# Optimal dynamic operation of chemical processes: Assessment of the last 20 years and current research opportunities

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# Outline

1. The last 20 years — what tools have researchers developed
2. Industrial impact of these ideas
3. Have all the questions been answered?
   - Control of large-scale systems
   - Optimizing economics
4. Conclusions and future outlook

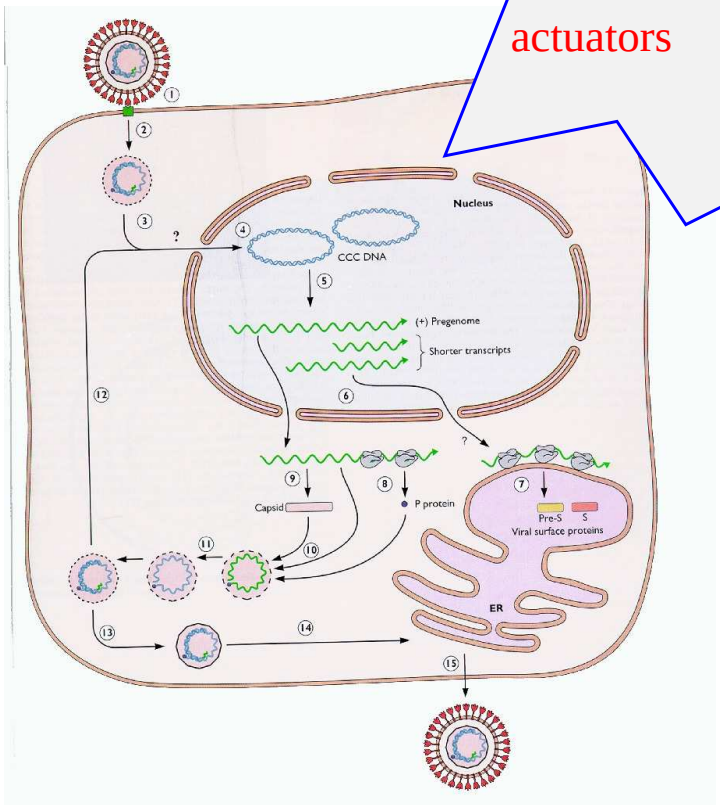
# The power of abstraction

process

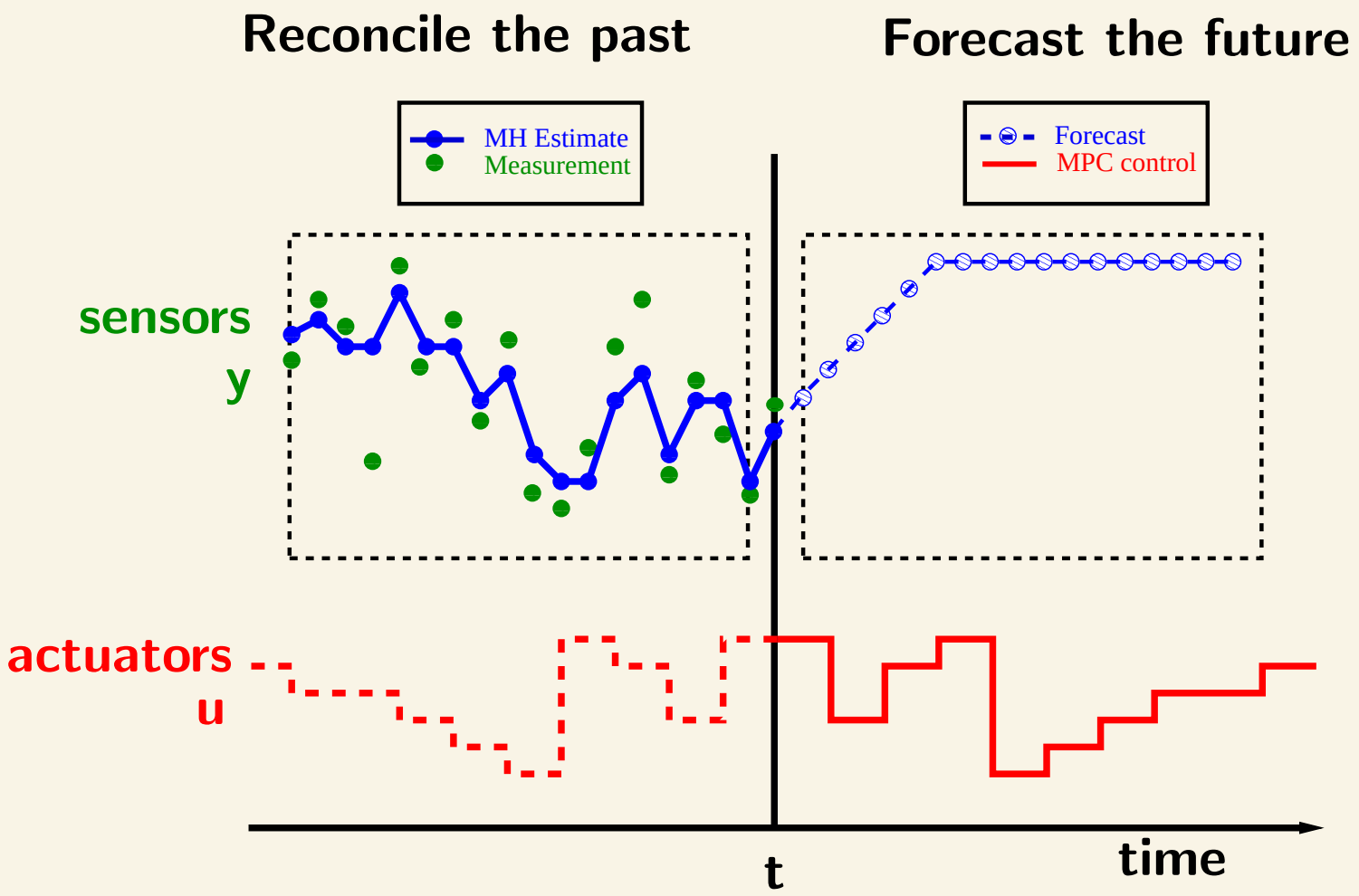
$$\frac{dx}{dt} = f(x, u)$$

$$y = g(x, u)$$

actuators sensors

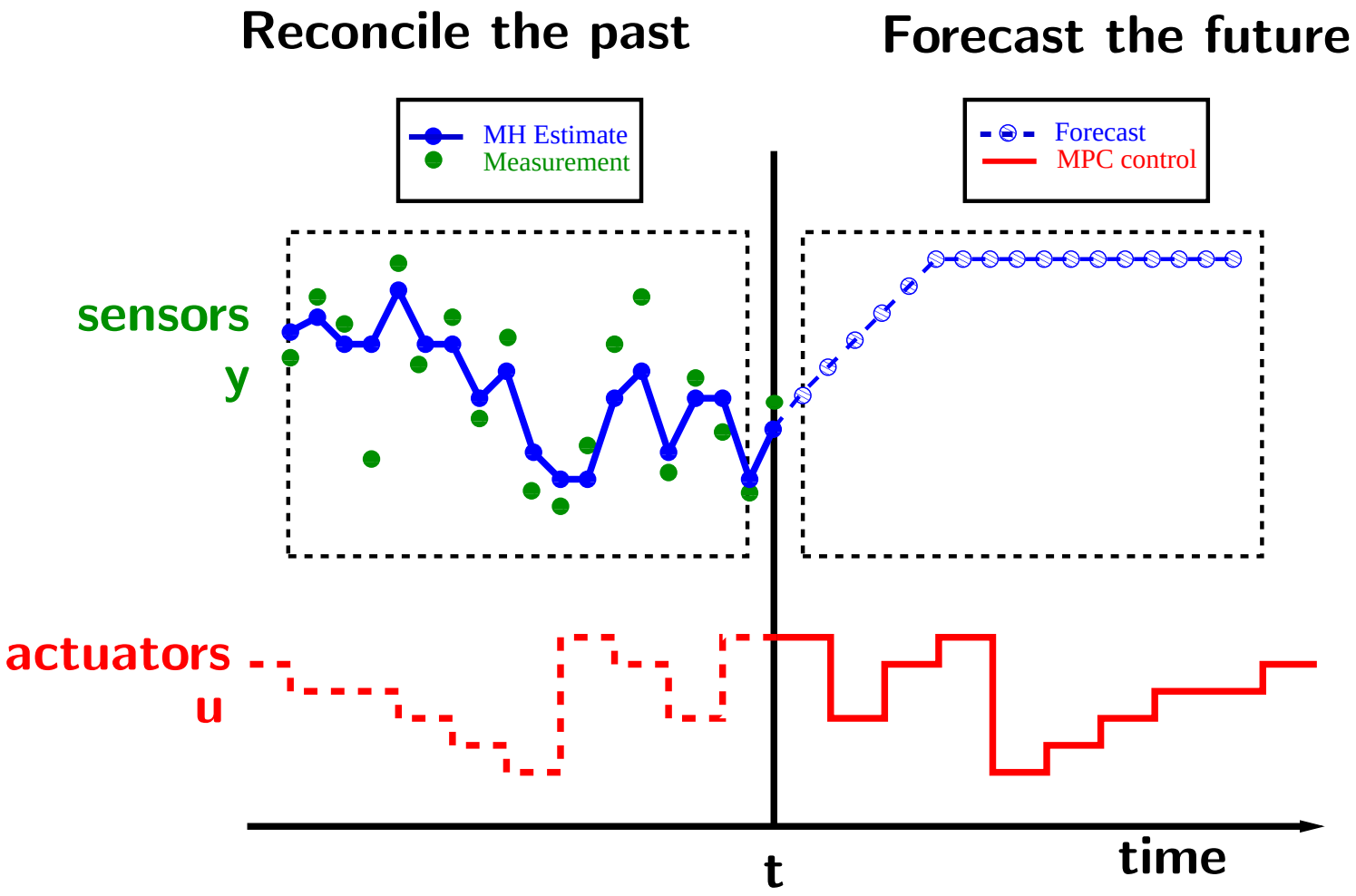


# The model predictive control framework



# Predictive control

The future influences the present just as much as the past does.



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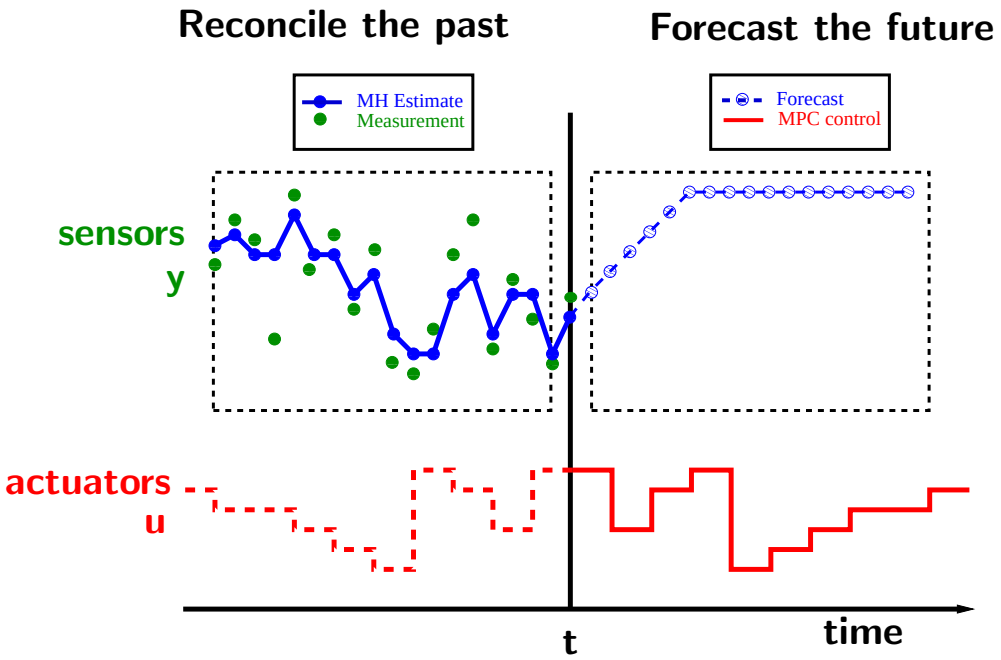



$$\min_{u(t)} \int_0^T |y_{sp} - g(x,u)|_Q^2 + |u_{sp} - u|_R^2 \, dt$$

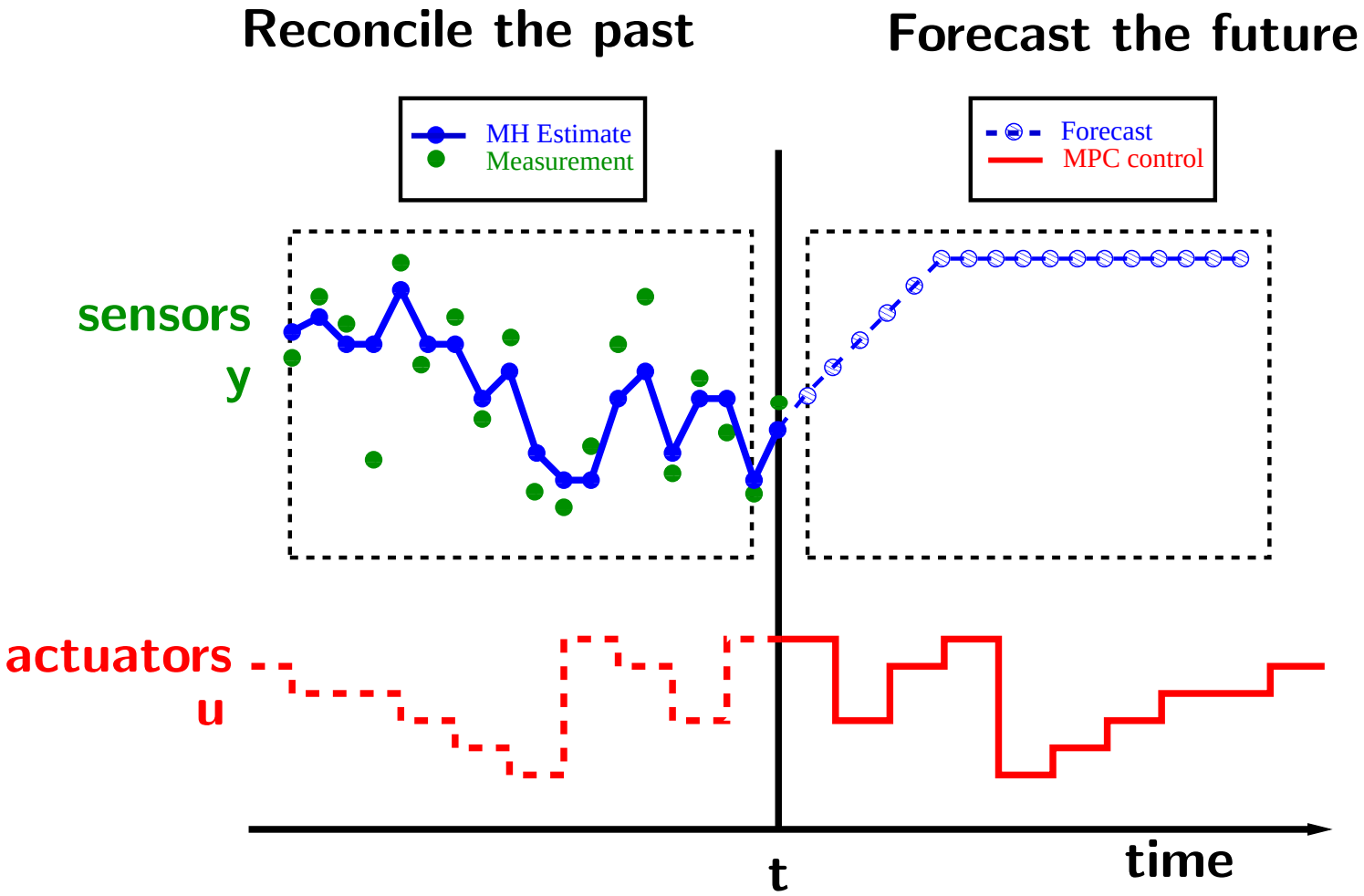
$$\dot{x} = f(x,u)$$

$$x(0) = x_0 \quad \text{(given)}$$

$$y = g(x,u)$$

# State estimation

When I want to understand what is happening today or try to decide what will happen tomorrow, I look back.



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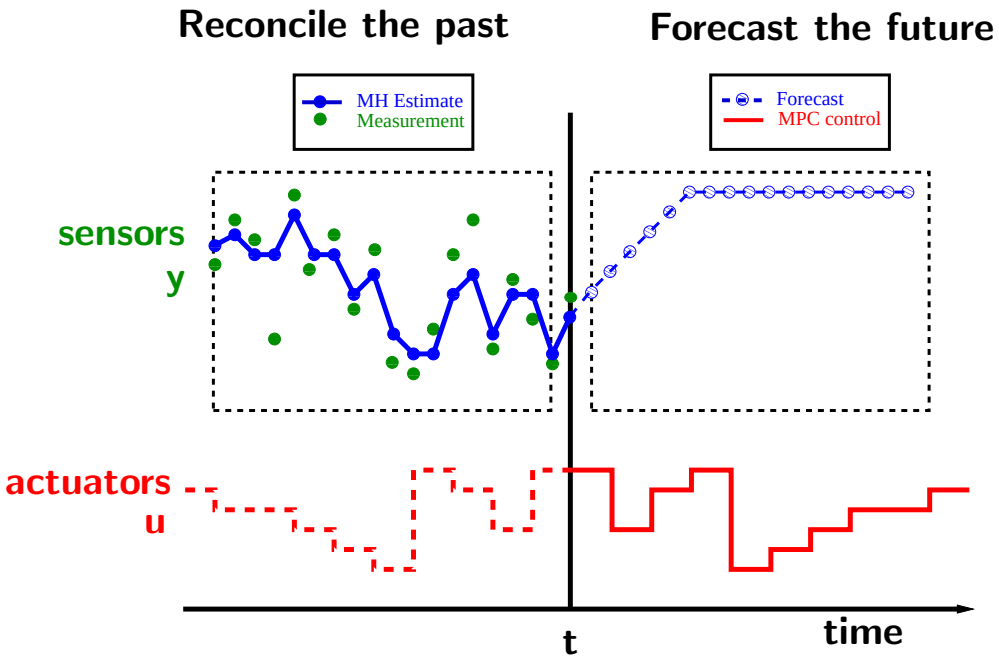


$$\min_{x_0, w(t)} \int_{-T}^{0} |y - g(x,u)|_R^2 + |\dot{x} - f(x,u)|_Q^2 \, dt$$

$$\dot{x} = f(x,u) + w \quad \text{(process noise)}$$

$$y = g(x,u) + v \quad \text{(measurement noise)}$$

# Feedback

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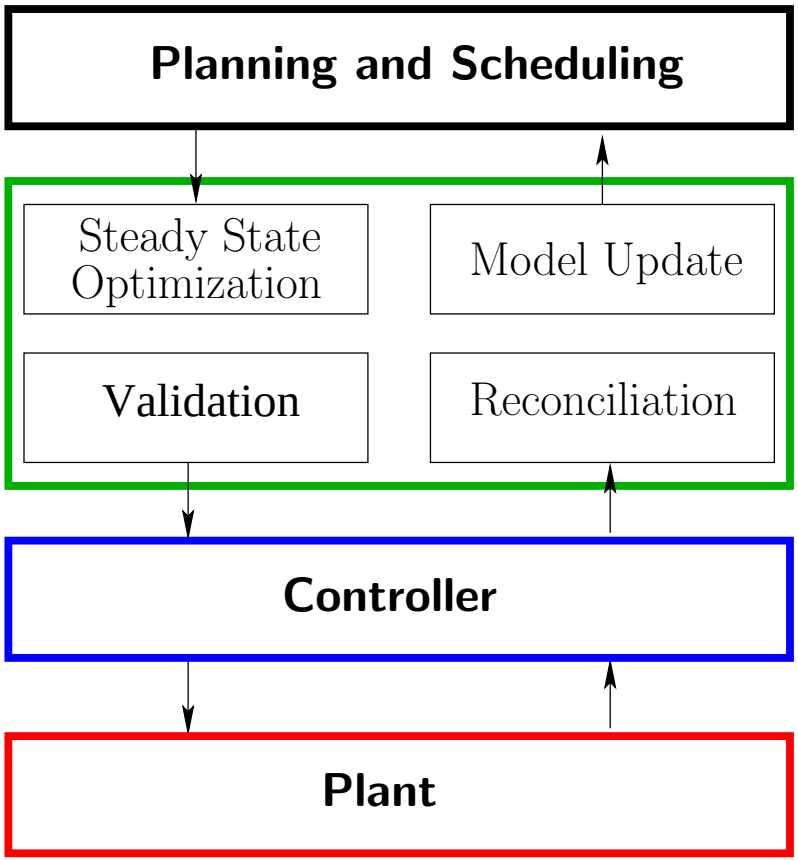
*Everything has been thought of before, but the problem is to think of it again.*

*— Goethe*

# Industrial practice of MPC




Two layer structure

- Steady-state layer
  - RTO optimizes steady state model
  - Optimal setpoints passed to dynamic layer

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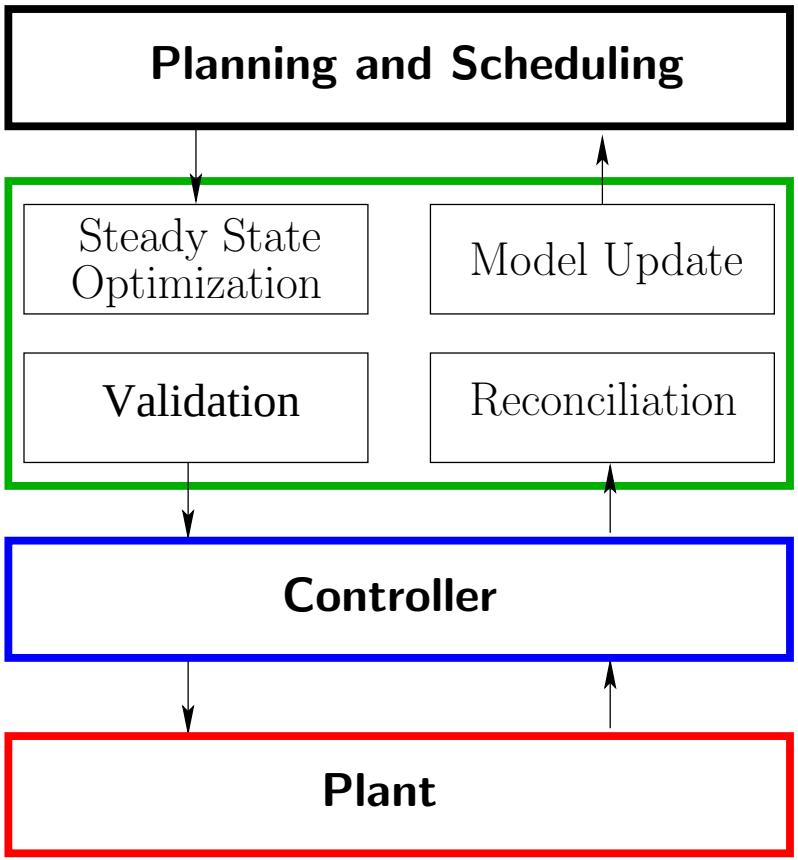


Two layer structure

- Steady-state layer
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  - Optimal setpoints passed to dynamic layer
- Dynamic layer
  - Controller tracks the setpoints
  - Linear MPC (replaces multiloop PID)

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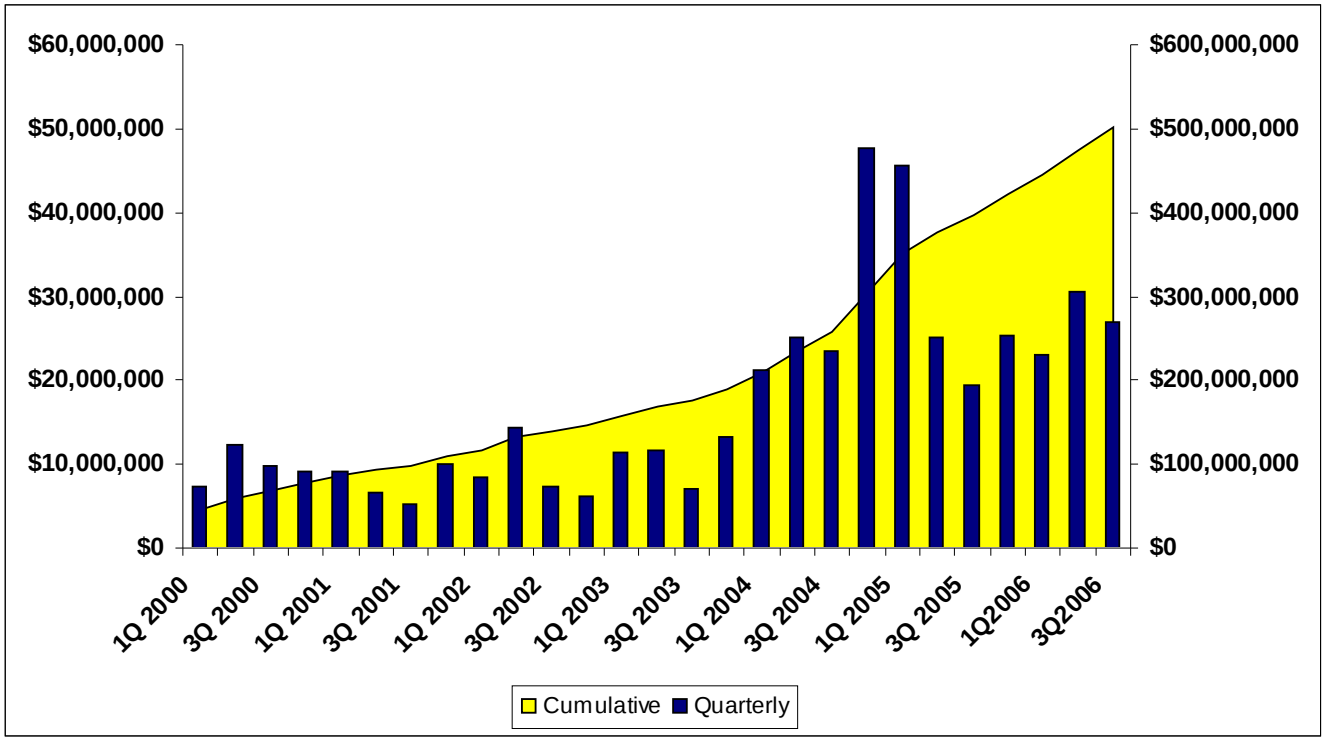
- 16 M$/year increased profit (2008)

# Impact for 13 ethylene plants (Starks and Arrieta, 2007)



## We're Doing it For the Money

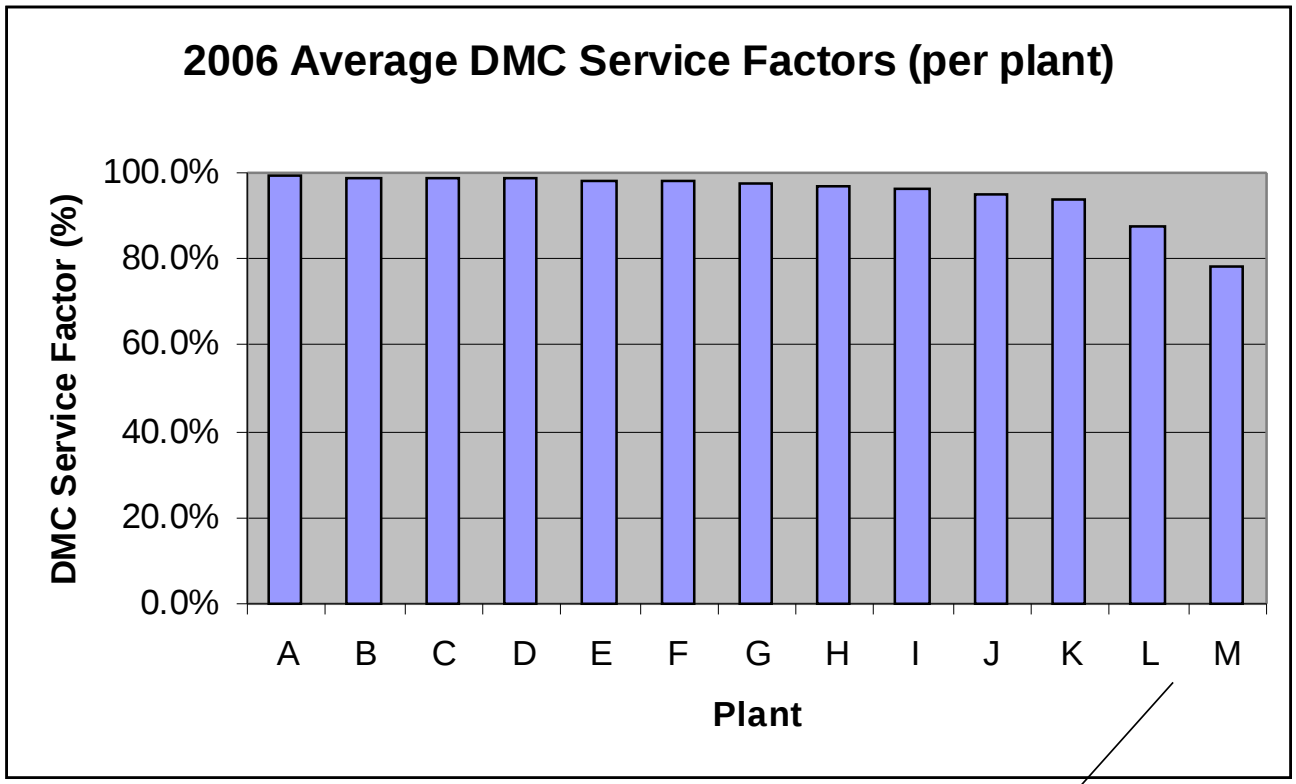



Advanced Control & Optimization

# Maintaining technology (Starks and Arrieta, 2007)



## Challenges (continued 1)




Plants L & M experienced APC personnel changes

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# Broader industrial impact (Qin and Badgwell, 2003)

| Area | Aspen Technology | Honeywell Hi-Spec | Adersa | PCL | MDC | Total |
|---|---|---|---|---|---|---|
| Refining | 1200 | 480 | 280 | 25 | | 1985 |
| Petrochemicals | 450 | 80 | - | 20 | | 550 |
| Chemicals | 100 | 20 | 3 | 21 | | 144 |
| Pulp and Paper | 18 | 50 | - | - | | 68 |
| Air & Gas | - | 10 | - | - | | 10 |
| Utility | - | 10 | - | 4 | | 14 |
| Mining/Metallurgy | 8 | 6 | 7 | 16 | | 37 |
| Food Processing | - | - | 41 | 10 | | 51 |
| Polymer | 17 | - | - | - | | 17 |
| Furnaces | - | - | 42 | 3 | | 45 |
| Aerospace/Defense | - | - | 13 | - | | 13 |
| Automotive | - | - | 7 | - | | 7 |
| Unclassified | 40 | 40 | 1045 | 26 | 450 | 1601 |
| Total | 1833 | 696 | 1438 | 125 | 450 | 4542 |
| First App. | DMC:1985<br>IDCOM-M:1987<br>OPC:1987 | PCT:1984<br>RMPCT:1991 | IDCOM:1973<br>HIECON:1986 | PCL:<br>1984 | SMOC:<br>1988 | |
| Largest App | 603x283 | 225x85 | - | 31x12 | - | |

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- Is the technology mature?
- Is the theory complete?
- Do we have tools to decompose *large-scale systems* into manageable problems?
- Do we have tools to optimize dynamic *economic* operation?
- Have control researchers stopped working on *linear systems?*

# Has the application base stopped growing?

**European Commission**

**DG information Society & Media**

**Monitoring and control: today's market, its evolution till 2020 and the impact of ICT on these**

Workshop:

9th of October 2008

*A report & a presentation prepared by:*

DECISION Etudes & Conseil RPA

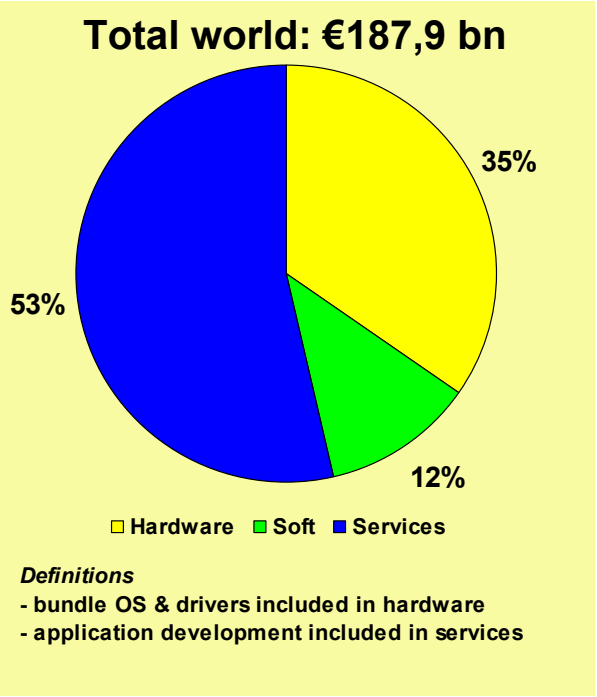
*Available for download: http://www.decision.eu/smart2007.htm*

# Has the application base stopped growing?



## 3. Worldwide Monitoring & Control Market

- The worldwide market for Monitoring & Control products and solutions is around 188 billion euros.
- This represents 8% of total ICT expenditures worldwide.
- In the field of ICT, this is comparable to:
  - the whole semiconductor industry world revenues;
  - twice the world mobile phone manufacturers revenues.
- **Services**, with **more than 50% of the market value**, have the biggest share.
- The 3 larger sub markets represent together over 100 billion euros, namely:
  - integration, installation & training services with 38 billion euros;
  - control hardware with 36 billion euros;
  - maintenance, repair & overall services with 30 billion euros.
- The 3 larger application markets are Vehicles, Process and Manufacturing industries.
- **Europe represents 32 % of the world total market value.**



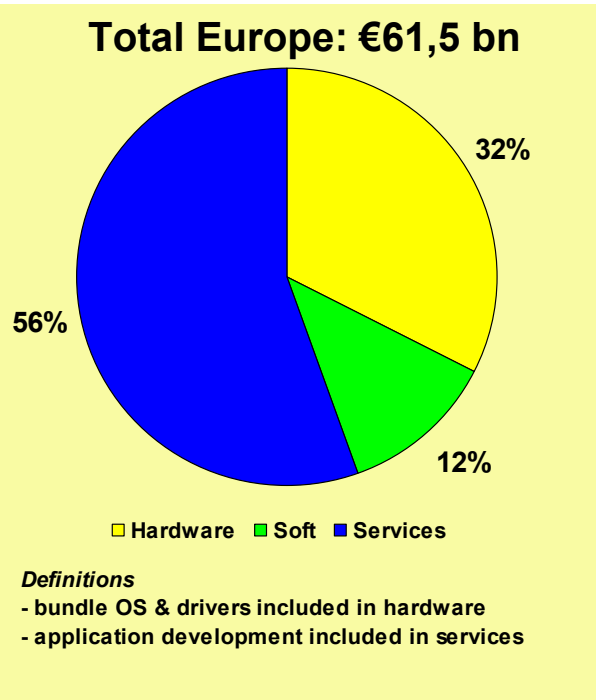
# Has the application base stopped growing?



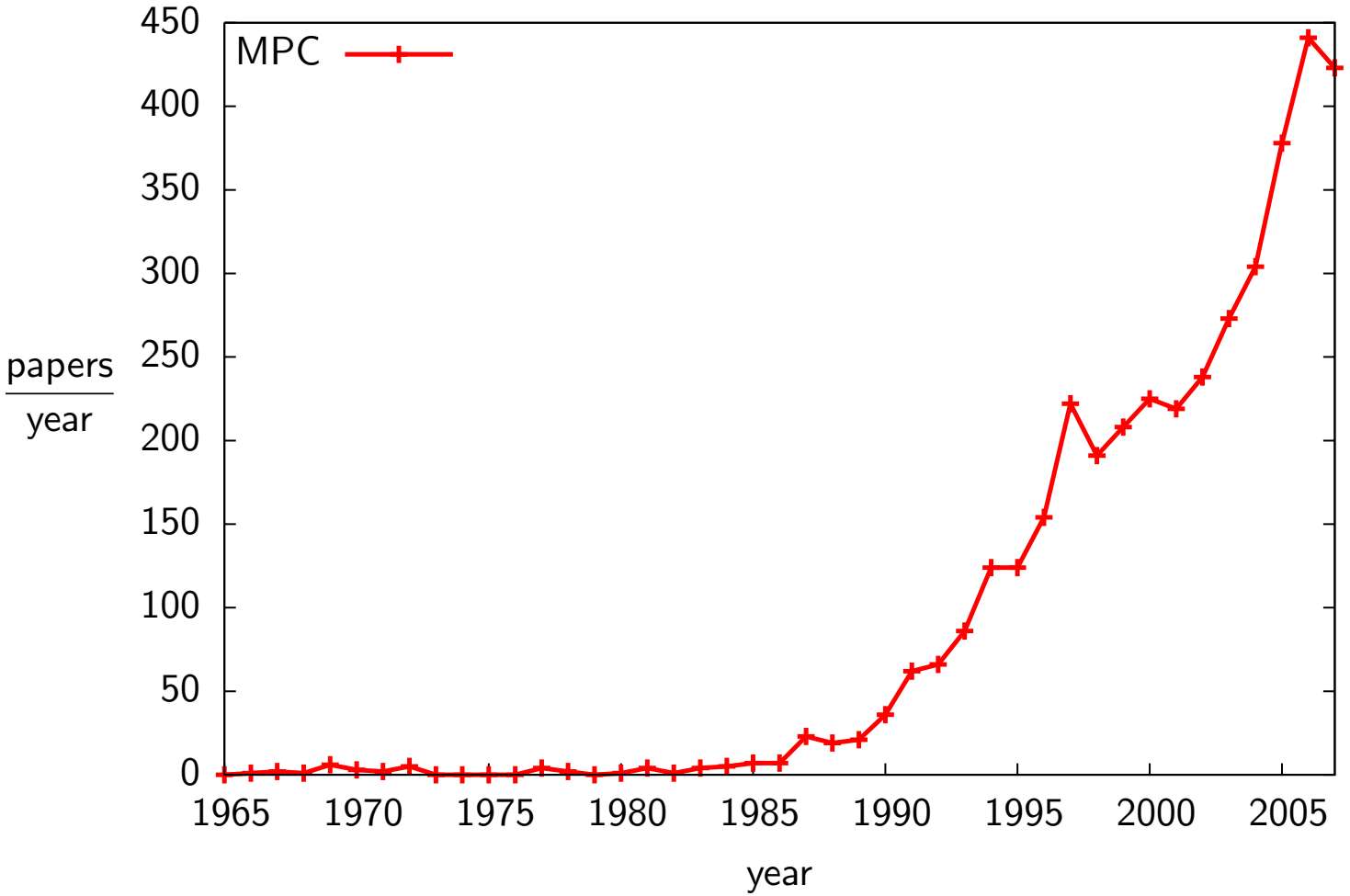
## European Monitoring & Control Market

- The European M&C market is around 62 billion euros:
  - In relative terms, compared to the European economy, this is more than 1 day of the total EU-27 yearly Gross Domestic Product.
  - Compared to services businesses, it represents 8% of the EU-27 Telecoms & Transport sector gross value-added.
  - Compared to total employment inside EU-27 and with a value added share of 70%, it is worth 750 000 jobs.

- Structural European details are quite comparable to Worldwide ones:
  - More than 50% of services.
  - 3 same major application markets.
  - 3 same majors product and solutions sub segments.



# Is the theory complete?



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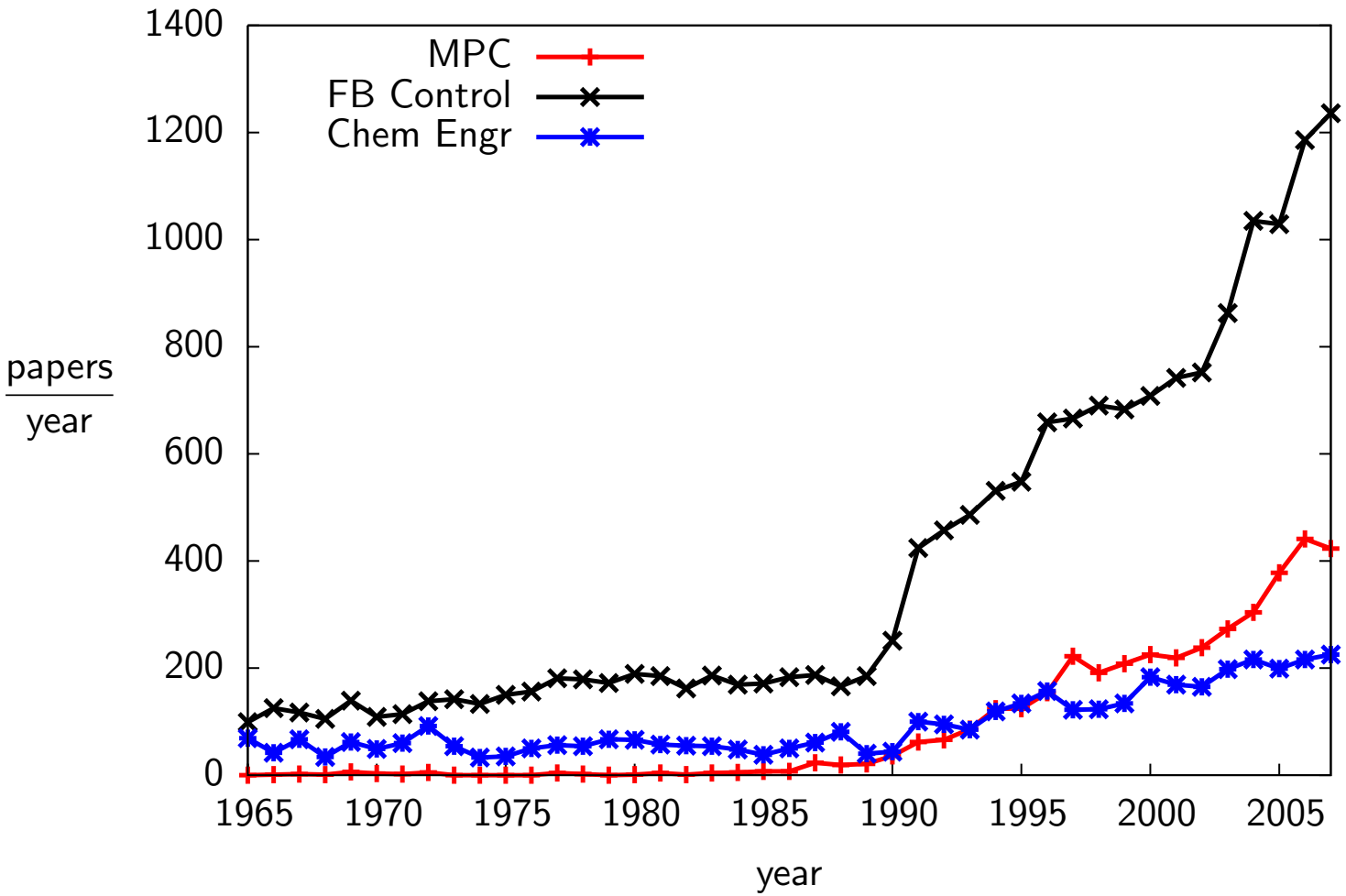
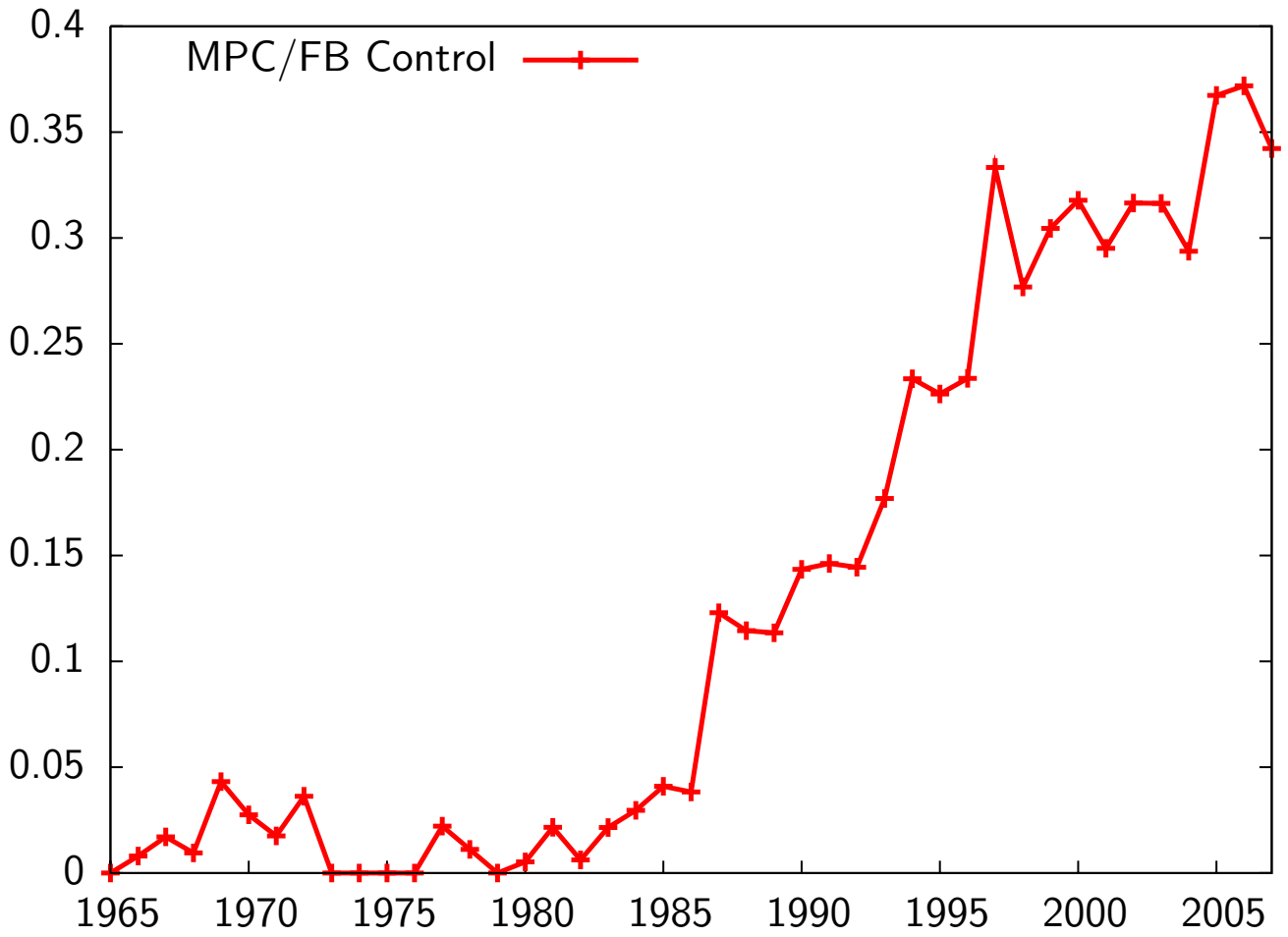
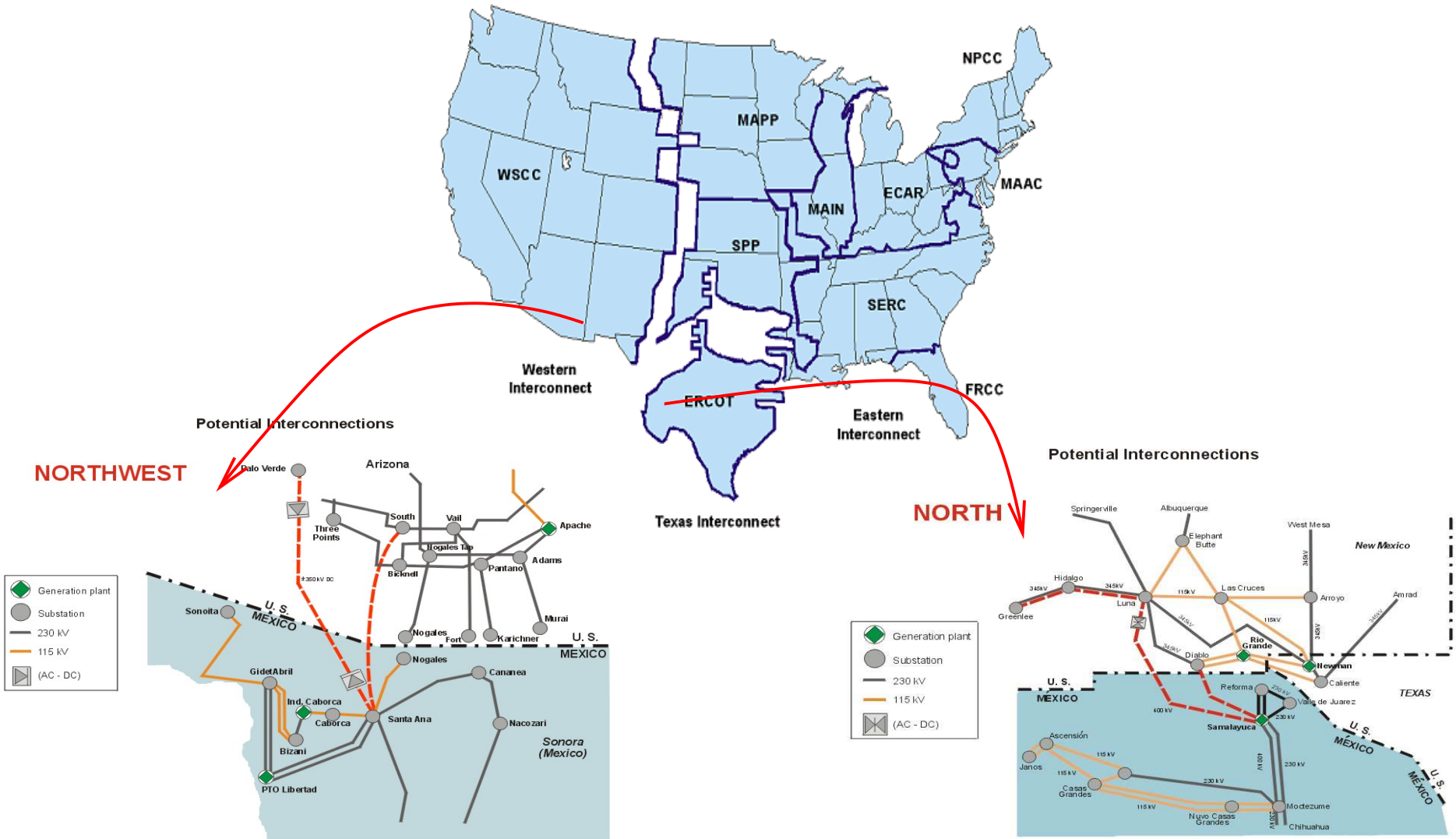


# Ratio of MPC papers to feedback control papers



# Decomposing large-scale systems?



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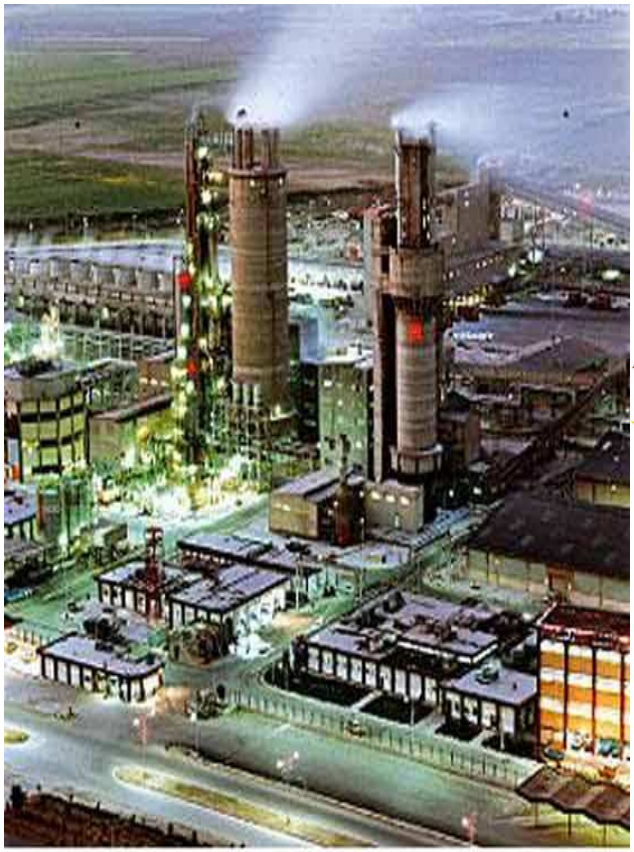
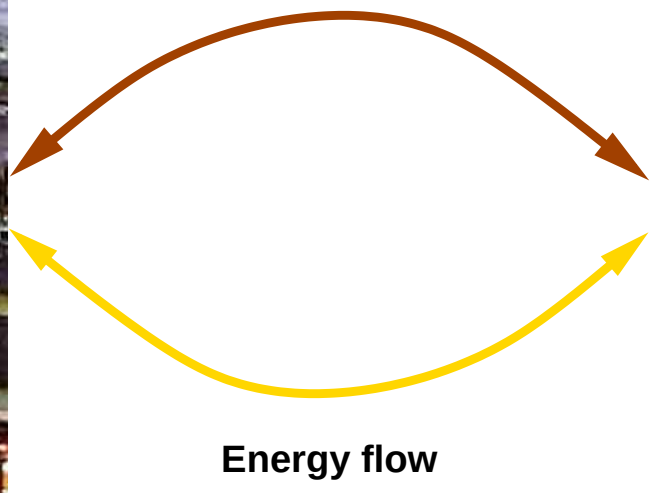
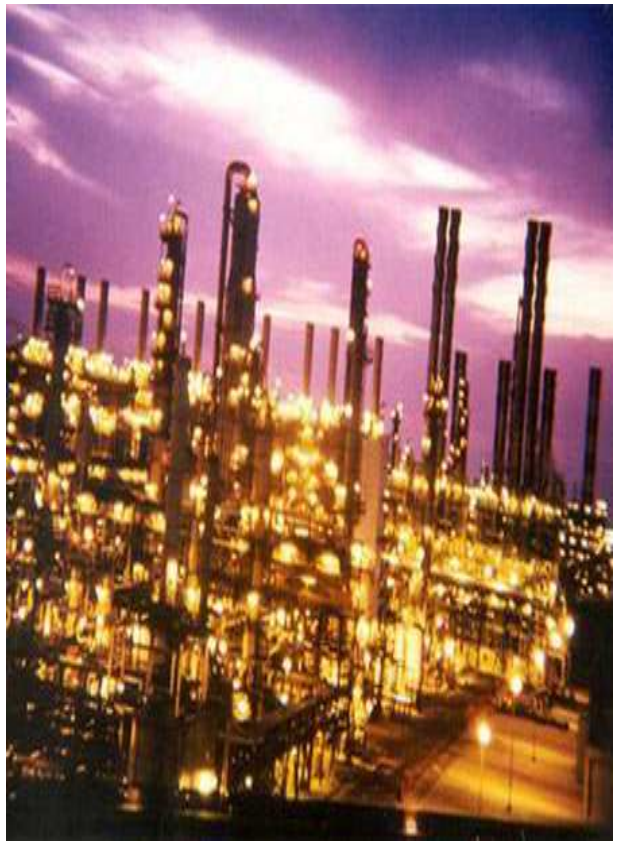
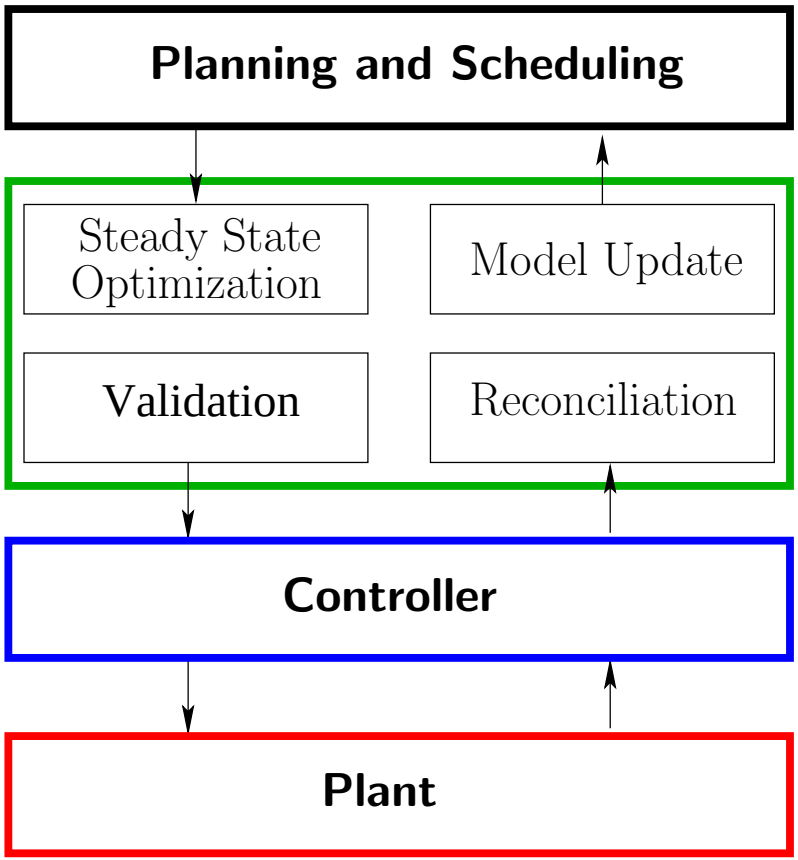




# Optimizing economics: Current industrial practice




- Two layer structure
- Drawbacks

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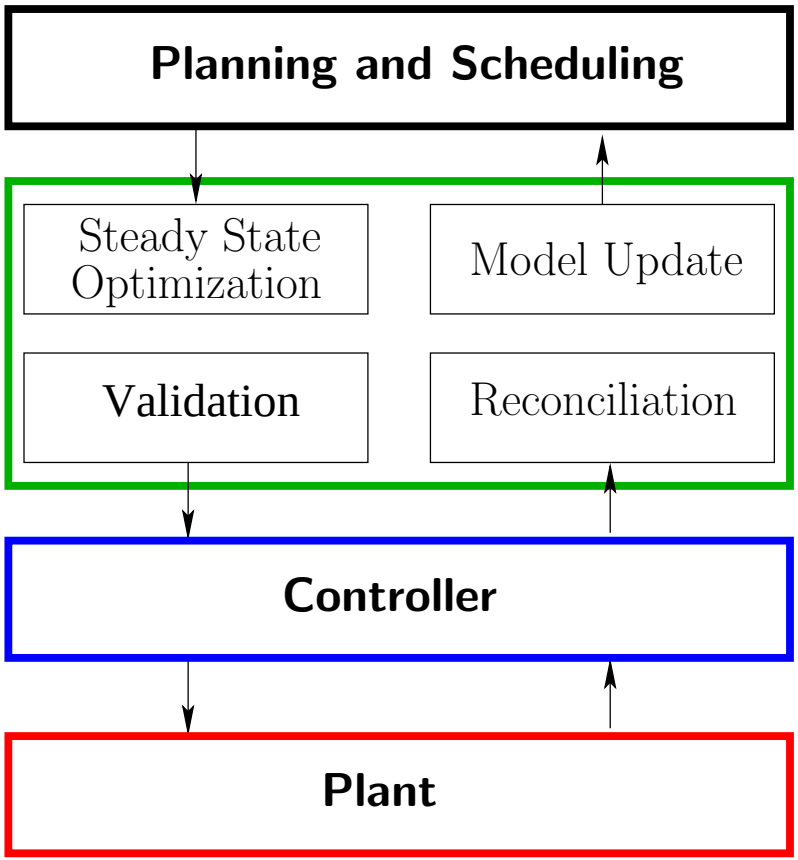
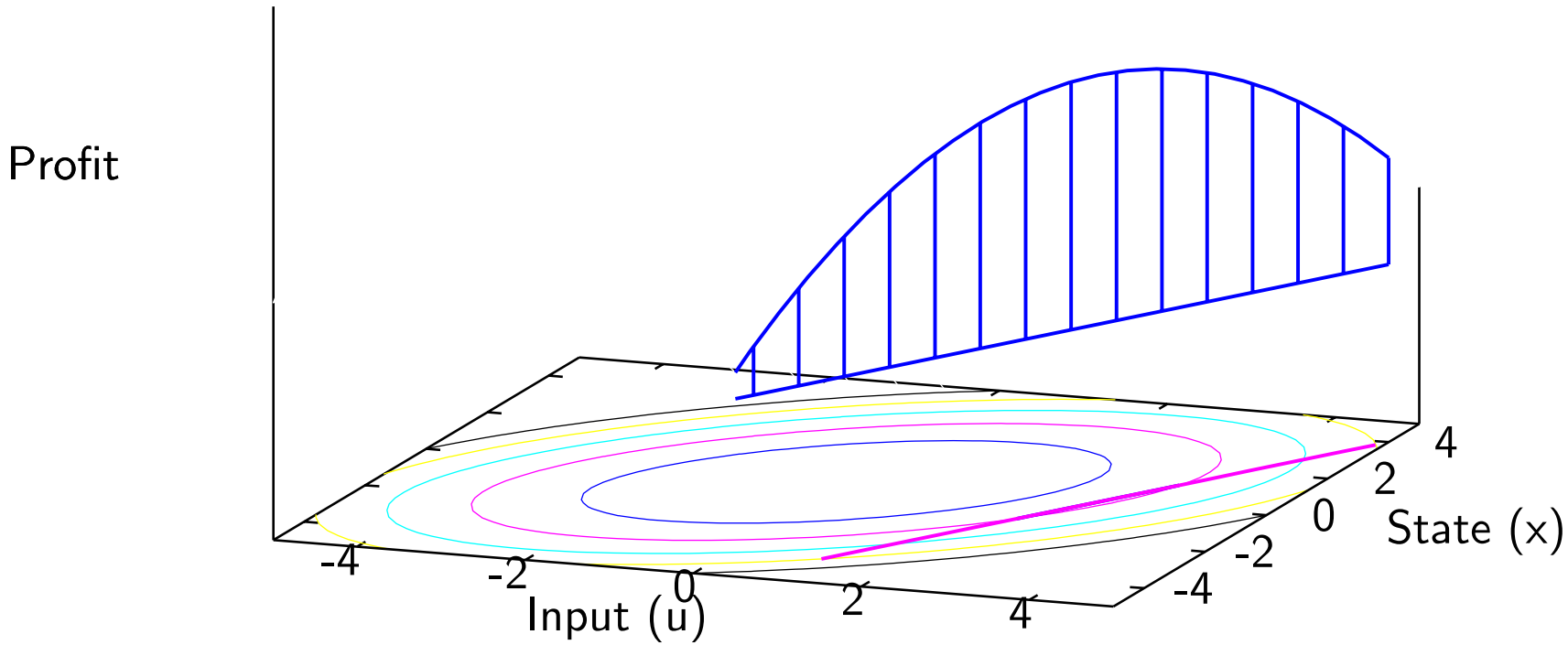



- Two layer structure
- Drawbacks
  - Inconsistent models
  - Re-identify linear model as setpoint changes
  - Time scale separation may not hold
  - Economics unavailable in dynamic layer

# Optimizing economics: what's desirable?



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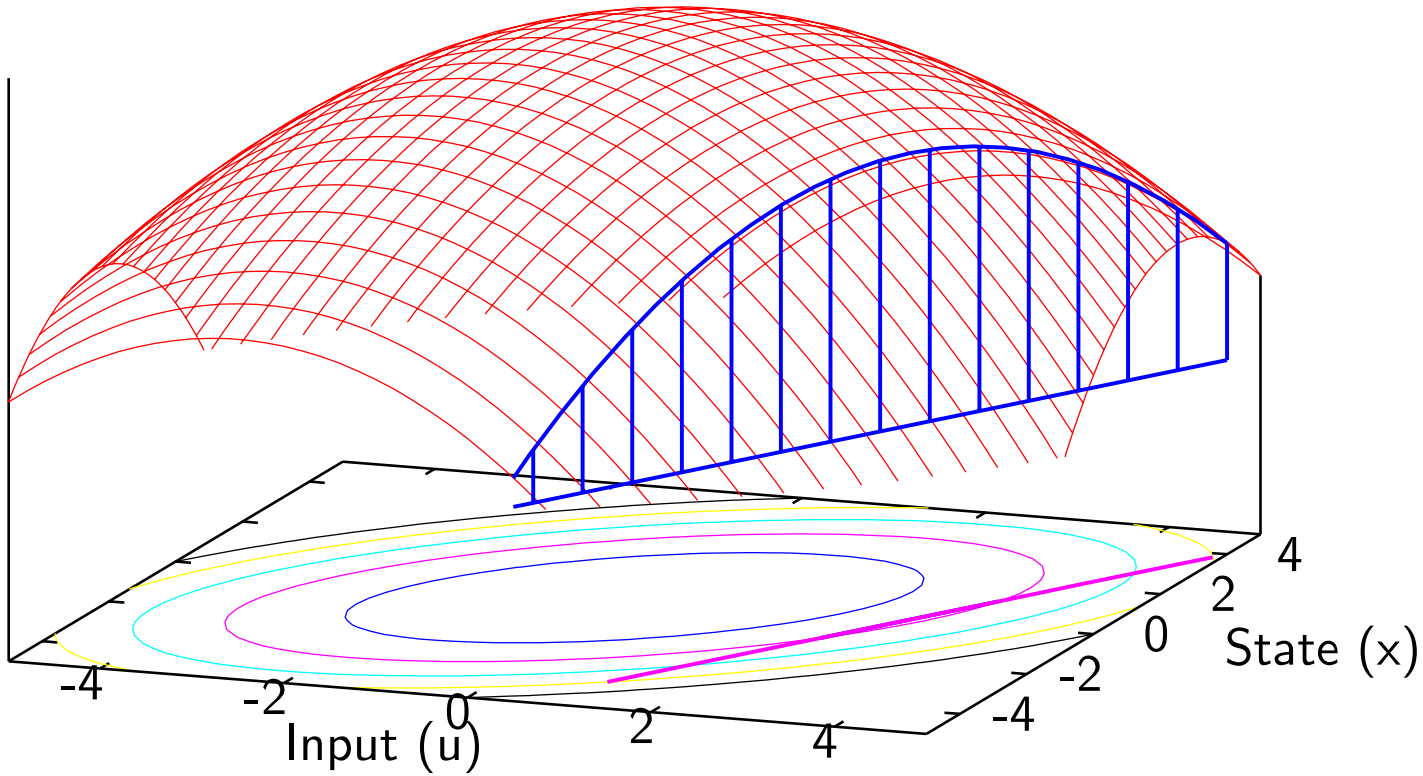

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- Industrial implementations and vendor software are basically keeping pace with the best available theory and algorithms. That is a surprising and noteworthy outcome!
- Obtaining the dynamic models remains a significant bottleneck.

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- Researchers in this community have *not* done a good job communicating the significant advances in this field to their colleagues outside the field.

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  - Dynamic economic optimization subject to settling at the optimal steady state

# Acknowledgments


- Don Bartusiak, ExxonMobil
- Tom Badgwell, Aspentech
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- Rahul Bindlish, Dow
- Financial support from NSF #CTS-0825306, 0456694 and Texas Wisconsin California Control Consortium (TWCCC) members

# Further reading

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D. M. Starks and E. Arrieta. Maintaining AC&O applications, sustaining the gain. In *Proceedings of National AIChE Spring Meeting*, Houston, Texas, April 2007.