

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

James B. Rawlings

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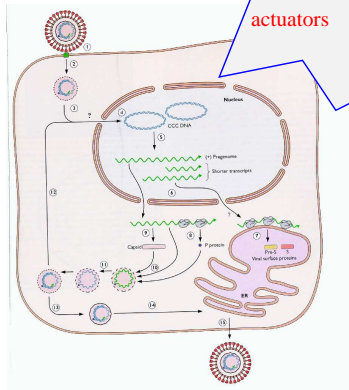
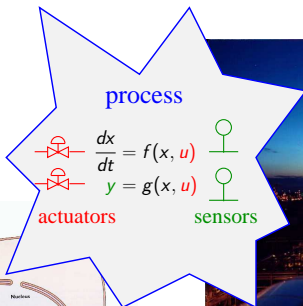


June 22, 2009

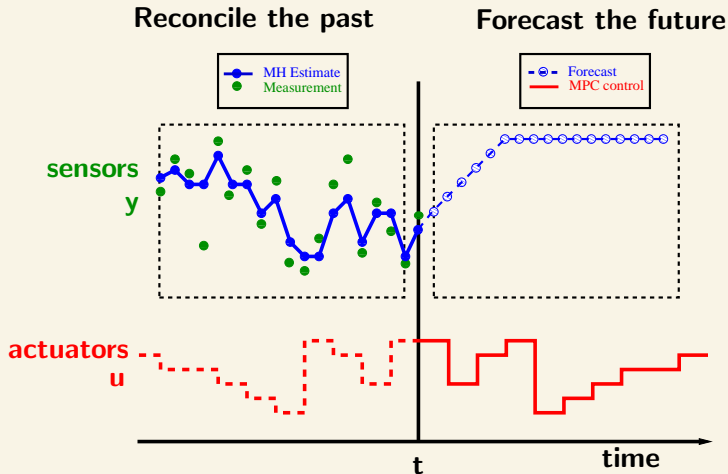
Center for Systems and Control  
Delft University of Technology

- 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

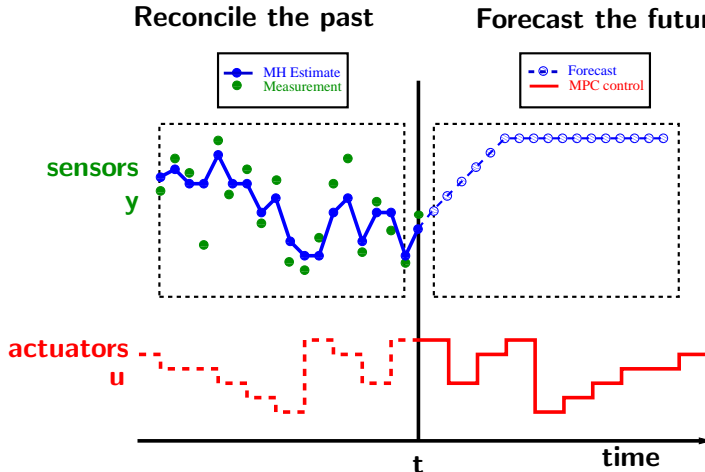


# The model predictive control framework

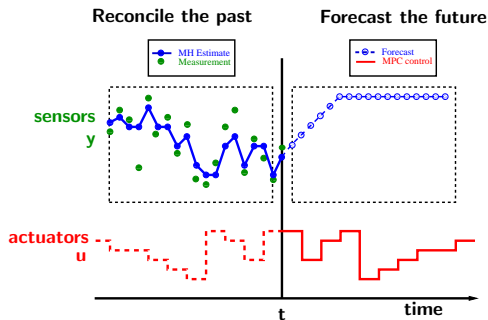


# Predictive control

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



# Predictive control



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

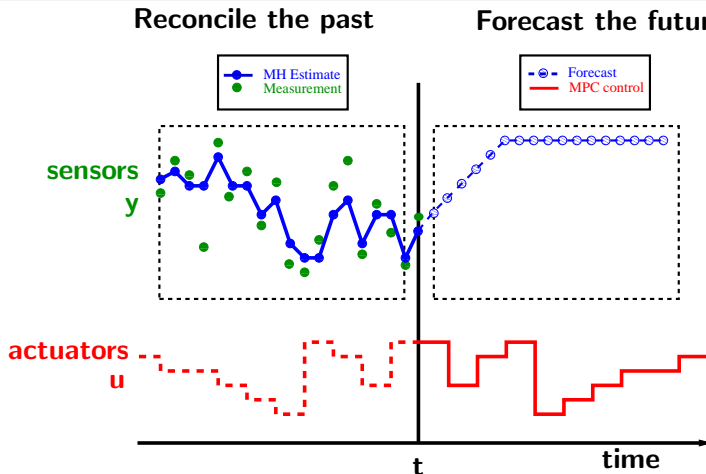
$$\dot{x} = f(x, u)$$

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

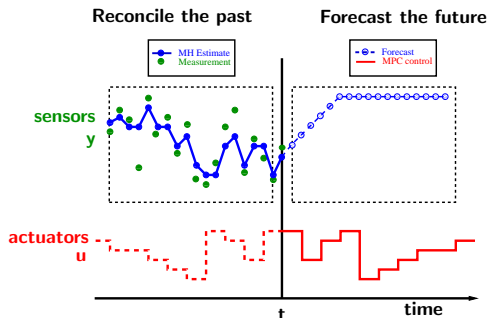
$$y = g(x, u)$$

# State estimation

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



# State estimation



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

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

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

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# Feedback

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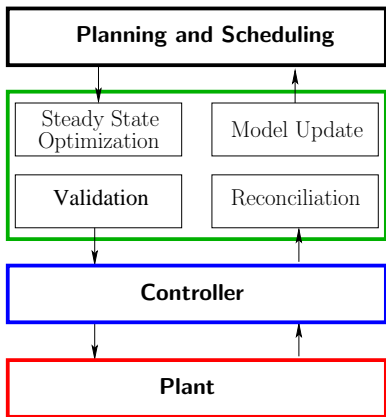
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*Everything has been thought of before, but the problem is to think of it again.*

— Goethe

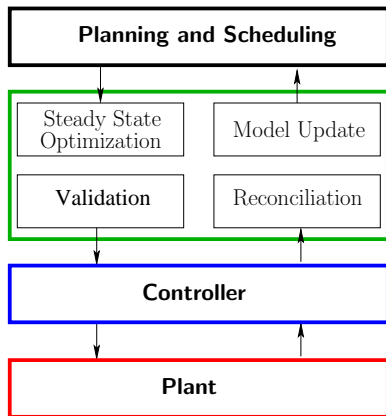
# Industrial practice of MPC



Two layer structure

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

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- **Steady-state layer**
  - ▶ RTO optimizes steady state model
  - ▶ Optimal setpoints passed to dynamic layer
- **Dynamic layer**
  - ▶ Controller tracks the setpoints
  - ▶ Linear MPC (replaces multiloop PID)

# Large industrial success story!

## Linear MPC and ethylene manufacturing

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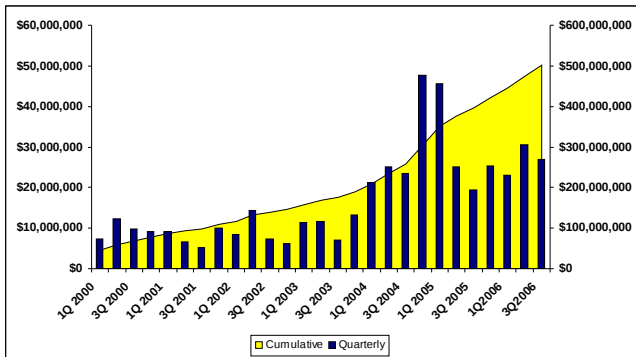
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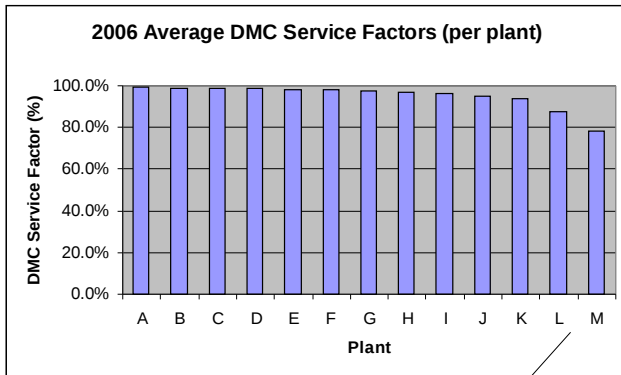
## Praxair experience with MPC

- Praxair currently has more than 150 MPC installations
- 16 M\$/year increased profit (2008)

## We're Doing it For the Money



## Challenges (continued 1)



Plants L & M experienced APC personnel changes

# 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 IDCOM-M:1987 OPC:1987	PCT:1984 RMPCT:1991	IDCOM:1973 HIECON:1986	PCL: 1984	SMOC: 1988	
Largest App	603x283	225x85	-	31x12	-	

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- Has the application base stopped growing?
- 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:

9<sup>th</sup> of October 2008



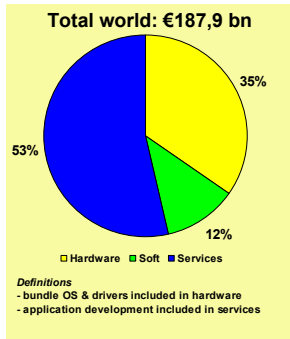
Available for download: <http://www.decision.eu/smart2007.htm>

# 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.**

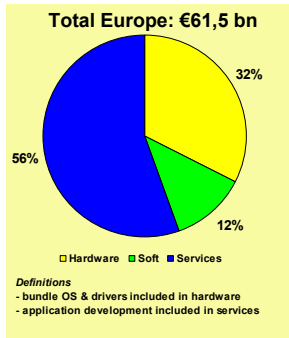


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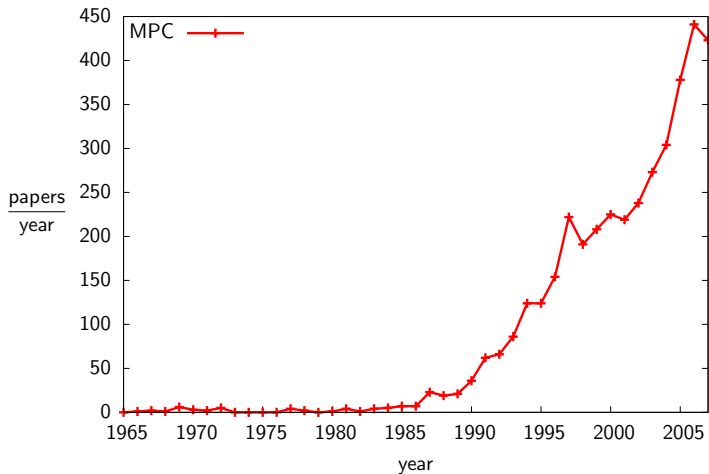


## European Monitoring & Control Market

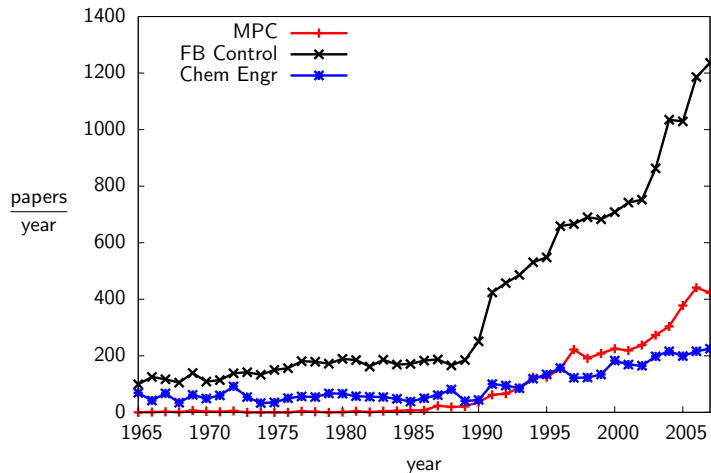
- The European M&C market is around 62 billion euros:
  - In relative terms, compared to the European economy, this is more than 1 day of the total EU-27 yearly Gross Domestic Product.
  - Compared to services businesses, it represents 8% of the EU-27 Telecoms & Transport sector gross value-added.
 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



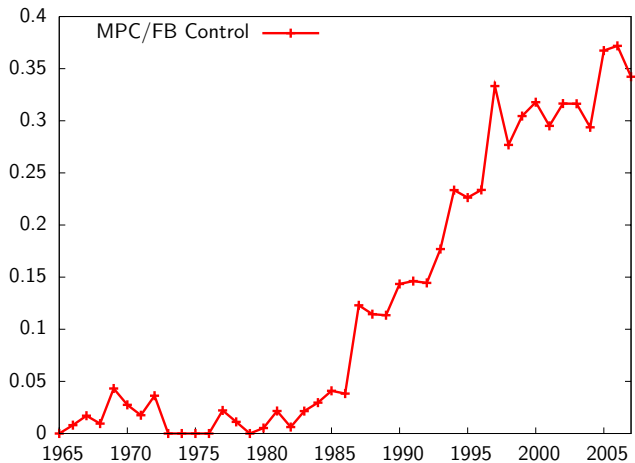
# Is the theory complete?



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# Ratio of MPC papers to feedback control papers





# Decomposing large-scale systems?



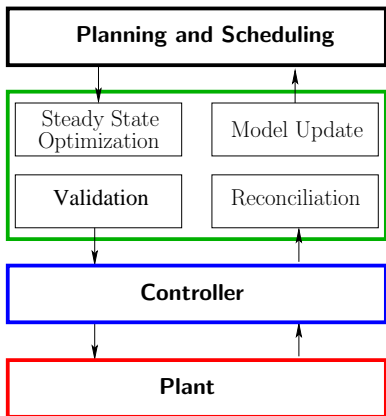
**Material flow**



**Energy flow**

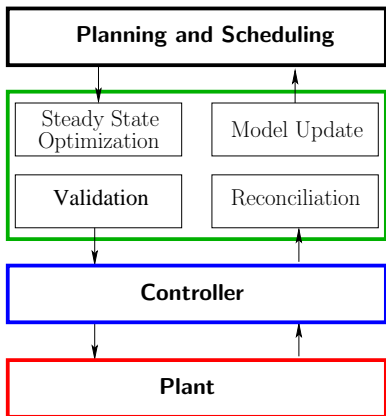


# Optimizing economics: Current industrial practice



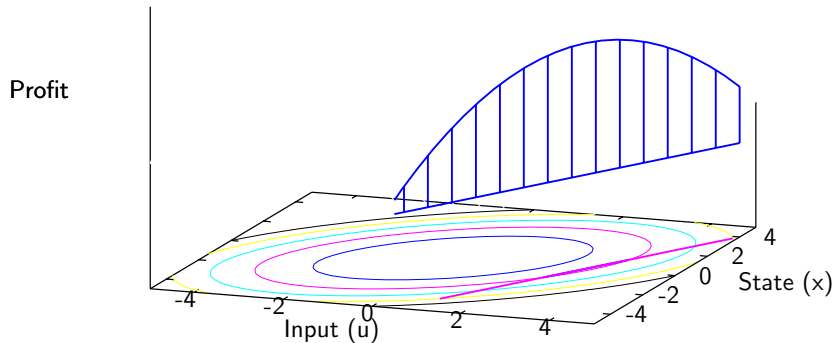
- Two layer structure
- Drawbacks

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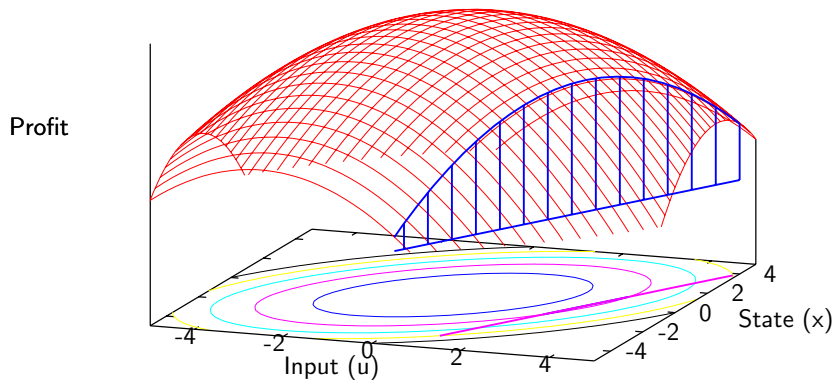


- Two layer structure
- Drawbacks
  - ▶ Inconsistent models
  - ▶ Re-identify linear model as setpoint changes
  - ▶ Time scale separation may not hold
  - ▶ Economics unavailable in dynamic layer

# Optimizing economics: what's desirable?



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- 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.

- The abstraction level is high and barrier to entry is significant.

# Critiquing the research enterprise

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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
- Jim Downs, Eastman Chemical
- Larry Megan, Praxair
- 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.