Scheduling, Optimization and Control of Power for Industrial Cogeneration plants

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Outline

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  - Highlights
  - Process Model development
  - Model validation
  - Power Scheduling
  - Real-time Optimization and Control
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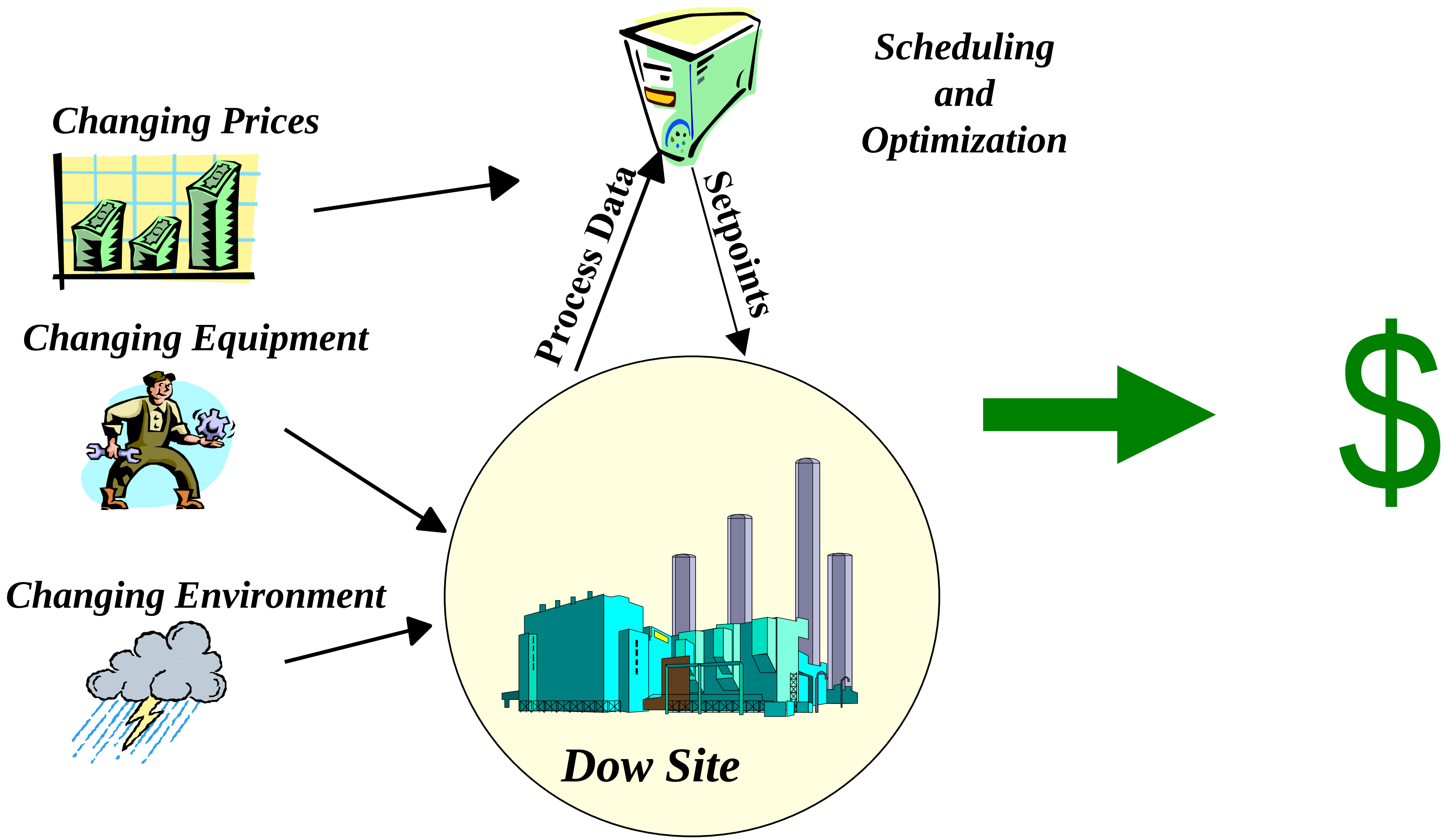
- Conclusions

Literature

- Survey of short-term planning of cogeneration plants: Salgado and Pedrero (*Electric Power Systems Research,* 2008)
- Scheduling: Havel and Simovic (*Electric Power Systems Research,* 2008), Mitra et al. (*Energy,* 2013), Alipour et al. (*Energy,* 2014), Bindlish (Comp. and Chem. Eng.,2016)
- Fundamental nonlinear models for design: Varbanov et al. (*Chem Eng Res and Design,* 2004), Koch et al. (*Chem. Eng. and Processing,* 2007), Godoy et al. (*Applied Thermal Engineering,* 2011)
- Fundamental nonlinear models for on-line optimization: Emoto et al. (*Proc of the 1998 IEEE International Conference on Control Applications,*1998)

Scheduler


Changing Prices
Changing Equipment
Changing Environment
Scheduling
and
Optimization
Process Data
Setpoints
Dow Site
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Scheduler Highlights

Application of first principle, non-linear models with following details:

1. Model tuned continually with plant data and also used for online optimization
2. Accounts for equipment that gets switched on or off
3. Includes process control strategy that may use different equipment in an hierarchical manner
4. Control curves and design performance curves for equipment

Scheduler Highlights

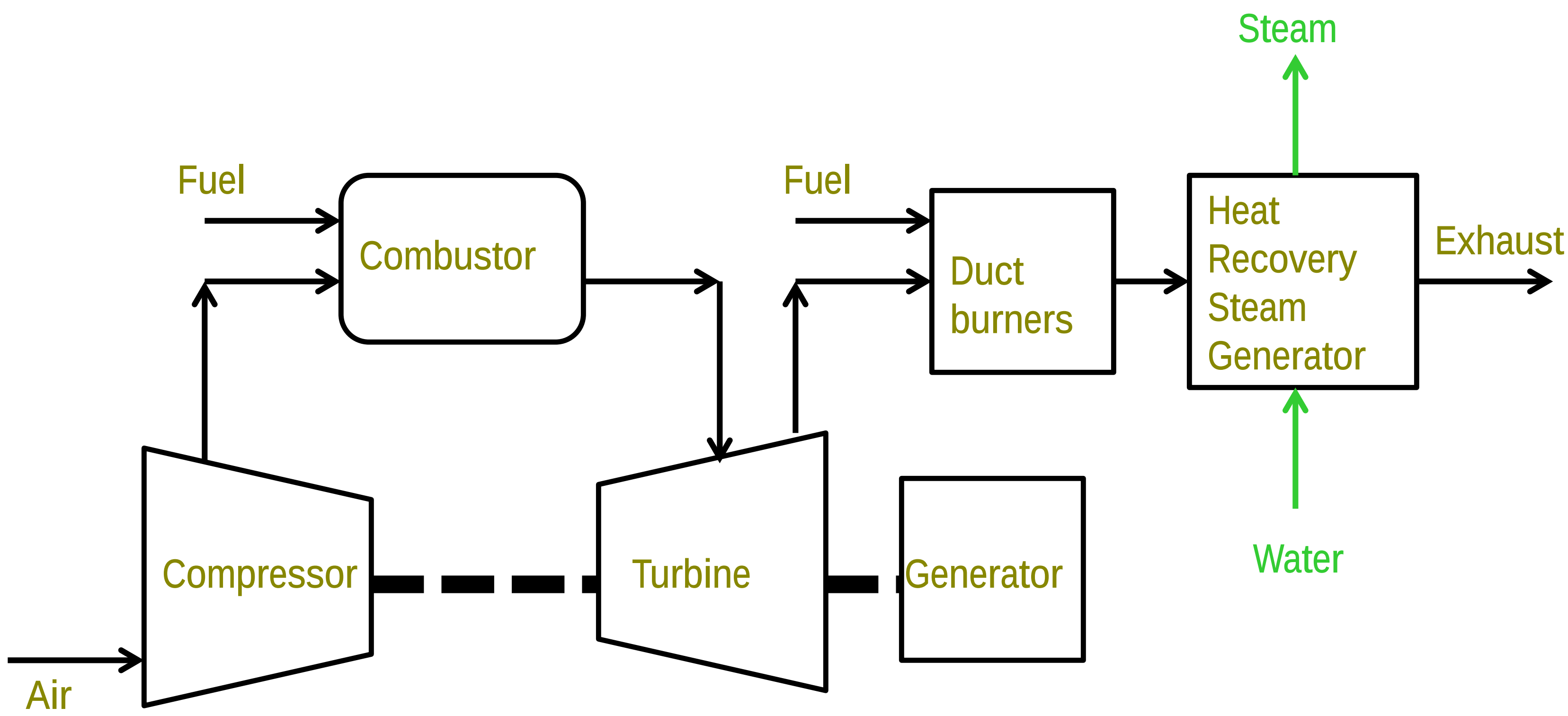
Scheduling application also has following capabilities:

1. User can input future ambient temperature
2. User can switch parts of plant on or off to account for equipment contingency

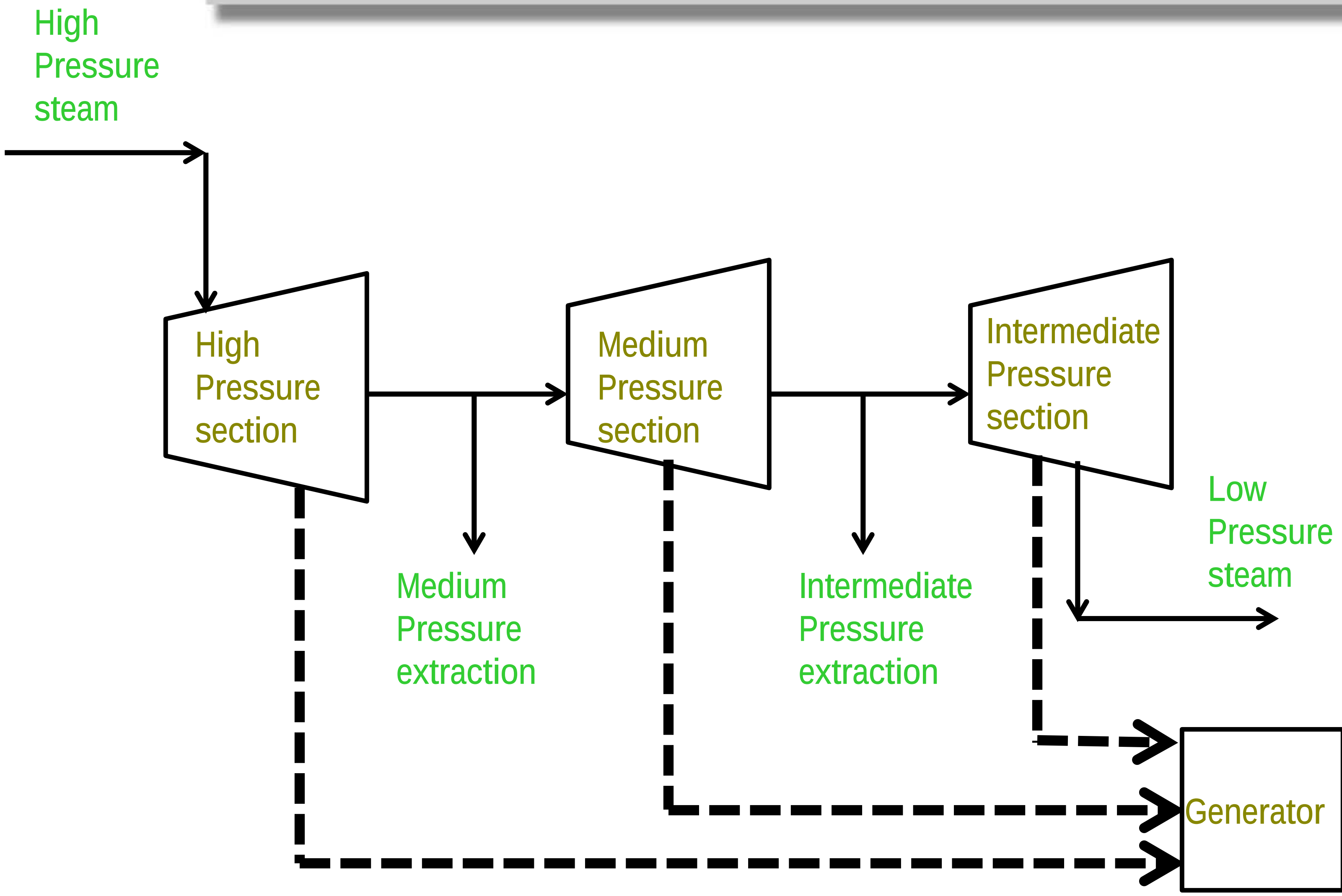
Process Model Development

- Model developed using Aspen Plus Optimizer; Aspen Technology, Inc.'s equation oriented modeling environment
- Process has seven gas turbines and five steam turbines
- Steady-state model has component material balances, energy balances and thermodynamics
  - Approximately 18000 equations

Gas Turbine

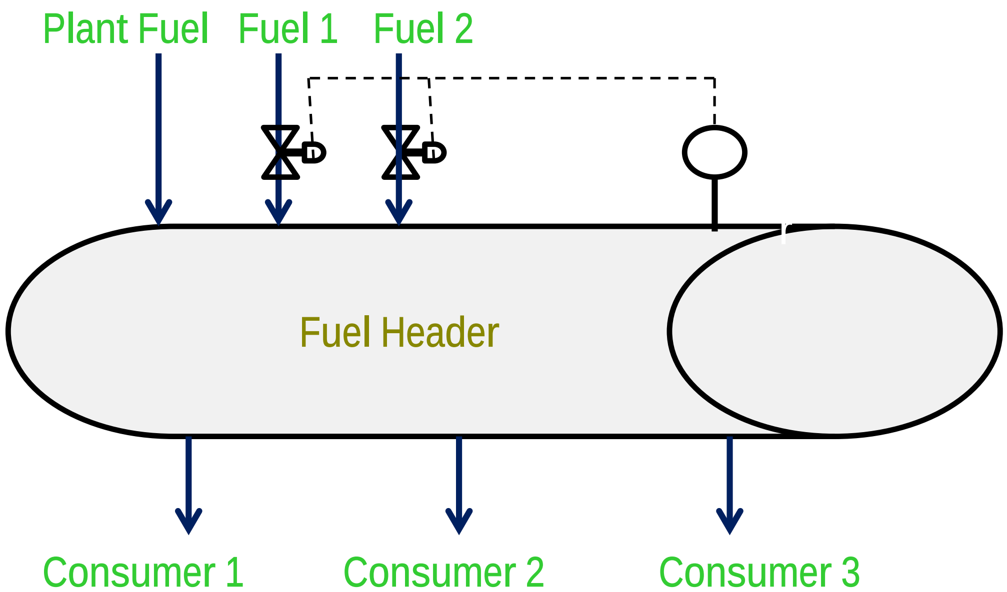

Steam
Fuel
Combustor
Fuel
Duct burners
Heat Recovery Steam Generator
Exhaust
Compressor
Turbine
Generator
Water
Air

Steam Turbine

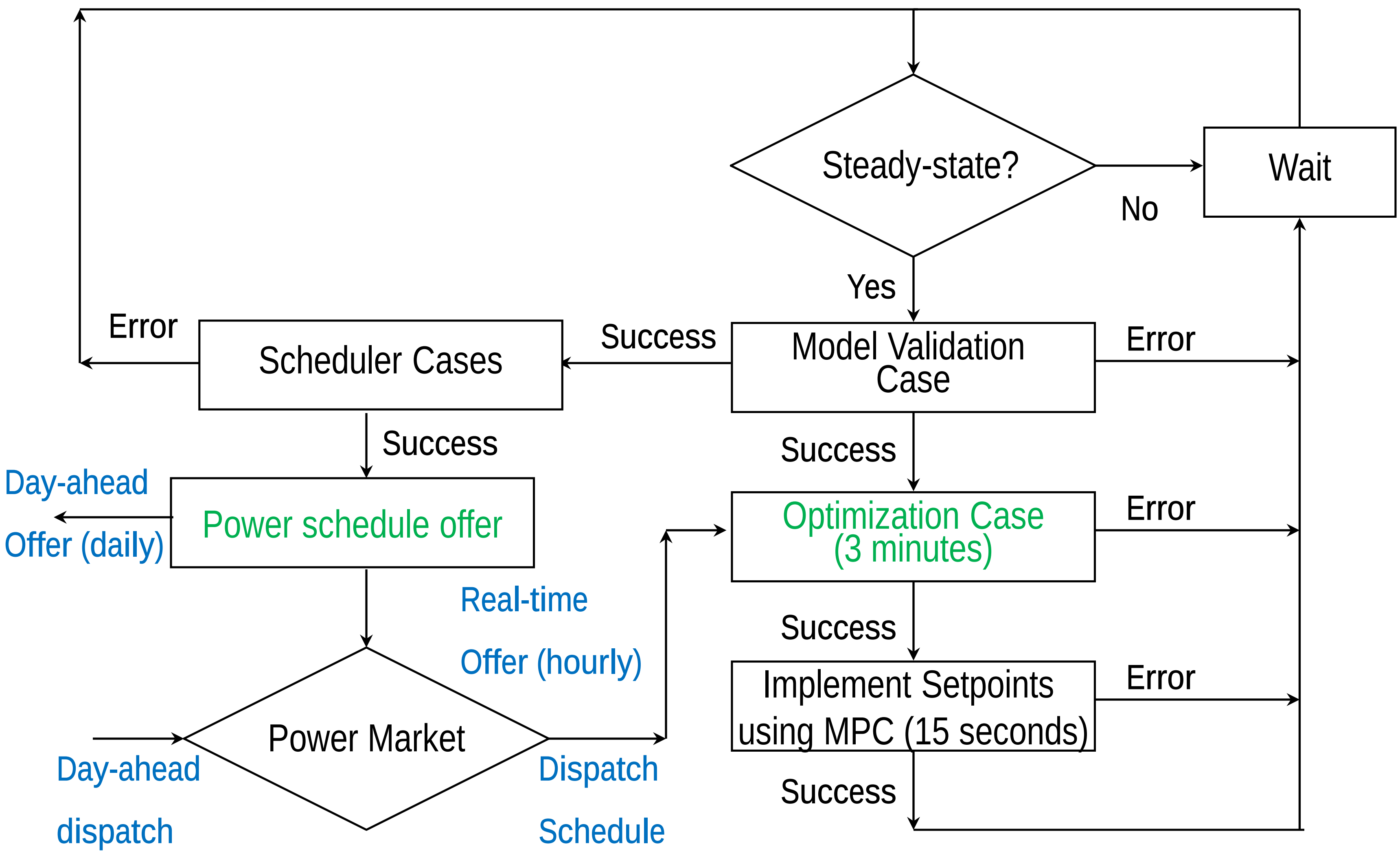


Fuel Header Control

- Hierarchical Control Strategy
  - Plant produced fuel will be used completely
  - First fuel will be used next till a certain flow limit
  - Second fuel will be used to fulfill the consumer requirements after the flow limit



Scheduler and Real-Time Optimization



Steady-state detection

Light and heavy filter applied to key measured data (X):

$$\bar{X}_L(t) = f_L\, X(t) + (1 - f_L)\bar{X}_L(t - 1), 0.7 < f_L < 0.95$$

$$\bar{X}_H(t) = f_H\, X(t) + (1 - f_H)\bar{X}_H(t - 1), 0.05 < f_H < 0.3$$

Short-term disturbance detection:

$$|\bar{X}_L(t) - \bar{X}_H(t)| \leq X_{tol}$$

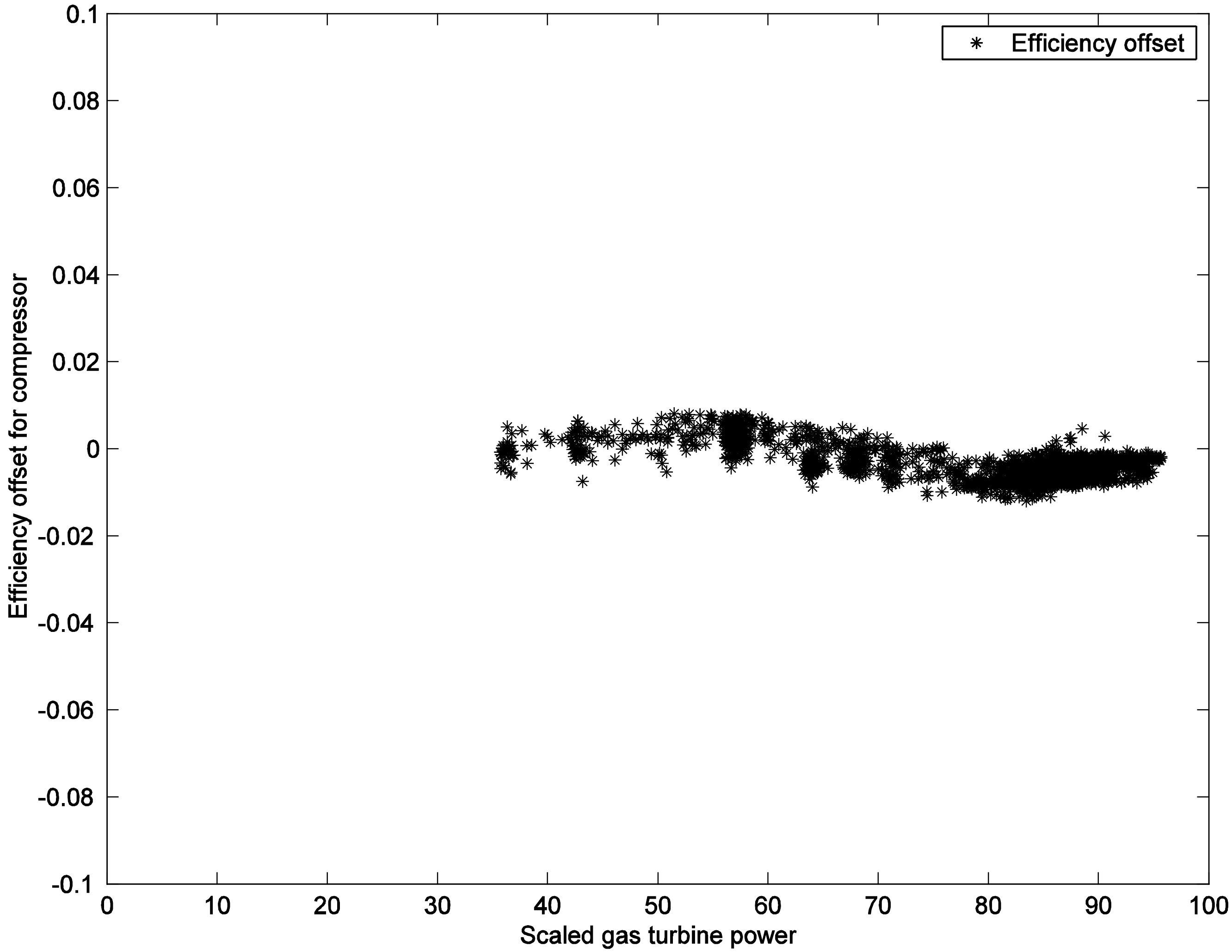
Long-term trend detection:

$$|\bar{X}_H(t) - \bar{X}_H(t - 5)| \leq X_{trend}$$

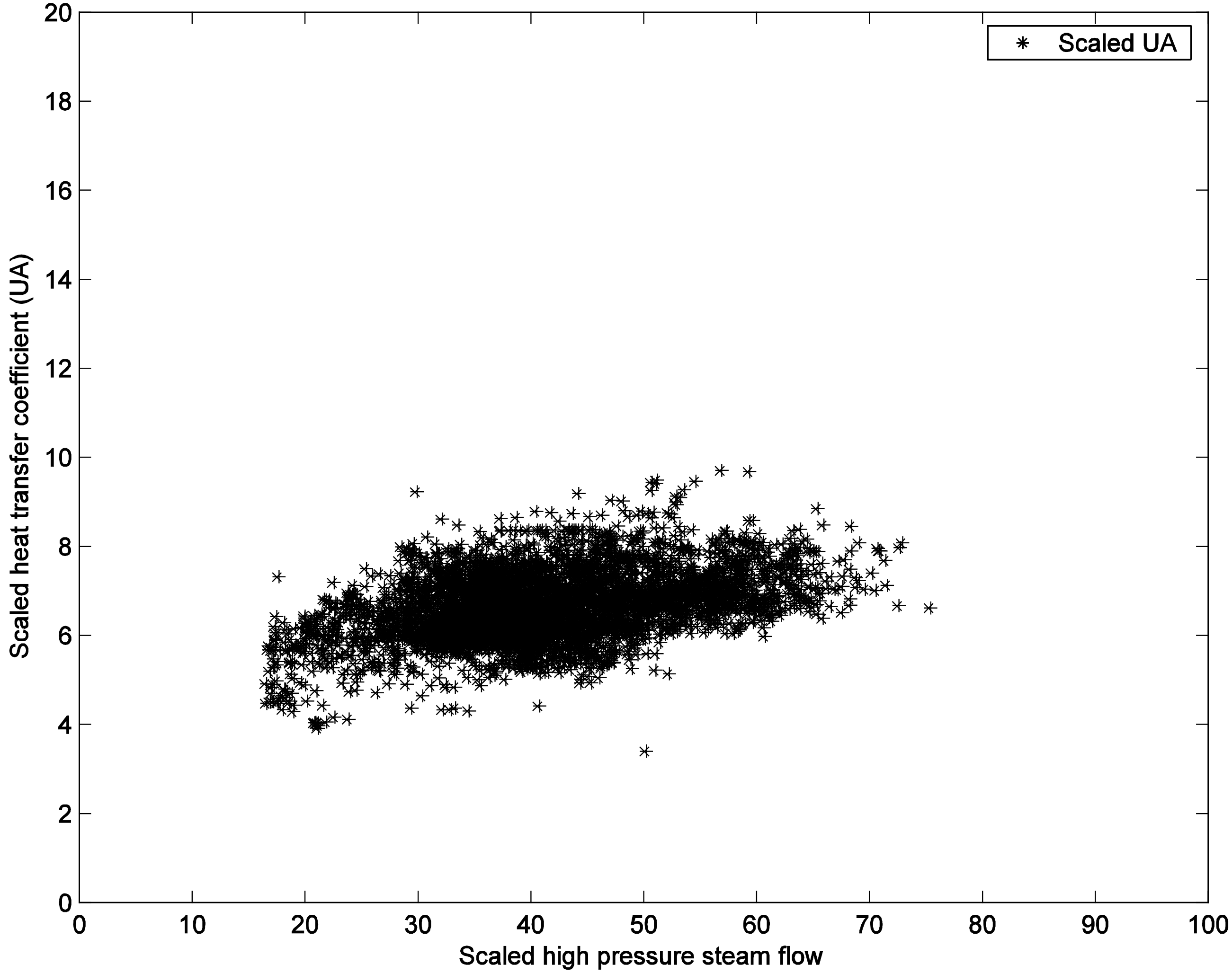
Model validation

- On-line model validation by fitting approximately 300 parameters
- Model parameters trended to ensure stability with varying plant rates and conditions
- Plant data screened against validity limits before using it for parameter calculations
  - » Use last good value of model parameter when data is invalid

Model Validation



Model Validation



Power Scheduling

Exported power:

$$Power_{\exp} = Power_{gas} + Power_{steam} - Power_{demand}$$

Heat rate:

$$Heat\ rate = \frac{Fuel\ input}{Output\ power}$$

Incremental heat rate:

$$Incremental\ Heat\ rate = \frac{\Delta Fuel\ input}{\Delta Output\ power}$$

Market heat rate:

$$Market\ Heat\ rate = \frac{Power\ Cost}{Fuel\ Cost}$$

Power Scheduling

Power offer curve for exported power and incremental heat rate includes:

1. Minimum exported power
2. Exported power with gas turbines at maximum load without supplemental firing of duct burners (Base load)
3. Maximum exported power

Real-time Optimization

Nonlinear objective function to minimize total operating cost subject to process constraints and tieline limits:

$$\min_{DOF} \Phi = \sum_j (Fuel_j \times Cost_j) + (Condensate \times Cost_{cond}) - (Power_{\exp} \times Cost_{power})$$

$$f(x,u,d,b) = 0,\ y = h(x,u,d,b)$$

$$(Power_{\exp}^{sched} - \delta) \le Power_{\exp} \le (Power_{\exp}^{sched} + \delta)$$

Exported power is optimized within a deviation band from the schedule

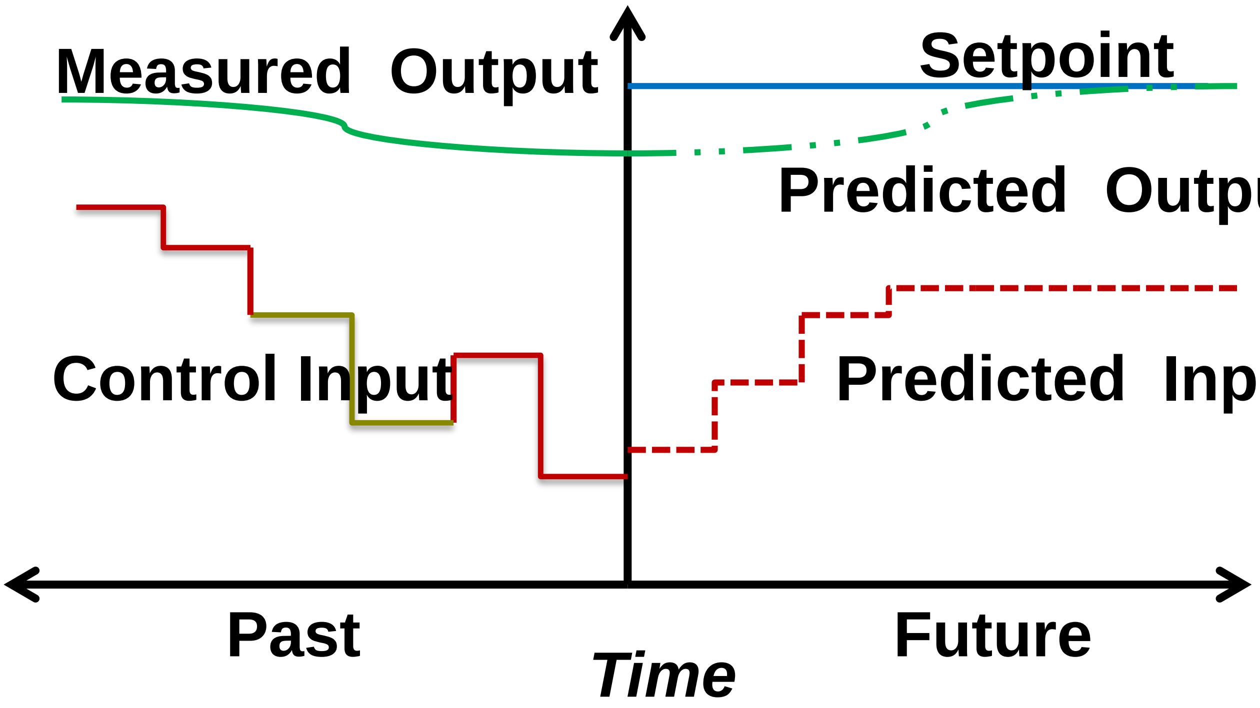
Real-time Optimization

<u>Degrees of Freedom (DOF) or optimized variables:</u>

- Gas turbine power
- Steam produced from duct burner firing (supplemental firing)
- Steam turbine power
- Steam turbine extraction flows

Model Predictive Control

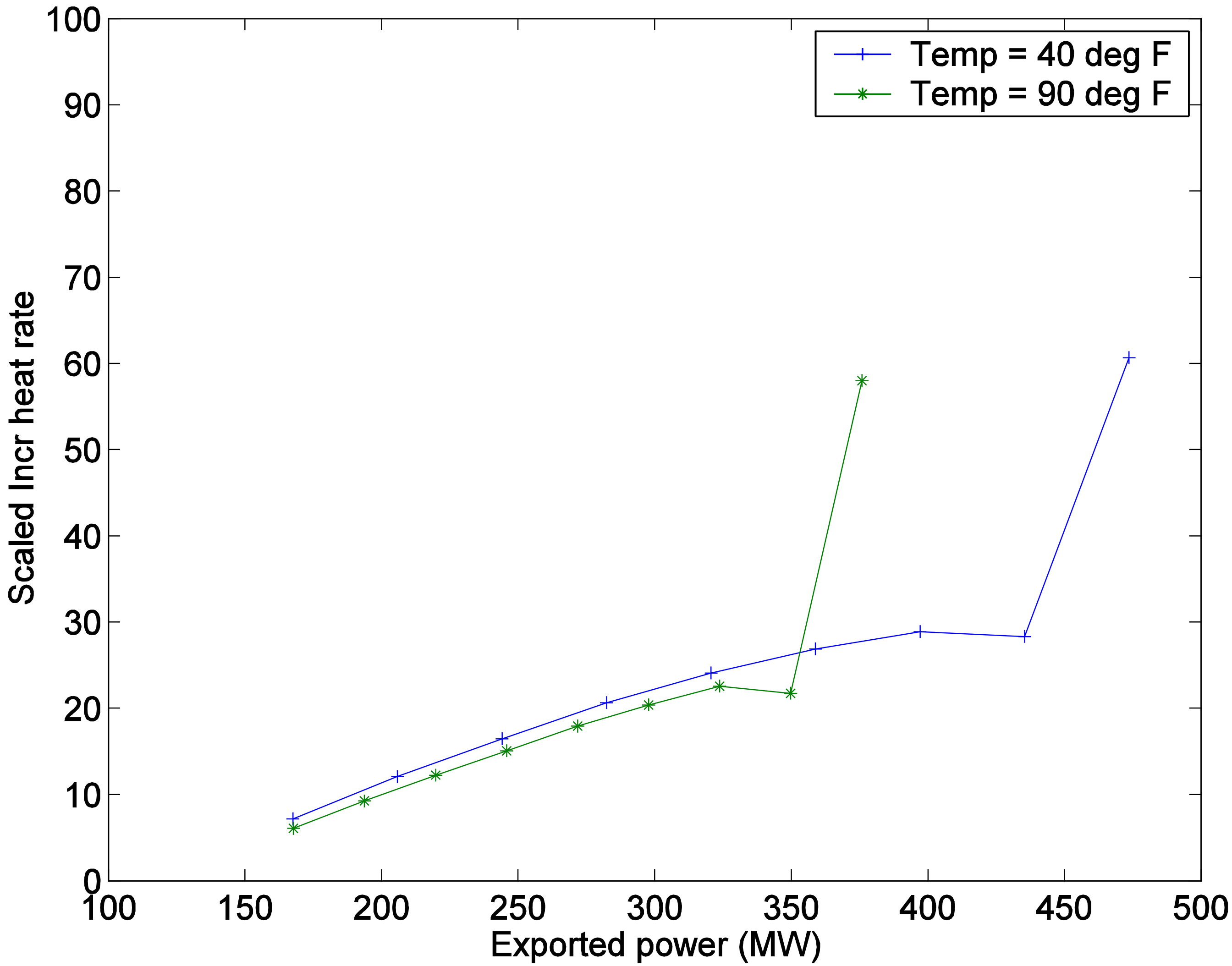
Implement inputs that minimize expected deviation of outputs from control objectives over a future horizon using a linear MPC (Aspen DMCplus)



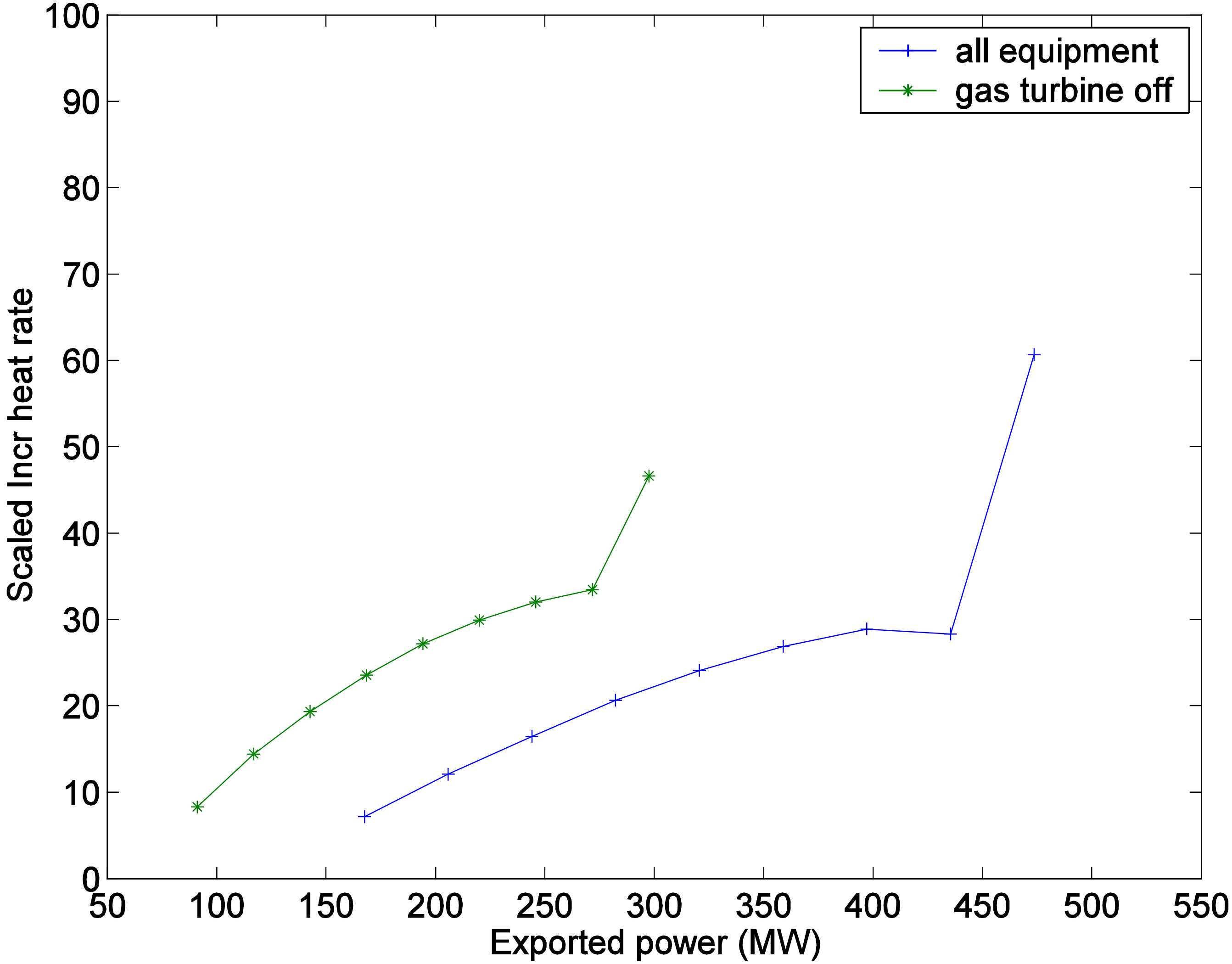
Process Constraints

Constraints	Relative Ranking (Priority)
Valve position	1
Environmental limits	2
Steam pressure	3
Fuel gas pressure	4
Fuel gas ratio	5
Exported power target	6
Gas turbine exhaust temperature	7
Steam condenser flow	8
Heat duty of duct burners	9
Gas turbine power	10
Steam turbine power	11

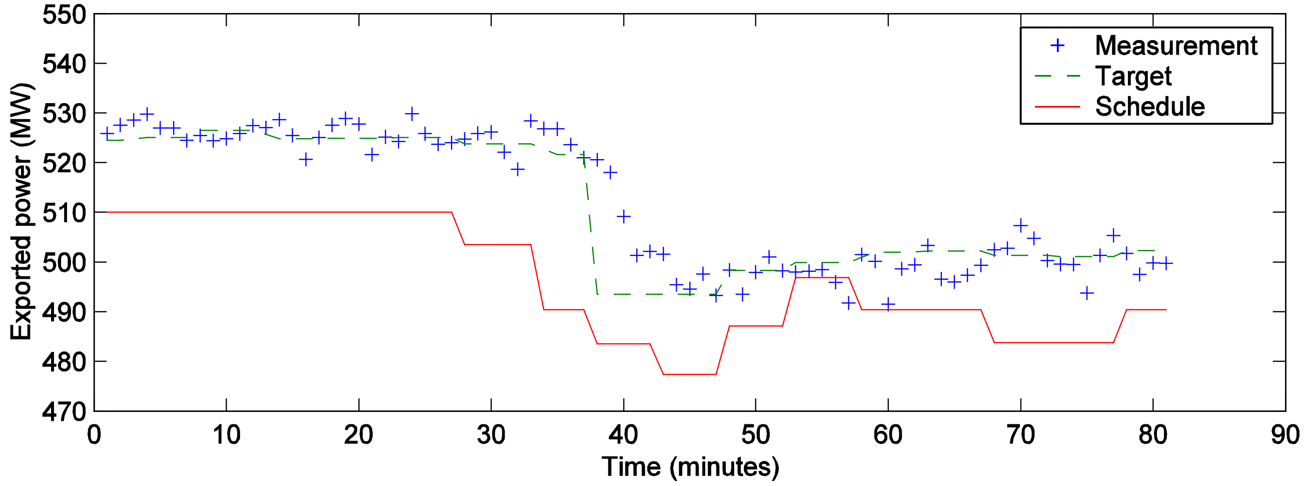
Power Schedule

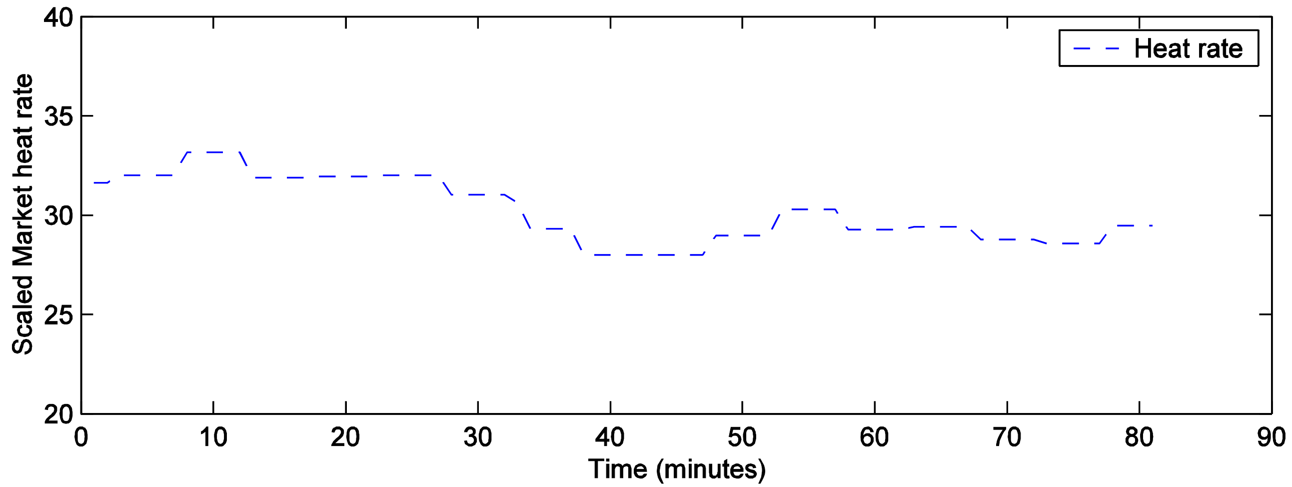


Schedule for Equipment Contingency



Exported Power Control





Results

- Scheduled power offer curve is accurate within 2 percent error from plant data
  - Uses fundamental nonlinear model with details of control strategies and equipment control curves
  - Continuous model validation with real-time plant data
  - Accounts for ambient temperature and equipment contingency
- Parameter stability is ensured over the entire operating range for model validation
- Linear model predictive controller (Aspen DMCplus) is shown to be effective for implementation of the optimized power schedule

Conclusions

- Scheduler has been in continuous use since January 2014
- Enabled realization of significant benefits
  - 12.8 percent improvement in power sales margin compared to selling power without scheduling
- Scheduler implementation has also resulted in more stable operation for plant

Questions