”Change is Certain, Future is Uncertain”

-- Bertrand Russell

Webcast: Design, Analysis, and Optimization of Integrated Power Plant and Water Management Systems

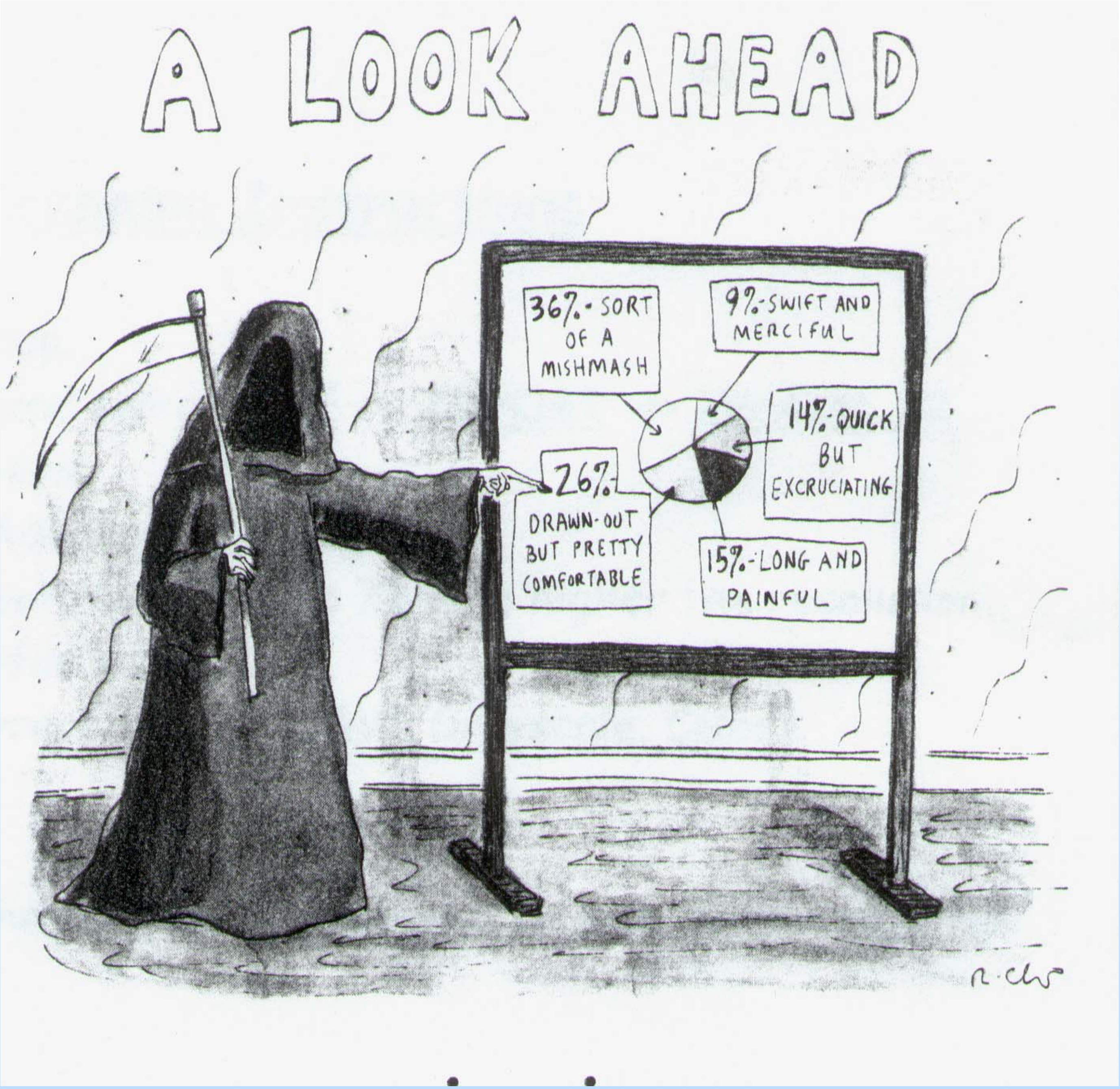
Thursday November 18th, 2010

View Recording

https://www.livemeeting.com/cc/epripremier/view

Recording ID: 27PQPB

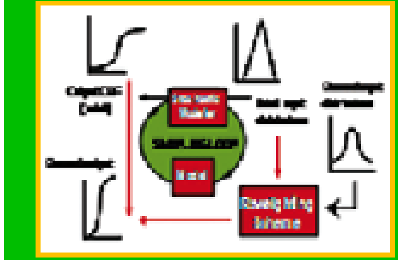
Attendee Key: ACT11/2010


A LOOK AHEAD
36%- SORT OF A MISHMASH
9%-SWIFT AND MERCIFUL
14%-QUICK BUT EXCRUCIATING
26%- DRAWN-OUT BUT PRETTY COMFORTABLE
15%-LONG AND PAINFUL

Center for Uncertain Systems: Tools for Optimization and Management

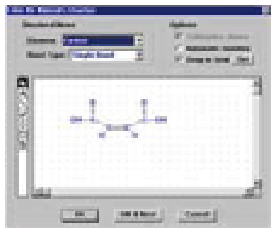
CUSTOM

Algorithms, Methods & Tools



The aim of this area is to develop state-of-the art mathematical techniques facilitating the main application areas of the institute. In most cases the decision making problem is posed as an optimization problem. Therefore, novel algorithms are developed for linear, nonlinear, mixed integer problems in the face of multiple objectives. Major efforts are devoted to uncertainty characterization, quantification, and propagation, necessitating efficient algorithms for sampling, optimization under uncertainty, and stochastic optimal control. Based on these algorithms, methods and tools are designed to handle real world problems in design, control, management and planning.

Materials & Molecular Modeling



The search for new molecules possessing desired physical, chemical, biological and health properties is an important and ongoing process in various industries. Such a search encompasses problems of designing polymers, refrigerants, solvents, composites and blends, drugs, agricultural chemicals, fuels, paints, varnishes and perfumes among others. It has a major role to play in the overall economics of these industries. The main focus of this area is to improve a accuracy and efficiency of the predictive models as well as the molecular and group selection methods.

Energy & Environment

The main focus of the energy research is greener & sustainable energy systems. This includes small to large scale systems for stationary as well as transportation applica-tions. The objective is to provide optimal design and management strategies for these systems. The energy options being looked at include, advanced power systems with environmental control, integrated gasification systems, fuel cell based power systems and renewable energy systems including bio-refineries. The environmental initiative carries the similar objectives for a much broader scale of industrial and socio-economic systems.

Sustainability & Security

Sustainability and security constitute highly interdisciplinary research fields, since the issues at the core concern a broad spectrum of entities, from the industries to socio-economic systems, and to ecosystems. The research work in this field, in collaboration with various national laboratories, contributes towards different aspects of these issues. This starts with the reliable identification, modeling and quantification of security risk and sustainability matrix, and paves way for devising innovative management strategies to achieve the desired objectives. Once the most appropriate management plan has been envisioned, the time dependent as well as independent strategies are derived to optimize the individual as well as the combined objectives of the various stakeholders, thereby achieving sustainability.

Manufacturing, Planning & Management

Financial management, environmental management, capacity planning, supply chain management, and control problems are integral part of a successful manufacturing facility. Uncertainties are inherent in operation, management, and planning. In fact, the essence of financial planning is the incorporation of risk in investment decisions. Both static and dynamic uncertainties enter in these problems making them the hardest in terms of decision making. Physical systems like molecular modeling can provide a framework for modeling financial decision process. Similarly, financial management theories like real option theory can help in deriving time-dependent decisions related to manufacturing and control. The multi-disciplinary approach in this institute. provides a framework for exploiting knowledge from one discipline to address question from other discipline.

Biomedical Engineering

The main focus of the VRI biomedical engineering research is drug delivery using optimal control and stochastic optimal control methods. Models in biomedical engineering are fraught with uncertainties and variabilities. Time dependent decisions are necessary for drug delivery which leads to optimal control problems. Modeling time dependent uncertainties is studied in financial literature. This research extends these theories to problems in biomedical engineering. The problems currently studied are drug delivery for diabetes, HIV, and cancer patients.

RESEARCH

Design, Analysis, and Optimization of Integrated Power Plant and Water Management Systems

Urmila Diwekar

Center for Uncertain Systems: Tools for Optimization & Management

Vishwamitra Research Institute

urmila@vri-custom.org

Presentation Outline

- Introduction
- Project Goals and Objectives
- Case Study
  - Existing Pulverized Coal (PC) Power Plant
  - Water Consumption
  - Cooling Tower Models
  - Uncertainties
  - Optimization under Uncertainty
- Results and Conclusions
- Future Work

Program Technology Area

DOE-NETL Water R&D

- General Water R&D Goal Addressed
  - Improve water reuse and recovery for coal-fired power plants, thereby reducing freshwater use and impacts of fossil fuel electric generation on the nation’s freshwater resources
- DOE-NETL Water R&D Goals Addressed
  - Short-Term (by 2015): Reduce freshwater withdrawal and consumption by 50% or greater for thermoelectric power plants equipped with wet recirculating cooling technology at a levelized cost of less than $4.40 per thousand gallons freshwater conserved.
  - Short-Term (by 2020): Reduce freshwater withdrawal and consumption by 70% or greater at a levelized cost of less than $2.90 per thousand gallons freshwater conserved.

Project Goals and Objectives

- Project Goals
  - Design new technologies for minimization of water reuse and recycle
  - Characterize uncertainties in weather conditions and their effect on plant performance
  - Optimize plant for water minimization under uncertainty
  - Configure plant to minimize water use and increase efficiency
- Project Objectives
  - Create process simulation-based tool for water management in a coal-fired power plant
  - Develop algorithm framework for the synthesis, design, analysis, and optimization of integrated power plant and water networks
  - Establish simulation baselines and evaluate new technologies
- Success Criteria
  - % savings in water consumption

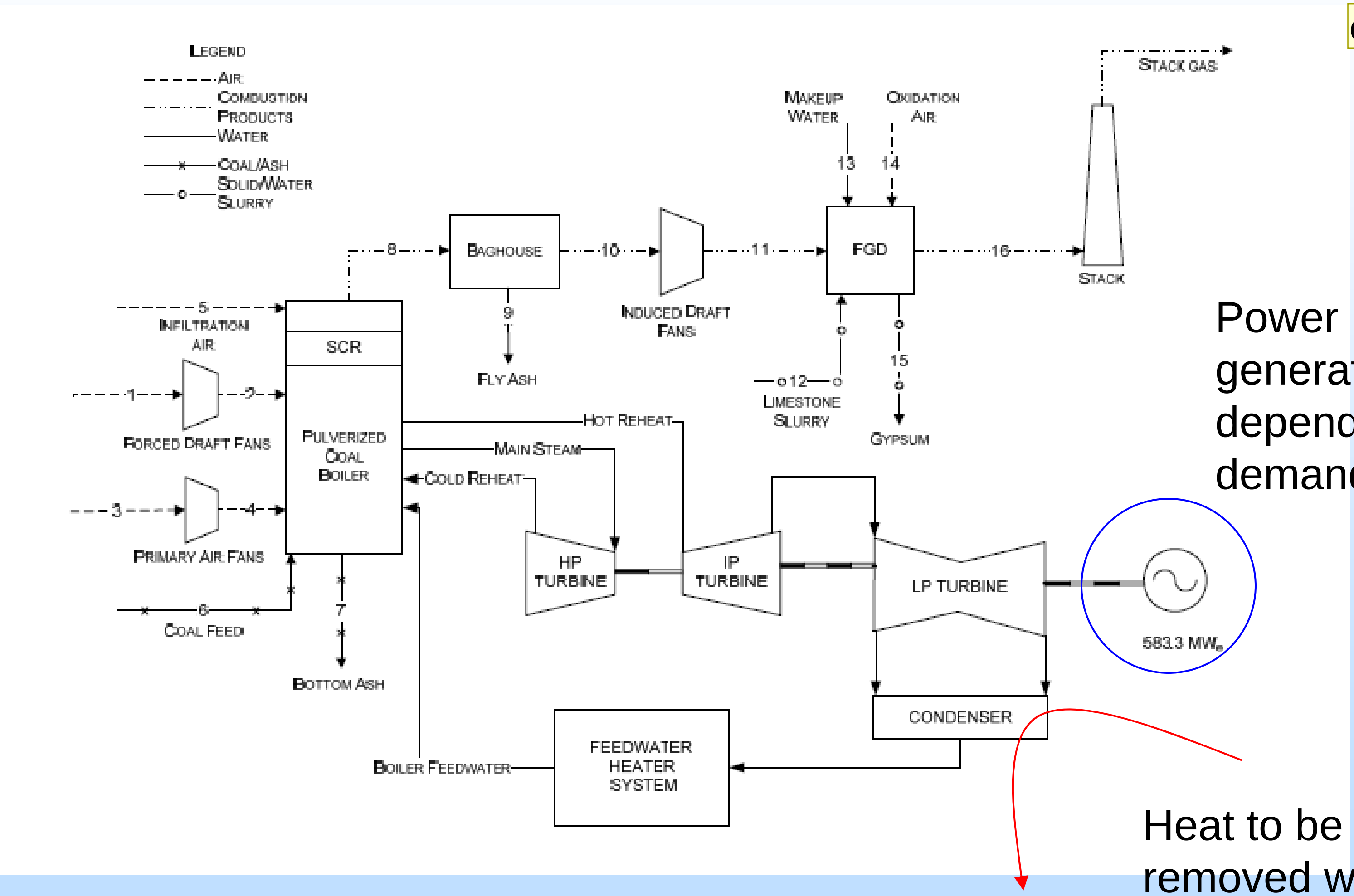
Case Study: PC Power Plant

Plant Type	ST Cond. (psig/°F/°F)	GT	Gasifier/ Boiler	Acid Gas Removal/ CO_2 Separation / Sulfur Recovery	CO_2 Cap
IGCC	1800/1050/1050 (non-CO_2 capture cases)	F Class	GE	Selexol / - / Claus	0%
				Selexol / Selexol / Claus	90%
			CoP E-Gas	MDEA / - / Claus	0%
	1800/1000/1000 (CO_2 capture cases)			Selexol / Selexol / Claus	88%[1]
			Shell	Sulfinol-M / - / Claus	0%
				Selexol / Selexol / Claus	90%
PC	2400/1050/1050		Subcritical	Wet FGD / - / Gypsum	0%
				Wet FGD / Econamine / Gypsum	90%
	3500/1100/1100		Supercritical	Wet FGD / - / Gypsum	0%
				Wet FGD / Econamine / Gypsum	90%
NGCC	2400/1050/950	F Class	HRSG		
				- / Econamine / -	90%

"Cost and Performance Baseline for Fossil Energy Power Plants Study, Volume 1: Bituminous Coal and Natural Gas to Electricity," National Energy Technology Laboratory, www.netl.doe.gov, August 2007.

Case Study: PC Power Plant

d1



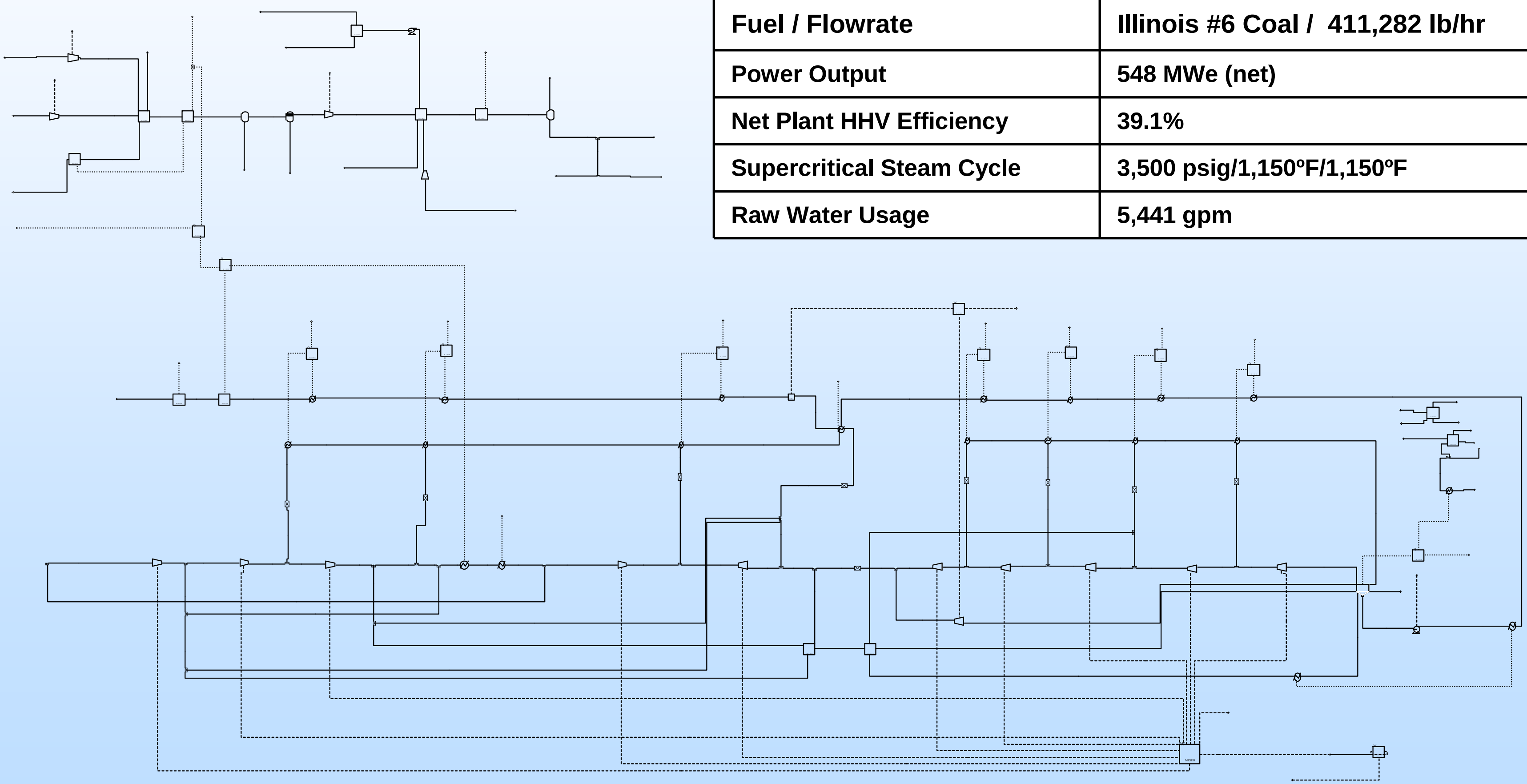
Power generation depending on demand

Heat to be removed with cooling water

d1 Forced draft cooling tower

diwekar, 4/26/2009

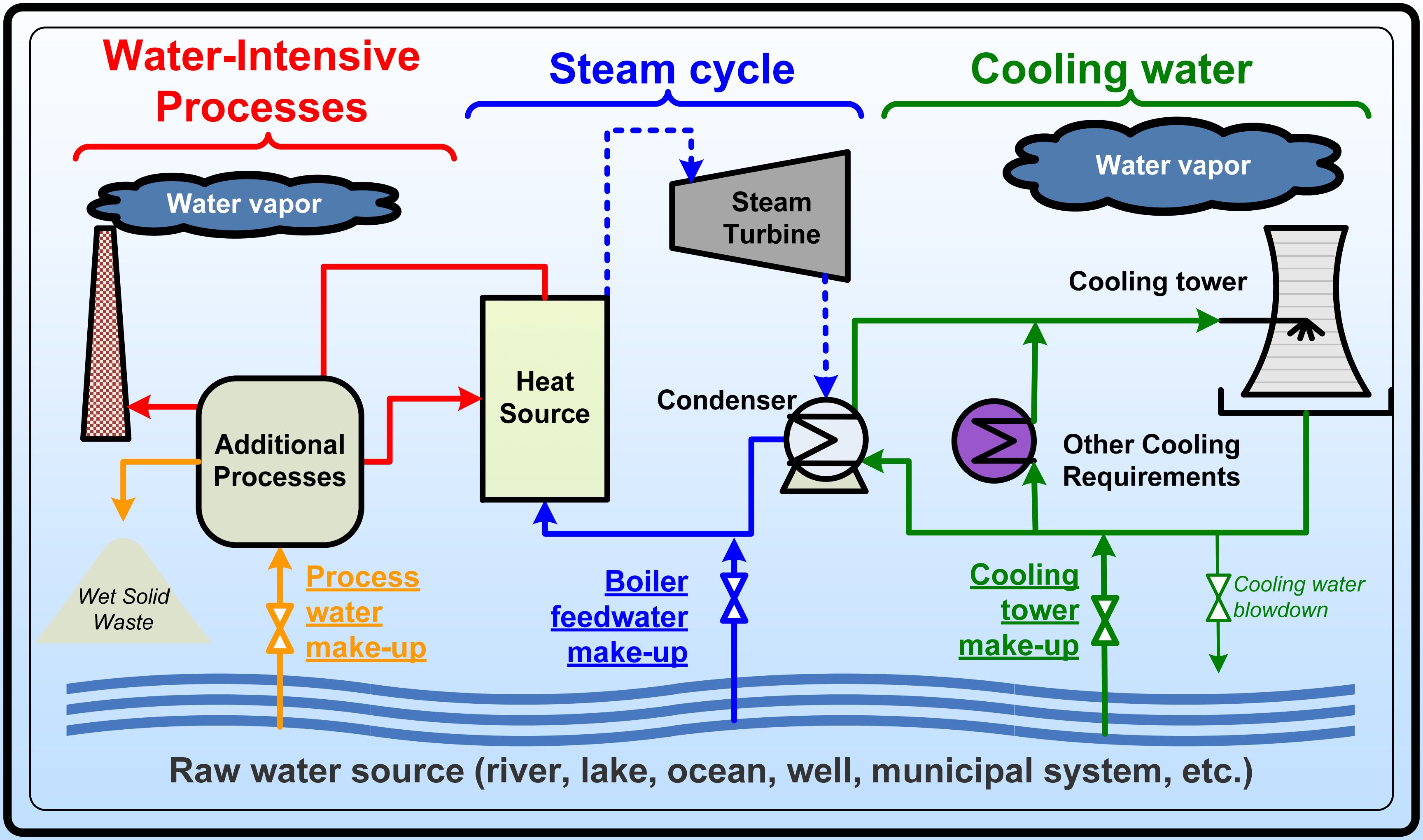
Case Study: PC Power Plant
Aspen Plus® Process Model



Baseline Case	Supercritical PC Case #11
Fuel / Flowrate	Illinois #6 Coal / 411,282 lb/hr
Power Output	548 MWe (net)
Net Plant HHV Efficiency	39.1%
Supercritical Steam Cycle	3,500 psig/1,150ºF/1,150ºF
Raw Water Usage	5,441 gpm

“Cost and Performance Baseline for Fossil Energy Power Plants Study, Volume 1: Bituminous Coal and Natural Gas to Electricity,” National Energy Technology Laboratory, www.netl.doe.gov, August 2007.

Water Flow Schematic for Power Plants

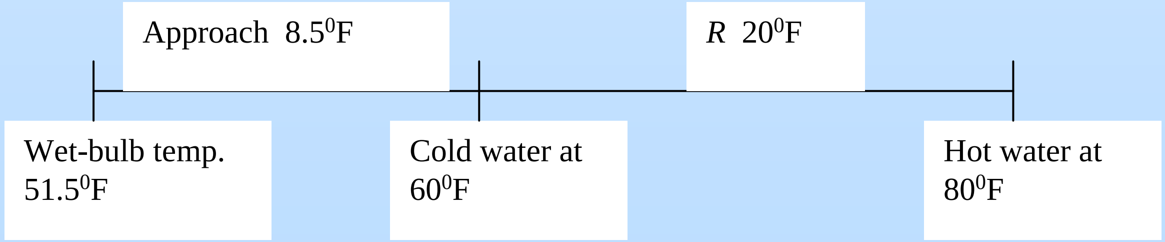


Water Consumption in PC Power Plant

- Cooling Tower:
  - Evaporative losses in GPM
  - coefficient changes with L/G ratio, R and air conditions

$$E = 0.0008 * \frac{heat\ load\ to\ condenser}{8.33 * R}$$

  - R varies when wet bulb temperature changes when the approach is maintained



Approach 8.5^0F

R 20^0F

Wet-bulb temp. 51.5^0F

Cold water at 60^0F

Hot water at 80^0F

Water Consumption (cont'd.)

– Other sources of water consumption:

- Blowdown (B): depends on the number of concentration cycles (C assumed to be 4) , the drift losses (D) and evaporative losses (E). Drift losses are considered about 25% of the evaporative losses.

$$B = \frac{E - \left(\left(C - 1\right) * D\right)}{C - 1}$$

- FGD water consumption: $CaCO_3$ slurry preparation and FGD water makeup

Phase I

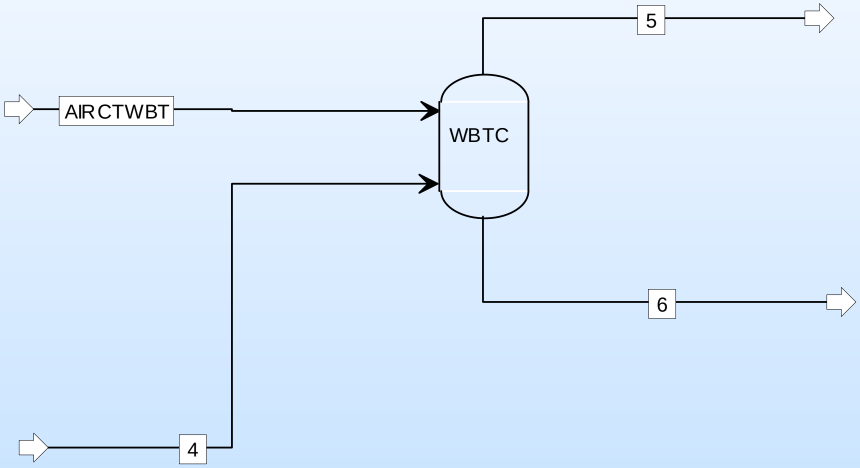
- Phase I Goals
  - Include cooling tower model in the PC base case flowsheet that better estimates evaporation losses and takes into account operational, design, and uncertain variables (air conditions)
  - Characterize uncertainty associated with atmospheric conditions so that it can be included in the simulation and optimization of the PC plant model to minimize water consumption
  - Use Better Optimization for Non-linear Uncertain Systems (BONUS) algorithm to identify potential process characteristics that minimize water consumption in reasonable amount of computational time

Cooling Tower Model

- Based on a simple model reported in literature to estimate the evaporative rates in cooling towers (Hamilton, Power Engineering, March 1977, 52)
- Three operating blocks were added to the PC flowsheet: Two flash separators and one cooler

Cooling Tower Model (New)

- Wet bulb temperature:
  - Adiabatic flash unit was used to calculate wet bulb temperature from dry bulb temperature and relative humidity data
  - Adiabatic flash at atmospheric pressure was defined WBTC
  - Water flow of stream 4 was calculated so that flowrate of stream 6 (liquid) is equal to 0 through a Design Specification
  - Final temperature of the flash is the wet bulb temperature



Comparison of Two Cooling Tower Models for Water Consumption (under different air conditions)

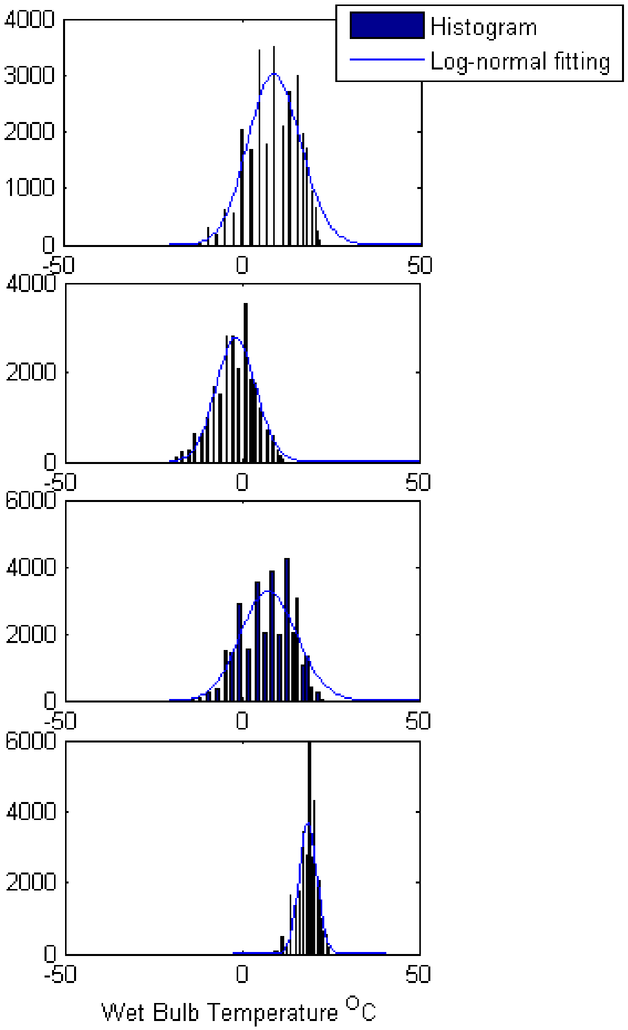
Dry bulb T (^{0}F)	**Rel. Hum. (%)**	**Wet bulb T (^{0}F)**	**Orig. Model X10^6 lb/h**	**New Model X10^6 lb/h**
48	72	44	2.644	2.531
35	68	32	2.643	2.463
59	60	51.5	2.644	2.603
73	78	67.4	3.195	3.225

Characterization of Uncertainty

- Two main uncertainties were initially identified within literature reports as affecting water consumption:
  - Power load
  - Weather conditions (e.g. Wet Bulb Temperature)
- Characterization was performed from NREL weather station data

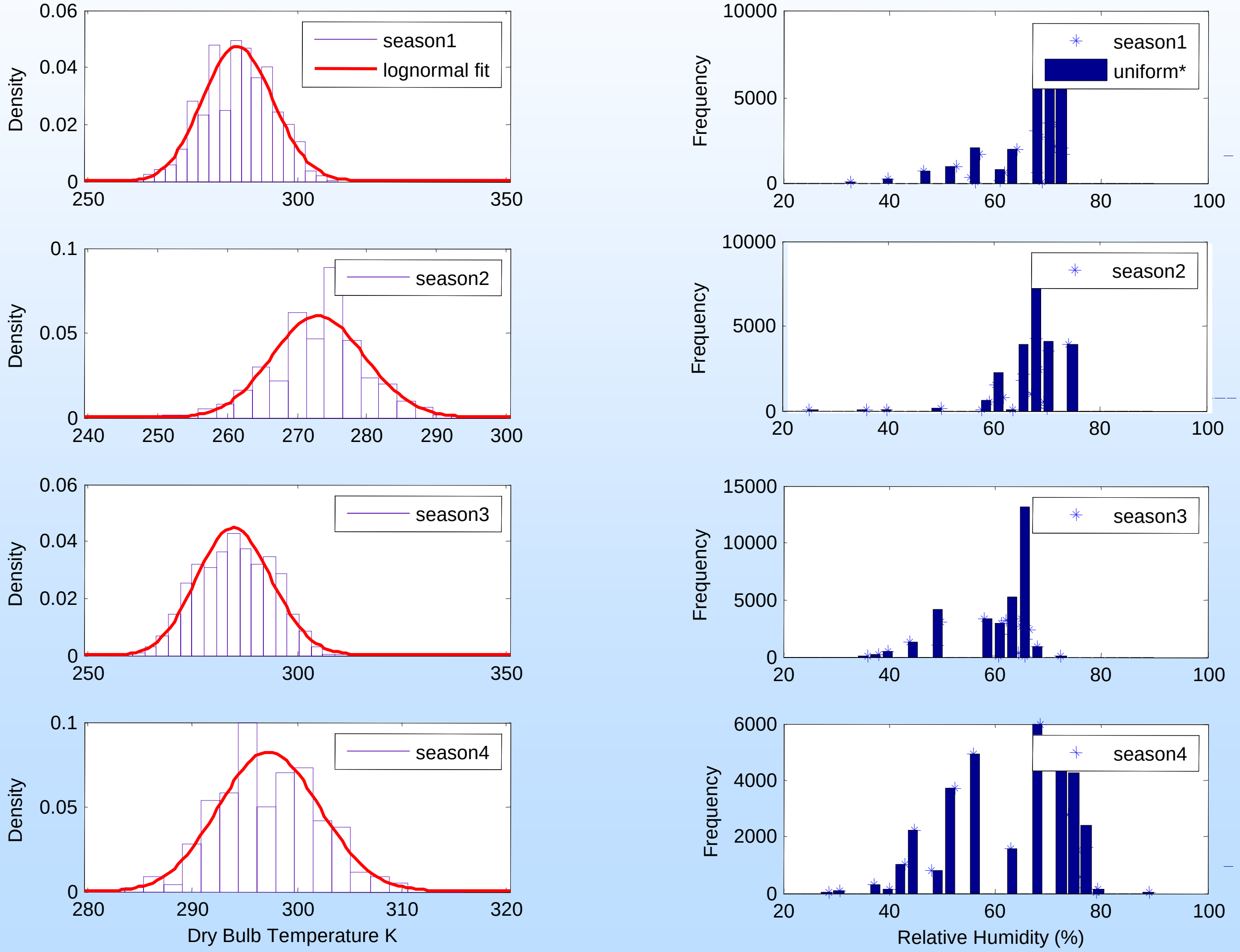
Probability Density Functions of Air Conditions

(for four seasons on eight US midwestern cities fall (season1) to summer (season4) from 2005 to 2007)

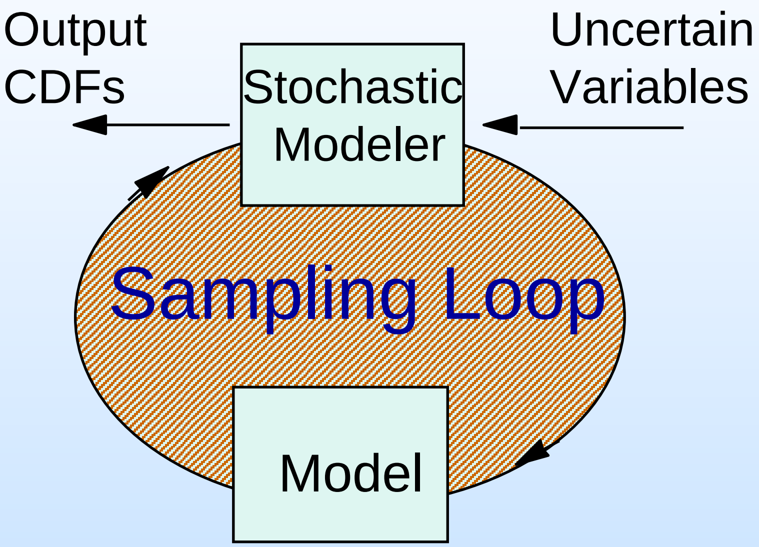


Probability Density Functions of Air Conditions

(for four seasons on eight US midwestern cities fall (season1) to summer (season4) from 2005 to 2007)



Stochastic Modeling



Output CDFs

Stochastic Modeler

Uncertain Variables

Sampling Loop

Model

Efficient Sampling Technique: Hammersley Sequence Sampling

Stochastic Modeling & Water Consumption

- Variability is more relevant when a more detailed model of the cooling tower is introduced
- Deterministic estimations may be low even with conservative models such as the original one

	Original Model $X10^6$ lb/h	New Model $X10^6$ lb/h
Expected Value	2.641	2.722
STD	0.0007	0.32
Deterministic Value	2.643	2.531

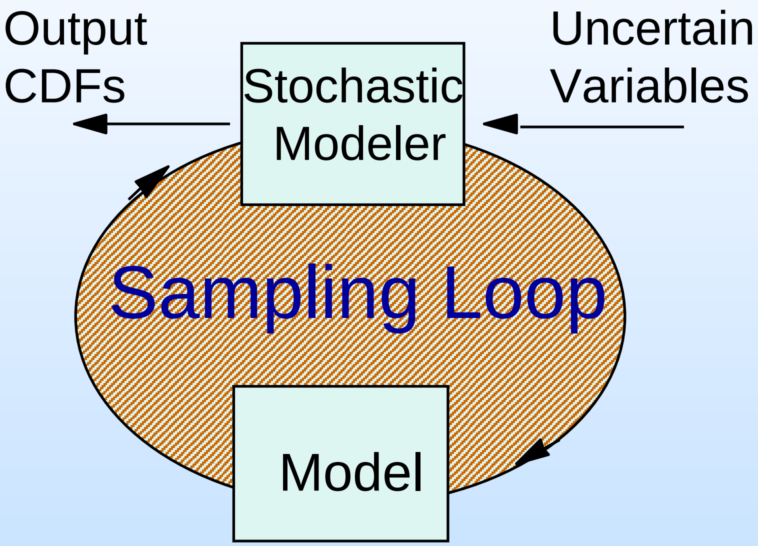
Sensitivity Analysis

(with Original Cooling Tower Model)

- Stochastic simulation was carried out employing CO application and analyzed according to literature.
- Absolute values of partial ranked correlation coefficients indicate the influence of each parameter on water consumption

Potential decision variable	Partial ranked correlation coefficient
Air excess	**0.230024**
Air temperature	0.017965
Air humidity	-0.003656
FGD efficiency	-0.011624
Boiler Temperature	**0.295324**
O_2/SO_2 ratio	**-0.028274**
$CaCO_3/SO_2$ ratio	**-0.043097**
Water content of FGD slurry	-0.007045
Pressure losses at reheater	-0.009876
Generator losses	**-0.031358**

Recursive Loops



Output
CDFs

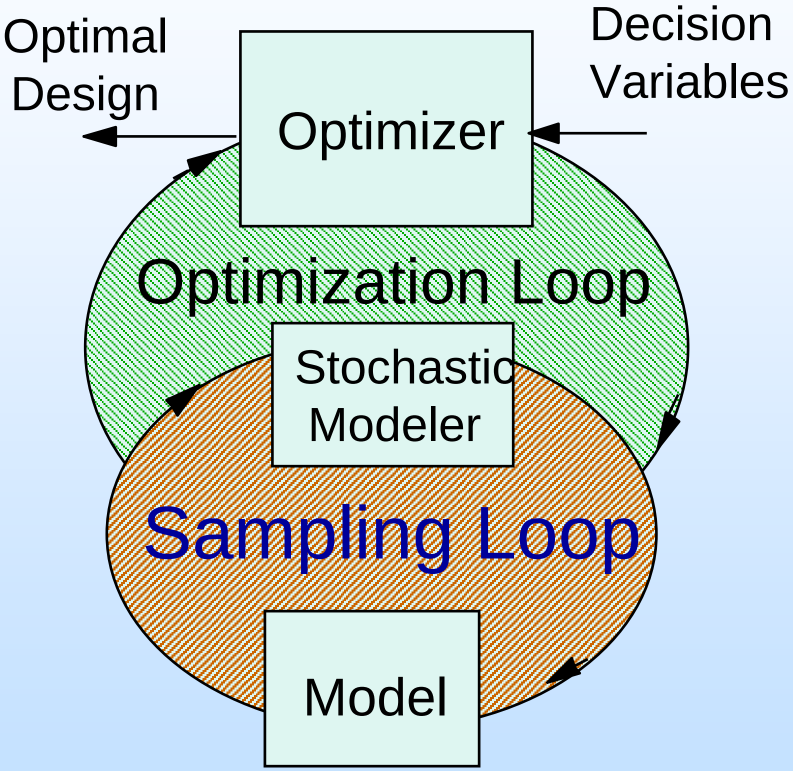
Stochastic
Modeler

Uncertain
Variables

Sampling Loop

Model

Stochastic Modeling



Optimal
Design

Optimizer

Decision
Variables

Optimization Loop

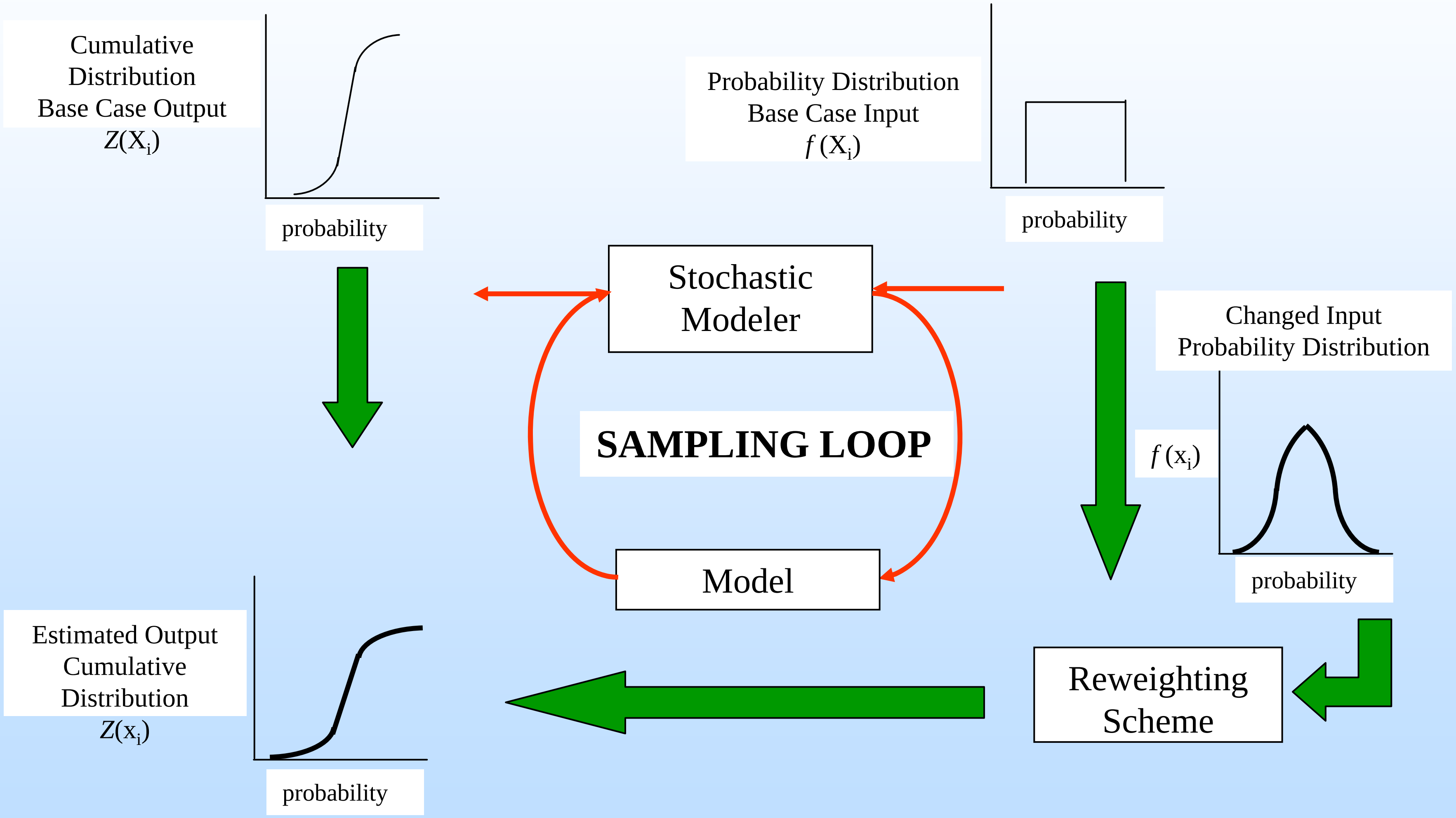
Stochastic
Modeler

Sampling Loop

Model

Stochastic Optimization

Better Optimization of Nonlinear Uncertain Systems (BONUS)



Cumulative
Distribution
Base Case Output
$Z(X_i)$

probability

Probability Distribution
Base Case Input
$f(X_i)$

probability

Stochastic
Modeler

SAMPLING LOOP

Model

Changed Input
Probability Distribution

$f(x_i)$

probability

Reweighting
Scheme

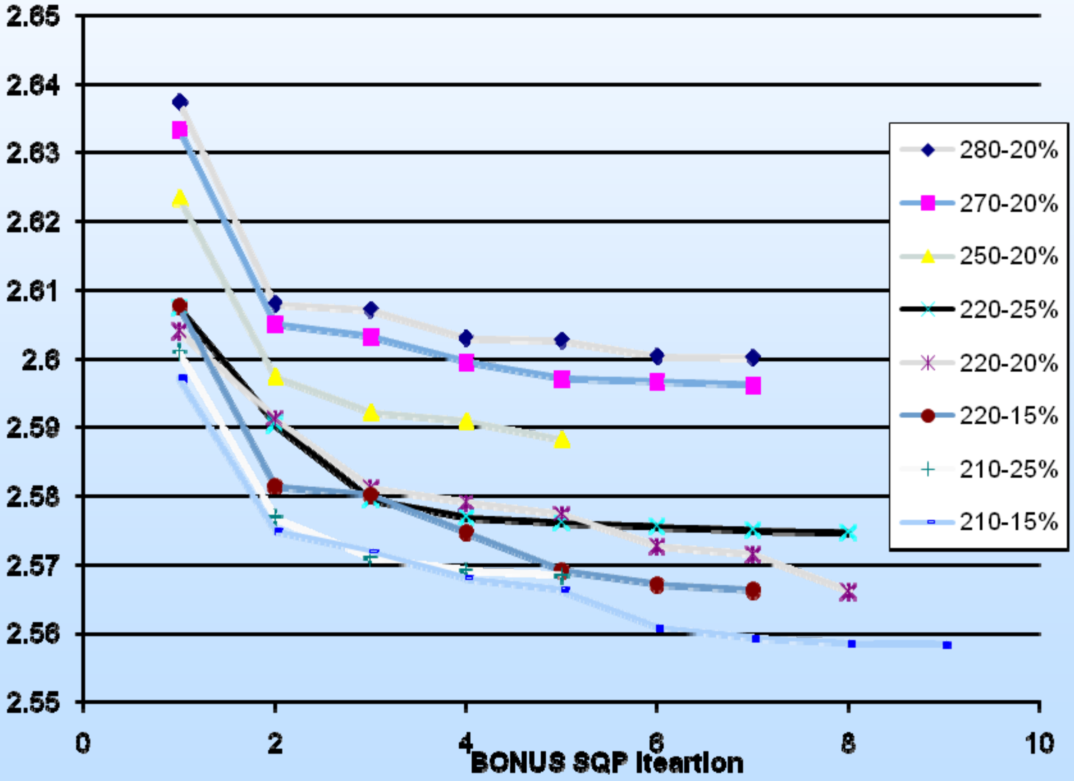
Estimated Output
Cumulative
Distribution
$Z(x_i)$

probability

Minimization Water Consumption

(with Original Cooling Tower Model)

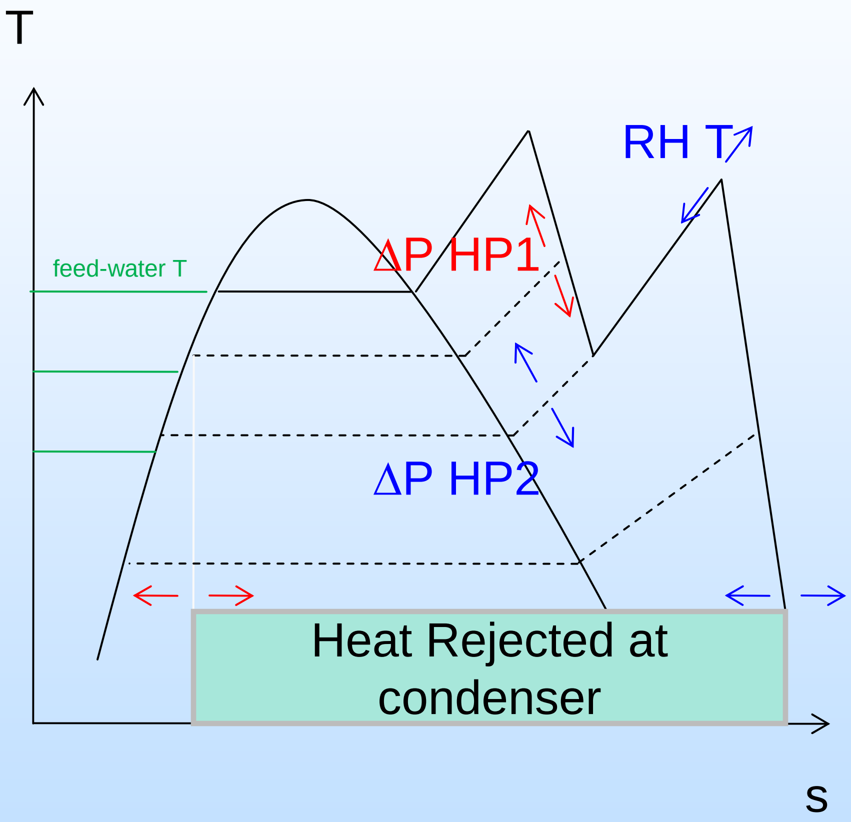
- Different starting points were analyzed due to the highly non-convex system
- Water consumption is reduced by 4.3%
- BONUS reduced computational time by 97%



Decision Variables

(with New Cooling Tower Model)

- For the proposed model of the cooling three more variables were included
- Heat rejected at the condenser directly affects the water evaporation
- Shaded area can be changed by modifying:
  - The pressure of the steam coming out of the first extraction stage (red arrows)
  - The temperature and pressure at which the steam is reheated when it is returned to the boiler (blue arrows)



Sensitivity Analysis

(with New Cooling Tower Model)

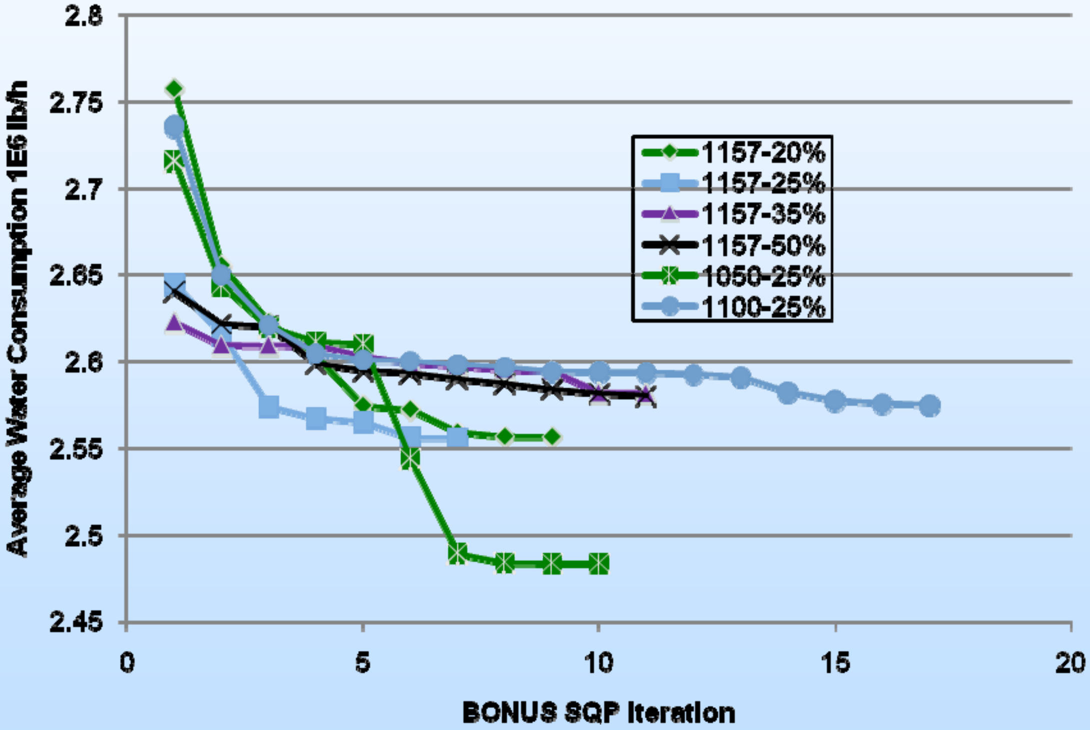
- With new variables included the influential parameters changed
- The newly included variables (as expected) are highly influential
- Air excess is directly associated with the boiler efficiency therefore is expected to play an important role in the FGD water consumption as well as the FGD water contents
- Naturally the generator losses influence the cycle efficiency and the amount of heat rejecter at the condenser so water evaporation will be affected

Potential decision variable	**Partial ranked correlation coefficient**
Air excess	**0.256642**
Re-heater T	**0.228009**
FGD efficiency	-0.125901
Boiler T	-0.018852
O_2/SO_2 ratio	-0.021453
$CaCO_3/SO_2$ ratio	-0.032031
Water content of FGD slurry	**0.191058**
Pressure drop at HP1	**-0.294448**
Generator losses	**0.183865**
Pressure Drop at HP2	**-0.266594**

Minimization Water Consumption

(with New Cooling Tower Model)

- The variables considered with different starting points.
- Starting point of 1050ºF and 25% air excess yielded the lowest value.
- Water consumption is reduced by 12%
- BONUS reduced computational time by 99.7%.



Minimization Water Consumption

Original Cooling Tower Model

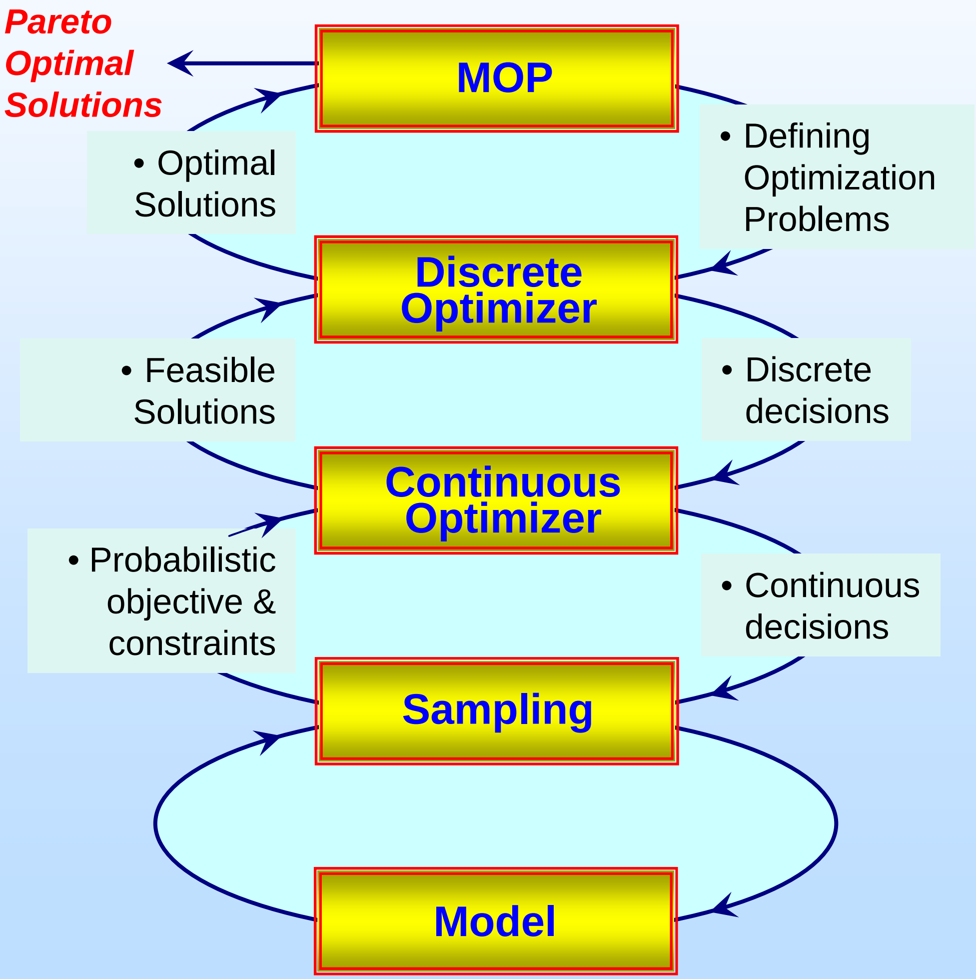
Variable	Base Case	Optimal
Boiler Temperature (^{0}F)	270	210
Air excess (%)	20	16.2
$CaCO_3$/ SO_2 molar ratio	1.04	1.01
Generator losses	0.015	0.005
O_2/SO_2 molar ratio	1.1	1.0
BONUS estimation water consumption (X10^6 lb/h)	2.63	2.56
Water consumption from stochastic simulation (X10^6 lb/h)	2.641	2.52

New Cooling Tower Model

Variable	Base Case	Optimal
Re-heater Temperature (^{0}F)	1155	1052
Air excess (%)	20	33.2
ΔP HP1	0.385	0.31
Generator losses	0.015	0.005
ΔP HP2	0.637	0.61
Slurry preparation ratio	0.3	0.24
BONUS estimation water consumption (X10^6 lb/h)	2.75	2.48
Water consumption from stochastic simulation (X10^6 lb/h)	2.72	2.37

Future Plans

Multiobjective Optimization under Uncertainty



Pareto Optimal Solutions

MOP

- Optimal Solutions

- Defining Optimization Problems

Discrete Optimizer

- Feasible Solutions

- Discrete decisions

Continuous Optimizer

- Probabilistic objective & constraints

- Continuous decisions

Sampling

Model

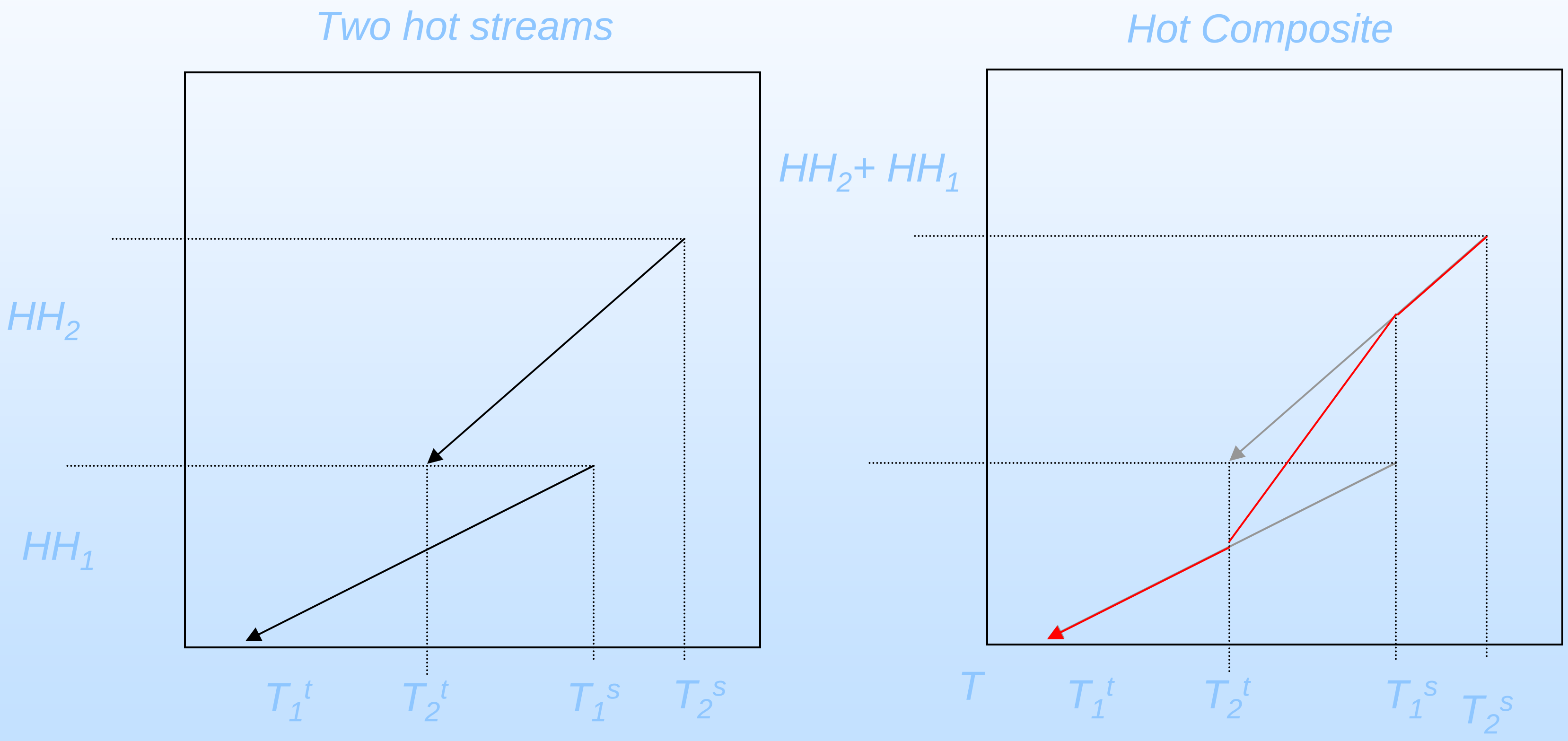
Future Plans

Optimal Synthesis Approach

- Heat Exchanger Network Synthesis
- Mass Exchanger Network Synthesis
- Optimization Approach to Process Synthesis

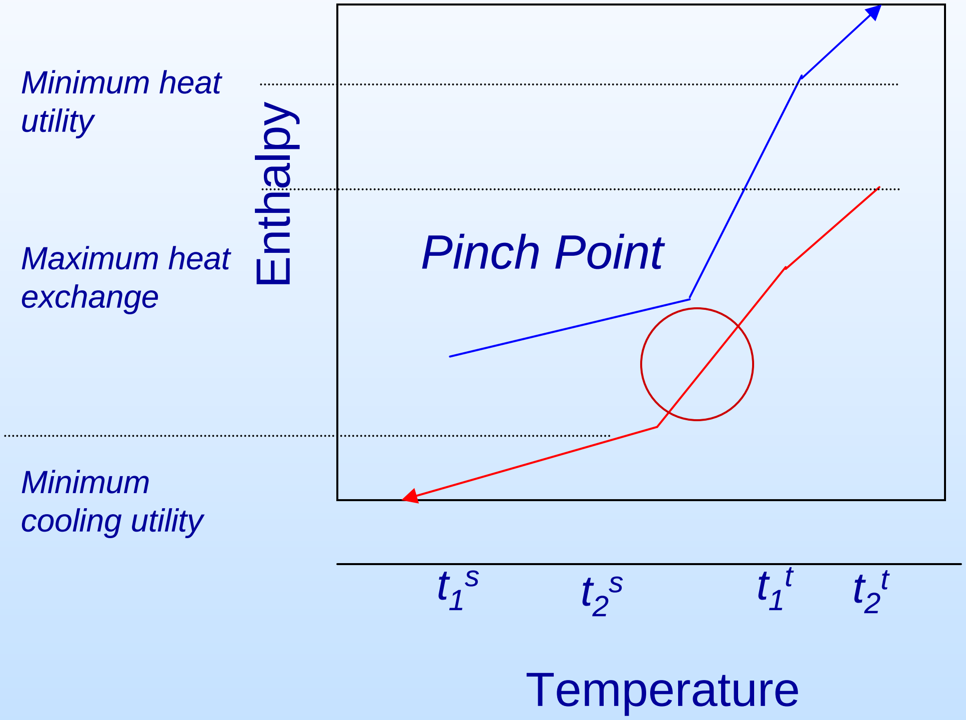
Heat Exchanger Network Synthesis

- Heat exchange pinch diagrams



$$HH_u = F_u Cp_u (T_u^s - T_u^t)$$

Heat Exchange Pinch Diagram

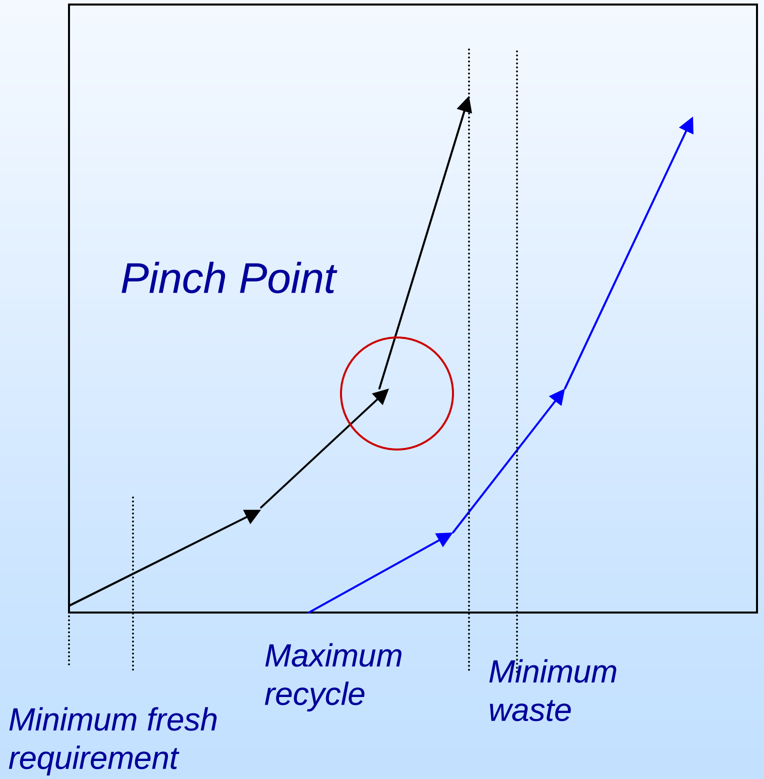


Analogy between MENs and HENs

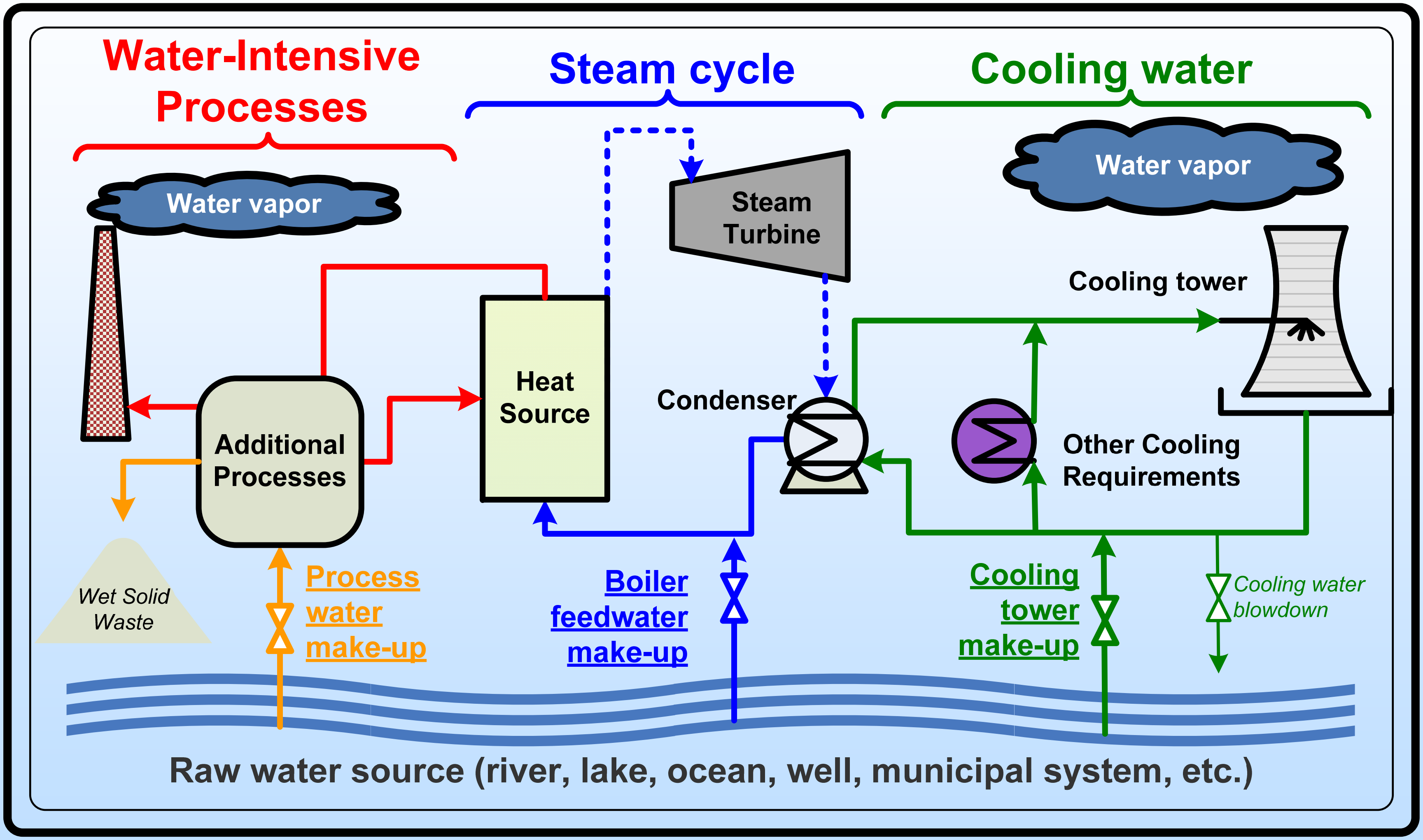
Category	MENs	HENs
Transferred Commodity	Mass	Heat
Donors	Rich streams	Hot streams
Recipients	Lean streams	Cold streams
Rich variable	Composition y	Hot temperature T
Lean variable	Composition x	Cold temperature t
Slope of equilibrium	m	1
Intercept of equilibrium	b	0
Driving force	e	ΔT^{min}

– Move source composite horizontally until it touches the Sink diagram

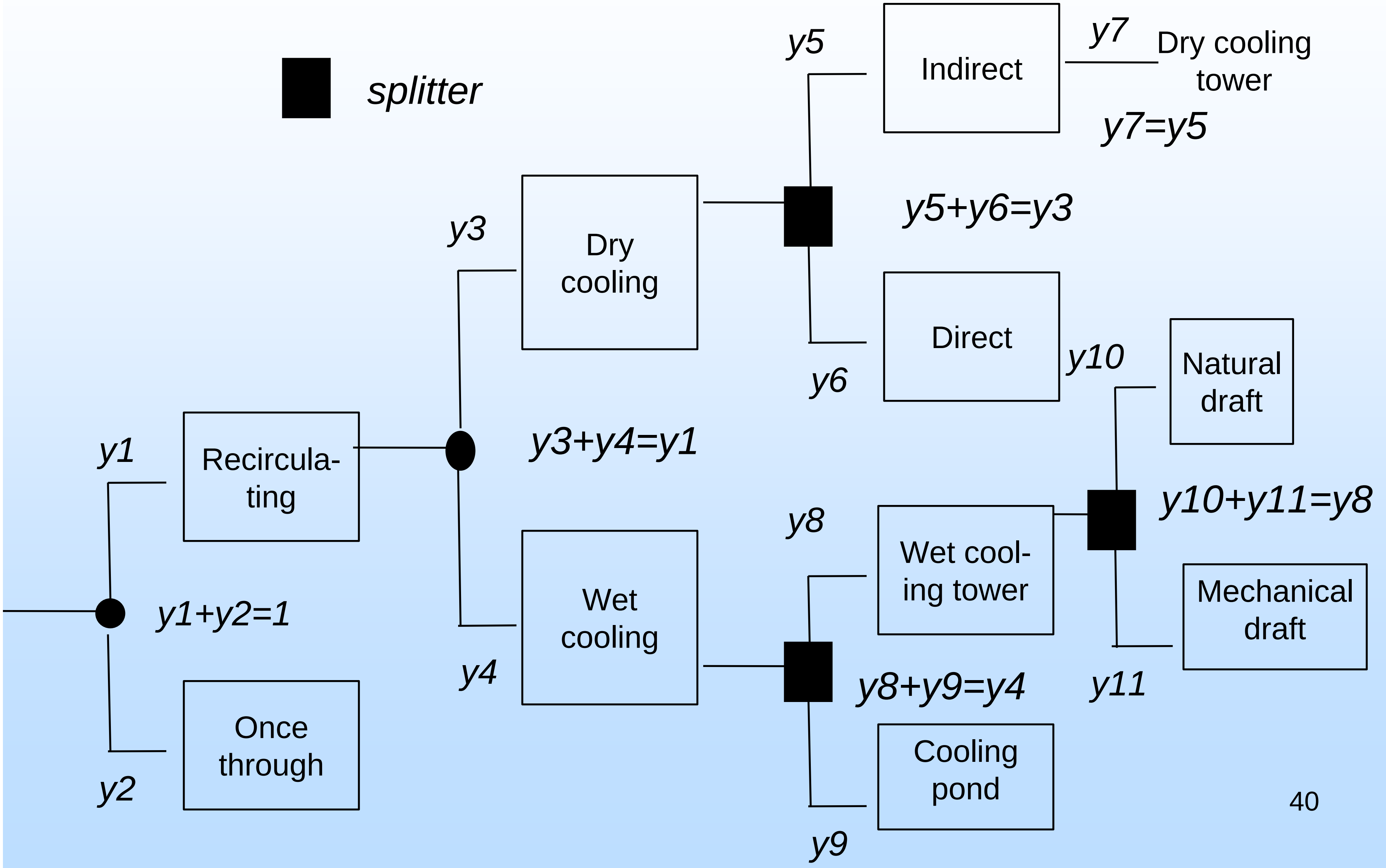
Material Recycle Pinch Diagram



Water Flow Schematic for Power Plants



Optimization Approach



■ *splitter*

y1

Recircula-ting

y2

Once through

y1+y2=1

y3

Dry cooling

y4

Wet cooling

y3+y4=y1

y5

Indirect

y7

Dry cooling tower

y7=y5

y6

Direct

y5+y6=y3

y8

Wet cool-ing tower

y9

Cooling pond

y8+y9=y4

y10

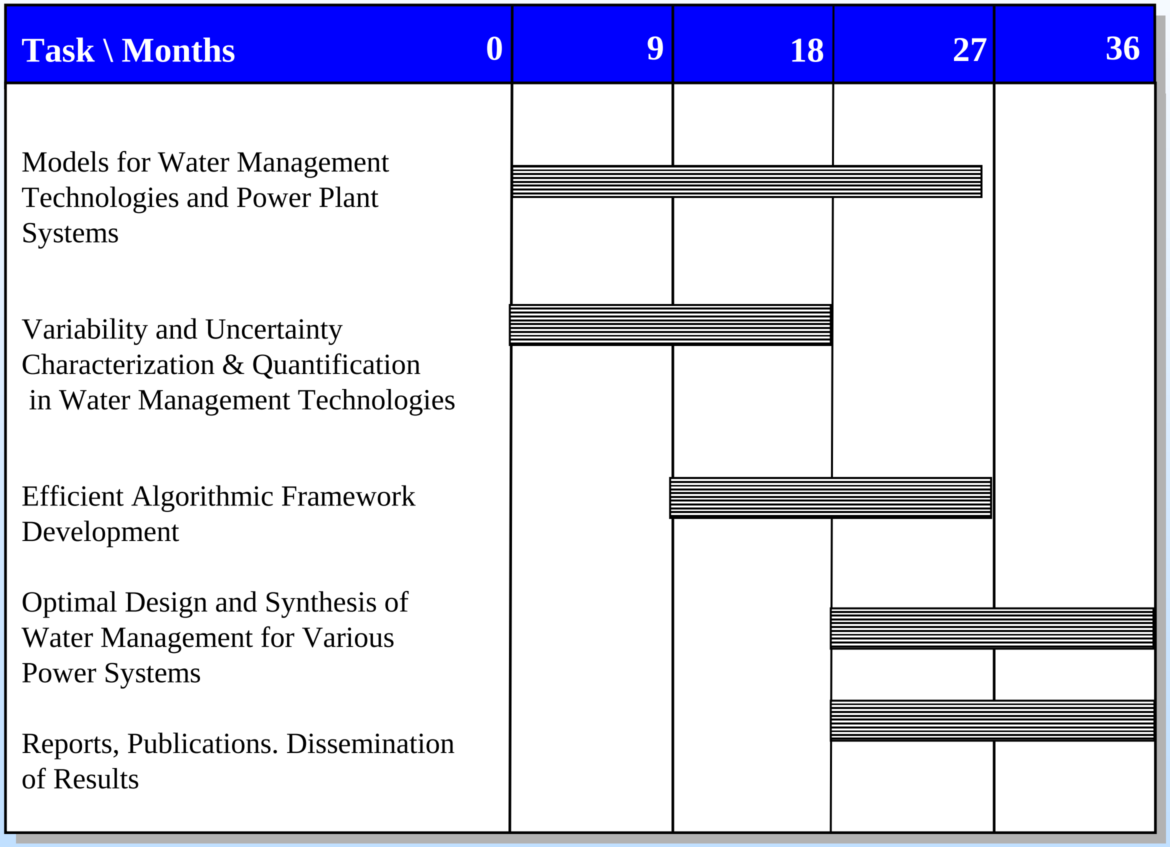
Natural draft

y11

Mechanical draft

y10+y11=y8

Scope of Work and Timetable



Task \ Months **0**	**9**	**18**	**27**	**36**
Models for Water Management Technologies and Power Plant Systems	▨	▨	▨	
Variability and Uncertainty Characterization & Quantification in Water Management Technologies	▨	▨		
Efficient Algorithmic Framework Development		▨	▨	
Optimal Design and Synthesis of Water Management for Various Power Systems			▨	▨
Reports, Publications. Dissemination of Results			▨	▨

Technology Risks

- Modification of water consumption in some units such as FGD or carbon sequestration (to be considered later on) may impact the emission levels. This risk would need to be considered by adding constraints to the optimization or using multi-objective optimization as proposed in the future work.
- Feedback from designers is needed to ensure the actual feasibility of the optimal policy that results from these approaches.

Benefits

- Software and algorithm framework for the synthesis, design, analysis, and optimization of integrated power plant and water networks will identify strategies for improving water reuse and recovery for coal-fired power plants.
- The number of decision variables comprising the optimal policy can be changed without having an exponential increase in computational time for the optimization under uncertainty.
- Similarly, computational expense is avoided when different starting points have to be evaluated due to the non-convex nature of the problem.
- The accuracy of the most complex part of the optimization procedures (which is the process model) can be guaranteed by the comprehensive simulation in Aspen Plus®.
- Robust designs in the face of uncertainties are obtained for integrated power plant and water networks.