Institution: Imperial College London

Unit of Assessment: 13A – Electrical & Electronic Engineering

Title of case study:

Case 1 – Efficient and Economical Plant Management via Model Predictive Control

1. Summary of the impact

Model Predictive Control (MPC) is a controller design methodology involving on-line dynamic optimisation of a user-defined objective. The research of **Prof. D.Q. Mayne** FRS and his colleagues at Imperial College has resulted in the first MPC algorithms capable of dealing with both linear and nonlinear systems and hard constraints on controls and states, thus making MPC a viable technique for industrial applications. His research in linear and nonlinear MPC has been exploited by multinational companies such as Honeywell and ABB. Evidence of impact is found in: 1) ethylene production by Basell Polyolefins GmbH resulting in economic benefits in millions of dollars annually; 2) Sinopec's JinShan power plant efficiency, reducing fuel consumptions of 500 tons of coal and 1,700 tons of coke per annum; 3) automotive powertrain design creating new business for Honeywell (based on OnRAMP design suite); 4) ABB's cpmPlus Expert Optimizer tools used for cement manufacturing, affecting companies such as Untervaz (Switzerland), Lägerdorf (Germany) and Buzzi (Italy); 5) ABB's BoilerMaz system for optimising boiler start-up mechanism resulting in energy savings per start-up of around 15%.

2. Underpinning research

The combined use of optimal control and optimization methods conceptually enables the optimized operation of complex processes. The most significant contribution of Model Predictive Control (MPC) resides in the construction of a feedback mechanism which approximately, and in real-time, optimizes process operation, while satisfying operational constraints. These goals cannot be achieved by any other control mechanisms. The underpinning research in MPC at Imperial was conducted in the EEE Department by Professor D.Q. Mayne. He has pioneered a number of research breakthroughs in the analysis, design and development of both linear and nonlinear MPC, which have resulted in him being awarded the prestigious "IEEE Control Systems Award" (http://www.ieee.org/about/awards/bios/controlsys_recipients.html) and the IFAC Quazza Medal (http://www.ifac-control.org/awards/major-medals).

The underpinning research in MPC by Mayne and his team are:

1. **Receding horizon control [R1, R2]** - In receding horizon control the current control is determined by solving on-line a constrained open-loop optimal control problem and applying this control over the following sampling interval after which this procedure is repeated. It is thus able to handle hard constraints on controls and states: this property is one of its main advantages and the cornerstone of the stability properties of MPC controlled nonlinear processes.

   Since in large-scale applications on-line solution of nonlinear optimal control problems may be impractical, Mayne provided a practical alternative: sub-optimal MPC that ensures closed-loop stability even if the optimal control problem is not solved exactly [R1].

   Subsequently, the ambitious task of evaluating systematically the stability and optimality properties of MPC methods was presented in his 2000 paper [R2]. The paper provides a rigorous analysis of solved problems and a lucid description of open problems in MPC. As stated in [R2]:

   > *"We distill ….. essential principles that ensure stability and use these to present a concise characterization of most of the model predictive controllers that have been proposed in the literature. In some cases the finite horizon optimal control problem solved on-line is exactly equivalent to the same problem with an infinite horizon; in other cases it is equivalent to a modified infinite horizon optimal control problem. In both situations, known advantages of infinite horizon optimal control accrue."*

After its publication in 2000, this paper has become the most widely cited MPC paper and was recognized in 2011 by the first IFAC High Impact Paper Award (http://www.ifac-control.org/awards/major-medals).

2. **Combined MPC and moving-horizon estimator [R3]** - When not all key variables can be measured – as is typical in industrial practice – moving horizon estimators play the role of virtual sensors, which can be combined, as shown in [R3], to yield an integrated control architecture. In later work, Mayne developed a new moving horizon observer for nonlinear systems that extends the memory of the observer in [R2]. Forward dynamic programming was employed to effect this improvement.

3. **Robust MPC for linear and nonlinear systems [R4, R5]** - When uncertainties and un-modelled nonlinearities are present – as typical in industry – the standard implementation of MPC computes the control by solving an open-loop optimal control problem that neglects the presence of disturbances. [R4] and [R5] improve the standard MPC algorithm by the addition of a local feedback loop that is relatively easily computed and counteracts the disturbances thereby maintaining almost optimal performance throughout the process operation.

3. References to the research (* References that best indicate quality of underpinning research.)

R1.* Scokaert, P.O.M., **Mayne, D.Q.,** Rawlings, J.B., "Suboptimal model predictive control (feasibility implies stability)", IEEE Transactions on Automatic Control, 44, 648–654, 1999, DOI: 10.1109/9.751369.

R2.* **Mayne, D.Q**., Rawlings, J.B., Rao, C.V., Scokaert, P.O.M. "Constrained model predictive control: Stability and optimality", Automatica, 36, 789–814, 2000 (winner of the 1st IFAC High Impact Paper Award, 2011 with over 3,500 citations), DOI: 10.1016/S0005-1098(99)00214-9.

R3.* Rao, C.V, Rawlings, J.B., **Mayne, D.Q**,, "Constrained State Estimation for Nonlinear Constrained Discrete-Time Systems: Stability and Moving Horizon Approximations ", IEEE Transactions on Automatic Control, 48 (2), 246–258, 2003, DOI: 10.1109/TAC.2002.808470.

R4. **Mayne, D.Q**., Rakovic, S.V., Findelsen, R., Allgöwer, F., "Robust output feedback model predictive control of constrained linear systems", Automatica, 42, (7), 1217-1222, 2006, DOI: 10.1016/j.automatica.2006.03.005.

R5. **Mayne, D.Q**, Kerrigan, E.C., "Tube-based nonlinear model predictive control", Proceedings of the 7th IFAC Symposium on Nonlinear Control Systems, 110-115, 2007, DOI: 10.1002/rnc.1758

4. Details of the impact

Mayne's pioneering research in robust MPC for linear and nonlinear systems made the MPC approach to controlling plants viable in practical, industrial applications. The impact of his work on industry can be quantified from two main vantage points: technical and economic. The technology relying on linear and nonlinear MPC is used for improving process performance, environmental impact and reliable operation.

The impact of Mayne's MPC research includes a number of industrial cases of success. In the following five success stories in two multinational companies, Honeywell and ABB, nonlinear MPC was the essential (or fundamental) component. In addition, direct reference to the company pioneering the introduction of MPC in the specific sector during the current REF period is made.

- **Honeywell** – The impact of Mayne's research to Honeywell's advanced control technology is evidenced by their testimony [E1]:

  "…. *Professor Mayne has introduced several significant advances in the area, especially in the extension of MPC to nonlinear systems*." They also stated that Professor Mayne's contributions in nonlinear MPC *"… has had the greatest impact on (our) industrial practice*."

Honeywell specifically cited three areas of their operations in which Mayne's MPC research work has been applied [E1]:

1) **Ethylene production** [E1, E2]: Ethylene is one of the largest-volume industrial bulk commodity in the world. The majority of ethylene is used in the production of ethylene oxide, ethylene dichloride, ethyl-benzene, and a variety of plastics ranging from plastic food wrap to impact-absorbing dashboards inside cars. Honeywell assisted Basell Polyolefins GmbH, the world's largest producer of polypropylene (PP) and advanced polyolefins products, in the implementation of nonlinear MPC solutions to maximize profits from their ethylene plant. This implementation has resulted, starting from 2008, in these key benefits: a) substantial economic benefits, including ".. *millions of dollars from increase production annually*" [E1]; b) improved quality control on key units as a result of reduced control-variable standard deviations (including a 52% reduction in standard deviation of top quality on the PP-Splitter and 58% reduction in standard deviation of bottoms quality on the PP-Splitter) [E2]; c) increased uptime: Basell has achieved an Advanced Process Control online time in excess of 90% [E2].


Basell's ethylene complex in Wesseling, Germany

2) **Power plants** [E1, E3]: Fuel costs, energy conversion efficiency, and environmental impacts of fossil-fuelled plants have become priorities in both developed and developing countries. Since 2008, the Honeywell MPC tool has been particularly effective in the operation of power plants [E1]. As a significant example, the deployment of a MPC-based tool in the JinShan power plant (China) has enabled Sinopec to increase the boiler efficiency by 0.5%, to increase the operating steam temperature by 2.8°C and to improve stability of key combustion process variables. In addition, the air pollutant emissions from the fuel and limestone consumption have been decreased to comply with environmental standards in the region. The reductions in coal and coke consumption are 500 tons and 1,700 tons per annum. [E3]

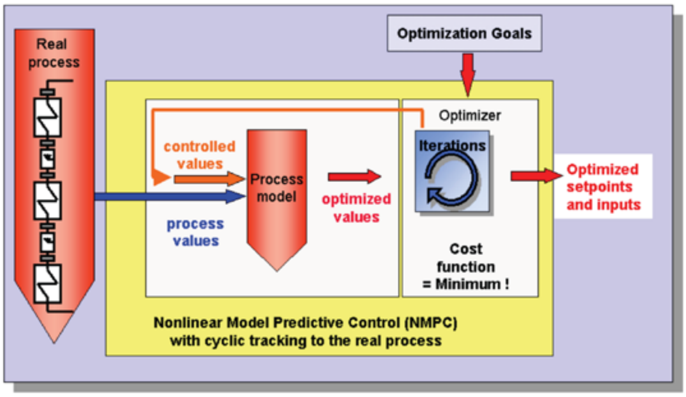
3) **Automotive Powertrains** [E4]: Automotive engines are highly nonlinear plants with significant model uncertainty due to production variability and ageing. At the same time the control must satisfy both input and output constraints. Honeywell developed a fully functional nonlinear MPC-based controller that can be deployed on an engine in 2-3 weeks of engine test time, and with superior performance, as contrasted with the performance achieved via several months required for traditional techniques [E4]. Based on this technology, they have established a new business division based around their OnRAMP design suite for automotive powertrains (http://www.honeywellonramp.com).

- **ABB** – ABB is another company where the successes of MPC for industrial applications are amply demonstrated [E5]. Based on their cpmPlus Expert Optimizer, an advanced process optimization product, they have successfully used MPC in a number of manufacturing systems. Two examples are cited [E5]:

4) **Cement Manufacturing** [E5, E6]: The cement industry of the 21st century is confronted with disparate goals that at first glance seem to conflict. For example, there is enormous pressure to increase profit and margins, while at the same time there is considerable public interest in the sustainable and environmentally friendly use of natural resources. In other words, plant operators find themselves in a situation where they need to react

fast and optimally to continuously changing conditions while still meeting various and probably conflicting objectives. MPC-based feedback operates the plants to their optimal economic performance within the technological, environmental, and contractual constraints. ABB has installed MPC on-line optimizers in the Untervaz material blending plant (Switzerland). Starting from 2008, the benefits achieved by the installation are reduction by 20% of raw mix quality variability and reduced kiln process variability. The nonlinear MPC-based optimizer has been also installed in the Holcim's Lägerdorf precalciner for temperature control (Germany), and Buzzi's Guidonis cements grinding system (Italy).

5) **Coal-Fired Power Plants** [E7]: Renewable energy sources have pushed conventional power plants to be more flexible and efficient. This has led to coal-fired power plants needing to have efficient boiler start-up mechanisms. ABB has successfully developed, commercialised and deployed numerous nonlinear model-predictive optimization solutions for boiler start-up in power plants [E7]. The complex dynamics of the boiler start-up mechanism are described by a nonlinear model subject to numerous constraints on energy usage and thermal stress. The ABB solution based on nonlinear MPC implementation has successfully shown to be able to solve the boiler start-up problem nearly optimally. On average, the energy savings per start-up are around 15%, while starting up is much faster than with standard procedures [E5].



ABB's BoilerMax Nonlinear MPC for drum-boiler control

5. Sources to corroborate the impact

E1. Letter from Corporate Fellow, Honeywell Automation and Control Solutions, Minneapolis, USA, **stating the impact of Mayne's work in nonlinear MPC on their process control business**.

E2. "Basell Optimize Ethylene Plant with Honeywell MPC and RTO", https://www.honeywellprocess.com/library/marketing/case-studies/SuccessStory_Basell-Wesseling.pdf. Archived here on 23/10/2013.

E3. "Sinopec Saves More than $1 Million in Energy Costs with Honeywell's Advanced Energy Solutions", https://www.honeywellprocess.com/library/marketing/case-studies/SuccessStory_Sinopec_AES.1.pdf.Archived here on 23/10/2013.

E4. "Streamlining Powertrain Control Development: A Systematic Approach to Model Based Control", https://www.honeywellonramp.com/TechnicalResources/Documents/2012 Workshop Madellbasierte Kalibriermethoden HONEYWELL v05.pdf. Archived here on 23/10/2013

E5. Letter from Head of ABB AG Corporate Research Centre Germany (on 5th March 2013) on how nonlinear MPC has impacted on their business.

E6. "Advanced Control for the Cement Industry", The Impact of Control Technology, 2011. http://ieeecss.org/sites/ieeecss.org/files/documents/IoCT-Part2-05CementIndustry-LR.pdf Archived here on 23/10/2013.

E7. "Boiler control and optimization", FFWD 1/11, Power Generation Special Issue, ABB Switzerland Ltd. pg 12. Archived here. http://www02.abb.com/global/gbabb/gbabb905.nsf/bf177942f19f4a98c1257148003b7a0a/4951ad3b82277aaec12579210051feda/$FILE/FFWD+Power+Generation+Special+Issue.pdf