Optimal control
Industrial applications

Flavio Manenti, Dept. CMIC “Giulio Natta”
“Terms and conditions”

- Acronyms and notations
  - Advanced **conventional** process control
  - Advanced process control → Model predictive control

- Model predictive control
  - Based on linear/linearized models
    - Dynamic matrix control (DMC, **LMPC**, MPC)
    - Several commercial packages
  - Based on nonlinear models
    - Model predictive control (MPC, **NMPC**)
    - No commercial packages

- Features of NMPC
  - A dynamic (convolution) model is used to foresee the future behavior of the plant on a specific time horizon (prediction horizon, H_P) consisting of p sampling times
  - Receding horizon methodology (moving horizon, not rolling horizon)

Integration Pyramid

Plant Management

Maintenance and Production Management

Enterprise Management

Scheduling

Real Time Dynamic Optimization

Field

Conventional Control

Advanced Control (NMPC)

\[ \min \Phi = \sum_{j=k+1}^{k+h_p} \omega_y \left( T_{\text{react}}(j) - T_{\text{SET}}(j) \right)^2 + \sum_{l=k}^{k+h_p-1} \omega_T \left[ F_c(l) - F_{\text{TAR}}(l) \right]^2 + \sum_{i=k}^{k+h_p-1} \omega_u \left[ F_c(i) - F_c(i-1) \right]^2 \]
Algorithm

- MPC
Receding horizon methodology

PLANT

Set-point

Controlled Variable

Manipulated Variable

MODEL

1

2

3

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NMPC

PET plant

Manenti, Rovaglio

Integrated multilevel optimization in large-scale poly(ethylene terephthalate) plants

_Industrial & Engineering Chemistry Research_

Case Study: PET Plant
Jacobian Matrix

- Primary esterifier
- Secondary esterifier
- Low polymerizer
- Intermediate polymerizer
- High polymerizer
- Solid state polymerizer

Resulting DAE:
- 1356 diff. eqs.
- 164 alg. eqs.
- 15 controls
- 2 controlled
- 16 constrained
Frequent Grade Changes

**Grade A:** PET as textile fibres (*melt process*)
- I.V. = 0.55 ÷ 0.65 dl/g

**Grade B:** PET for bottles production (*bottle grade*)
- I.V. = 0.72 ÷ 0.85 dl/g

**Grade C:** PET for special fibres (*tire-cord resins*)
- I.V. = 0.95 ÷ 1.05 dl/g
Comparison

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Comparison

![Graph showing comparison between IV PHCR and IV SSP (dl/g) over time (min)].

**IV PHCR (dl/g):**
- Values range from 0.640 to 0.710.
- The graph shows two curves, one labeled NMPC.

**IV SSP (dl/g):**
- Values range from 0.760 to 0.840.
- The graph also shows two curves, one labeled NMPC.

**Time (min):**
- The x-axis ranges from 0 to 3000 minutes.
- The curves show changes over time, indicating the performance of different methods.
NMPC

Ethylene splitter

Eni, Italy
The C2-splitter

Column design:
- **Total tray number**: 110
- **Feed**: tray #55 (*)
- **Ethylene cut**: tray #104 (*)

Feed composition (**) :
- $C_2H_4$ – 79%
- $C_2H_6$ – 19%
- Others – 2% ($H_2$, $CO$, $CO_2$, $CH_4$, $C_3H_8$, $C_3H_6$)

(*) bottom-up numeration
(**) molar basis
Validation

**Reflux flowrate change effects on overhead stream impurities**

- Overhead impurities [ppm]
- Reflux flowrate [ton/h]

**Boil-up flowrate change effects on overhead stream impurities**

- Overhead impurities [ppm]
- Boil-up flowrate [ton/h]

**Reflux flowrate change effects on temperature at tray #5**

- Tray 5 temperature [°C]
- Reflux flowrate [ton/h]

**Boil-up flowrate change effects on temperature at tray #5**

- Tray 5 temperature [°C]
- Boil-up flowrate [ton/h]
Servo-mechanism problem

Ethylene molar fraction in cut stream

Reflux flow rate

Ethane molar fraction in bottom stream

Reboiler thermal duty

- PI
- DMC
- NMPC
- SP Distillate

- PI
- DMC
- NMPC

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Servo-mechanism problem

Ethylene molar fraction in cut stream
- PI
- DMC
- NMPC
- SP Distillate

Ethane molar fraction in bottom stream
- PI
- DMC
- NMPC
- SP Bottom

Reflex flow rate

Reboiler thermal duty

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Regulation problem (feed composition disturbance)

Ethylene molar fraction in cut stream

Reflex flow rate

Ethane molar fraction in bottom stream

Reboiler thermal duty
Regulation problem (feed composition disturbance)
Self-adaptive NMPC
Deisobutanizer

Mongstad Refinery, Norway

Dones, Manenti, Preisig, Buzzi-Ferraris
Nonlinear Model Predictive Control: a Self-Adaptive Approach
*Industrial & Engineering Chemistry Research*
49(10), 4782-4791, 2010
Spoiled Jacobian
Results

- Use of compartmental models
- Model self-adaptation
  - To the problem
  - To the dynamic
  - To the computational effort
- Benefits
  - Accurate when needed
  - Fast when possible
  - (viceversa)
D-RTO
Olefins plant

Invensys, USA

Manenti et al.
Process Dynamic Optimization Using ROMeo
Computer Aided Chemical Engineering
29, 452-456, 2011
Tools

DYNSIM
- Mathematical Modeling
- Dynamic Simulation
- Optimization

ROMeo
- Dynamic Optimization

Is it possible?

Outlier Detection
Robust methods
Linear/nonlinear Regressions
Performance Monitoring
Yield Accounting
Soft sensing

Data Reconciliation

Parallel Computing

Nonlinear Systems
Optimizers
DCS, OTS, Plantwide control,
Soft sensing, process transients, grade/load changes

Solvers

Scheduling

Just in time
Market-driven
Conscious MGM

Supply Chain Management

Optimal production
Optimal grade changes
Multi-objective
Real-time optimization
High accuracy
Reliable process control
Production improvement

Efficiency

Decisions

Raw Data

Parallel Computing

Mathematical Modeling
Dynamic Simulation
Optimization
Dynamic Optimization

DYNSIM
Mathematical Modeling
Dynamic Simulation
Optimization

Just in time
Market-driven
Conscious MGM

Scheduling

Optimal production
Optimal grade changes
Multi-objective
Real-time optimization
High accuracy
Reliable process control
Production improvement

Efficiency
Decisions
Raw Data
The Idea

• On-line Optimization

\[ \min_{x,b} Z = Profits - Costs \]
\[ s.t.: f(x,b) = 0 \]
\[ g(x,b) \leq 0 \]
\[ \min_{x,u,b} \sum_{i} \sum_{2} \ldots \sum_{n} (\ldots) \]

• Dynamic Optimization

\[ \min \sum_{i} f(x_{i}^{R}, x_{i}^{SET})^{T} w_{i} (x_{i}^{R}, -x_{i}^{SET}) = 0 \]
\[ s.t.: f(\dot{x}, x) = 0; \quad g(\dot{x}, x) = 0 \]
\[ g(\dot{x}, x) \leq 0; \quad g(\dot{x}, x) \leq 0 \]
\[ x \in \mathbb{R}^{n}; \quad u \in \mathbb{R}^{p}; \quad b \in \mathbb{N}^{m}; \mathbb{N}^{m} \]

• Data Reconciliation

\[ \min \sum_{i} (x_{i}^{M} - x_{i}^{R}) w_{i} (x_{i}^{M} - x_{i}^{R}) \]
\[ s.t.: f(x) = 0; \quad g(x) \leq 0 \]
Example

• Series of three ideal CSTRs
  - Open-loop
  - Closed-loop
Open-loop in C++

Key-component molar flow exiting the reactor:

- #1
- #2
- #3
Open-loop in DYNSIM

UAM MODELS inserted into the ICON PALETTE (C++ dynamic library)
Open-loop in DYNSIM

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Using BzzMath in DYNSIM

No changes at the DYNSIM M’s interface
Closed-loop in C++
Full Integration (All-in-one)
Drag & Drop

DYNSIM

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Drag & Drop
Drag & Drop

ROMeo

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Drag & Drop

ROMEo

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Smart Dynamic Simulation with ROMeo
D-RTO with Multiple Shooting
Friendly Interface for D-RTO

Possibility to give the user to enter any kind of data for D-RTO

Specific D-RTO TAB
Preliminary Comparison

RTO vs D-RTO

0.095
0.1
0.105
0.11
0.115
0.12
0.125
0
10
20
30
40
50
60
70
80
90

Traditional approach
Two-shooting
Multiple-shooting
Validation Case (Olefins)

- Cracking Furnace (SPYRO-based D-RTO)
Software Integration

All-in-one tool for SPYRO-based smart dynamic simulation and optimization of olefins plant

- SPYRO (FORTRAN)
  - Mixed-language (FORTRAN-C++)
- Cracking furnace SPYRO-based dynamic model (C++)
  - Very performing ODE/DAE solver (BzzOde, BzzDae, BzzDaeSparse... BzzMath)
- Smart dynamic simulation (grade change, DYNSIM)
  - Full integration in DYNSIM
- Dynamic real-time optimization (multiple shooting, ROMeo)
  - Full integration and OPERA synchronization
SPYRO-based (Smart) Dynamic Simulation

- C3H6/C2H4 Severity Change from 0.62 to 0.67

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SPYRO-based (Smart) Dynamic Simulation

- Severity Change Convergence
SPYRO-based (Smart) D-RTO

As per DYNSIM, UAM inserted into the ICON PALETTE (C++ dynamic library)
8-shoots flowsheet
32-shoots flowsheet

No changes at the ROMeo’s interface
Converging Path

No changes at the traditional control level
High Benefits, Few Shoots
Market dynamics

- Market dynamics (the current market condition is a higher demand of propylene, thus higher price) imposes a severity change in ethylene/propylene production:

![Graphs showing market dynamics](image)
Severity change

Coil outlet temperature [°C] of the radiant section of the cracking furnace

Fuel flowrate [kg/h] entering the cracking furnace

TRADITIONAL

4 SHOOTS

Supposed practical upper bound

16, 32 SHOOTS

4 SHOOTS

820
800
780
760
740
720
700
0 20 40 60 80 100 120
Time [min]

16, 32 SHOOTS

4 SHOOTS

TRADITIONAL

8000
7000
6000
5000
4000
3000
2000
0 20 40 60 80 100 120
TIME [min]
Quantitative comparison

- To operate at the optimum conditions dictated by the market, the RTO requires more than 2h to accomplish the severity change, whereas the D-RTO requires about 1h.
- Consider that severity changes are not only imposed by market dynamics, but even by feedstock changes, load changes… As a result, frequent severity changes are required in each coil of each cracking furnace of each olefins plants.
Industrial feasibility

D-RTO with ROMeo

• Feasible
• D-RTO is more stable than RTO
• D-RTO halves off-spec periods
• On-line feasibility for the industrial scale
• Computational times are comparable
• No visible changes to the user in ROMeo environment
• No changes to the existing control scheme
• Easy-to-use when implemented (few parameters to be defined)