierarchical Computer Control Configuration

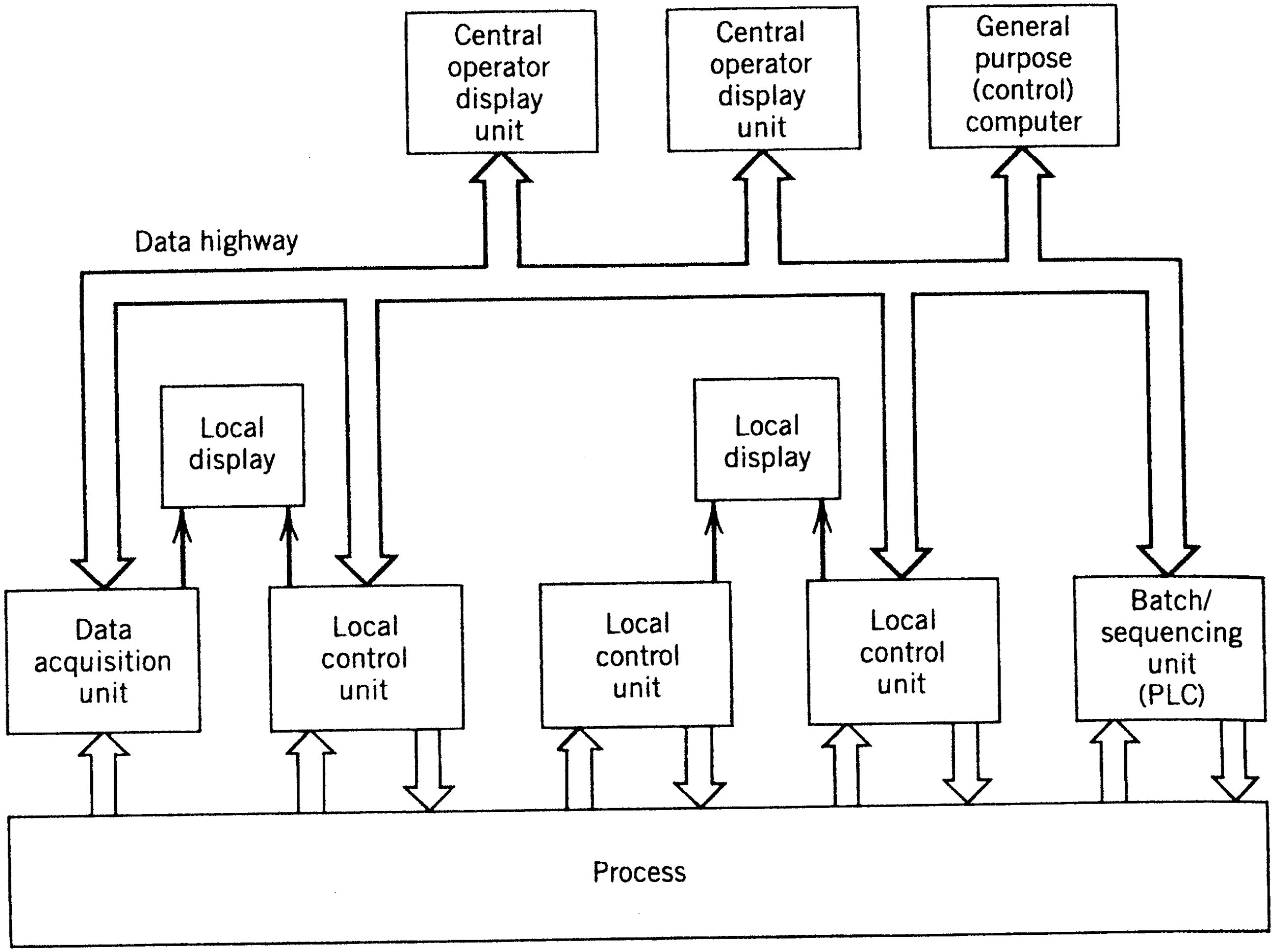
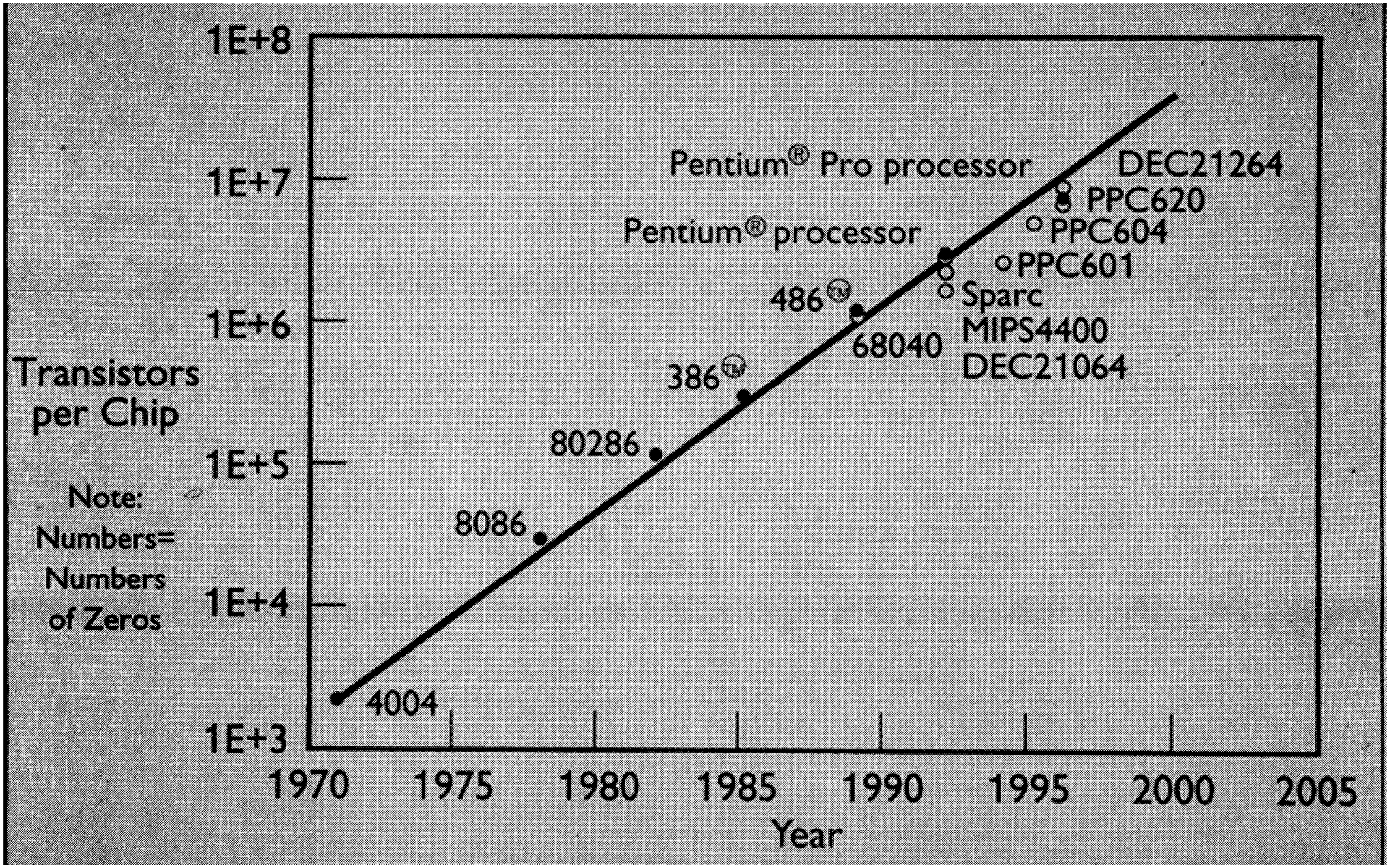


Figure 21.4. A distributed digital instrumentation and control system.


1E+8
1E+7
1E+6
1E+5
1E+4
1E+3
Transistors per Chip
Note: Numbers= Numbers of Zeros
1970
1975
1980
1985
1990
1995
2000
2005
Year
4004
8086
80286
386™
486™
68040
Pentium® processor
Pentium® Pro processor
Sparc
MIPS4400
DEC21064
PPC601
PPC604
PPC620
DEC21264

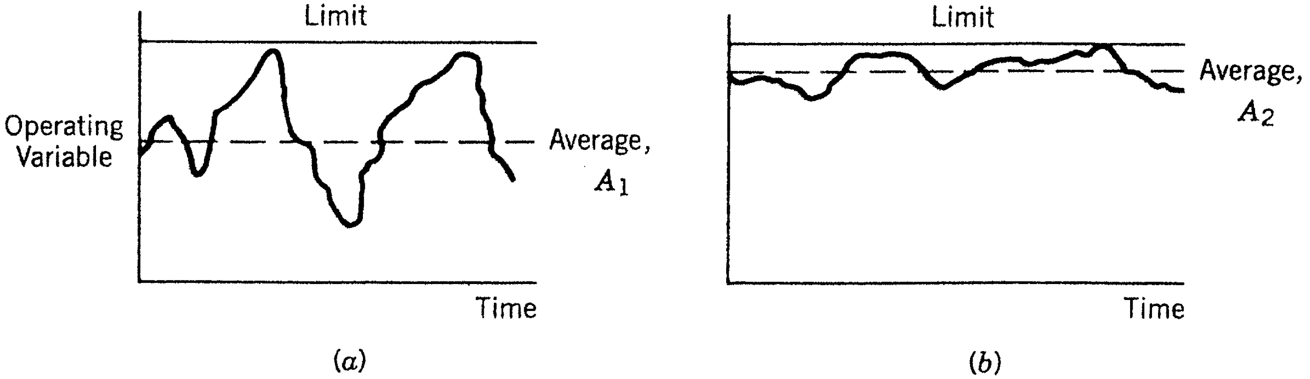


Figure 1.5. Product variability over time: (*a*) before improved control; (*b*) after. The operating variable is % ethane.

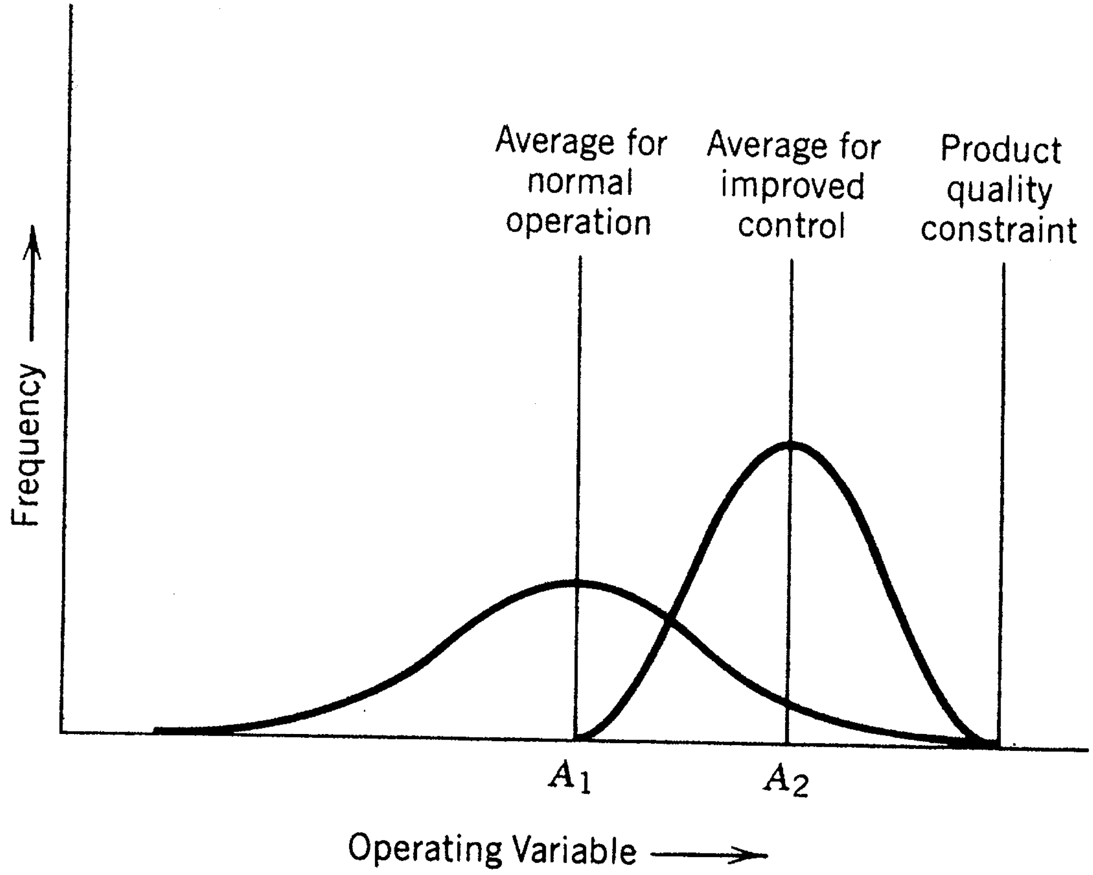


Figure 1.6. Product quality distribution curves showing justification for improved control.

Product Quality and Economics

- It is often difficult to relate quality problems to sales volume, market share, or selling price
- Make products right the first time (avoid rework, blending)
- Controlling variability avoids troublesome process conditions, shutdown
- Cycle time is improved by lower variability
- Transfer variability to variables that are less important

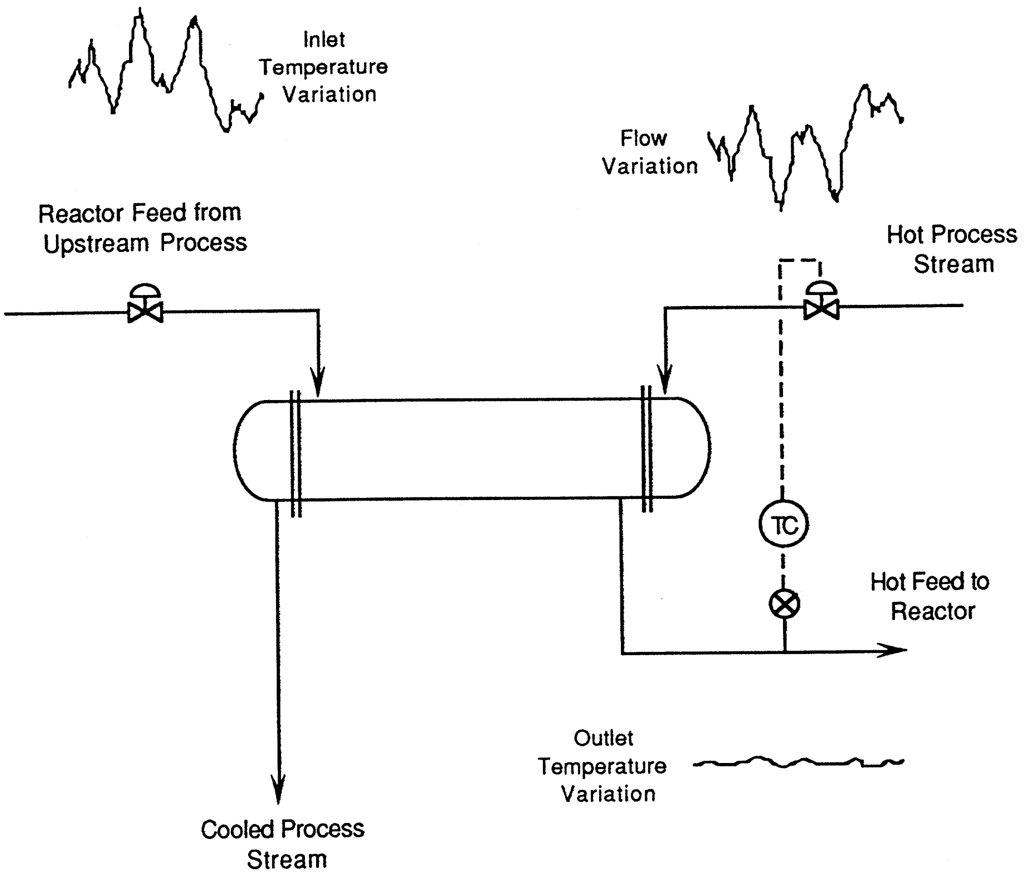


Fig. 1. Transformation of variation from temperature to flow for a reactor feed preheater.

Process Control Economics 101

- Energy savings of 1-4% arise from advanced control (Foxboro)
- Dupont (1988) estimated $200 - $500 million savings from application of advanced control
- Successful RTO application delivers 3% of economic value added (Shell)

Process Control Economics 101

- APC generates an average of 3 to 5% capacity increase (Aspentech)
- APC projects have payback period of 3 months to 2 years and significant labor cost reduction (Mitsubishi)

Changing Manufacturing Requirements

$$\left.\begin{array}{l}\text{Good}\\ \text{Fast}\\ \text{Cheap}\end{array}\right\}\text{any two out of three before 1990,}$$

and

Green: new addition for 21st Century

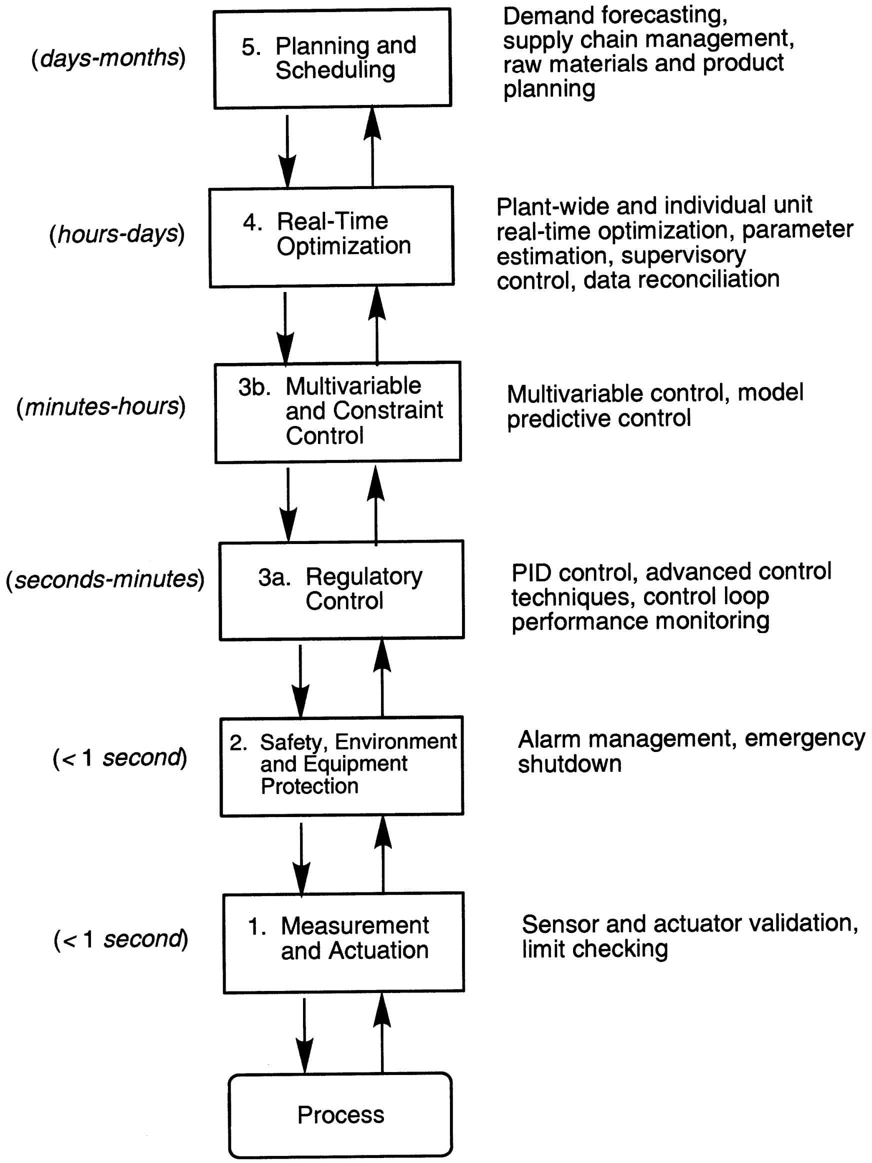


Figure 19.1 The five levels of process control and optimization in manufacturing. Time scales are shown for each level.

Model Predictive Control (MPC)

- Most widely used multivariable control algorithm in chemical process industries
- Makes explicit use of process model (related to Kalman filter)
- Control actions obtained from on-line optimization (QP)
- Handles process variable constraints
- Unifies treatment of load, set-point changes
- Many commercial packages

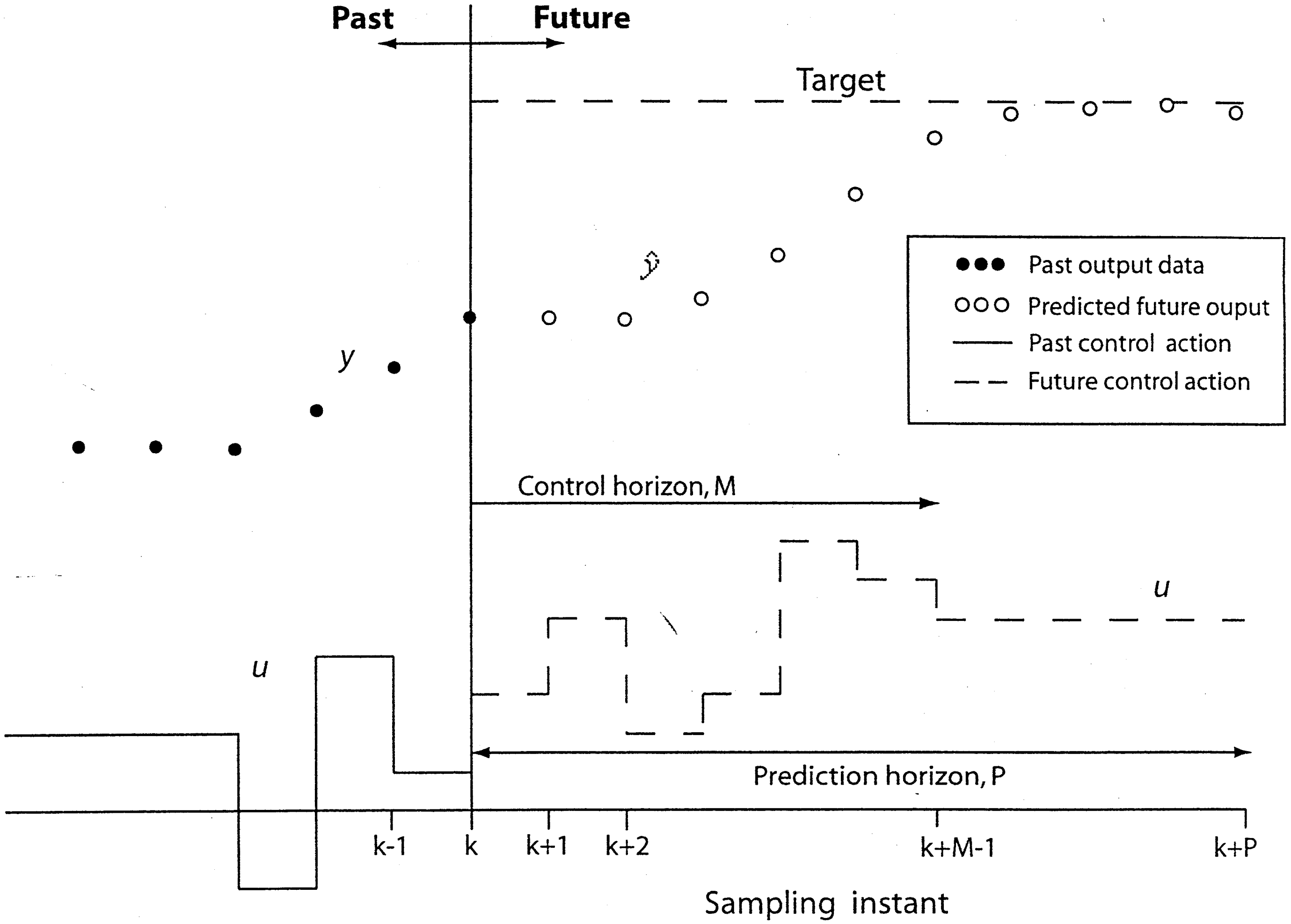
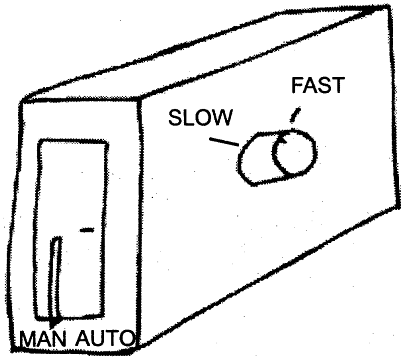
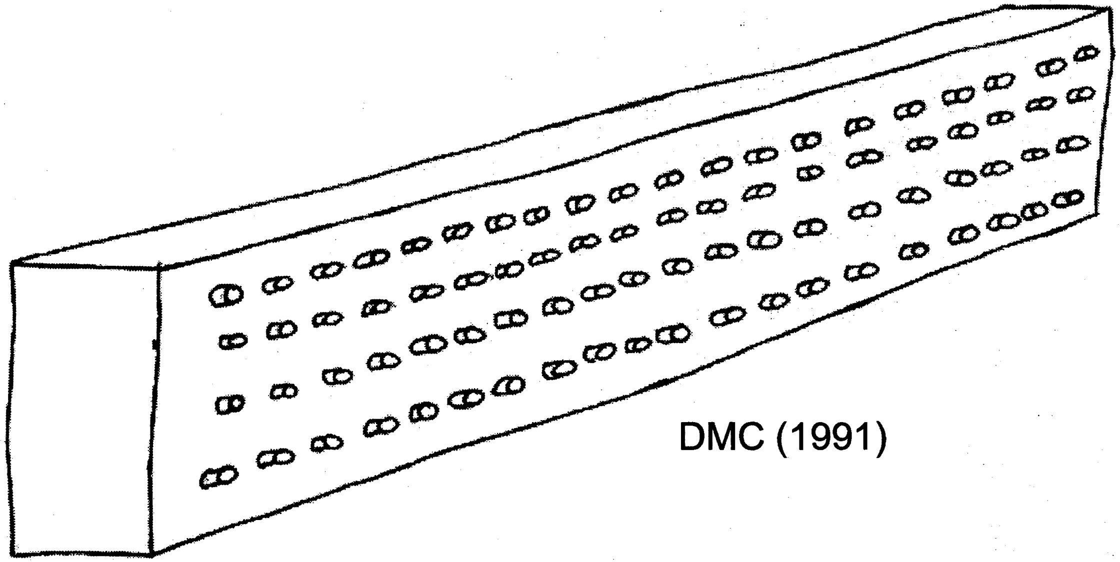


Figure 20.2 Basic concept for Model Predictive Control

Progress in APC

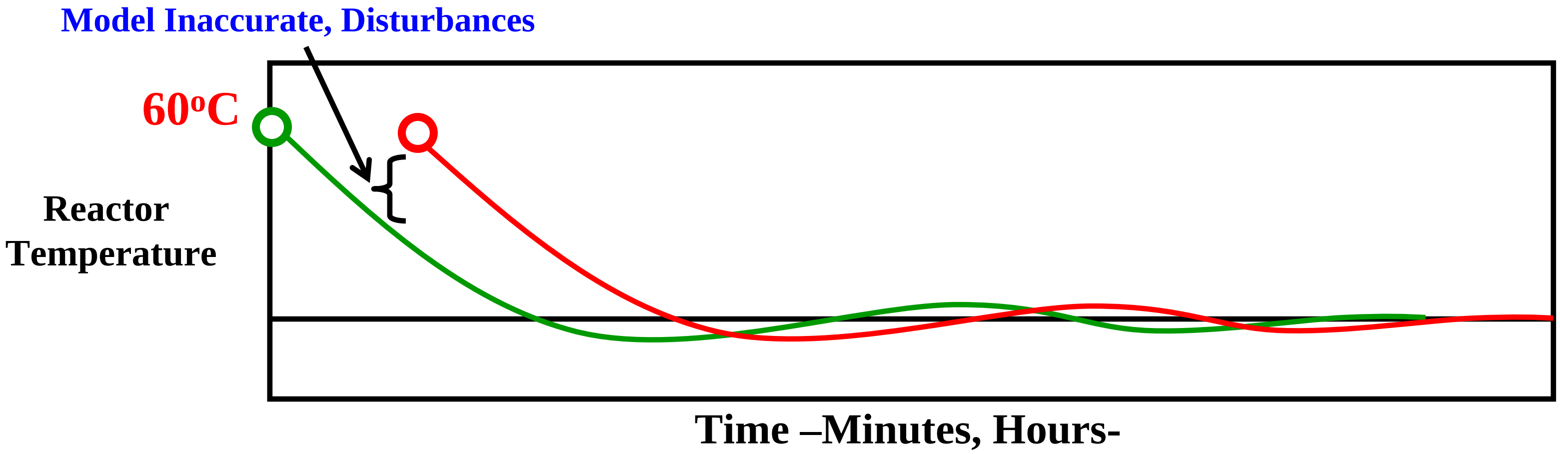


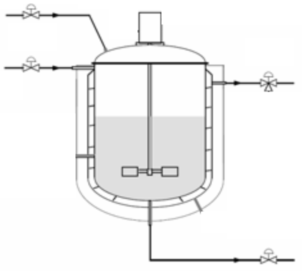
IMC (1986)



DMC (1991)

Model Predictive Control





New RTO Steady-State

50°C

Quadratic Programming Problem

$$\begin{aligned} \min \ & \sum_{k=1}^{N} (z_k - z_k^{sp})^T \mathrm{Q} (z_k - z_k^{sp}) \\ \text{s.t. } z_{k+1} &= \mathrm{A} z_k + \mathrm{B} u_k \\ z_k &= x(k) \end{aligned}$$

Minimize Transition Time

Linear Dynamic Model

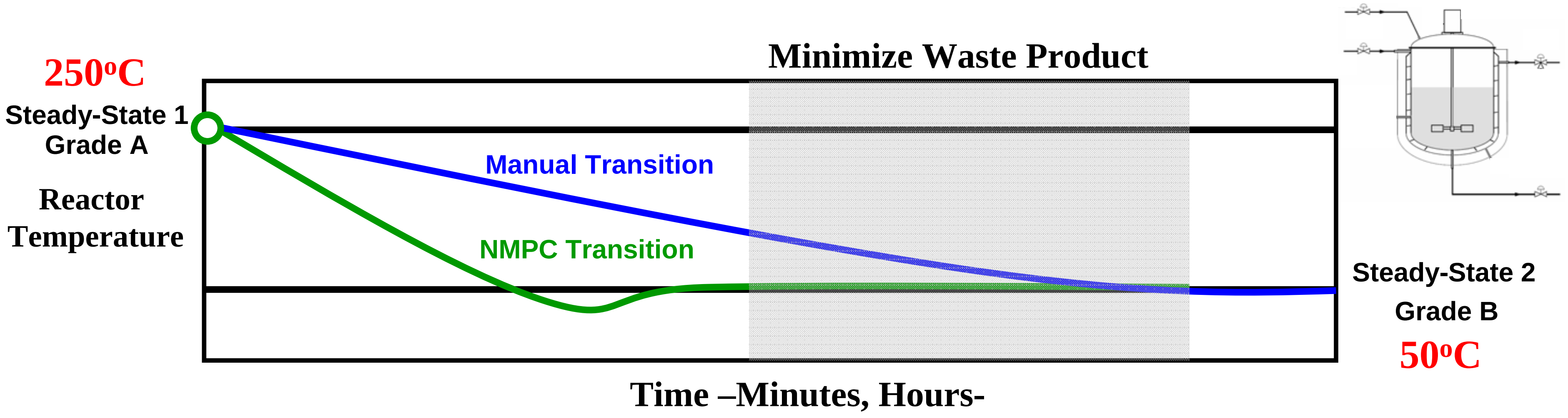
Current State

- MPC Successful in Many Applications (> 2000 Installed Applications) *Qin & Badgwell, 2003*
  - Solution Algorithms and MPC Stability Theory Mature

Fundamental Issue MPC

- Not Applicable in Wide Operating Windows

Nonlinear Model Predictive Control



$$\min \sum_{k=1}^{N} (z(t_k) - z_k^{sp})^T \mathbf{Q} (z(t_k) - z_k^{sp})$$

Minimize Transition Time

Dynamic Optimization Problem

$$\begin{aligned} \frac{dz}{dt} &= \mathbf{F}\left(z(t), y(t), u(t)\right) \\ 0 &= \mathbf{G}\left(z(t), y(t), u(t)\right) \\ z(0) &= x(k) \end{aligned}$$

First-Principles Dynamic Model

Kinetics, Thermodynamics, Transport -DAEs-

Current State

- **Grade Transitions Continuous Polymerization Processes** *Bartusiak, 2007*
- **Recent Advances in Dynamic Optimization and Stability Theory** *Biegler, 2003; Diehl, 2001; Rao, et.al. 2000*
- **Batch Polymerization, Bioreactors, Crystallization, Thin-Film, Cancer Treatment, etc.**
- **First-Principles Models = Computationally Expensive**
- **Problem: Difficult to Justify Economic Benefits of NMPC vs MPC**

How is MPC Implemented?

At each control interval, the MPC algorithm answers three questions:

1. **Update:** ***Where is the process going?***
2. **Target:** ***Where should the process go?***
3. **Control:** ***How do you get it there?***

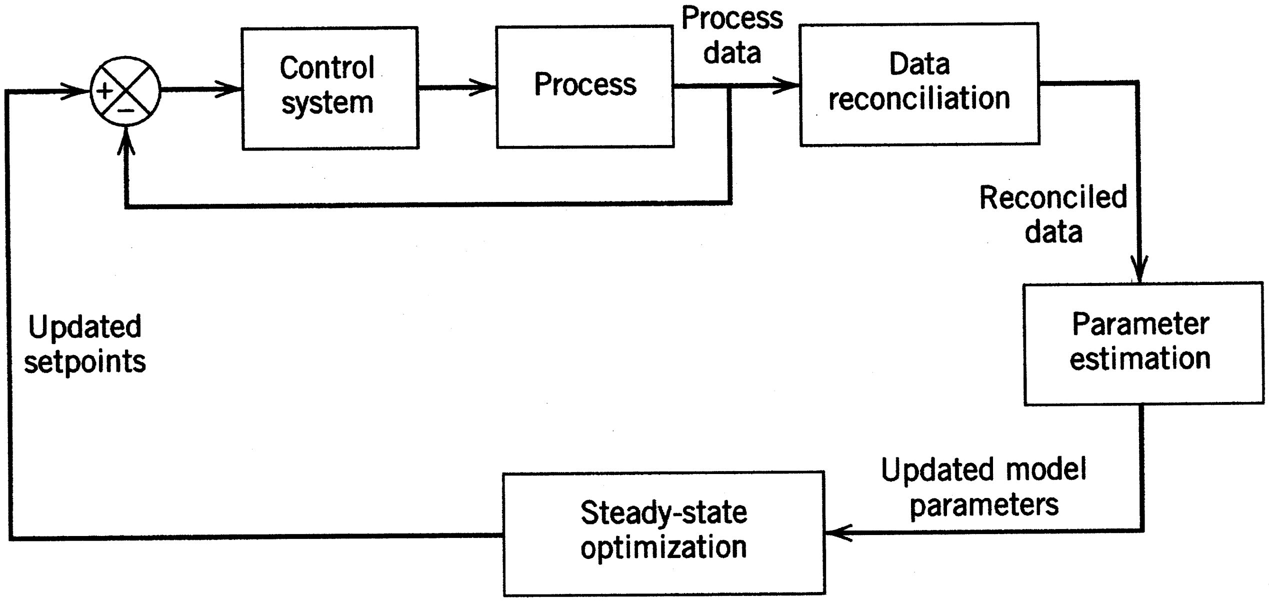


Figure 19.2 A block diagram for RTO and regulatory feedback control.

Target: Local Steady-State

- Most controllers use a separate steady-state optimization to determine steady-state targets for the inputs and outputs

- Most controllers provide a Linear Program (LP) option for SS optimization; the LP is used to enforce input and output constraints and determine optimal input and output targets

- Most controllers also provide a Quadratic Program (QP) option to compute the steady-state targets

- All controllers enforce hard MV constraints at steady-state; CV constraint formulations vary

- The DMCplus controller solves a sequence of separate QPs to determine optimal input and output targets; this allows CV constraints and MV targets to be ranked.

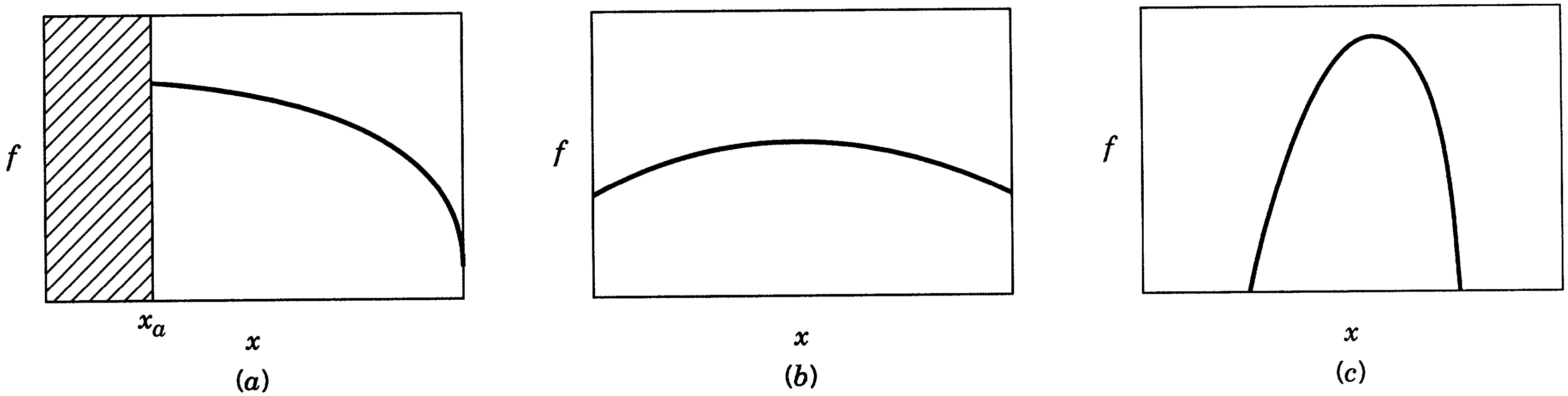


Figure 19.5 Three types of optimal operating conditions.

Operating at the Optimum

- At the unconstrained optimum, there is a change in sign of the process gain
  - one solution: operate near optimum
- At constraint, gain sign change may not occur

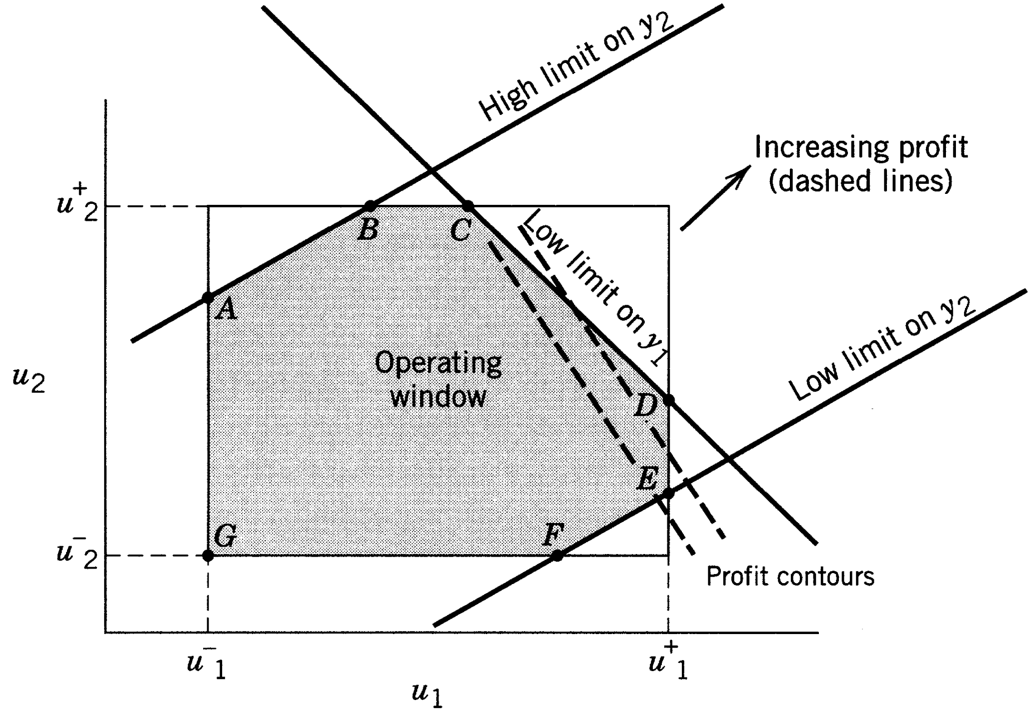
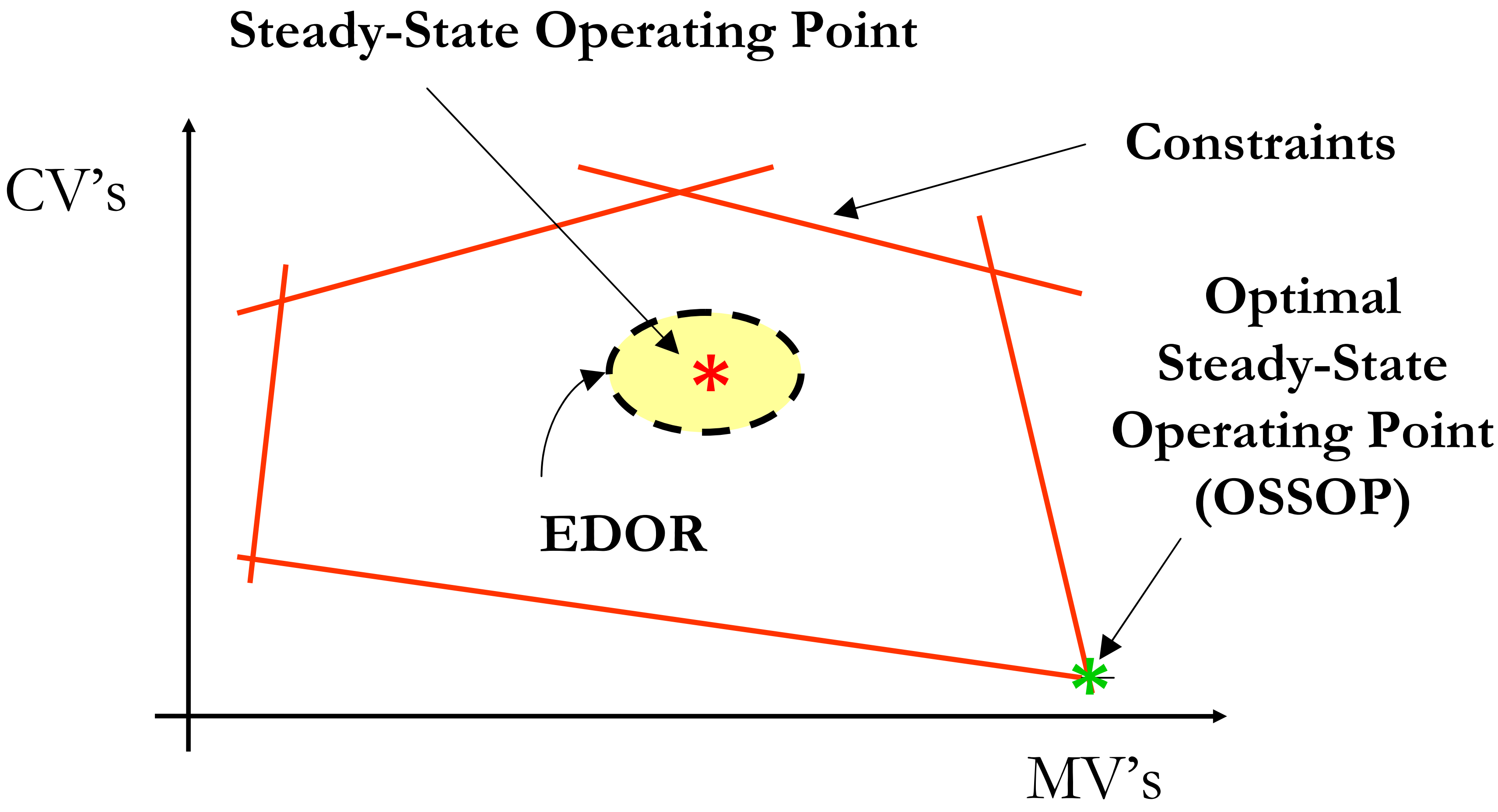
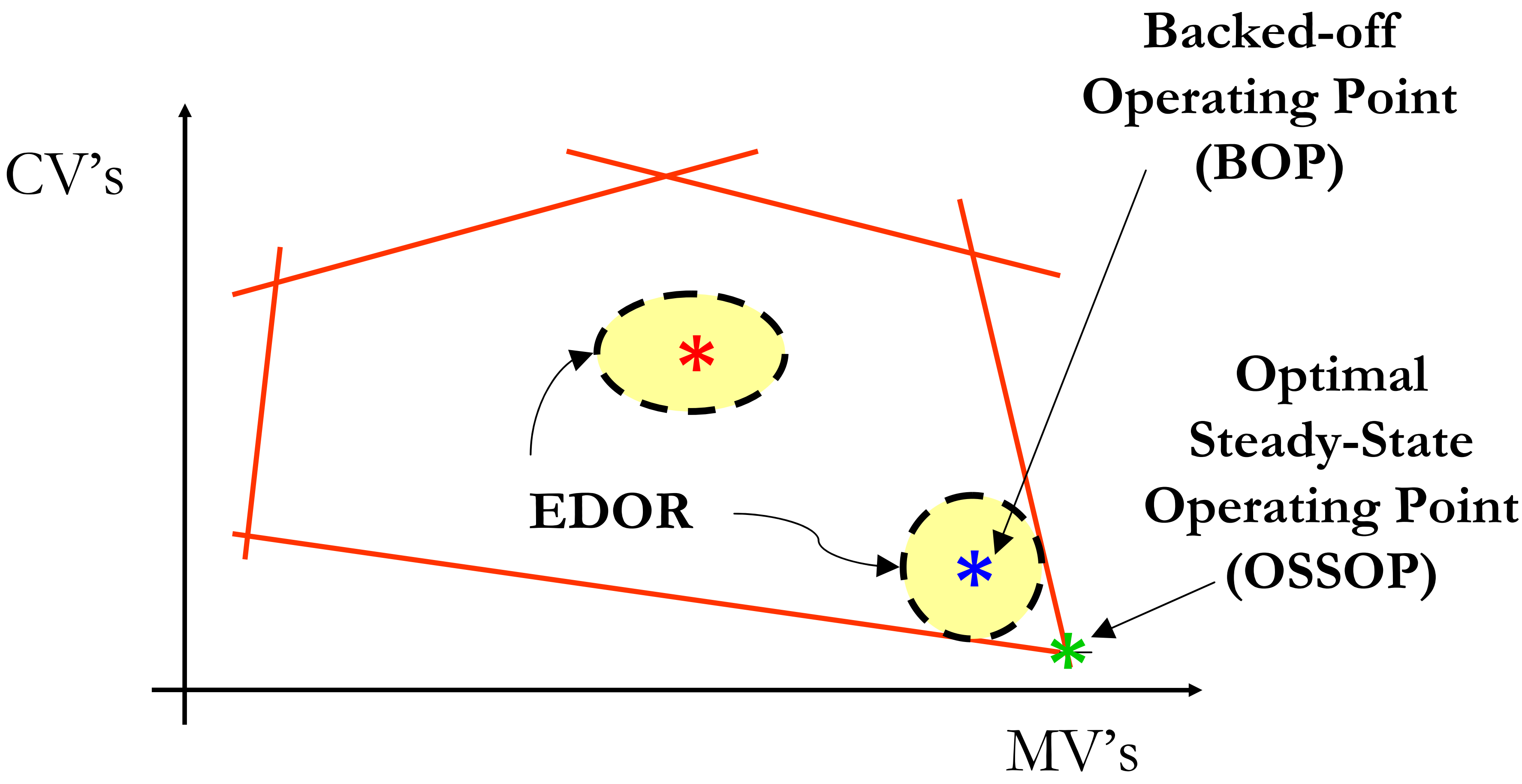


Figure 19.6 Operating window for a 2 x 2 optimization problem. The dashed lines are objective function contours, increasing from left to right. The maximum profit occurs where the profit line intersects the constraints at vertex *D*.

Real-Time Optimization



Backed-off Operating Point



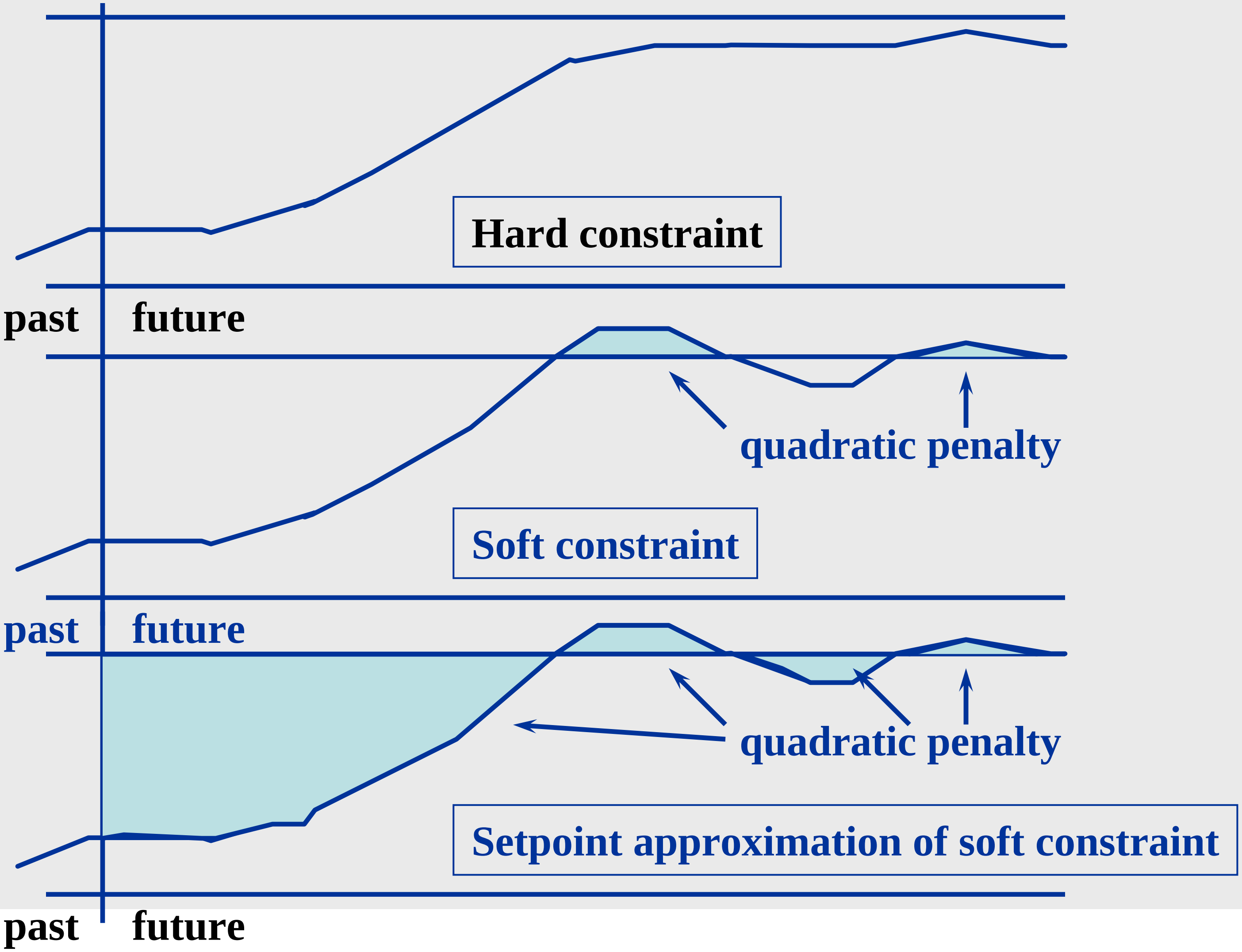
Backed-off
Operating Point
(BOP)

EDOR

Optimal
Steady-State
Operating Point
(OSSOP)

Control: Constraint Formulations

- There are two basic types of constraints: Hard constraints are never violated; soft constraints may be violated but the violation is minimized
- Soft constraints are sometimes approximated using a setpoint



Hard constraint

Soft constraint

Setpoint approximation of soft constraint

Economic Trade-off Between Process Design and Control

- Use surge vessels to dampen upsets
- Justify computer control system based on reduced variability (1980s)
- Fixed costs (vessel costs) vs. variable costs (cost of variation) addressed as plantwide control problem (2000)
- Tight tuning of level regulators can de-stabilize units

Batch Processing Used in Manufacturing

- Electronic materials
- Specialty chemicals
- Metals
- Ceramics
- Polymers
- Food and agricultural materials
- Biochemicals
- Multiphase materials/blends
- Coatings
- Composites

	REFINING/ CHEMICAL (CONTINUOUS)	SPECIALTY/ PHARMA (SEMICONTINUOUS)	SEMICONDUCTOR (BATCH/DISCRETE)
Primary objectives	Product quality, throughput	Product physical/ chemical properties	Wafer electrical properties
Secondary objectives	Temperature, MWD	Temperature	Linewidth, critical dimension
Economic objectives	Minimize product variability, RTO (ss)	Product quality, equipment utilization	Yield, cycle time
Mfg Tolerance	Forgiving (blending, mixing)	Somewhat forgiving (limited blending, FDA)	Not forgiving (can rework)
Measurements	Lots of data (T, p, w, h, c)	Mostly specialized analytical measurements	Most wafer quality measurements not in situ, many indirect tool measurements

Control Hierarchy in Batch Processing

1. Sequential control to step the process through a recipe
2. Logic control to deal with device interlocks
3. Within-the-batch control to make set point changes and reject disturbances
4. Run-to-run control to meet final quality constraints
5. Batch production control to maximize utilization of equipment and minimize cycle time

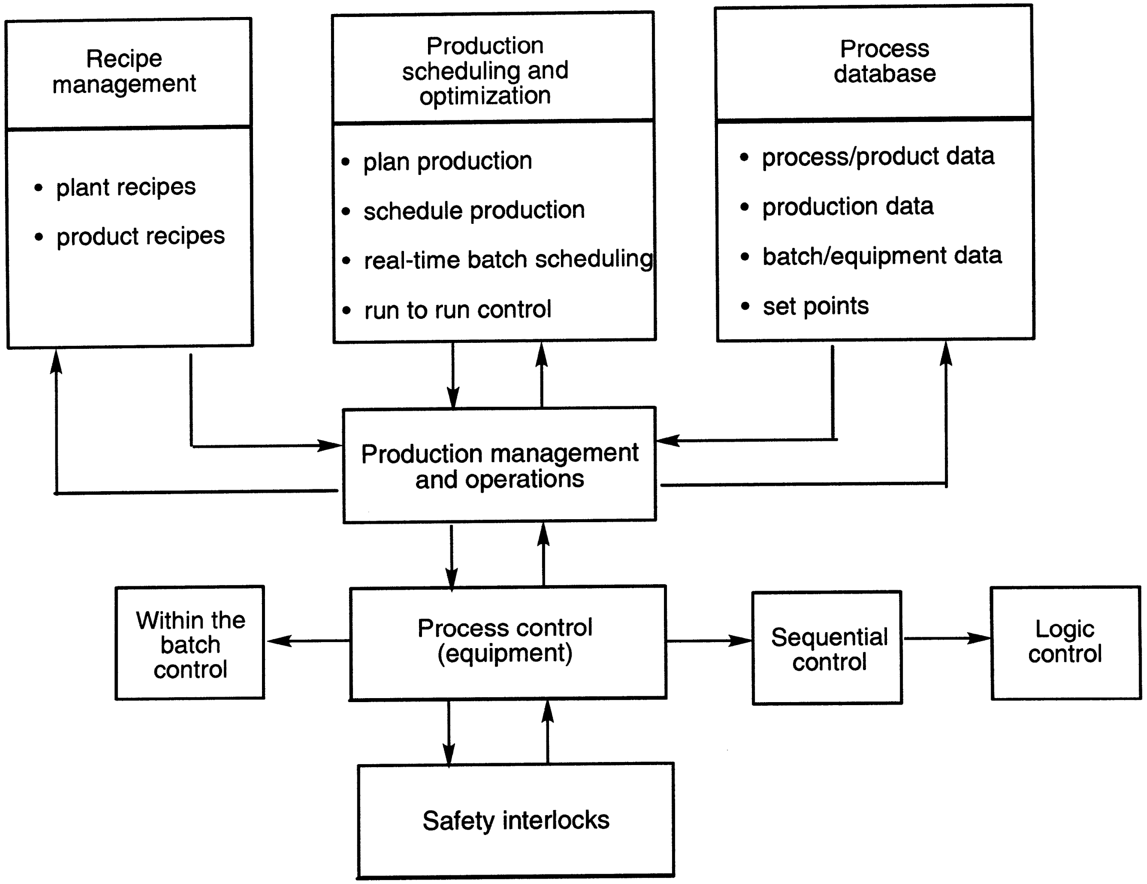


Figure 22.19 Batch control system – a more detailed view

Run-to-Run (RtR) Control

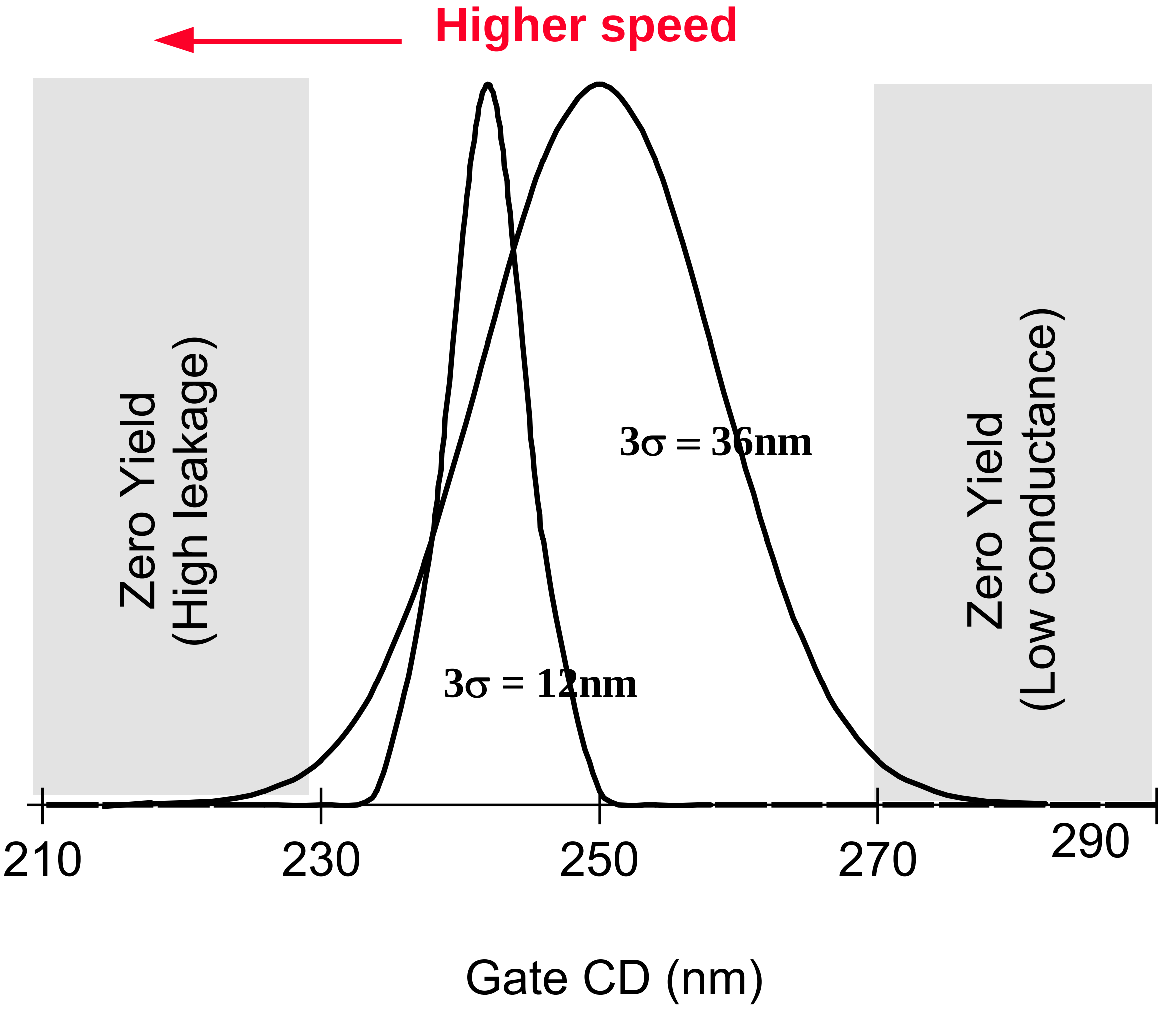
- Keeps batch process product on target by using feedback to manipulate batch recipe for consecutive batches
- Required due to a lack of in situ, real-time measurements of product quality of interest
- Extremely useful where initial conditions or tool states are variable and unmeasurable
- Supervisory controller determines optimal setpoints for real-time control loops (typically PID)

Use of RtR Control

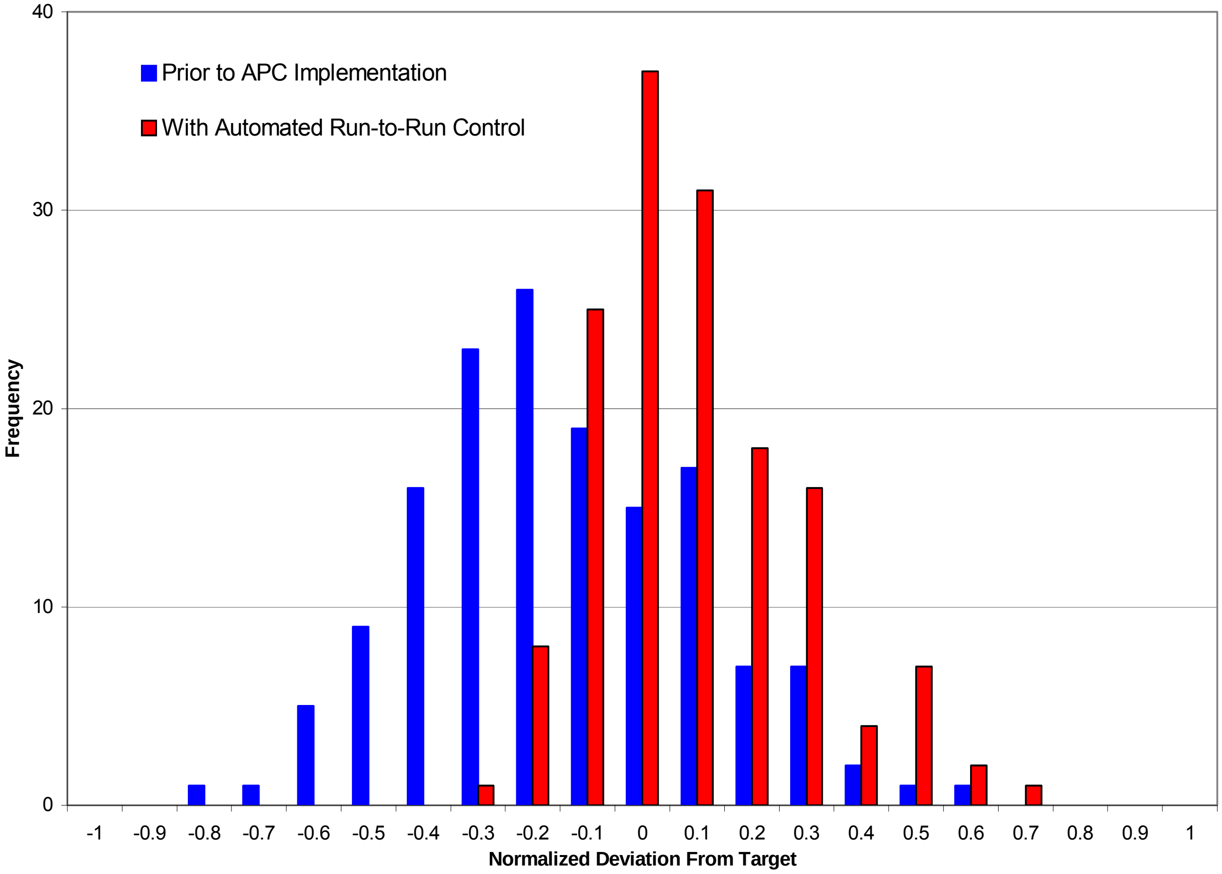
- Examples of events which can have slow dynamics or infrequent step changes
  - equipment aging
  - periodic machine maintenance
  - changes in feedforward signal
    - measure disturbance
  - major fault, such as instrumentation degradation

Why Control Critical Dimension (CD)?

- Small changes in CD distribution = Large $ values lost

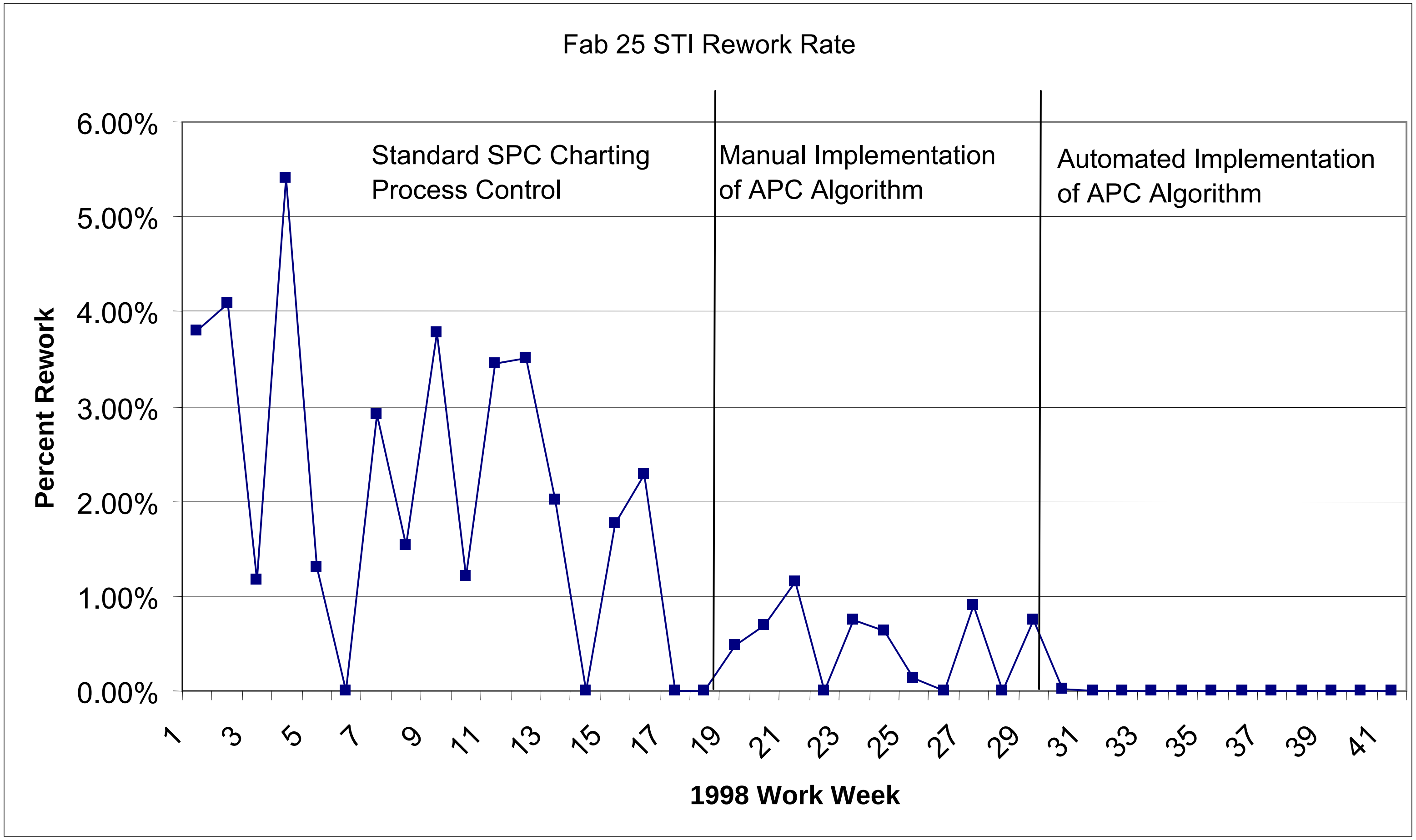


Results – Increased C_{pk}



Metric	Uncontrolled	Controlled	% Change
Mean Deviation From Target	**-0.201**	**0.045**	**-77%**
Standard Deviation	**0.254**	**0.188**	**-26%**
Cpk	**1.05**	**1.7**	**+62%**

Reduction in STI Rework with RtR



Batch Process Control and Profitability

- Reduced production time maximizes number of batches/shift
- Maximize product quality (without blending)
- Improve process performance using batch-to-batch control
- Adjust rapidly to changing market conditions

Benefits of APC (Semiconductor Industry)

- Improved process capability
  - minimize variability and maximize yield/quality
  - reduced misprocessing, which eliminates waste
- Increased profitability

Benefits of APC (Semiconductor Industry)

- Increased equipment availability and productivity
  - maintenance and qualifications scheduled more efficiently
  - reduced number of test wafers
- Decreased manufacturing cycle time
  - reduced setup/inspection/pilot cost or time
  - reduced cost of tool ownership

	Model-Based Optimization (MBO)	Model Predictive Control (MPC)
Goal or cost function	Maximize yield or minimize time	Minimize quadratic cost function (quality of control)
Main process type	Batch process	Continuous process
Model	Nonlinear	Linearized (LMPC) or nonlinear (NMPC)
Role of constraints	Ensure feasibility while optimizing objective	Avoid constraints by compromise between tracking of setpoint and input effort

Exceptions: MPC of batch processes, grade changes

Improved Batch Control Can Achieve Improved Manufacturability

At AMD (Semiconductors), APC

- Addresses small feature sizes
- Provides faster device performance with lower power
- Improves predictability and uniformity
- Reduces wafer cost and maximizes revenue

Business Drivers Since 1950

	1950 – 1970	1970 – 1980	1980 – 2000	2000 -
BD1 Meet customer specs	X	X	X	X
BD2 Maximize cost benefits	X	X	X	X
BD3 Minimize variability	X	X	X	X
BD4 Safety and environment			X	X
BD5 Asset utilization				X
BD6 Improve operability				X

Integration of Dynamic Optimization and Economics

- Backx: add sum of profit along a trajectory and a capital inventory term
- Determine optimal path to recover from disturbances
- Value of products varies with properties/customer specs
- A return to nonlinear optimal control! But with highly accurate models (DAEs)

Dynamic Real-Time Optimization

Dynamic Real-Time Optimization *Backx & Marquardt, 2000*

Profit = Value Product - Cost Energy - Cost Raw Materials-…

$$\min \sum_{k=1}^{N} (z(t_k) - z_k^{sp})^T \mathbf{Q}(z(t_k) - z_k^{sp}) \overbrace{- \text{Profit}(t_k)}$$

Minimize Transition & Maximize Profit

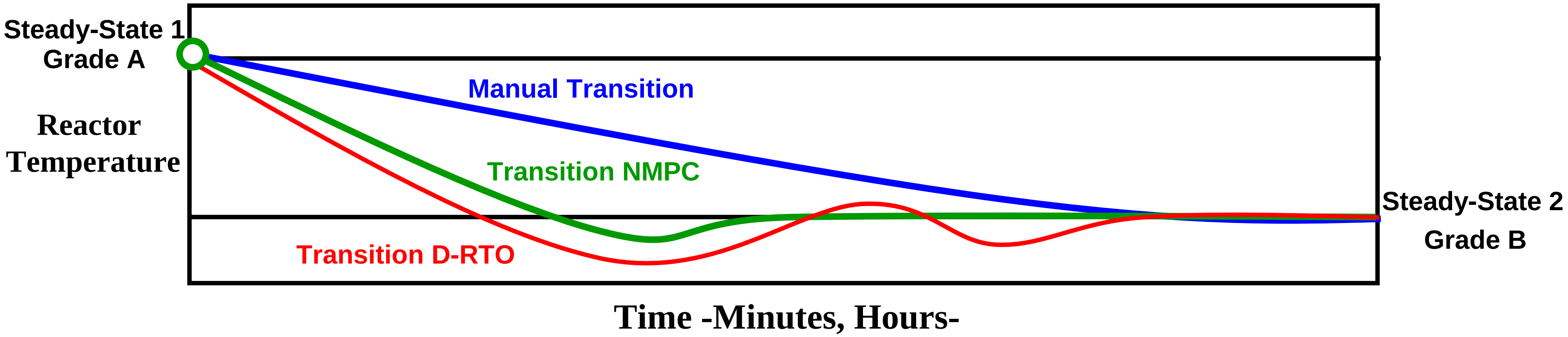
$$\begin{aligned} \frac{dz}{dt} &= \mathbf{F}\left(z(t), y(t), u(t)\right) \\ 0 &= \mathbf{G}\left(z(t), y(t), u(t)\right) \\ z(0) &= x(k) \end{aligned}$$

First-Principles Dynamic Model

Kinetics, Thermodynamics, Transport -DAEs-

Current State

- Used for Transitions (Polymerization, Start-Ups)

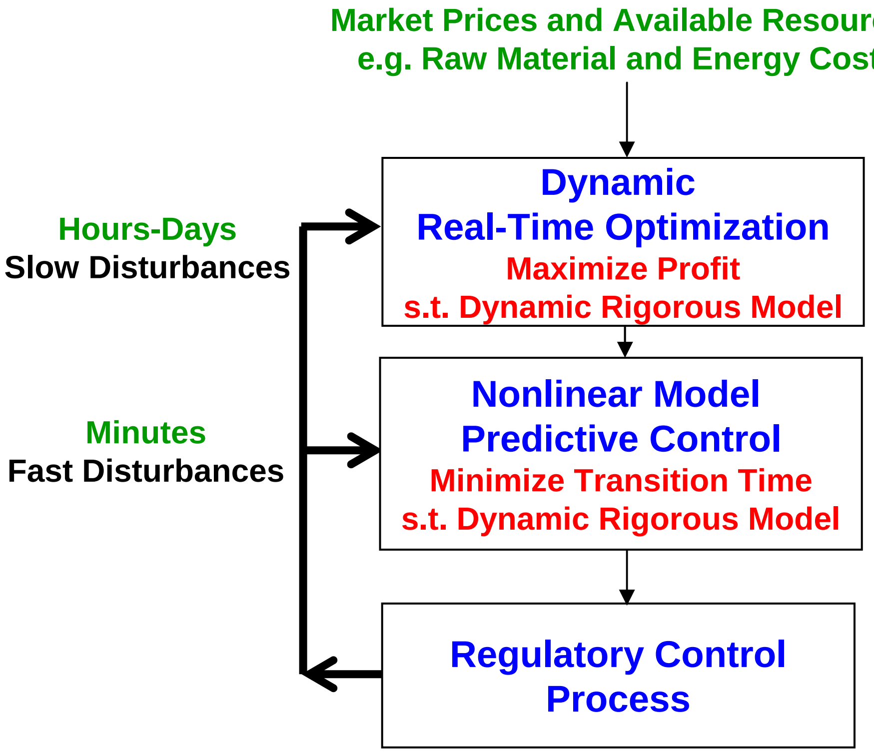


- NMPC Exploit Available Resources Efficiently (As in RTO)

- **- ABB Start-Up Power Plant (10% Energy Costs Reduction),** *Franke, et.al. 2006*
- **- Same Concept Used in Linear MPC by Honeywell**

Dynamic Real-Time Optimization

D-RTO Hierarchical Control *Kadam & Marquardt, 2007*



Market Prices and Available Resources
e.g. Raw Material and Energy Costs

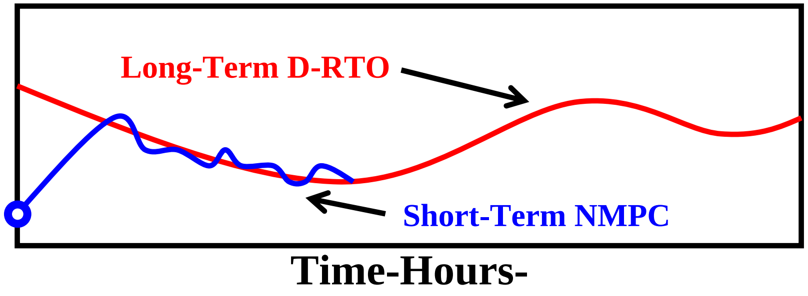
Hours-Days
Slow Disturbances

Dynamic
Real-Time Optimization
Maximize Profit
s.t. Dynamic Rigorous Model

Minutes
Fast Disturbances

Nonlinear Model
Predictive Control
Minimize Transition Time
s.t. Dynamic Rigorous Model

Regulatory Control
Process



- D-RTO/NMPC Hierarchy –Consistency in Decision-Making-
  - D-RTO in Hours, NMPC in Minutes (Not Applied in Continuous Processes)
  - Used -Required- In Batch Processes

- Open Issues:
  - Stability of Economics-Based Control
  - Handling Extremely Long Horizons (Days)
  - Justify Economic Advantage of D-RTO Over RTO

Does Controllability Equal Profitability?

- Batch vs. continuous processing
- New processing schemes (bio, nano)
- More detailed objective functions
- Nonlinear optimal control (redux)

Control: Dynamic Optimization

A vector of inputs $\mathbf{u}^{M}$ is found which minimizes performance index J subject to constraints on the inputs and outputs:

$$J = \sum_{j=1}^{P} \left\| \mathbf{e}^{y}_{k+j} \right\|^{q}_{\mathbf{Q}_j} + \sum_{j=0}^{M-1} \left\| \Delta \mathbf{u}_{k+j} \right\|^{q}_{\mathbf{S}_j} + \sum_{j=0}^{M-1} \left\| \mathbf{e}^{u}_{k+j} \right\|^{q}_{\mathbf{R}_j} + \left\| \mathbf{s} \right\|^{q}_{\mathbf{T}}$$

$$\mathbf{u}^{\mathbf{M}} = \left(\mathbf{u}_0^{T}, \mathbf{u}_1^{T}, \ldots \mathbf{u}_{M-1}^{T} \right)^{T}$$

$$\mathbf{x}_{k+1} = \mathbf{f}\left(\mathbf{x}_k, \mathbf{u}_k \right)$$

$$\mathbf{y}_{k+1} = \mathbf{g}\left(\mathbf{x}_{k+1} \right) + \mathbf{b}_k$$

$$\underline{\mathbf{y}} - \mathbf{s} \le \mathbf{y}_k \le \overline{\mathbf{y}} + \mathbf{s}$$

$$\underline{\mathbf{u}} \le \mathbf{u}_k \le \overline{\mathbf{u}}$$

$$\Delta \underline{\mathbf{u}} \le \Delta \mathbf{u}_k \le \Delta \overline{\mathbf{u}}$$

$$\mathbf{s} \ge \mathbf{0}$$

Additional Reading

- Edgar, T.F., *Computers and Chemical Engineering*, Vol. 29, 41 (2004).
- Peng, J.K. et al., *IEC Research*, Vol. 44, 7816 (2005).
- Bauer, M. and Craig, I.K., *J. Process Control*, Vol. 18, 2 (2008).
- Zavala, V., presentation at University of Texas, February, 2008.
- Kadam, J. and Marquardt, V., in Lecture Notes in Control and Information Sciences, 2007.