Model-based Optimization and Online Scheduling: A Candid Practitioner View

Philippe Hayot – The Dow Chemical Company
About Dow

• Founded by Herbert Henry Dow, 1897 in Midland, MI
• Delivers a broad range of technology-based solutions to customers in approximately 180 countries
• Integrated value chain aligned to high-growth markets such as packaging, water, electronics, agriculture, transportation, infrastructure
• $49 billion sales in 2015
• 53,000 approximate employees worldwide
• 6,000 product families manufactured at 200 sites in 36 countries

Corporate Values

• Integrity
• Respect for People
• Protecting our Planet
What “Process Operations” are we dealing with?

- Customers
- Logistics
- Supply Chain Planning

- Shared Utilities and Recovery Systems

- Logistics
- Supply Chain Planning

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A Global Operation …
50 global Production, Systems House, Application Development Sites

Manufacturing  Systems Houses  R&D Centers  Customer Service Centers

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Semi-Batch Process Operation with Modeling and Optimization – Making the most from existing assets within constraints

Optimization within current operating constraints
Short term value generation, no capital investment
Using fundamental models
Using advanced mathematics
Using Advanced Control and Optimization
Using Batch Data Analysis tools for fast opportunity identification

Optimization beyond current operating constraints
Understanding Equipment Reliability constraints
Understanding Quality constraints
Understanding Safety constraints
Implementing new ideas …

Off-line Optimization
Steady value generation year after year

First implementations in 2014

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Off-line Optimization
Design of semi-batch reactor recipes using simulation

Using a fundamental dynamic model and process know how.
Includes business process safety rules for safe recipe design.
Made accessible to Production Engineer, Plant Support Engineers, Research Engineers at all plants across the globe through a web based interface.

- Still leads to relatively simple recipe designs.
- Depends on the expertise/experience of the users.
- Time consuming.
  - Yet delivered results and still does
    - Top Process Safety performance
    - Cycle time reduction
    - Capture and distribute knowledge
Off-line Optimization
Dynamic Optimization of semi-batch reactor recipes

Using a fundamental model of the process + Dynamic Optimization
Has been described and applied to many literature examples for many years
Several commercial tools claiming capability for dynamic optimization
Yet still a challenge to assemble a complete dynamic model of a specific process and use it for multiple applications like simulation, dynamic optimization, design, …

- Leads to more complex profiles
- Uses more variables to optimize
- Challenges the experienced recipe designer
- More focus on defining constraints
Dynamic Optimization of Semi-batch Reactors for Living Copolymerization

From a reaction scheme ...

\[
\frac{d\lambda_k^A}{dt} = V^{-1} \left( k_i^A G_0 M^A + k_p^{AA} \sum_{i=0}^{k-1} \left( \frac{k}{i} \right) \zeta_i^A M^A + k_p^{BA} \sum_{i=0}^{k} \left( \frac{k}{i} \right) \zeta_i^B M^A - k_p^{AB} \zeta_k^A M^B \right)
\]

... to thousands of equations describing our reactors and their constraints ...

... and a 40% reduction in batch time

Off-line Optimization
A successful collaboration between Dow and CMU

CMU: Larry Biegler
Dow PI: Carlos Villa

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Optimizing is also understanding constraints

Fundamental studies to better understand the process safety and quality constraints ultimately leads to higher productivity without compromising quality and safety standards

- By lack of understanding, constraints may be set conservatively, limiting the optimization space.
- A study showed that the constraint is changing as a function of another variable and hence as the batch proceeds.
- Further investigation showed that the constraint is different depending on the type of product.
Online Application
Development of on-line inferentials based on the fundamental model

On-line estimates for key process variables

On-line estimates for abnormal scenario such as adiabatic runaway
  • Off-line recipe design require conservative designs to avoid reaching Never Exceed Limits under worst case scenario
  • Having on-line estimates provide additional protection layers and enables less conservatism in the off-line recipe design

Used in constraint controllers to stay within constraints

Used in Independent Protection Layers to stop
What about post processing units?

After the semi-batch reactor, semi-continuous finishing process with multiple unit ops and intermediate buffer tanks to manage the frequent product transitions.

Reactors and finishing systems can be associated in different ways:

- Delays in reactor batches can lead to a stop of the finishing systems => bad for reliability, stop/restart takes time.
- Delays in finishing trains can lead to reactors waiting for transfer => Increased cycle times.

How do we optimize that?
• A simplified process representation
  • Ignore process units insignificant in mass balance
  • Ignore product storage limits
• Improve productivity by reducing reactor transfer wait times
  • Model input: equipment size, unit inventory level, control logic states
  • Optimized decision: rate targets for the front and back ends
Practical challenges in the problem

- Measurement noise
- Fast emptying for transition
- System flushing
- Variable flush time
- Product storage availability
- Unreliable unit mass measurement
- Raw material shortage
- Rate target manual override
- Back-end recycle
- Early/delayed batches
- Tank low-level protection
- Unknown batch schedule
- Raw Material target level
- Smooth continuous operation
- Operation intervention/preference
- Data uncertainty
- Plant-model mismatch

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Synchronizing batch and continuous operations

Batch Process Units
- Product assignment
- Batch sequencing
- Batch timing

Continuous Process Units
- Flow rate manipulation
- Product changeover

Optimization technology coordinating the batch units and downstream process to minimize batch wait times
Dynamic real time optimization system overview

- Campaign length
- Product sequence
- Units in use

Schedule Optimizer

- Unit status
- Flow limits

Multivariate Constraint Controller

- Flows
- Levels
- Valves
- Dp’s

DCS

- Valve positions
- Process measurements
- Analytical results

Flow Profiles

Flow Set Points

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Dynamic optimization using Resource-Task Network (RTN)

Any process can be represented as interactions between Resources and Tasks

RESOURCES
- Equipment
- Raw Materials
- Utilities
- Labor
- Products

TASKS
- React
- Filter
- Dry
- Process
- Drum
- Store
- Ship

A simple resource-task network (RTN)

e.g. Make X in Reactor
Dynamic simulation model for off-line testing

- Tuning and testing for the dynamic optimizer
  - Tuning parameters
    - Model prediction horizon, optimization frequency, step length
    - Penalty weights in the objective function
    - Etc.
  - Testing scenarios
    - Early/late reactor batches
    - Temporary manual override
    - Etc.

- Off-line tests with the simulation environment
  - Enabling fast commissioning
  - Fully configurable
  - 180X faster than real time

- Dynamic simulator in Aspen Custom Modeler™
- Optimization-simulation interface between optimizer (GAMS) and simulator
Example of off-line closed-loop simulation

- Baseline: Plant data from 8:00 pm 02/15/2015 to 7:45 am 02/17/2015
  - 35 hour time horizon with 15 min optimization step interval
  - Same initial condition and product sequence
  - Different CONTINUOUS FEEDRATE

- Total BATCH wait times reduced to 22 min from 145 min
**Optimization model procedures**

1. **Pre-processing**
   - Calculated model initial states based on input data
   - Fix erroneous data due to measurement noise (e.g., negative inventory level)

2. **Solve the RTN model to optimize rate targets**

3. **Post-processing**
   - Tweak optimized rate targets under specific circumstances to meet operators’ desires
Addressing practical issues within the solution

Pre/Post-Optimization Data Processing
- Measurement noise
- Fast emptying for transition
- Early/delayed batches
- Tank low-level protection
- Equipment constraint
- DMC

Frequent Re-optimization with Feedback
- System flushing
- Variable flush time
- Product storage availability
- Unknown batch schedule
- Intermediate target level
- Smooth continuous operation

Optimization DOF Adjustment
- Unreliable unit mass measurement
- Raw material shortage
- Rate target manual override
- Back-end recycle
- Operation intervention/preference
- Data uncertainty
- Plant-model mismatch

Customized Objective Function
- Optimization DOF Adjustment
- Pre/Post-Optimization Data Processing
- Frequent Re-optimization with Feedback
- DMC

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A complete solution package for plant operations

Operator Interface Detail Panel

- Inventory Histories
- Inventory Predictions
- Flow Predictions

- Batch prediction
- Flow Rate Profiles
- Level prediction

Documentation

- User manual
- Training material
- Engineering document
- Research reports

Room for Improvement to better interact with Panel Operator
Closed-loop results: over $5 million/yr

Improved productivity
- Batch wait time decreased > 50%
- Capacity increased 5%

Smoother operation
- Fewer manual intervention
  Before: 60 times/month
  After: 15 times/month
Training for Plant Operations …

... should focus on what the optimizer does rather than how it does it

... should advertise that the optimizer takes similar decisions as what they would do manually, it just does it all the time and consistently.

... should advertise the simplicity of the system (for them)

... should be clear on limitations (when do they need to take control manually)
Some of the remaining challenges …

Hitting limitations of upstream, downstream or shared systems
• Where do we draw the line when scoping a project?
• Using one big optimizer or multiple optimizers with a supervisory layer?

Predictability of future events?
• Planned events: such as product transitions, cleaning, scheduled maintenance … but need to be able to predict the length of the event … optimizer could also advise on when to plan the event – typically an operator intervention.
• Unplanned events: by definition, non predictable so can only re-optimize based on the new situation caused by the event
• Automation Logic can become extremely complex and difficult to oversee

Maintenance and Support + expertise required for implementation
• DMC is a commercial tool with a pool of SME’s for implementations, Maintenance and Support
• The rest is not and relies on the expertise of a few
How to represent the automation logic in the optimization model?

Batch ready to transfer

- Process measurement
- Operator input
- Binary Variable
- More logic
From Production Unit to Production Facility

Shared Utilities and Recovery Systems

Supply Chain Planning

Logistics

Customers

Supply Chain Planning

Logistics

P1

P2

P3

Pn

P1

P2

P3

Pn

RM

RM

RM
From Production Facility to Global Production Network

Global Asset and Supply Chain Optimization

- Where do we make it?
- When do make it?
- When do we schedule maintenance?
- How do we minimize the impact of unplanned events?
Summary

- Modeling and Optimization applications in semi-batch plant operation delivers value with no capital investment

- Optimization is also about understanding constraints

- Dynamic Real Time Optimization was successfully applied to an industrial scale semi-batch/semi-continuous process.

- The approach integrates scheduling and control

- Maintenance and Support is key for long term sustainability

- There are challenging research directions ahead
Key contributors

Rob Hoogerwerf
Bao Lin
Bryan Matthews
Yisu Nie
Carlos Villa
John Wassick
Thank You