Control-Oriented Approaches to Inventory Management in Semiconductor Manufacturing Supply Chains

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Motivation

- Billions of dollars in potential savings in the semiconductor industry alone by eliminating supply chain inefficiencies (PricewaterhouseCoopers, 2000)
- Increasing realization that inventory management is a control problem, and not just an optimization/OR problem.
- Previous work (Braun *et al.*, (2001, 2002)) presented a partially decentralized MPC-based approach for a three echelon, six-node problem involving assembly/test, distribution, and retailing.
- Need to "reflect" on issues of controller design and structure. The IMC design procedure is used to build insight, while MPC represents an appropriate implementation environment.

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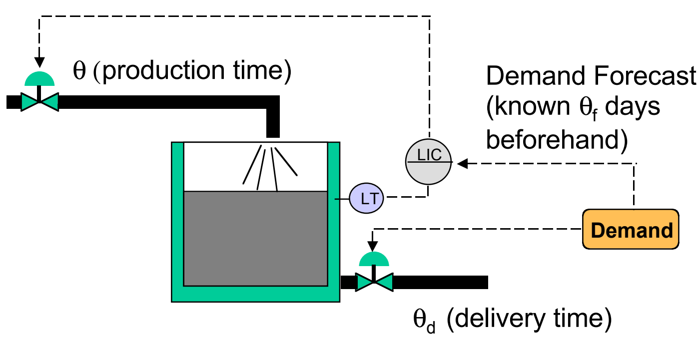
Presentation Outline

- Motivation
- Internal Model Control (IMC)-based decision policies for a Single Node Inventory System
  - Demand "Pull" Control Structure
  - Demand "Push" Control Structure
- IMC-based Analysis of a Two Node Problem
  - Decentralized (with Demand "Pull")
  - Decentralized (with Demand "Push")
  - Centralized (with Demand "Push")
- Application of Model Predictive Control to the Two Node Problem
- Extensions, Summary and Conclusions

Single Node Inventory Control Problem - Demand "Pull" Structure



Meet demand (with forecast given θ_f days beforehand) for a node with θ day production (or order fulfillment) time and θ_d delivery time.

Single Node Equations (Laplace Domain)

$$
\begin{aligned}
y_1(s) &= \frac{e^{-\theta s}}{s}\, u(s) - \frac{1}{s}\, d(s) \\
y_2(s) &= e^{-\theta_d s}\, d(s) \\
&= e^{-\theta_f s}\, \hat{d}(s) + e^{-\theta_d s}\, n(s) \\
d(s) &= e^{-(\theta_f - \theta_d)s}\, \hat{d}(s) + n(s)
\end{aligned}
$$

$y_1(s) \equiv$ Inventory (Net Stock)
$y_2(s) \equiv$ Supply to downstream node (received by customer)
$u(s) \equiv$ Starts (or Orders)
$\hat{d}(s) \equiv$ Demand Forecast
$d(s) \equiv$ Actual Demand (ordered by customer)
$n(s) \equiv$ Demand Forecast Error
$\theta \equiv$ Production (or Order Fulfillment) Time
$\theta_d \equiv$ Delivery Time
$\theta_f \equiv$ Forecast Time Horizon

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Internal Model Control (IMC)

- The IMC (or *Q*-parametrization) structure is an alternate yet equivalent means of representing a classical feedback-feedforward structure.
- The IMC design procedure is a convenient two-step procedure for designing *Q*-parametrized control systems.

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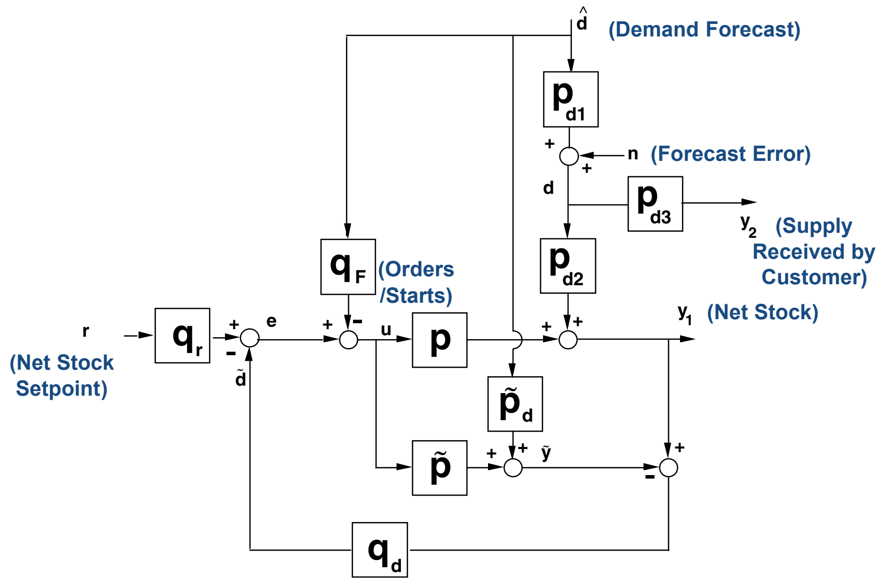
Three-Degree-of -Freedom FB/FF IMC structure



Internal Model Control Design Procedure

- Step 1 (*Nominal Performance*): Obtain H_2 optimal q's
  - Must specify a form for the external input (e.g, step, ramp).
  - Closed-form solutions can be obtained

  The controllers generated per step 1 are *stable* and *causal*.

- Step 2 (*Robust Stability and Performance*):

  Augment the IMC controller(s) from step 1 with a filter(s) (*f(s))*; the filter(s) are specified to insure that the q's are *proper* and that the control system demonstrates stability and performance in the face of uncertainty.

1. *Design for nominal optimal performance:* $\tilde{q}_r(s)$, $\tilde{q}_d(s)$, and $\tilde{q}_F(s)$ are designed for H_2-optimal setpoint tracking, unmeasured disturbance rejection, and measured disturbance rejection, respectively.

$$\min_{\tilde{q}_r} \| (1 - \tilde{p}\tilde{q}_r)\ r\|_2$$

$$\min_{\tilde{q}_d} \| (1 - \tilde{p}\tilde{q}_d)\, p_{d_2}\ n)\|_2$$

$$\min_{\tilde{q}_F} \|(\tilde{p}_d - \tilde{p}\tilde{q}_F) p_{d_1} p_{d_2} \hat{d}\|_2$$

subject to the requirement that $\tilde{q}_r(s)$, $\tilde{q}_d(s)$ and $\tilde{q}_F(s)$ be stable and causal.

2. *Design for robust stability and performance:* In this step $\tilde{q}_r(s)$, $\tilde{q}_d(s)$ and $\tilde{q}_F(s)$ are augmented with low-pass filters which can be tuned to detune the nominal performance (e.g., reduce aggressive manipulated variable action associated with the optimal controller per Step 1) or to satisfy a robust performance objective. The final controllers obtained from this step are

$$q_r(s) = \tilde{q}_r(s) f_r(s) \qquad q_d(s) = \tilde{q}_d(s) f_d(s) \qquad q_F(s) = \tilde{q}_F(s) f_F(s)$$

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IMC Controllers, Single Node Inventory Problem

$$p(s) = \frac{e^{-\theta s}}{s} \qquad p_{d_1} = e^{-(\theta_f - \theta_d)s} \qquad p_{d_2} = -\frac{1}{s} \qquad \hat{d}, r, n = \frac{1}{s}$$

1. Setpoint Tracking.

$$q_r(s) = \frac{s}{(\lambda_r s + 1)^{n_r}} \qquad \lambda_r \geq 0 \quad n_r \geq 1$$

2. Unmeasured Disturbance Rejection.

$$q_d(s) = \left(s(\theta s + 1) \frac{(n_d \lambda_d s + 1)}{(\lambda_d s + 1)^{n_d}} \right) \qquad \lambda_d \geq 0 \quad n_d \geq 3$$

3. Measured Disturbance Rejection.

$$q_F(s) = \begin{cases} e^{-(\theta_f - \theta_d - \theta)s} & \text{if } \theta_f \geq (\theta + \theta_d) \\ (\theta + \theta_d - \theta_f)s + 1 & \text{if } \theta_f < (\theta + \theta_d) \end{cases}$$

Filtering could be used with the measured disturbance IMC controller, but is not needed for physical realizability when $\theta_f \geq (\theta + \theta_d)$.

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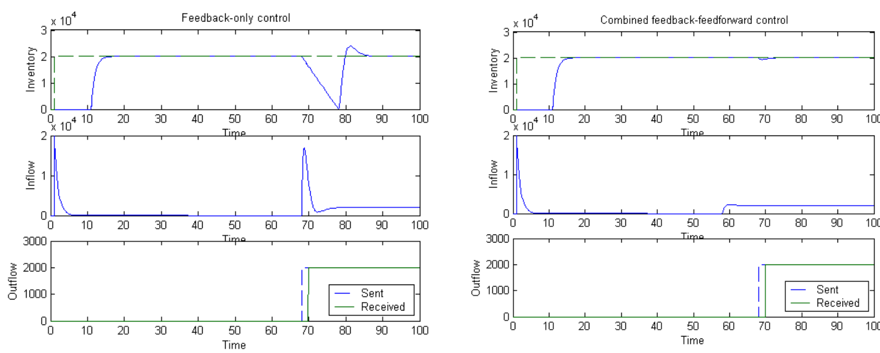
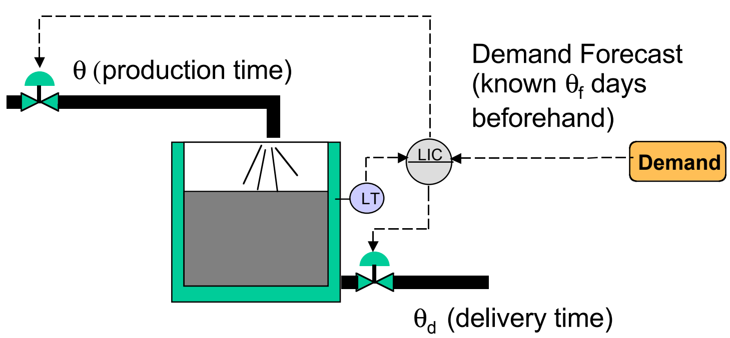
Three Degree of Freedom IMC Demand "Pull" Results

Feedback-only | Combined FB/FF



$\theta_f = 20,\ \theta = 10,\ \theta_d = 2,\ \lambda_f = 1,\ \lambda_r = 1,\ \lambda_d = 1$

Single Node Inventory Control Problem Demand "Push"



Track demand (with forecast given θ_f days beforehand) for a node with θ day production (or order fulfillment) time and θ_d delivery time. Controller now manipulates *both* the starts/orders and the stream out release to customer.

IMC Design: Decoupled Deadtime Compensation

Theorem. The diagonal $P_+^{decoupled}$ matrix such that the multivariable IMC controller $\tilde{Q}(s) = P^{-1}(s)P_+^{decoupled}(s)$ is realizable has the form

$$P_+^{decoupled} = \mathrm{diag}(r_{ii}, \cdots r_{jj}, \cdots r_{nn})$$

where

$$r_{jj} = e^{-s(\max_i \max(0,(\hat{q}_{ij}-\hat{p}_{ij}))}$$

and $\hat{p}_{ij}$ is the minimum delay in the numerator of element ij of P^{-1}, $\hat{q}_{ij}$ is the minimum delay in the denominator of element ij of P^{-1}.

Holt, B.R. and M. Morari, "Design of resilient process plants: the effect of deadtime on dynamic resilience," ***Chem. Eng. Science*****, 40, 1229, (1985)**

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Single Node Decoupled Deadtime Compensation

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = \begin{bmatrix} \frac{e^{-\theta s}}{s} & -\frac{1}{s} \\ 0 & e^{-\theta_d s} \end{bmatrix} \begin{bmatrix} u(s) \\ d(s) \end{bmatrix} + \begin{bmatrix} -\frac{1}{s} \\ e^{-\theta_d s} \end{bmatrix} n(s)$$

$$y(s) = P(s)\, u'(s) + P_d(s)\, n(s)$$

$$P_+^{decoupled}(s) = \begin{bmatrix} e^{-\theta s} & 0 \\ 0 & e^{-(\theta+\theta_d)s} \end{bmatrix} \qquad \tilde{Q}(s) = \begin{bmatrix} s & 1 \\ 0 & e^{-\theta s} \end{bmatrix}$$

$$Q(s) = \tilde{Q}(s)F(s) = \begin{bmatrix} \frac{s}{\lambda_1 s+1} & \frac{1}{\lambda_2 s+1} \\ 0 & \frac{e^{-\theta s}}{\lambda_2 s+1} \end{bmatrix}$$

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = \begin{bmatrix} \frac{e^{-\theta s}}{\lambda_1 s+1} & 0 \\ 0 & \frac{e^{-(\theta+\theta_d)s}}{\lambda_2 s+1} \end{bmatrix} \begin{bmatrix} r_1(s) \\ r_2(s) \end{bmatrix}$$

r_1 and r_2 are the net stock and demand setpoints, respectively.

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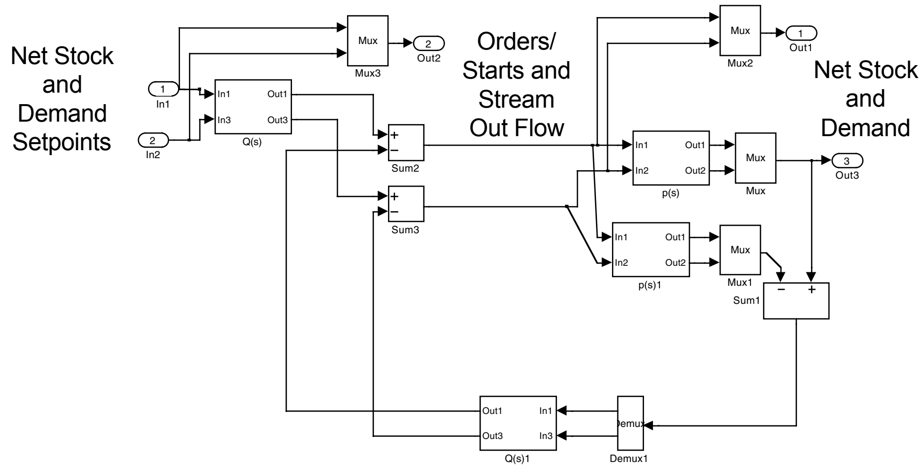
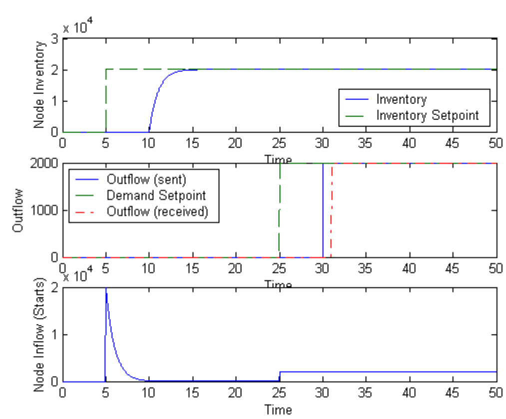
Decoupled IMC implementation

(two degrees of freedom but 4 adjustable parameters)



Decoupled IMC Demand "Push" Results



$\theta = 5, \theta_d = 2, \lambda_1 = 1, \lambda_2 = 0$

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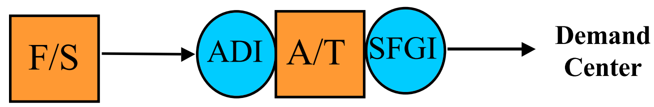
Two Node Example



○ =Inventory Holding ▭ =Mfg Node ⟶ =Transport Link

F/S: Fabrication/Sort Facility
A/T: Assembly/Test Facility
ADI: Assembly-die Inventory
SFGI: Semi-finished goods inventory

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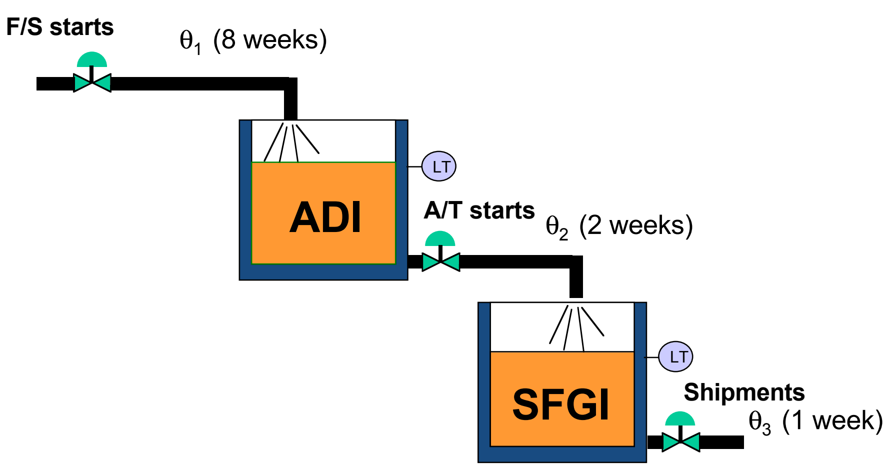
"Fluid" Analogy to the Two Node Network



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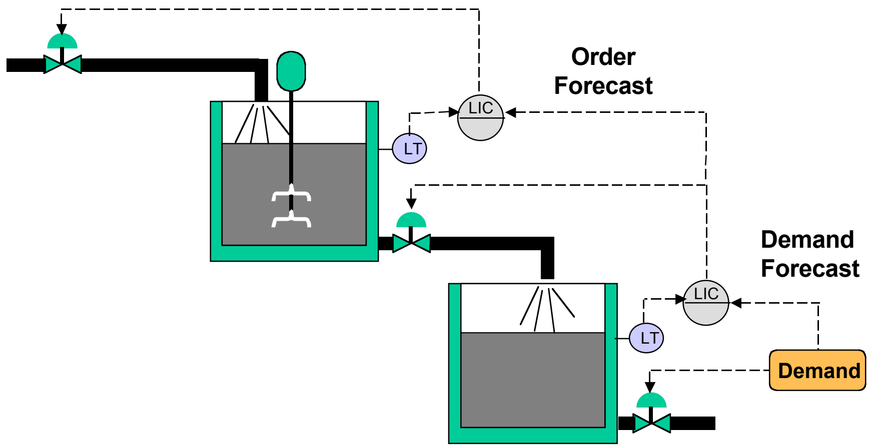
Two Node Inventory Control Problem
Decentralized Demand "Pull" Structure



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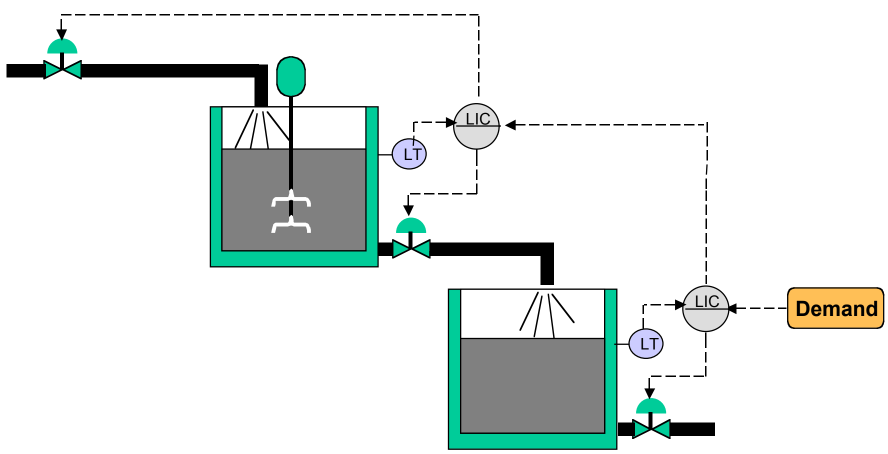
Two Node Inventory Control Problem
Decentralized Demand "Push" Structure



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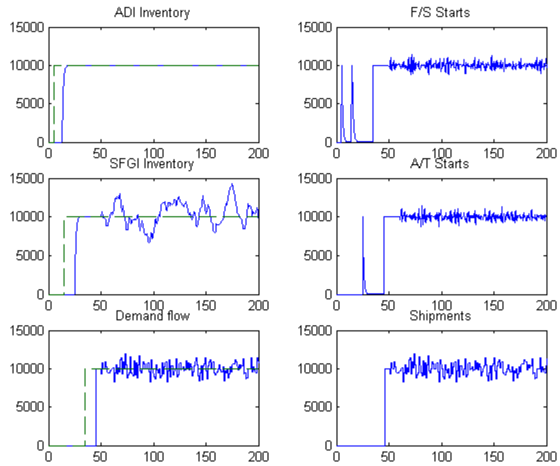
Decentralized Demand "Push" Results



$\lambda_1 = 1$, $\lambda_2 = 0$ for each node

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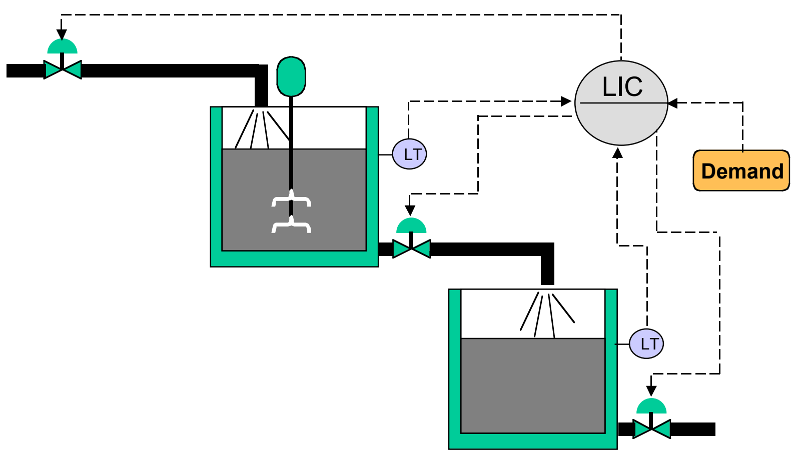
Two Node Inventory Control Problem Centralized Demand "Push" Structure



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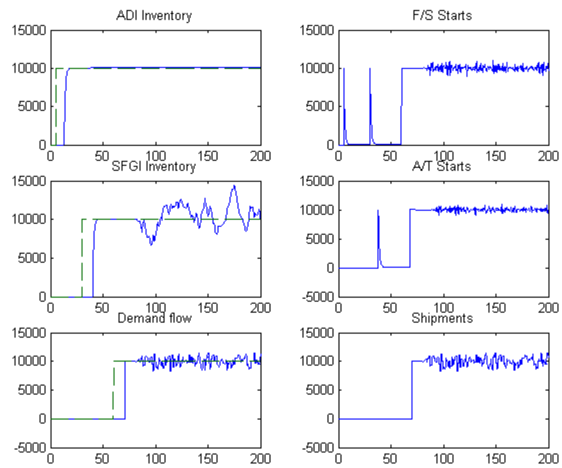
Centralized Demand "Push" Results



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MPC Appeal for Dynamic Inventory Management in Supply Chains

- As an *optimizer*, an MPC-based algorithm can minimize or maximize an objective function that represents a suitable measure for supply chain performance.

- As a *controller*, an MPC algorithm can be tuned to achieve stability, robustness, and performance in the presence of plant/model mismatch, failures and disturbances which affect the system.

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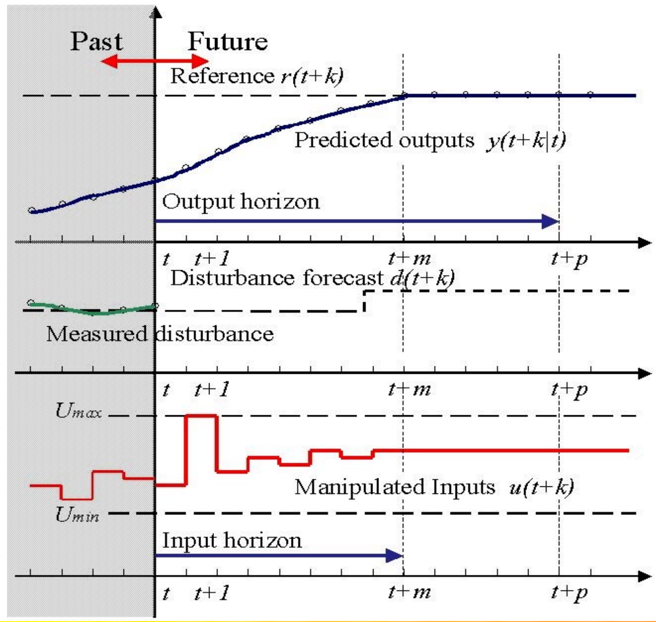

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The MPC optimization problem can be written

$$\min_{\Delta u(k|k) \ldots \Delta u(k+m-1|k)} J$$

$$J = \sum_{\ell=1}^{p} Q_e(\ell)(\hat{y}(k+\ell|k) - r(k+\ell))^2$$ <- Satisfy demand

$$+ \sum_{\ell=1}^{m} Q_{\Delta u}(\ell)(\Delta u(k+\ell-1|k))^2$$ <- Penalizes changes in order quantities (i.e. *move suppression*)

$$+ \sum_{\ell=1}^{m} Q_u(\ell)(u(k+\ell-1|k) - u_{target}(k+\ell-1|k))^2$$

s.t.

$$u_{min} \leq u(k+\ell-1|k) \leq u_{max},$$
$$\Delta u_{min} \leq \Delta u(k+\ell-1|k) \leq \Delta u_{min},$$
$$y_{min} \leq y(k+\ell-1|k) \leq y_{max},$$

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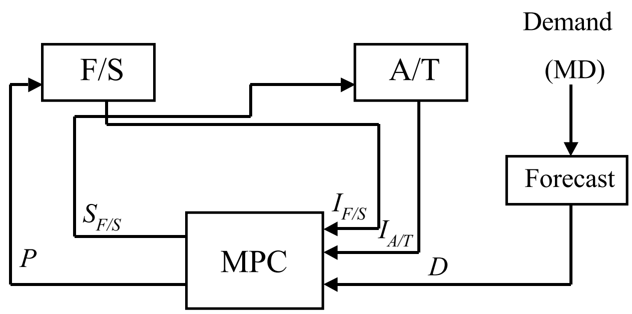
Centralized Demand "Pull" Structure

Information flow



Measured disturbance: D
Controlled Variables: $I_{F/S}$, $I_{A/T}$
Manipulated Variables: $S_{F/S}$, P

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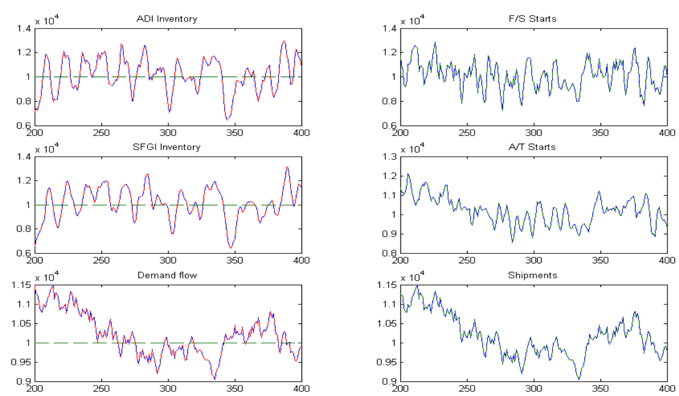
Centralized Demand "Pull" Structure with Autoregressive Demand Variability

Output Weights=[1 1]; Move Suppression=[1 1]



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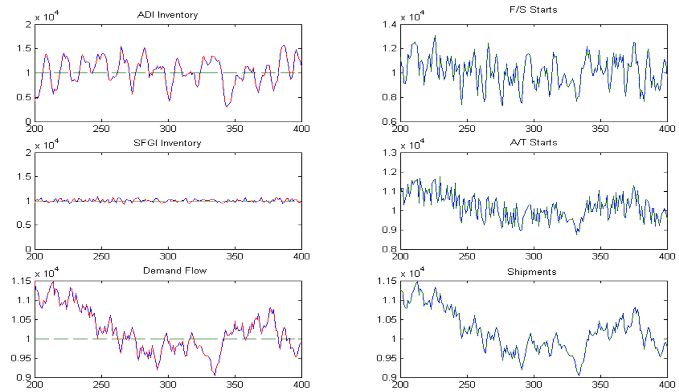
Centralized Demand "Pull" Structure with Autoregressive Demand Variability

Output Weights=[1 100]; Move Suppression =[1 1]



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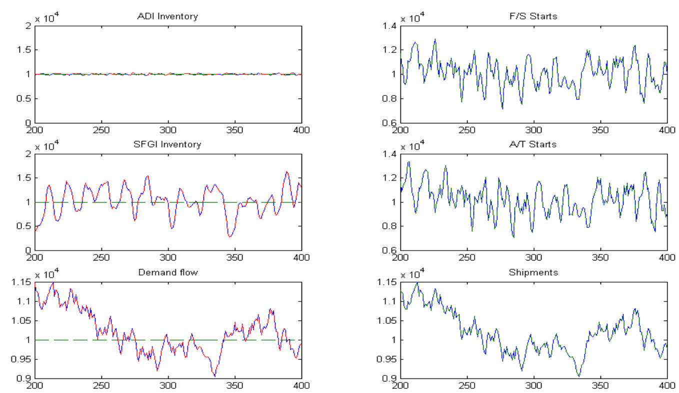
Centralized Demand "Pull" Structure with Autoregressive Demand Variability

Output Weights=[100 1]; Move Suppression =[1 1]



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RMS Error Comparison

Output Weights	ADI	SFGI
Centralized:[1 1]	1013.3	968.6
Centralized:[1 100]	1982.6	221.7234
Centralized:[100 1]	91.6364	2035.4

Output weights can be used to shift variability between inventories, as desired by the enterprise!

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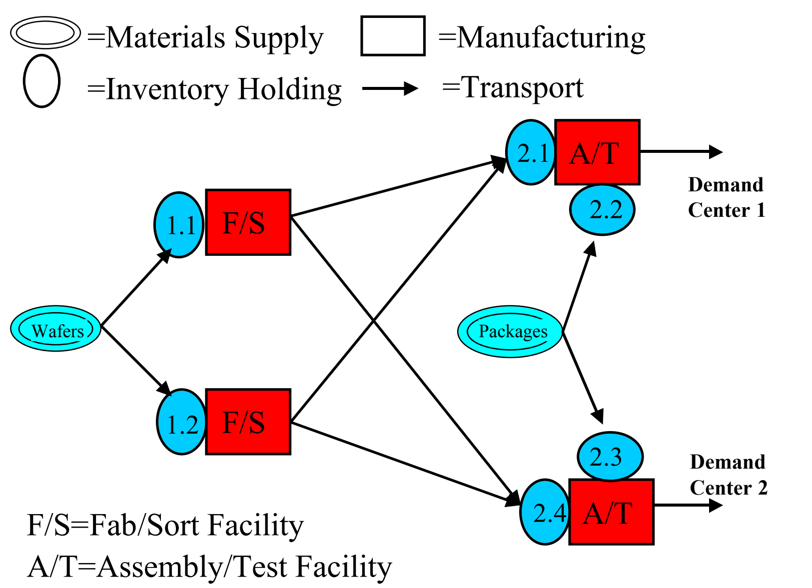

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Summary and Conclusions

- Supply chains (demand networks, value chains) are dynamical systems whose efficient operation merits a control-oriented approach
- The IMC design procedure provides important insights into controller structure and tuning.
- MPC offers a powerful implementation environment that has the potential for good performance in uncertain, noisy environments.

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