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# Dynamic Modeling and Optimization of Advanced Energy Systems

**Bethany Nicholson** [a], David Thierry [b], Robert Parker [b], John Eslick [c], Jinliang Ma [c], Quang Minh Le [d], Debangsu Bhattacharyya [d], Lorenz Biegler [b]

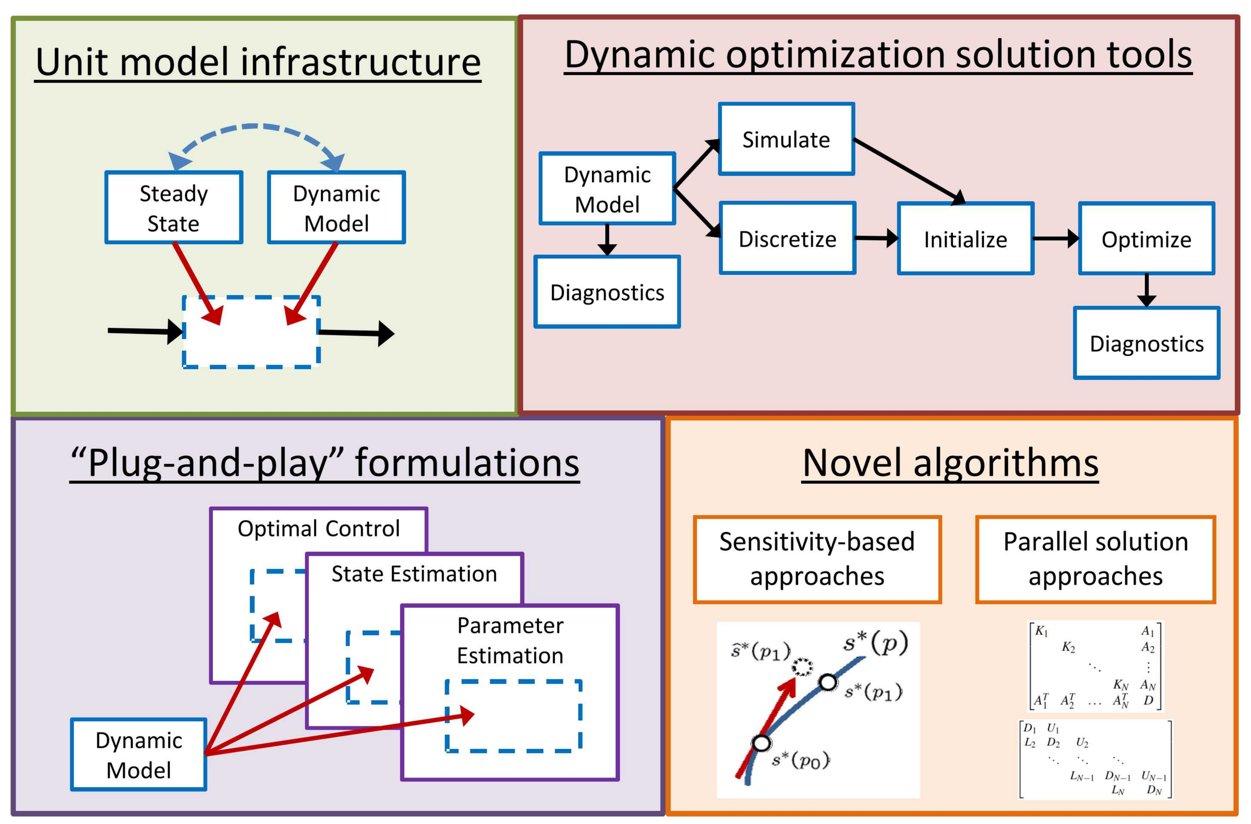
[a] Sandia National Laboratories, [b] Carnegie Mellon University, [c] National Energy Technology Laboratory Contractor, [d] West Virginia University

## Motivation

- Existing fleet of power plants facing increasing pressure to operate more dynamically and participate in load following and ancillary power markets requiring frequent ramping
- For plants designed to operate at steady state there is significant uncertainty in how dynamic operation will affect different parts of the process and how to reconcile increased revenue from more dynamic operation with resulting increased maintenance costs
- Dynamic optimization will allow us to solve for optimal operating conditions while explicitly incorporating process dynamics and constraints

**BUT…** dynamic optimization problems can be difficult to formulate and solve

## Vision for the IDAES Dynamic Optimization Framework




## Advantages

- A single framework for dynamic process model development, simulation, and optimization; no longer need to convert dynamic models from one platform to another to access a wide variety of analysis and optimization tools
- Tools for dynamic model development including:
  - Infrastructure for switching between steady-state and dynamic operation
  - Model identification and parameter estimation tools
  - Sensitivity analysis tools
  - Model reliability and convergence testers
  - Timescale-based model reduction
- Implement models once and use them for a variety of applications using "plug-and-play" frameworks
- Access to general implementations of cutting-edge algorithms
  - Sensitivity-based state estimation and control
  - Decomposition-based parallel solution algorithms

## Timescale-Based Model Reduction

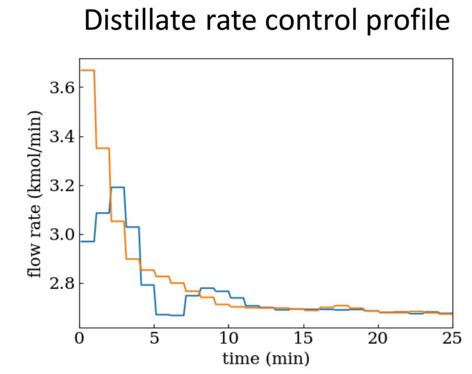
- A fast, accurate model can be created by removing differential states that have little long-time contribution to process dynamics; the challenge is to identify these states
- IDAES framework will incorporate tools for identifying and reducing these states, if they exist, in nonlinear dynamic models

### Standard singular perturbations

Fast states denoted $\hat{z}$: $\epsilon$, assumed small

$$\epsilon\dot{\hat{z}} = \hat{f}(\bar{z},\hat{z},v;\epsilon) \longrightarrow 0 = \hat{f}_z(\bar{z},v)$$

Distillate rate control profile

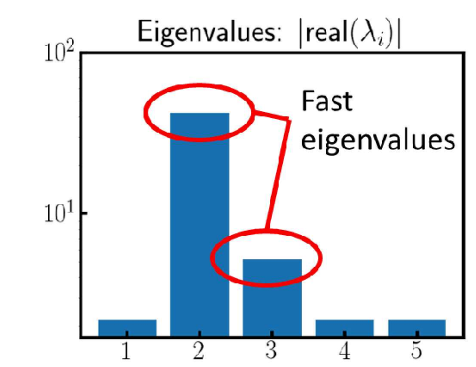



Total control error:
Full Model: 64.4 kmol/min
Reduced Model: 63.8 kmol/min

Average solve time:
Full Model: 207 seconds
Reduced Model: 114 seconds

### Eigenvalue separation

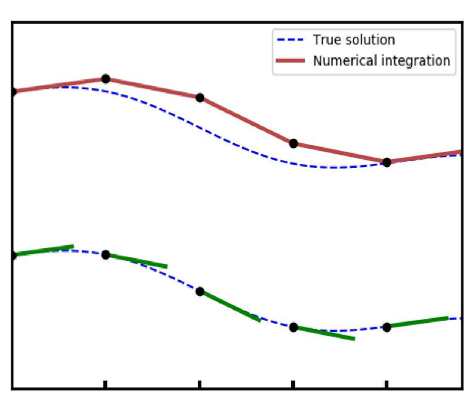
- For a relevant set of $\{\text{initial conditions}\} \times \{\text{perturbations}\}$:
  - Perform eigenvalue decomposition of Jacobian of $f$
  - Solve the corresponding linear system
- Eliminate differential equations corresponding to states associated with fast eigenvalues



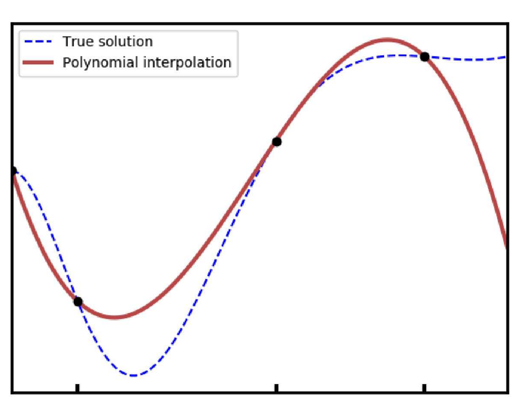

## Dynamic Model Initialization

- Optimization problems with nonlinear dynamic models often require sophisticated initialization strategies to solve reliably
- IDAES framework will include several strategies to initialize dynamic models and flowsheets
- Initialization strategies will include unit model specific initialization routines as well as general utility functions

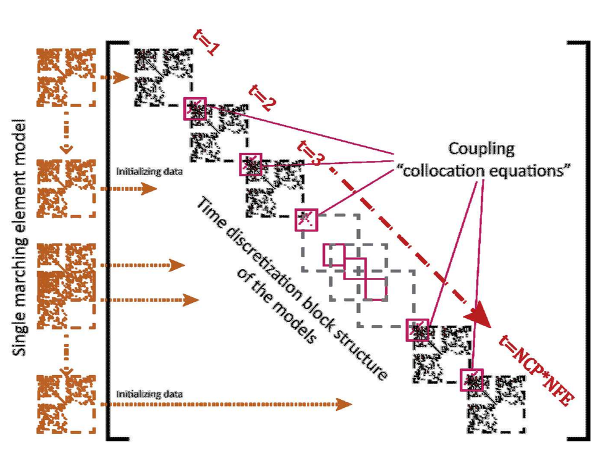
Explicit integration




Implicit integration




Decoupling




- Decoupling approach, or element-by-element initialization, is equivalent to running a fixed-step forward simulation of the dynamic model
- Can also be useful for simulating the dynamic model over long time horizons
- General implementation has been prototyped in the IDAES framework and should be available in the next IDAES-PSE release

Sample code for running decoupling initialization

```
# Declare and discretize dynamic model
...
# Apply decoupling initialization
initialize_by_time_element(m.fs, m.fs.time, solver=solver)
```

## PID Control Blocks

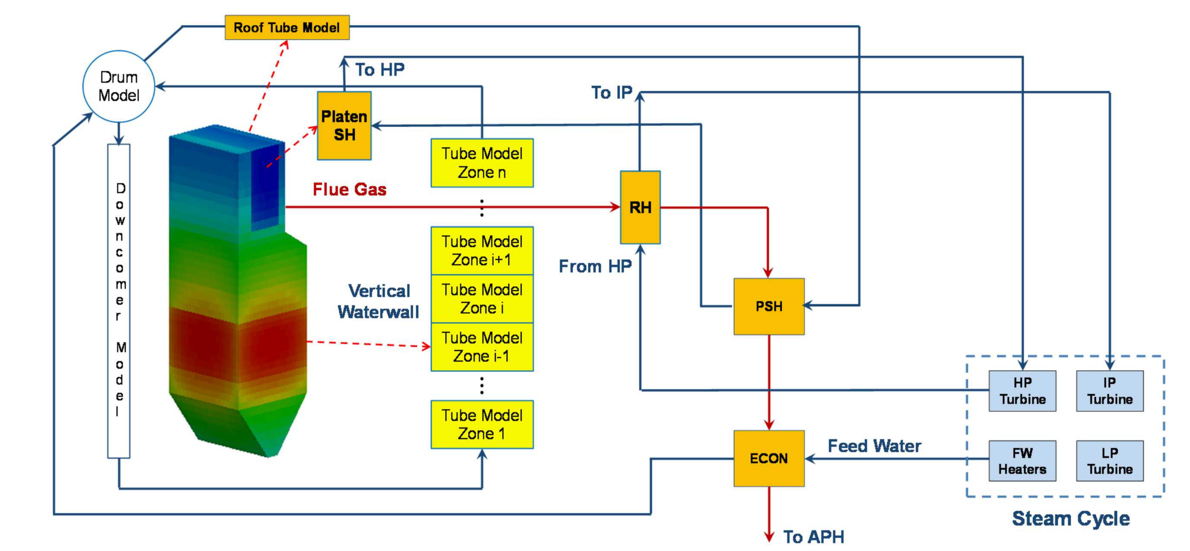
- PID controllers are commonly used for regulatory process control to drive a dynamic system to a steady state
- Modeling regulatory controllers can be important for understanding process dynamics and interactions between process units
- IDAES framework will include PID control blocks for streamlined modeling of regulatory controllers

Sample code for adding a PID control block to any IDAES flowsheet

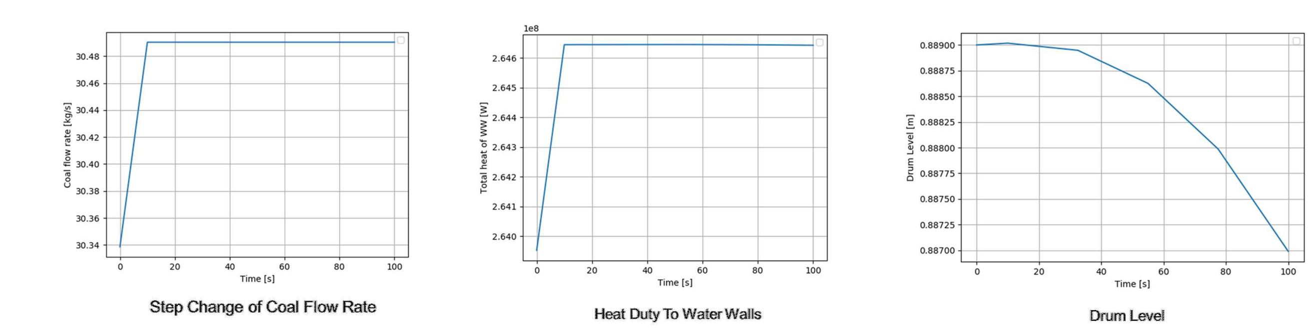
```
# Add a controller
m.fs.ctrl = PIDBlock(default={"pv":m.fs.tank_pressure,
                              "output":m.fs.valve_1.valve_opening,
                              "upper":1.0,
                              "lower":0.0,
                              "calculate_initial_integral":calc_integ})
m.fs.ctrl.gain.fix(1e-6)
m.fs.ctrl.time_i.fix(0.1)
m.fs.ctrl.time_d.fix(0.1)
m.fs.ctrl.setpoint.fix(3e5)
```

## Dynamic Power Plant Model

- Dynamic power plant unit models currently being tested and refined:
  - Drum
    - 0-D and 1-D
  - Downcomer
  - Waterwall sections for each boiler model zone
  - Steam heater (for platen and roof superheater)
  - Cross flow heat exchangers (for SH, RH, economizer)
    - 0-D and 1-D
  - Water tank (for condenser hotwell)




- Full subcritical power plant flowsheet
  - Includes both the boiler and steam cycle units
  - Steam cycle units modeled as steady-state (turbines, condensers, FWHs, pumps)
  - Open loop simulation: 28,532 variables
  - CPU time: ~20 minutes

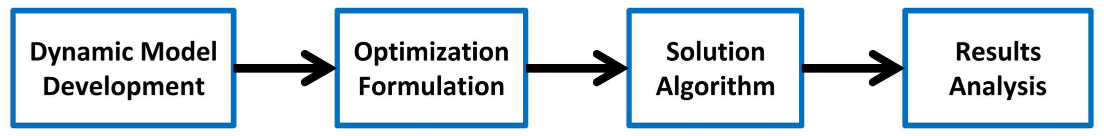



- Plans for 2020:
  - Enable dynamic features in steam cycle models
  - Dynamic data reconciliation and parameter estimation
  - Couple with stress/damage models to quantify cost of load following operation
  - Dynamic optimization and advanced control

## Conclusions

Explicitly modeling process dynamics creates opportunities for:
- improving the operation of existing plants
- designing efficient and flexible future energy systems

Dynamic optimization tools being developed with emphasis on:
- ease of use, flexibility, and complete life cycle support




## Contact

Bethany Nicholson: blnicho@sandia.gov



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