NTNU

Norwegian University of Science and Technology

Design of start-up and shut-down control systems

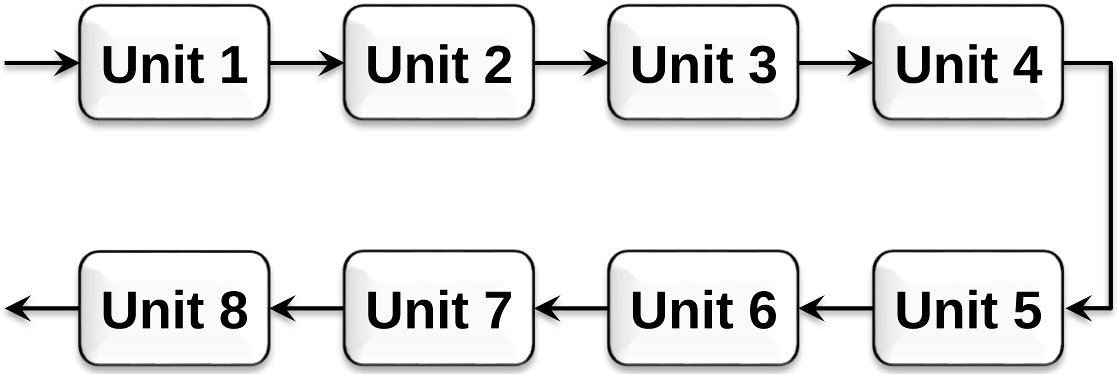
With emphasis on plant-wide in contrast to unit

Public Trial Lecture

Julian Straus

Start-up and shut-down

- Continuous manufacturing divided into 3 sequences:
  - Start-up
  - Continuous production
  - Shut-down
- Relative straight forward for sequential processes



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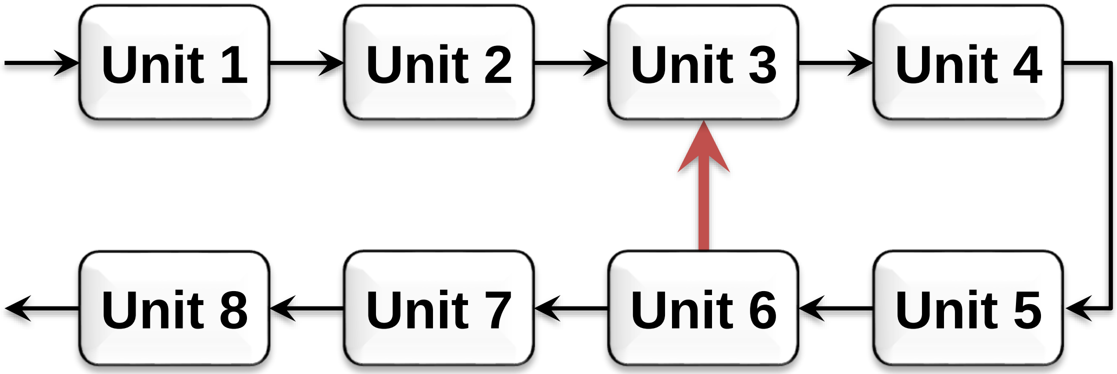
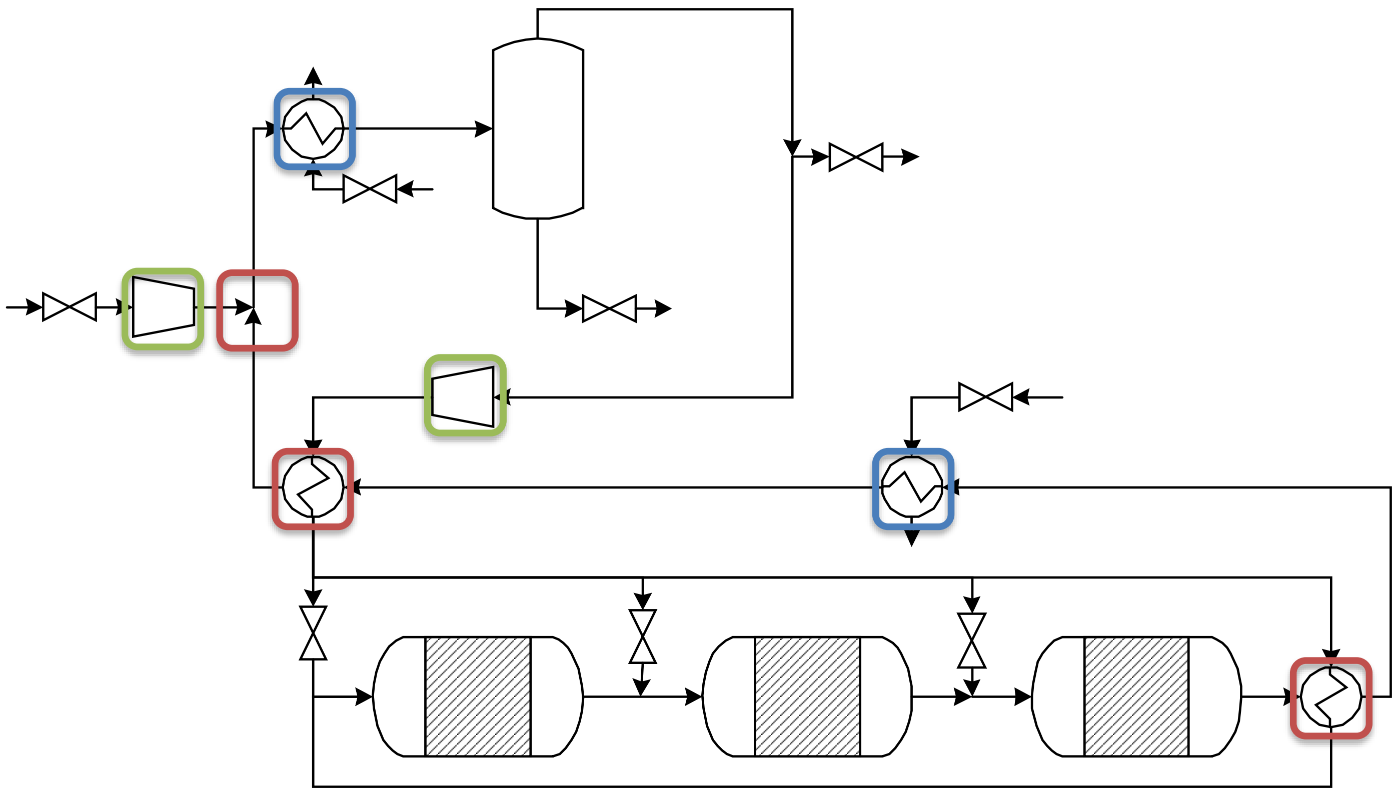


- How to do this in an integrated process?

Ammonia synthesis loop

- Example: Ammonia synthesis loop



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1. Introduction

Automated start-up and shut-down

- Start-up and shut-down of unit operations mature field:
  - Each unit in itself contains several control loops
  - Integrated logic controllers (programmable logic controllers)

- Motivation for automation on plant-wide level
  - Safety (Texas City refinery explosion, 2005)
  - Improved economic (and environmental) performance
  - Reduced start-up and shut-down time (Power plants)

- Start-up:
  - Cold
  - Warm
  - Hot

- Shut-down:
  - Standard
  - Emergency

Plant-wide control systems

- Additional unit operations required (*e.g.* burner or cooler)
- Consideration of utilities (steam, cooling water, etc.)
- ➢ Complicated, large-scale systems with logical variables (hybrid system)

- General considerations
  - Creation of inert atmosphere/presence of dangerous chemicals
  - Material properties (stress in heating/cooling)
  - Impact on materials through non-normal operation conditions

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1. Introduction

Focus of this lecture

- Introduce current industrial practice
- To give an overview of different approaches for plant-wide start-up and shut-down control systems
- Provide a starting-point for detailed analysis of different applicable methods
- Applicability analysis of the different procedures

Presentation outline

1. Introduction
2. Current Industrial Practice
3. Discrete event dynamic systems
4. Dynamic optimization problem
5. Final thoughts

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Chemical processes

- Start-up and shut-down based on procedures developed through engineering insights
- ➢ Running of the process manually by the operator through changing controller set points and opening/closing valves
- May involve manual inspections
- Procedures fairly complex with a large number of steps
- Operators do not necessarily follow the procedure precisely

- ➢ Can result in dangerous situations

Start-up of a steam methane reformer

- Harmonized procedures by Compressed Gas Association
  1. Nitrogen purging with manual leak tests
  2. Starting of burner
  3. Heating of reformer with nitrogen
  4. Introduction of steam and simultaneous reduction of nitrogen
     - Condensation has to be avoided
  5. Introduction of methane once temperatures exceed a certain level
     - Higher steam/carbon ratio to prevent coking
  6. Addition of downstream process
     - Consideration for damaging these unit operations
     - Can give additional fuel gas sources

Asis Industrial Gas Association

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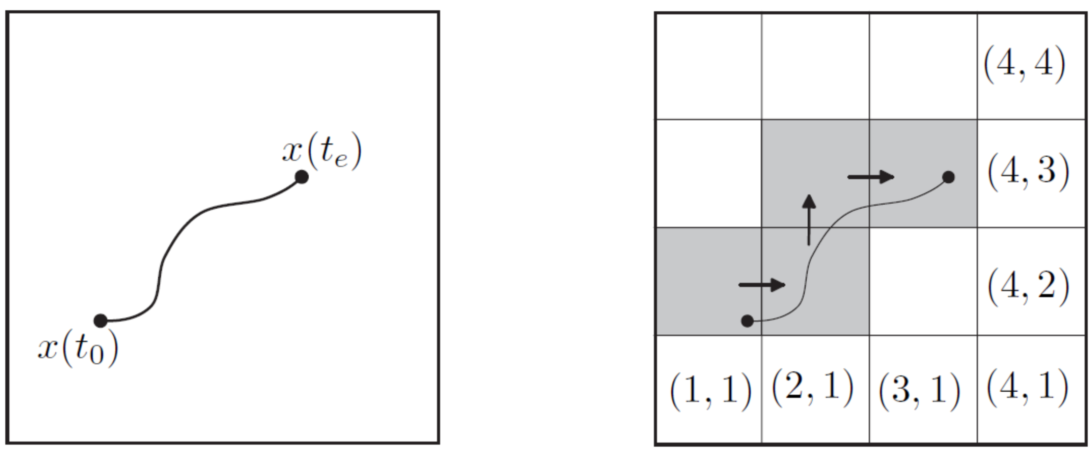
Concept

- Modelling of the system using discrete *states*
- *Transitions* between *states* triggered by *events*
- Intrinsically integer based
- From continuous to discrete:



(a) (b)

Philips et al. (2003)

Concept

- Several ways to model discrete event systems
  - Automata
  - Petri nets
- Different ways to identify states and events
  - Discretization of dynamic models
  - Process knowledge for identifying states
- Supervisor control
  - Formalism for triggering desired events
  - Using control inputs to move to nominal operation

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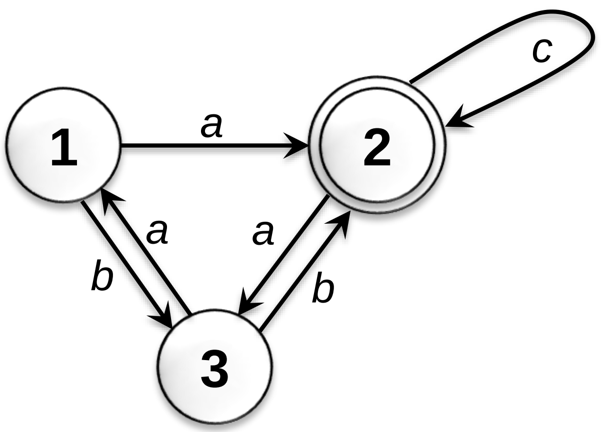
Discrete Event Dynamic Systems

3

Automata

- Directed graph for event systems
- Deterministic automata

$$G_d = (X, E, f, \Gamma, x_0, X_m)$$



$X = \{1, 2, 3\}$

$E = \{a, b, c\}$

$X_m = 2$

$f(1, a) = 2 \quad f(1, b) = 3$

$f(2, a) = 3 \quad f(3, b) = 2$

$f(3, a) = 1 \quad f(2, c) = 2$

$\Gamma(x) = \{a, b\}$ for $x = \{1, 2\}$, $\Gamma(3) = \{a, c\}$

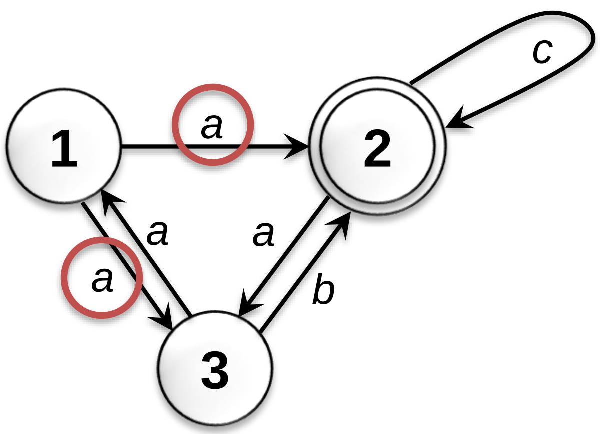
Automata

- Directed graph for event systems
- Deterministic automata

$$G_d = (X, E, f, \Gamma, x_0, X_m)$$

- Non-deterministic automata

$$G_{nd} = (X, E, f_{nd}, \Gamma, x_0, X_m)$$



$X = \{1, 2, 3\}$

$E = \{a, b, c\}$

$X_m = 2$

$f_{nd}(1, a) = \{2, 3\}$ $\quad f_{nd}(3, b) = 2$

$f_{nd}(2, a) = 3$ $\quad f_{nd}(2, c) = 2$

$f_{nd}(3, a) = 1$

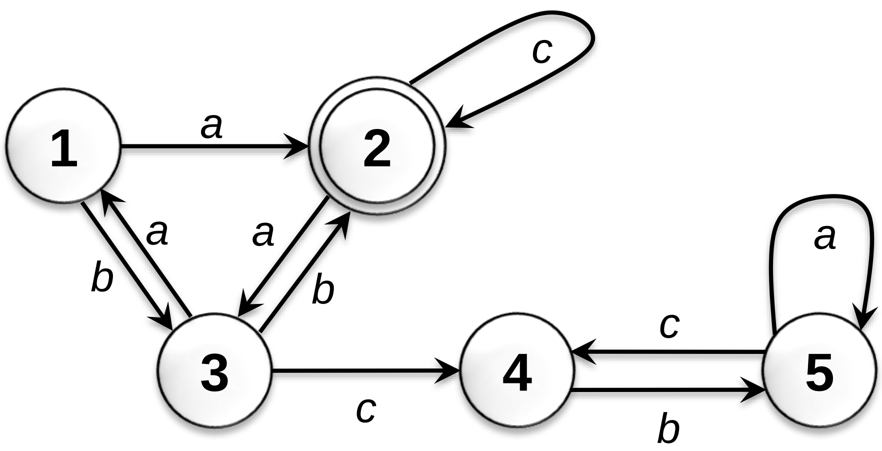
$\Gamma(1) = a$

$\Gamma(2) = \{a, c\}$

$\Gamma(3) = \{a, b\}$

Blocking in automata

- Blocking occurs if
  - States do not have events leading to a marked state — Deadlock
  - A set of unmarked states do not have events leading to a marked state



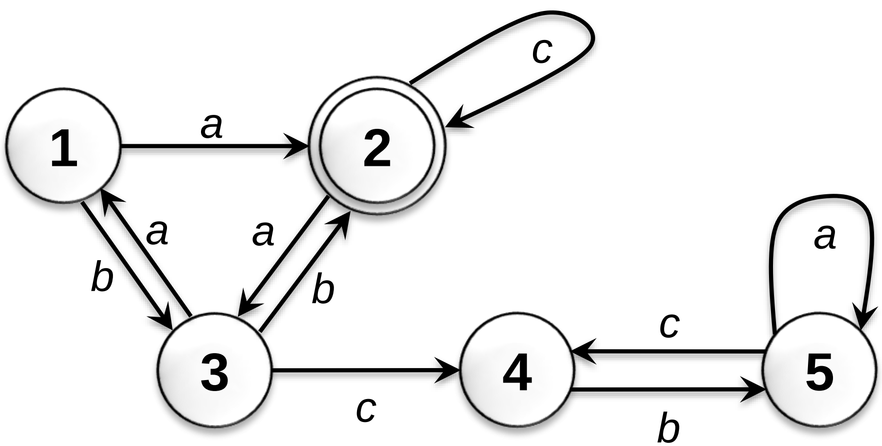
Blocking in automata

- Blocking occurs if
  - States do not have events leading to a marked state
  - A set of unmarked states do not have events leading to a marked state
- Results in undesired behavior

Deadlock

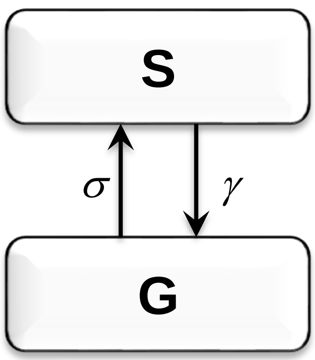
Livelock

→ Locks should be avoided



Supervisor control

- Differentiation between *observable*, *controllable (E_c)*, and *uncontrollable (E_u)* events
  - Controllable events can be disabled
- How does a supervisor look?



  - Automaton
  - Disables event for movement to desired end state
  - Formal rules for supervisor synthesis developed by Ramadge and Wonham
- Supervisor theory can be used for start-up and shut-down of processes

Ramadge and Wonham (1989)

Verification of control system

- Control systems need to be verified
  - Wrong sequences can result in large problems
  - Controller verification tools for hybrid models
- Sequence control system
  - System represented as system of Boolean equations
  - Specification formulated as temporal logic
  - Verification through solution of a series of Boolean satisfiability problems
- Large-scale automation systems
  - Automatically generated process independent tests
  - Coin of influence reduction for handling state explosion

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Mixed logical dynamical systems

- Transformation of propositional logic into linear inequalities
- Automata are MLD systems
- Set-up of a model predictive control (MPC) framework using a mixed integer quadratic program environment
  - Linear dynamic model with integer constraints
  - Quadratic cost function
  - Stability of model is proven
  - Can be used for tracking MPC
  - Allows incorporation of heuristics
- Problems:
  - Model accuracy of linear model over wide range during start-up
  - Consideration of technical constraints like maximum temperature gradient in reactor walls

Bemporad and Morari (1999)

Dynamic scheduling - Concept

- Similar to batch process scheduling
- Automation of procedure development and set-point ramps generation
- Based on a dynamic, detailed models of the overall process
  - Non-smooth formulation of a differential-algebraic system
  - $\dot{\mathbf{x}}(\mathbf{u},t) = \mathbf{f}\left(\mathbf{x}(\mathbf{u},t),\mathbf{y}(\mathbf{u},t),\mathbf{u}(t)\right)$

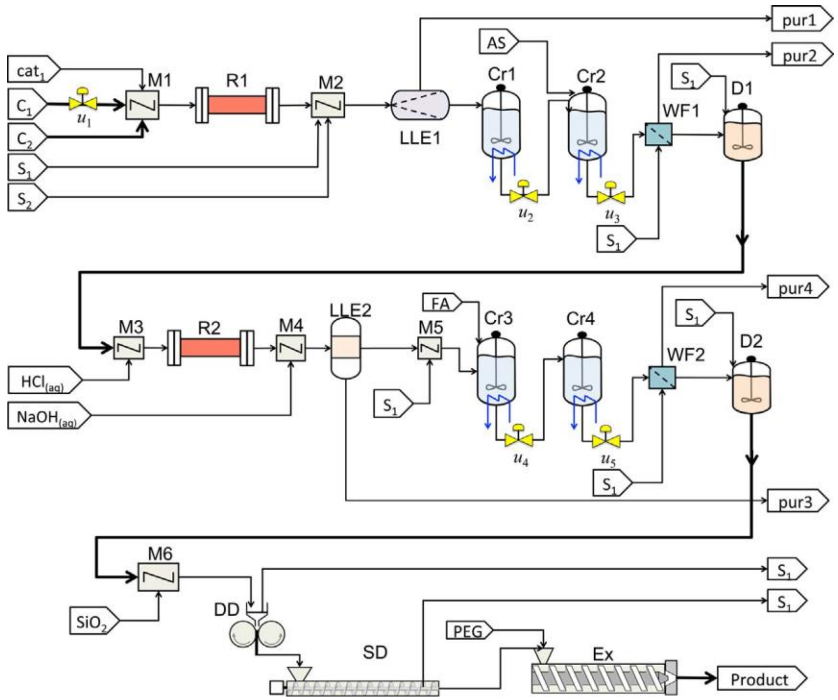
    $\mathbf{0} = \mathbf{g}\left(\mathbf{x}(\mathbf{u},t),\mathbf{y}(\mathbf{u},t),\mathbf{u}(t)\right)$

    $\mathbf{x}(\mathbf{u},0) = \mathbf{x}_0$
  - Production quality constraints
  - Non-smooth formulation through logical operators (min, max, mid)
  - Does not require steady-state for *on-spec* production

Petrescu and Barton (2018)

Continuous production of pharmaceuticals

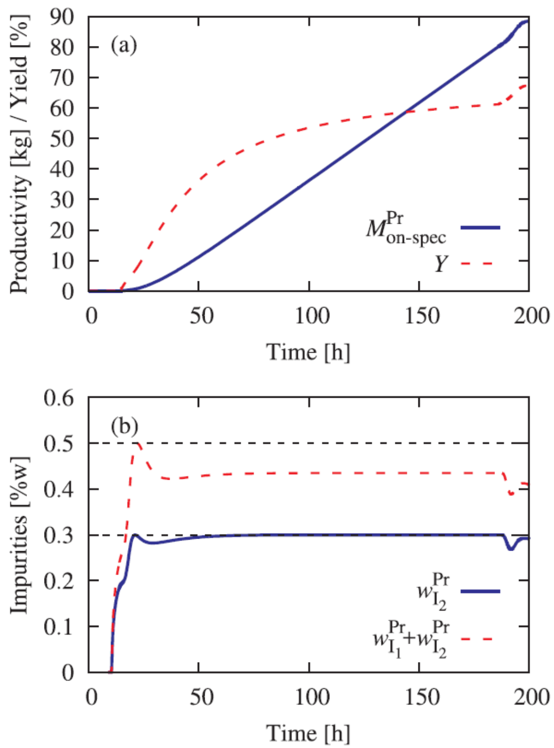
- Aim: Maximizing *on-spec* yield instead of minimizing start-up and shut-down time
- ➢ Can result in *on-spec* in transients

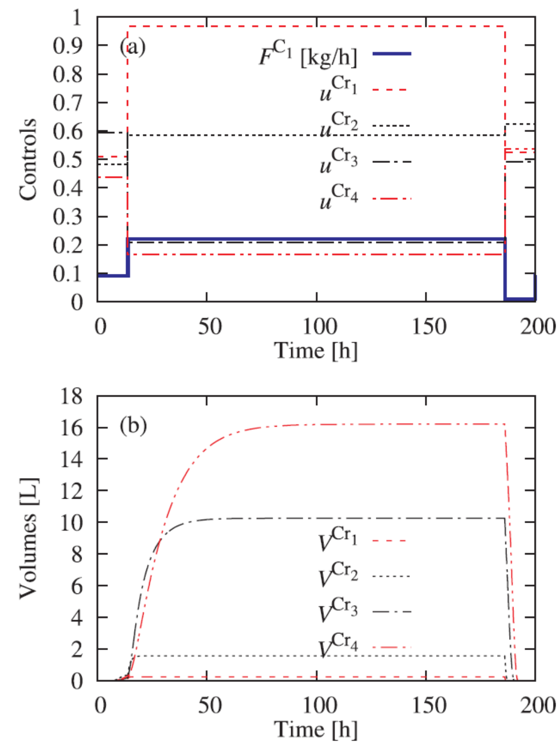


Optimization variables
- 5 valves discretized in time
- Time of each discretization

Petrescu and Barton (2018)

Results of dynamic scheduling





Petrescu and Barton (2018)

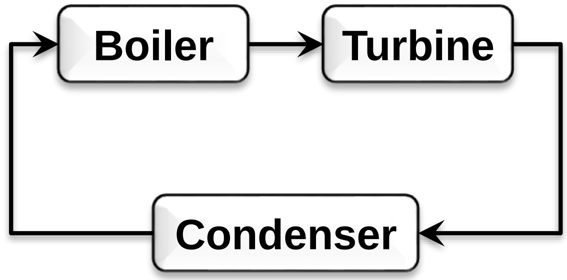
Summary of dynamic scheduling

- Improves *on-spec* production through exploitation of transient operations

- Problems:
  - Simple process results in computational large problems:
    - 878 dynamic equations
    - 1254 algebraic equations
  - Number of decision variables and input discretization small
  - Computational cost: Several hours
  - Plant-model mismatch?

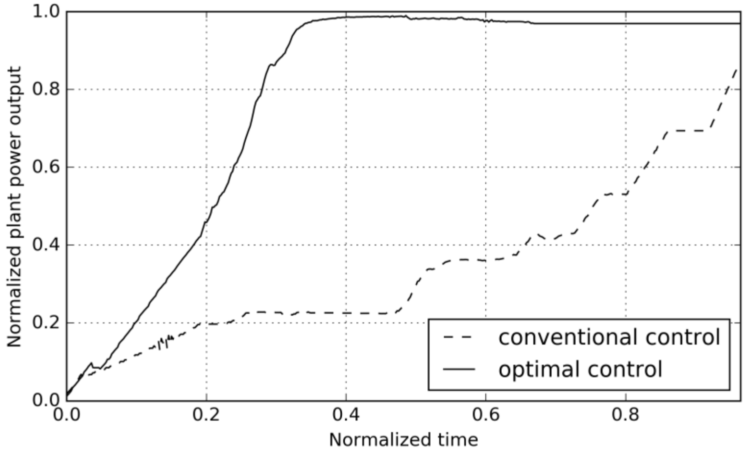
Thermal power plants

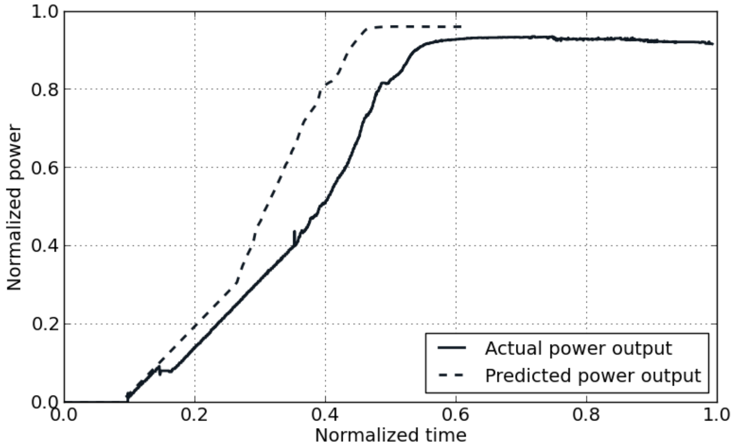
- Extensive research for integration of intermittently available renewable energy sources
- Requires frequent load changes and shut-down/start-up
- Can be seen as simple chemical recycle processes



NMPC in start-up

- Application of NMPC investigated
- Cost function: Maximize profit
- Constraints: Maximum wall temperature gradient





- Included a lower level stabilizing controller
- Does not include explicitly integer variables

Presentation outline

Conclusion

- Current industrial practice follow procedures developed by engineers and based on manual operator set points
- Academic research is less focused on start-up and shut-down of processes
- Lack of communication between different communities

- Discrete event dynamic systems:
  - Process not considered to be continuous but discrete
  - Possibility to introduce a supervisor control (RW framework)

- Dynamic optimization problems:
  - Continuous dynamic model (non-smooth or with integer variables)
  - Give optimal trajectory for the start-up and shut-down

Personal thoughts

- Development of automated control systems useful, when
  - Safety considerations require automated control
  - Development is achievable
  - Start-up and shut-down is frequent

- Problems with current approaches
  - Curse of dimensionality for discrete event dynamic systems
  - Difficulty of developing (and maintaining) accurate plant models for dynamic optimization
  - Limitations imposed by computational hardware and modelling capabilities

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