Model-Based Sensor Placement for Component Condition Monitoring and Fault Diagnosis in Fossil Energy Systems

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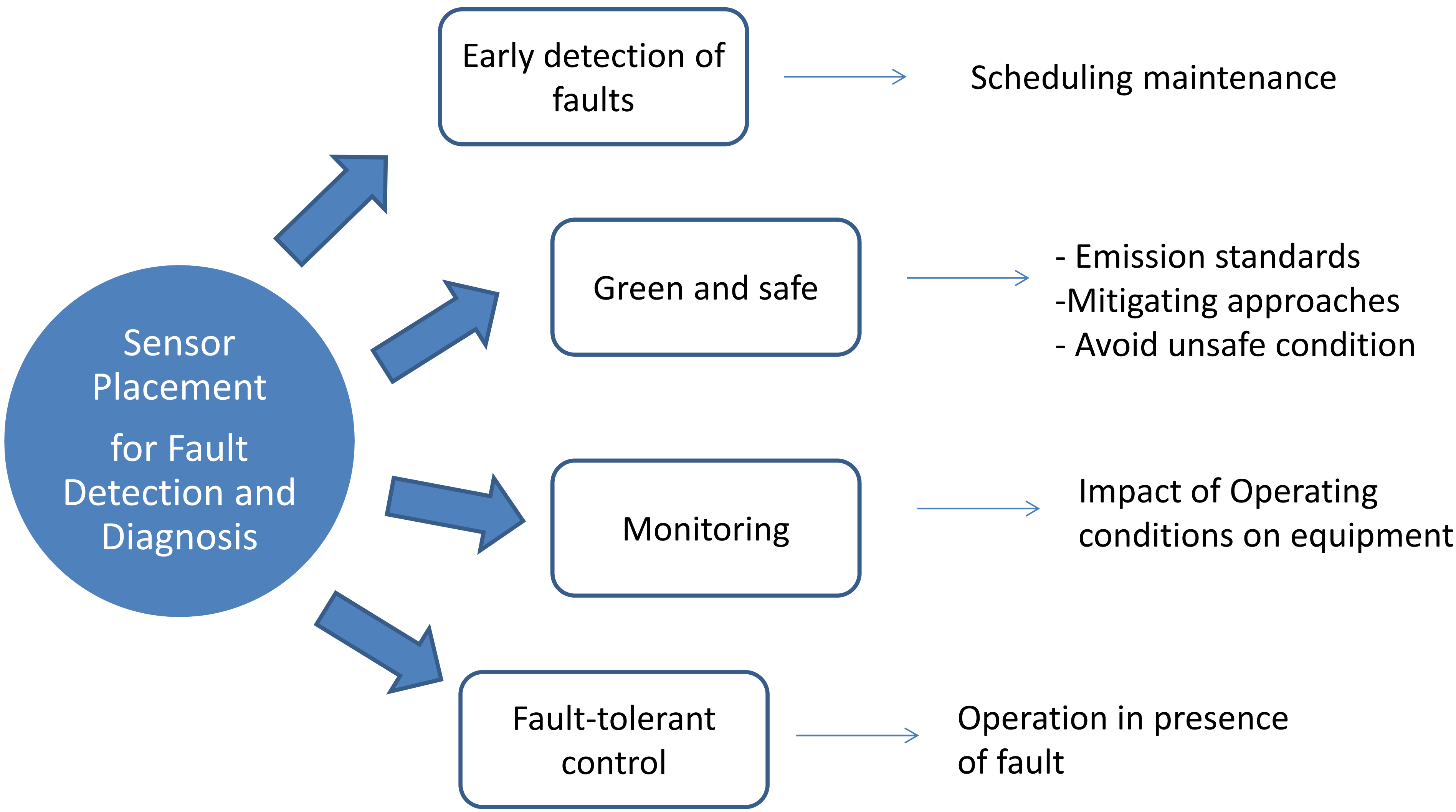
Sensor Network Design Problem

- Problem
  - Which variables to measure and where (if spatial variation considered)
  - Which physical sensors (with different properties, cost) should be used
  - How many sensors (hardware redundancy) should be used for measuring a variable
  - What should be the frequency of sampling (measurement) for different variables
  - Maintenance policies

Design as well as a Retrofit problem

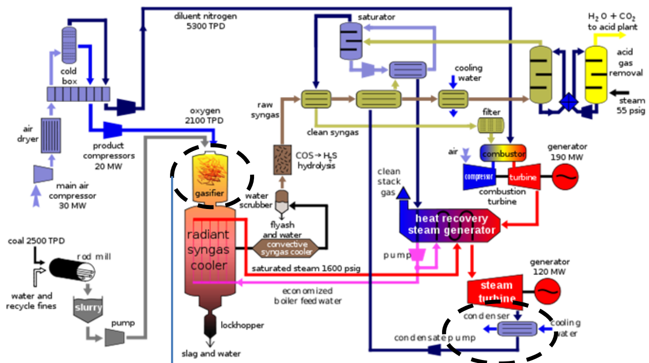
Motivation


Sensor Placement
for Fault Detection and Diagnosis
Early detection of faults
Scheduling maintenance
Green and safe
- Emission standards
-Mitigating approaches
- Avoid unsafe condition
Monitoring
Impact of Operating conditions on equipment
Fault-tolerant control
Operation in presence of fault

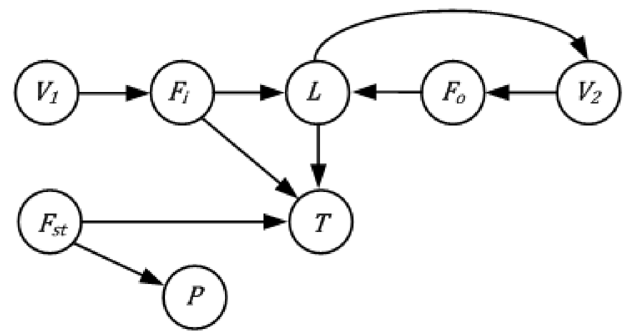
Two-tier approach

Tier 1 – Plant level

Plant level model



Cause and effect

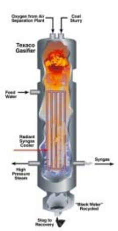


a

b

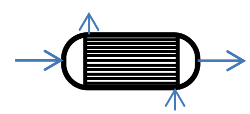
Tier 2 – Equipment Level

a



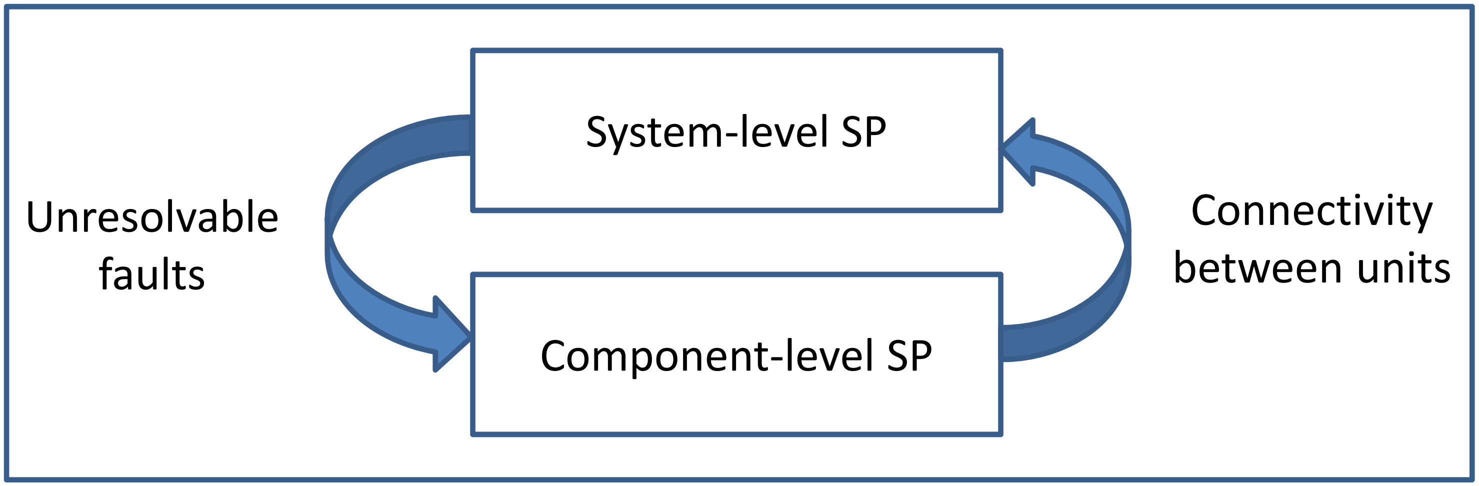
- Distributed model
- Estimator

b



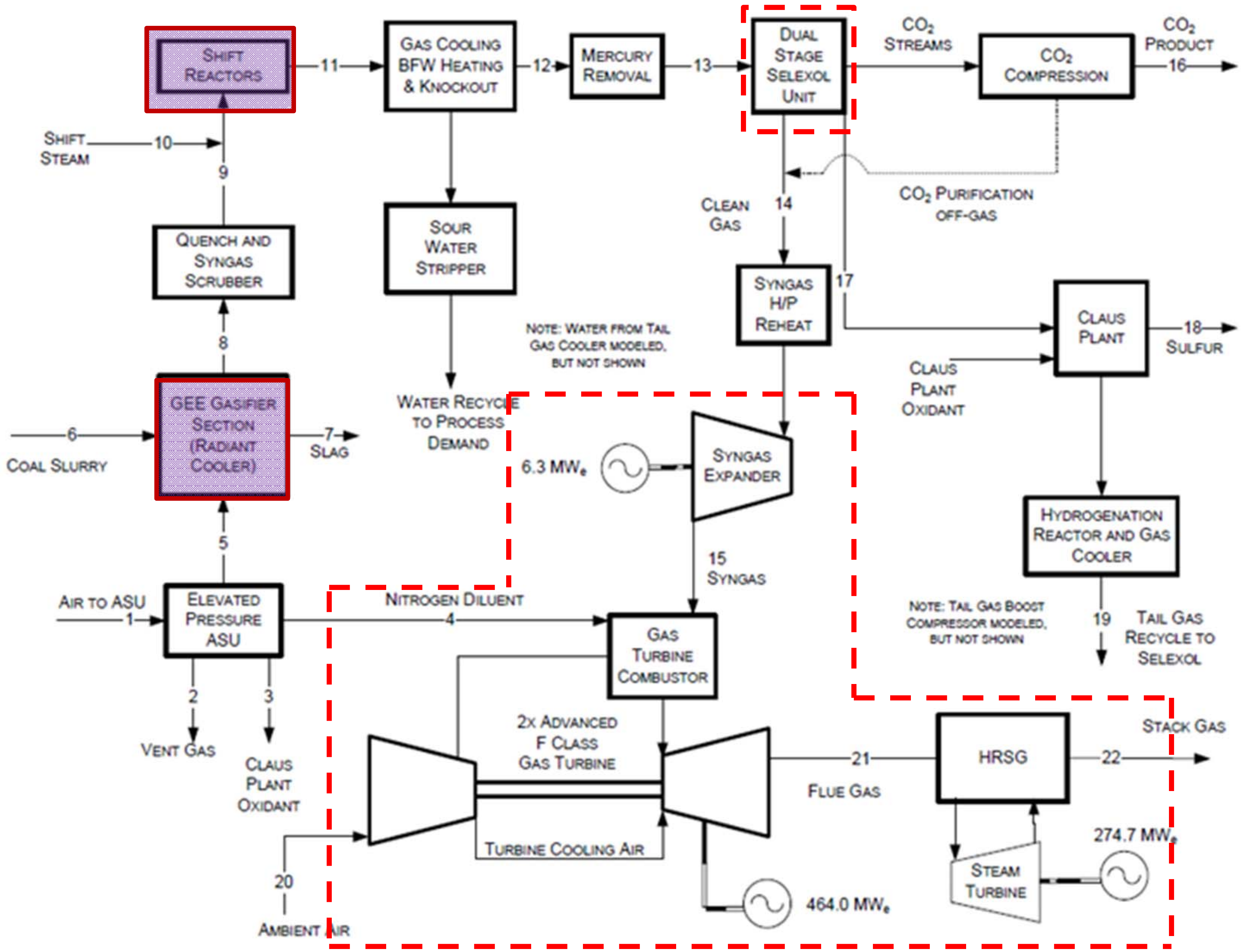
- Distributed model
- Estimator

Two-tier approach



- Maximizing efficiency of sensor network
- Resolve component-level faults while taking advantage of system-level interactions
- SP problem divided into two levels, solved, and then integrated.
- Use high fidelity models for component-level fault simulation

Component level and system level for an IGCC plant with CO_2 Capture



Approach

Component-level

1. WGSR
2. Gasifier

System-level

1. SELEXOL unit
2. Combined cycle

Integrated-level

1. Gasification island
2. Plant-wide model

Model development / enhancement

- System-level units are modified for fault simulation
- Component-level units are developed as high fidelity models

Fault simulation

- Commonly occurring faults are identified from open literature
- Responses of variables that can be measured by current technology are recoded

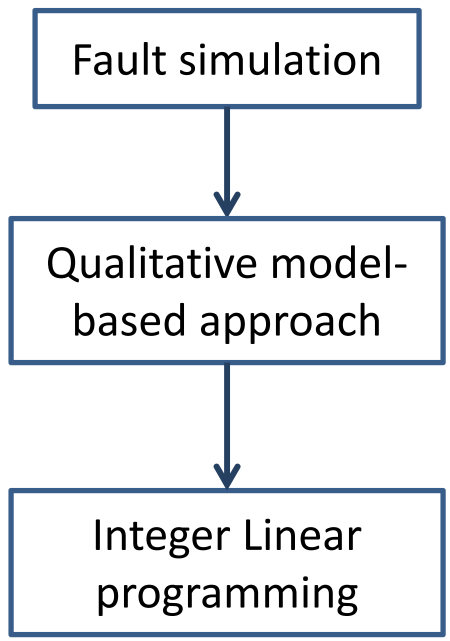
Sensor placement

- Quality / quantity based approaches are used depending upon the level
- Once selected, the process is validated by placing sensors and simulating faults again

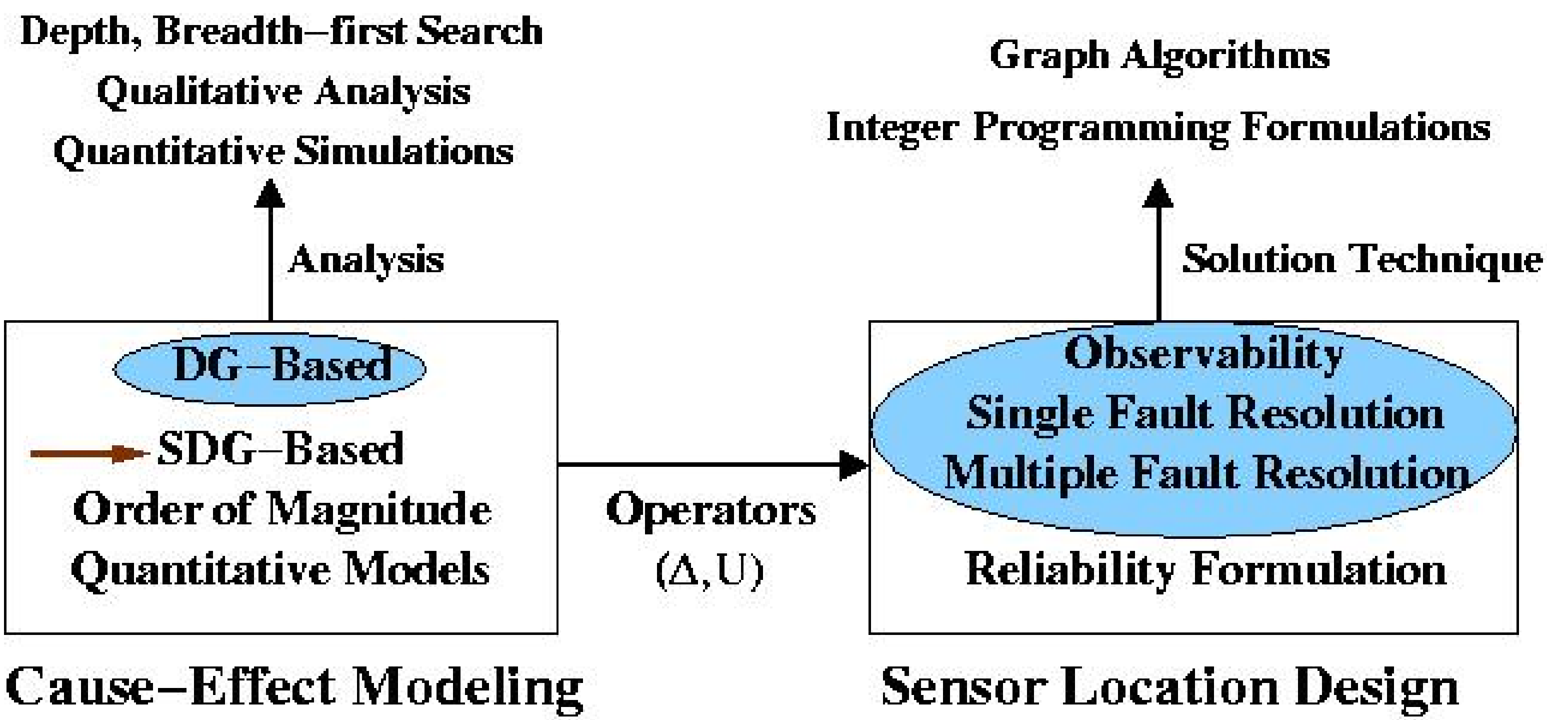
Tier 1: System Level Sensor Placement

System-level SP

- Qualitative approach: Has a fault occurred?
- Take advantage of the flowsheet connectivity
- No quantitative information of fault magnitude available

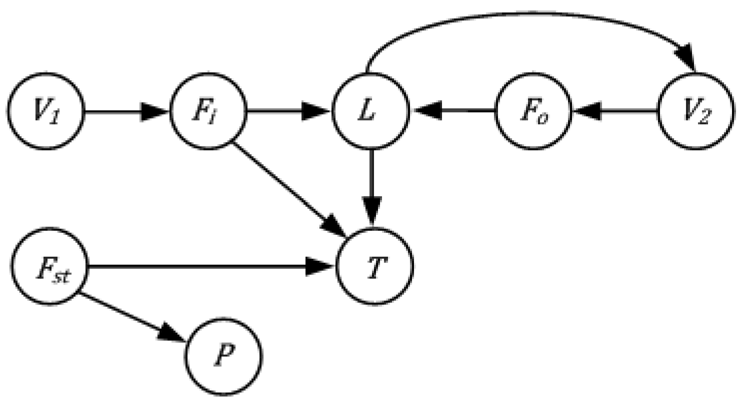


System-Level SP: General Strategy



Graph Based Approaches

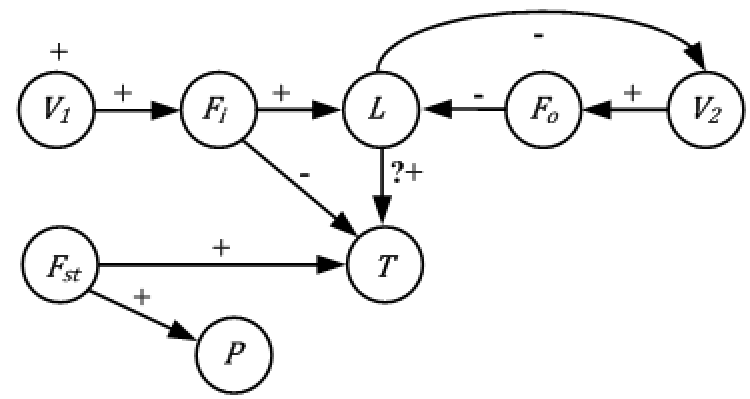
DG Representation



DG

- Change in variable > Threshold → Assign **"1"**
- Otherwise → Assign **"0"**

SDG Representation



SDG

- Variable goes over threshold → Assign **"1"**
- Variable goes below threshold → Assign **"-1"**
- Otherwise → Assign **"0"**

Fault observability

- Observability → Only response, not the direction → Matrix from DG
- SDG carries same information

$$A = \begin{bmatrix} 1 & 0 & 0 & 1 & \cdots & 1 \\ 0 & 0 & 1 & 1 & \cdots & 1 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 1 & 0 & 1 & \cdots & 1 \end{bmatrix}_{M \times N}$$

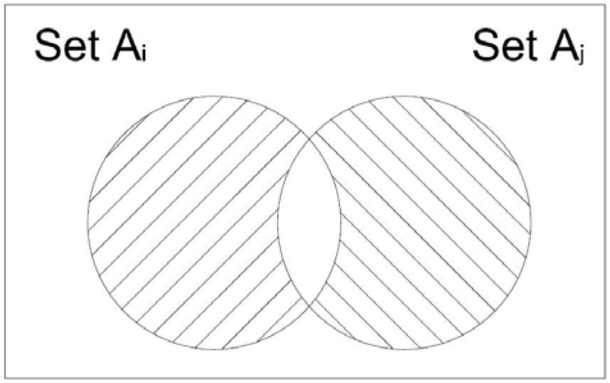
- Faults must be observed by at least one sensor

$$x_1 + x_2 + x_3 + \cdots + x_N \geq 1 \quad \rightarrow \quad b = \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}_{M \times 1}$$

Fault resolution

- Add $\binom{M}{2}$ pseudo faults
- <u>Pseudo-fault</u>: Symmetric difference of a pair of faults
- Symmetric difference:
  - From Venn diagram
  - Matrix from SDG

$$B_{ij} = A_i \cup A_j - A_i \cap A_j$$



- Constraint matrix
  - *A* → Augment observability and resolution
  - b → vector of ones

Integer Programming

Objective function

- Minimize sensor network cost $\min\ f = \sum_{j}^{N} w_j x_j$

Constraint

- Observability and resolution $Ax^T \geq b$

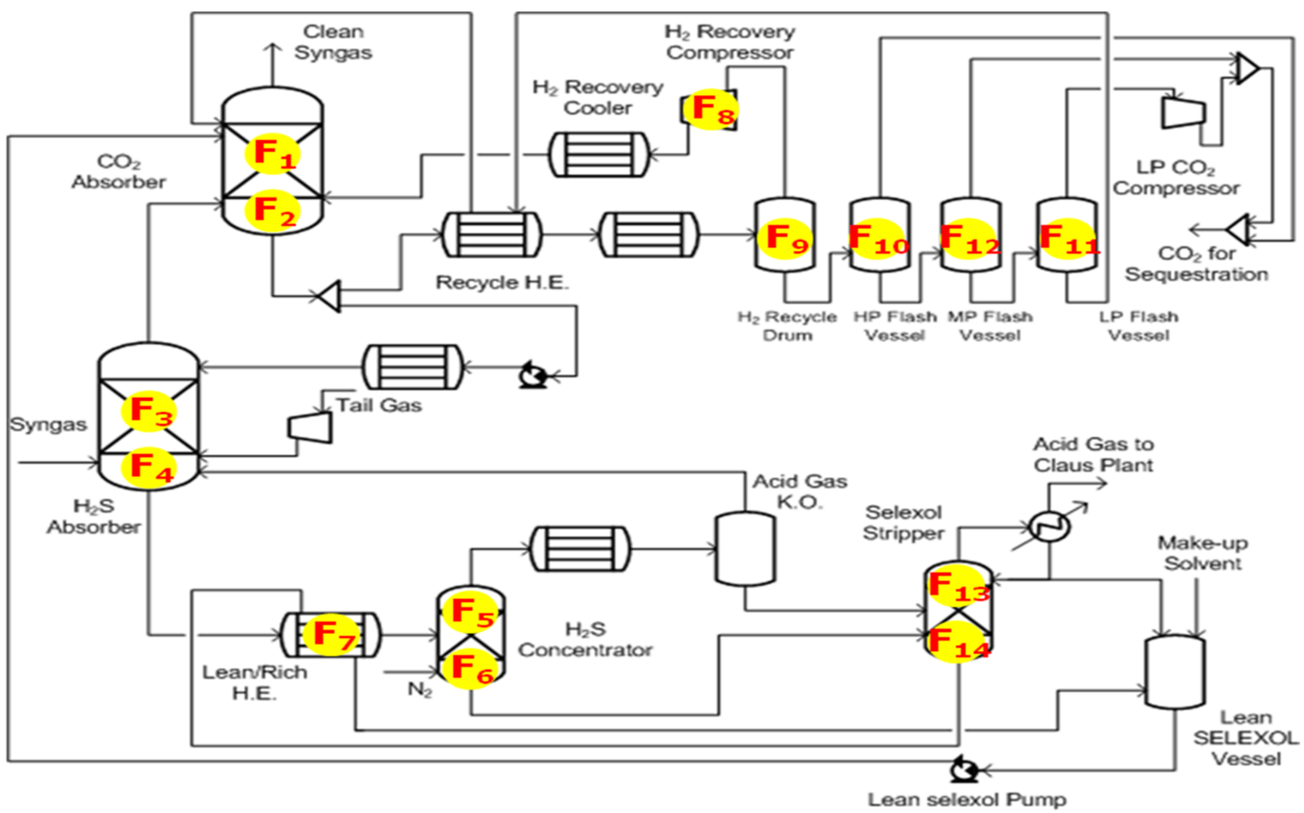
Decision variables

- Binary → **"1"**: Variable measured "**0**": Variable not measured
- Weight **→** Cost of measuring sensor

Fault Simulation

Faults

- Type: Process knowledge/experience/open literature
- Magnitude: Designed/desired and tolerance



Results for plant wide sensor placement

Observability:

Sensor: Make-up solvent flow

Resolution:

DG: 4 Temperature sensors + 2 Flow sensors
Irresolvable faults: 15 faults

SDG: 2 Temperature sensors + 2 Flow sensors
Irresolvable faults: 15 faults , same as DG

- Number of sensors reduced in SDG
- All faults are not resolvable by DG/SDG

Enhancement to these algorithms helps in resolving more faults

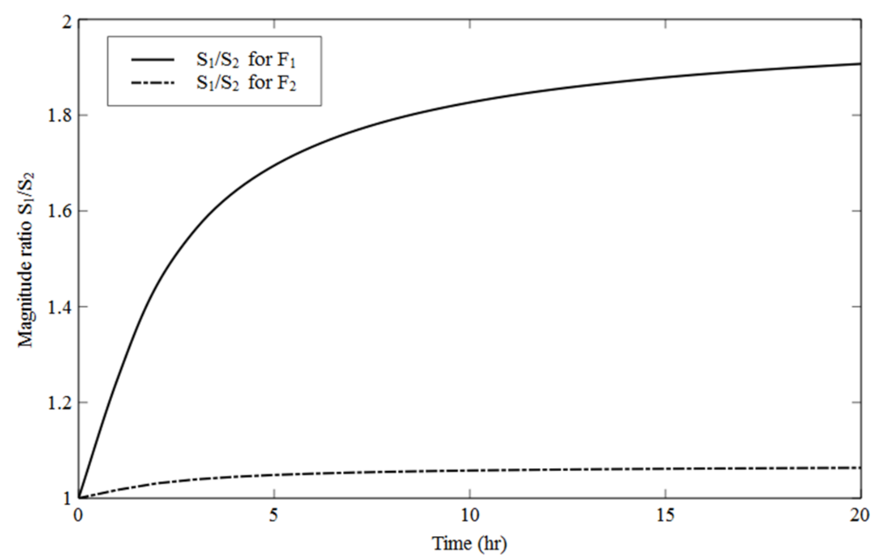
Magnitude Ratio Algorithm

Motivation

A = S1/S2 for F1
B = S1/S2 for F2

- A >>B
- B>>A
- A≅B≅1

Fault	Sensor	
	S_1	S_2
F_1	1	-1
F_2	1	-1



Magnitude Ratio Algorithm

Magnitude ratio is defined as:

$$\mathbf{R_{ij}} = \frac{\mathbf{S_i}/\mathbf{S_{i,ss}}}{\mathbf{S_j}/\mathbf{S_{j,ss}}}$$

– R_{ij} is pair of all variables and treated as a pseudo-sensors

Magnitude ratio algorithm:

– Define: Threshold ($\boldsymbol{\lambda}$)
– If $\mathbf{R_{ij}} > \boldsymbol{\lambda}$, assign "1"
– If $\mathbf{R_{ij}} < \mathbf{1}/\boldsymbol{\lambda}$, assign "-1"
– Otherwise, assign "0“

Magnitude Ratio Algorithm

- $\binom{\mathbf{N}}{\mathbf{2}}$ pseudo sensors added to the decision variables
- Cost of the pseudo-sensors is set to zero
- Constraints:

$$(1-x_i)+(1-x_j)+x_{ij} \geq 1$$
$$(1-x_{ij})+x_i \geq 1$$
$$(1-x_{ij})+x_j \geq 1$$

Further Enhancement to SDG Algorithm

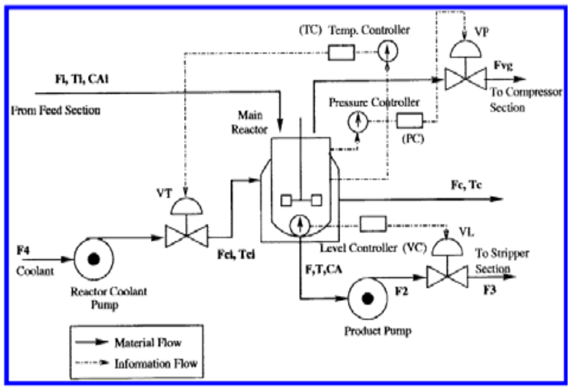
Fault evolution sequence algorithm

- Fault response sequence
- Comparing sequence of pairs can help in resolving faults

Fault	Sequence	Pairs
F1	$S_1\ S_3\ S_2\ S_4$	$\{S_1,S_3\}$ $\{S_1,S_2\}$ $\{S_1,S_4\}$ $\{S_3,S_2\}$ $\{S_3,S_4\}$ $\{S_2,S_4\}$
F2	$S_1\ S_2\ S_3\ S_4$	$\{S_1,S_2\}$ $\{S_1,S_3\}$ $\{S_1,S_4\}$ $\{S_2,S_3\}$ $\{S_2,S_4\}$ $\{S_3,S_4\}$

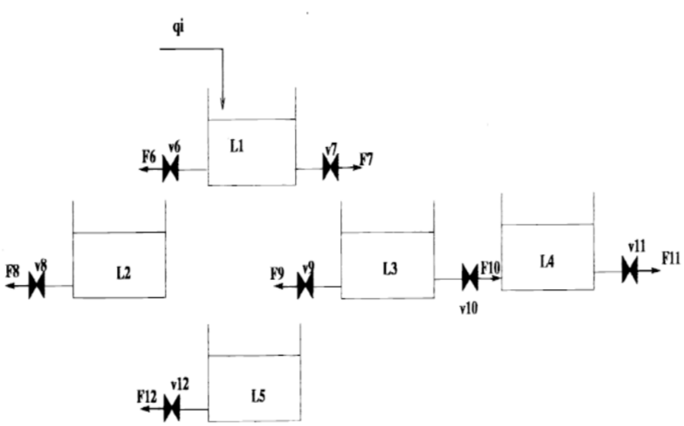
Magnitude Ratio Results

CSTR system



Algorithms	Sensors	Irresolvable
SDG	*$[T_c, VT, VP]$, C_A*	1 fault
FES	*$[T_c, VT, VP]$*	1 fault $\subseteq$ SDG
MR	*$[T_c, VT, VP]$*	[ ]
FES & MR	*$[T_c, VT, VP]$*	[ ]

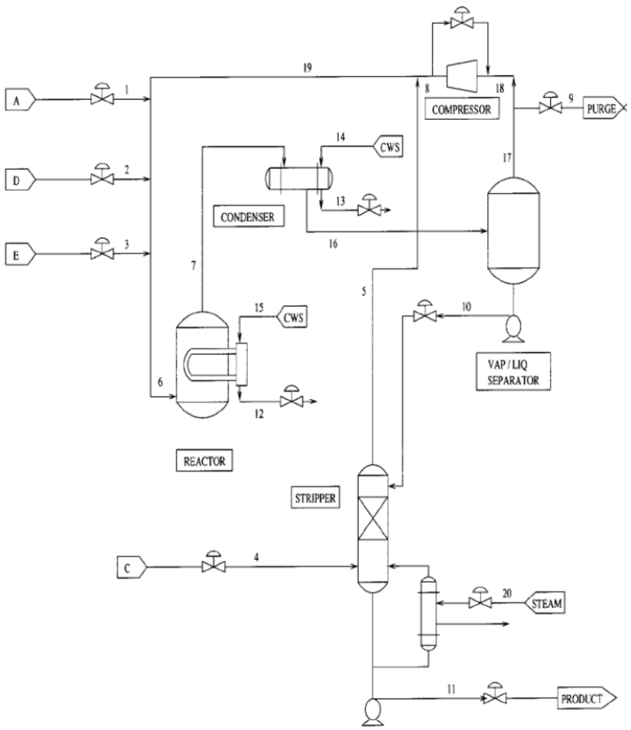
Five-tank



Algorithms	Sensors	Irresolvable
SDG	*[L2,F10],L5,L4*	1 fault
FES	*[L2,F10],F12*	[ ]
MR	*[L2,F10],L5*	[ ]
FES & MR	*[L2,F10]L5*	[ ]

Magnitude Ratio Results

TE process



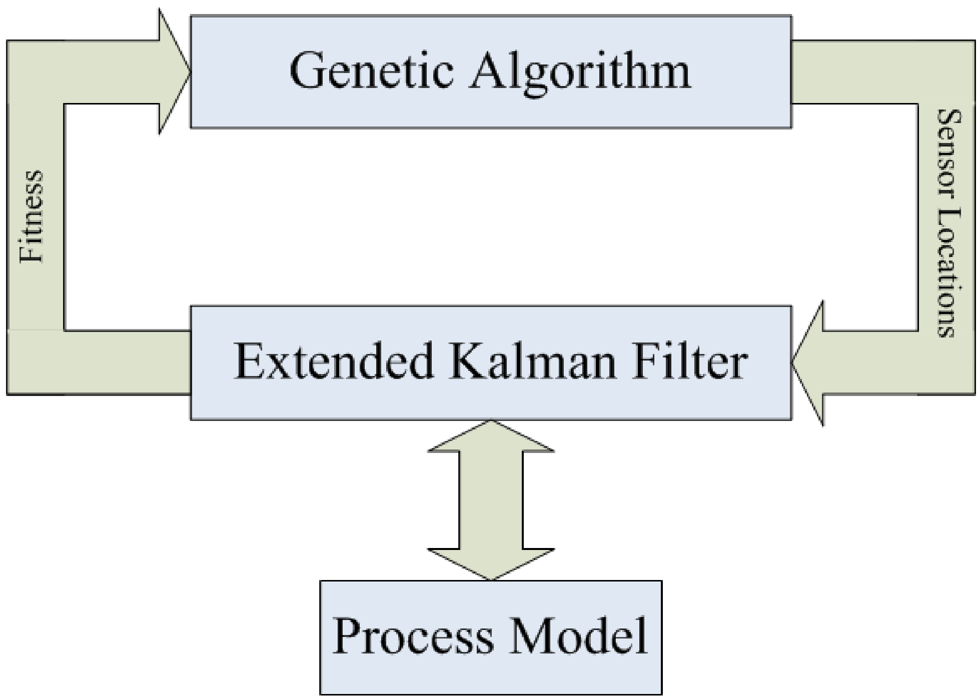
Alg.	Sensors	Irresolvable
SDG	*[F1,F9,F11,Tcs,VLs,VLp],F10,F2,Tcr* *5 Flow, 2 Temp. and 2 Level Sensors*	10 fault sets
FES	*[F1,F9,F11,Tcs,VLs,VLp],F10,Pr* *4 Flow, 1 Temp. , 2 Level and 1 Pressure Sensors*	6 fault sets ⊆ SDG
MR	*[F1,F9,F11,Tcs,VLs,VLp],Pr* *3 Flow, 1 Temp., 2 Level and 1 Pressure Sensors*	Same as FES
FES&MR	*[F1,F9,F11,Tcs,VLs,VLp],Pr* *3 Flow, 1 Temp., 2 Level and 1 Pressure Sensors*	Same as FES

Tier II: Distributed Sensor Placement

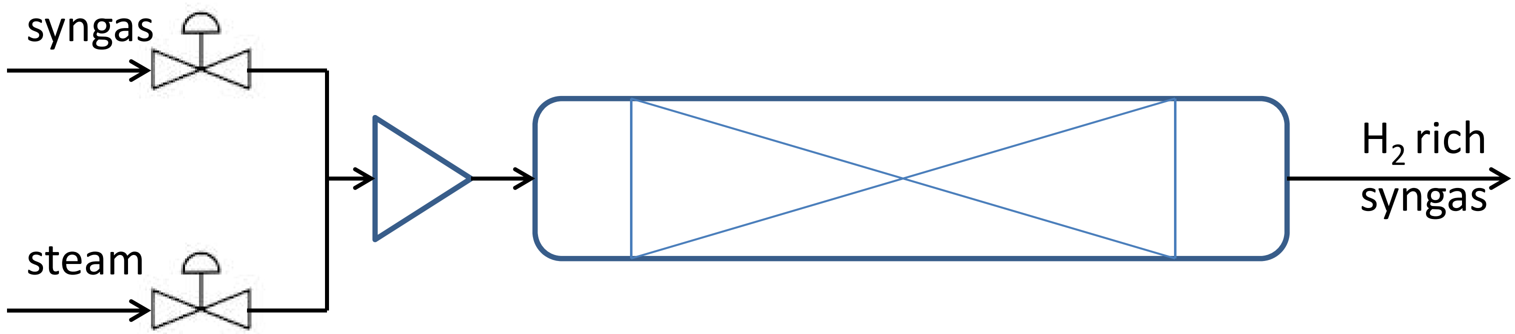
Component-level SP

- Interested in condition monitoring
- Faults cannot be resolved from a system-level scope
- Estimation of unmeasurable states

Component-level SP algorithm



Water gas shift reactor (WGSR)



- 1^{st} principle, 1-D, PDAE model developed using conservation equations in MATLAB
- Reaction kinetics obtained by data reconciliation from erroneous / noisy data from literature
- Simulate faults such as catalyst deactivation over time

Model Summary

- Total equations : 76
  - 53, differential
  - 23, algebraic
- Hence the system becomes a DAE system
- Total states are 76
- The equations are solved in MATLB with ODE15S

Estimator

- State Estimation
  - Process models is nonlinear with a system of differential and algebraic equations (DAE)

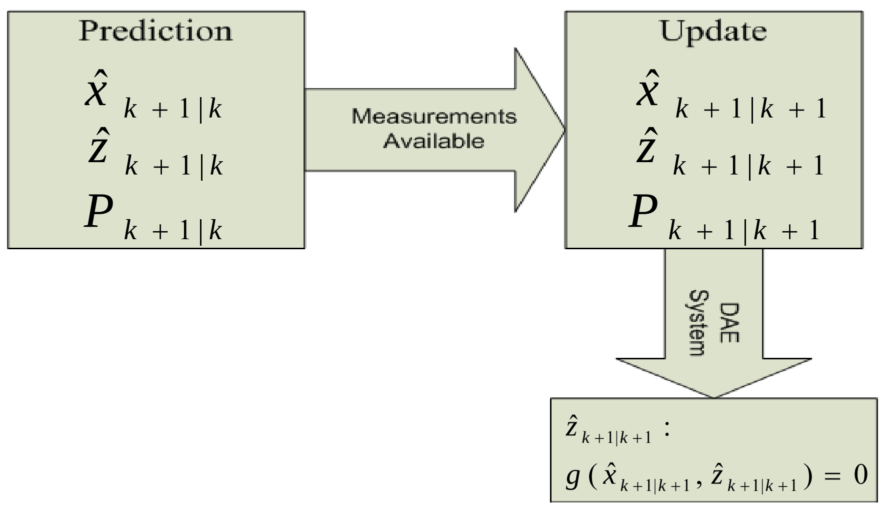
- Nonlinear estimator that can handle DAE systems is required
  - Extended Kalman filter for DAE systems

Summary of State Estimation

- DAE system is linearized at each time step as:

$$\begin{cases} \dot{x} = Ax + Bz \\ 0 = Cx + Dz \end{cases} \rightarrow \begin{bmatrix} \dot{x} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} A & B \\ -D^{-1}CA & -D^{-1}CB \end{bmatrix} \begin{bmatrix} x \\ z \end{bmatrix}$$

- Prediction and update steps of EKF for DAE systems:

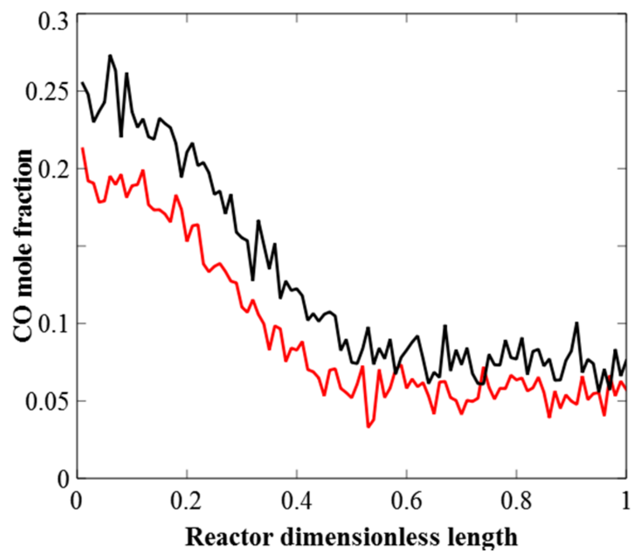


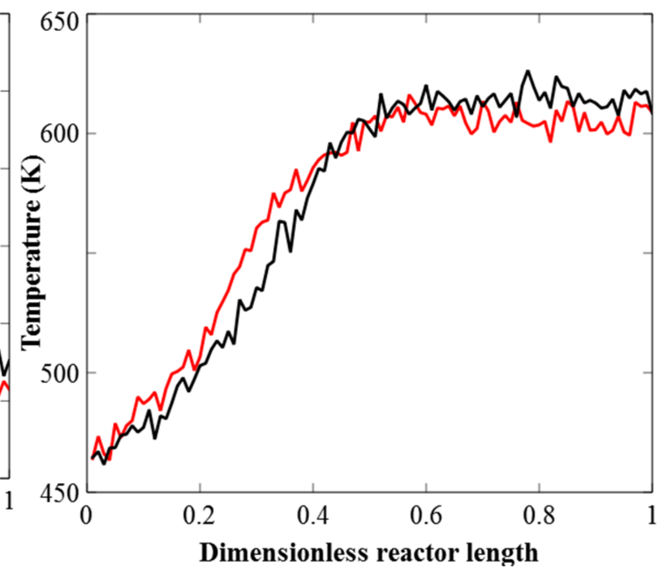
Fault Simulations

- Porosity of the catalyst bed → modify ε
- Catalyst deactivation → change the pre-exponential factor at specific location of the reactor
- Change in surface area of the catalyst leading to changes in the effectiveness factor

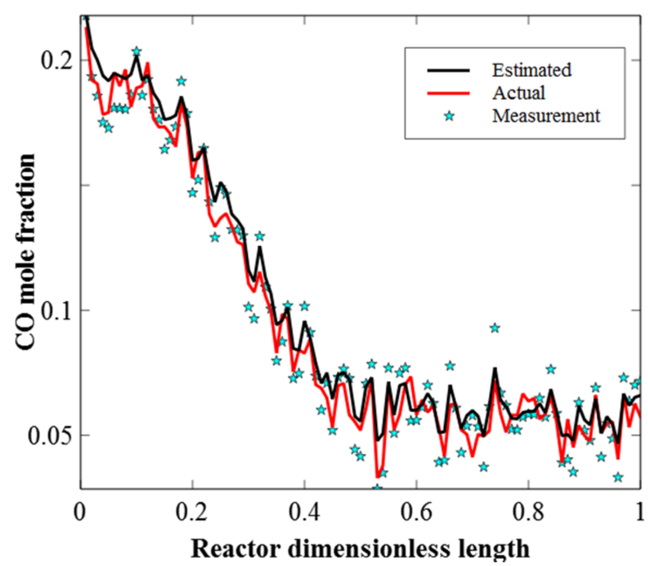
Estimation of states in presence of noise

- Catalyst deactivation





- State estimation



Problem formulation for optimization

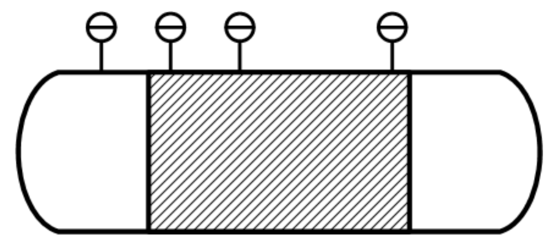
- At each time step, a noisy measurement of the states are made:

$$y_k = Hx_k + v_k$$

- where, H matrix is constructed from a binary vector

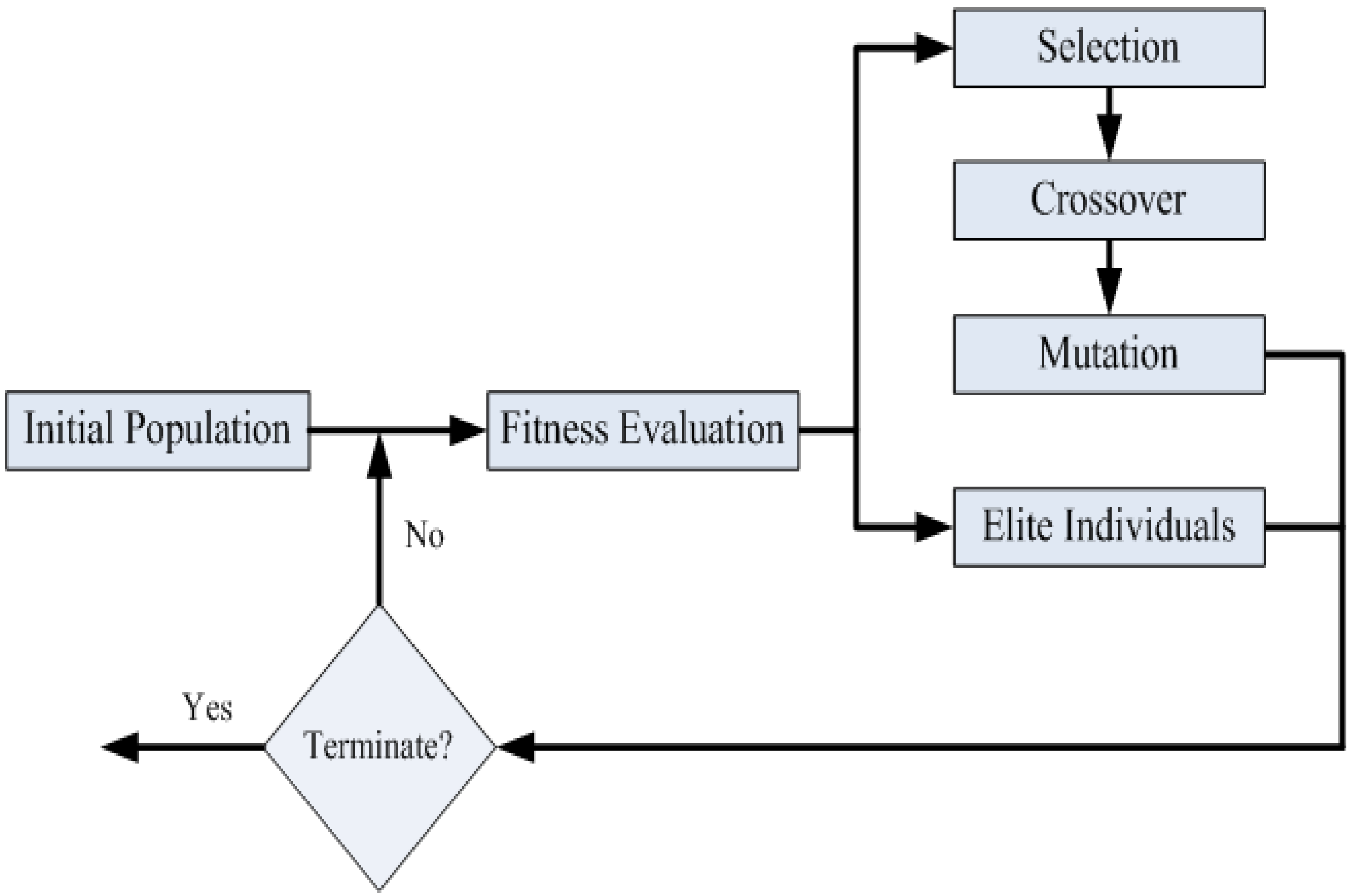
$$\begin{bmatrix} 1 & 0 & 0 & 1 & . & . & . & 0 & 1 & 1 \end{bmatrix}$$

- The binary vector contains the sensors information:
  - Location
  - Number
  - Type



- Search space for measurement model is huge (2^{400})
- Evolutionary algorithm can help us surf the space to find optimal model
- **Genetic Algorithm!**

Genetic Algorithm



Simulation

- The nonlinear system is simulated with ramp disturbances which includes:
  - 5% increase in inlet temperature (from 550 to 575.5 K)
  - 20% increase in syngas CO mole fraction (from 0.31 to 0.372)
- The system is simulated with the following specifications:
  - Process noise: 10^{-2}
  - Concentration, pressure and temperature measurement noise: 10^{-2}
  - Error covariance: 10^{-4}

Genetic Algorithm

- The fitness function, as reported previously, is calculated as:

$$e_{total} = \sum_{1}^{707} (x_{estimated} - x_{actual})^2$$
$$Fitness = \exp(-e_{total})$$

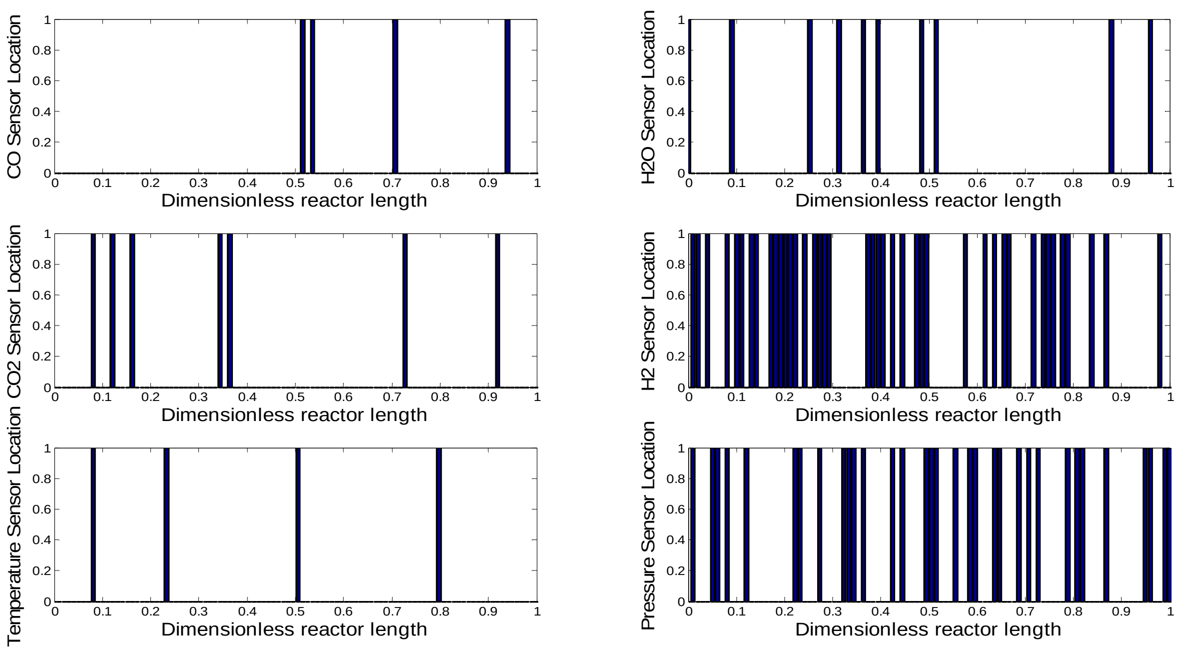
- Fitness function is normalized by the fitness of the individual where all states are measured.

$$Normalized\ Fitness = \frac{\exp(-e_{total,100\ sensors})}{\exp(-e_{total,607\ sensors})}$$

GA Results

• Value 1, shown as a bar, indicates that a sensor has to be placed at the specified location of the reactor

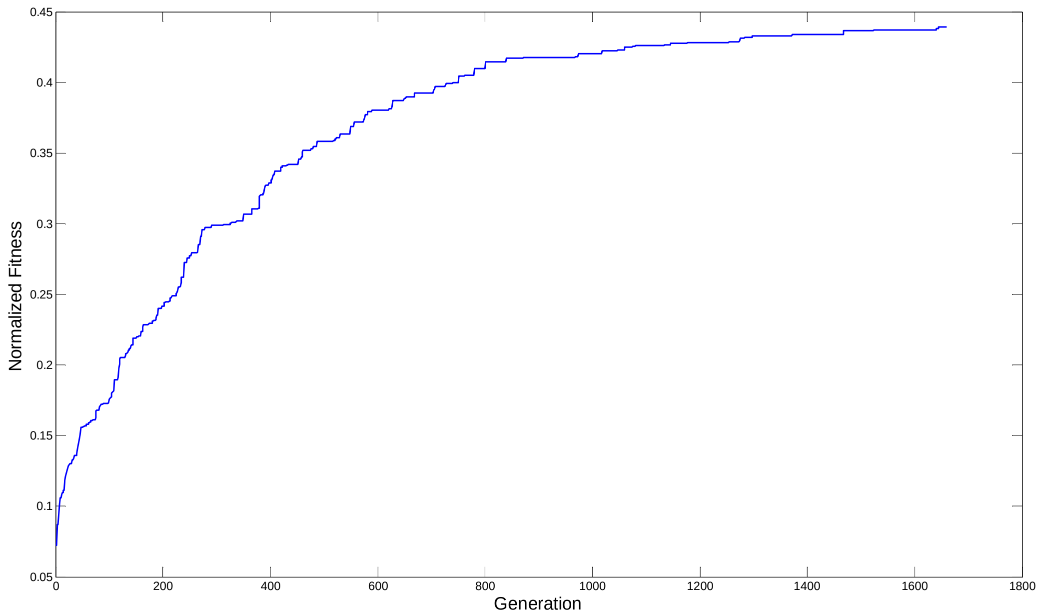
• The figure is prepared with information from current generation of the GA algorithm.



Sensor locations on the dimensionless reactor length after 470 generations

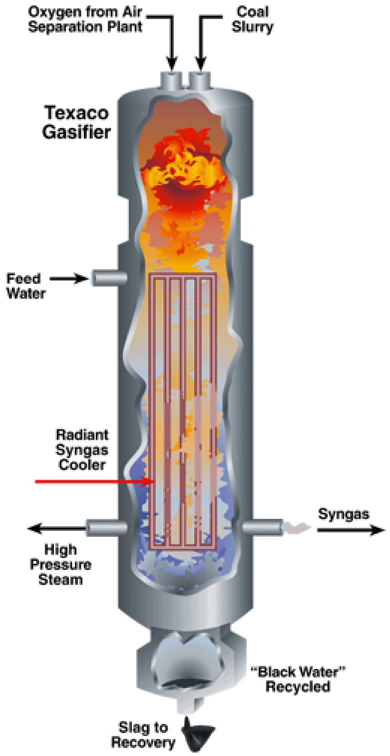
GA results

- A fixed number of sensors (=100) is assumed and the genetic algorithm is run to find best combination of the sensors.
- The fitness is normalized with the case that all measureable states are measured.



Distributed Sensor Placement In Gasifier

Gasifier-Model



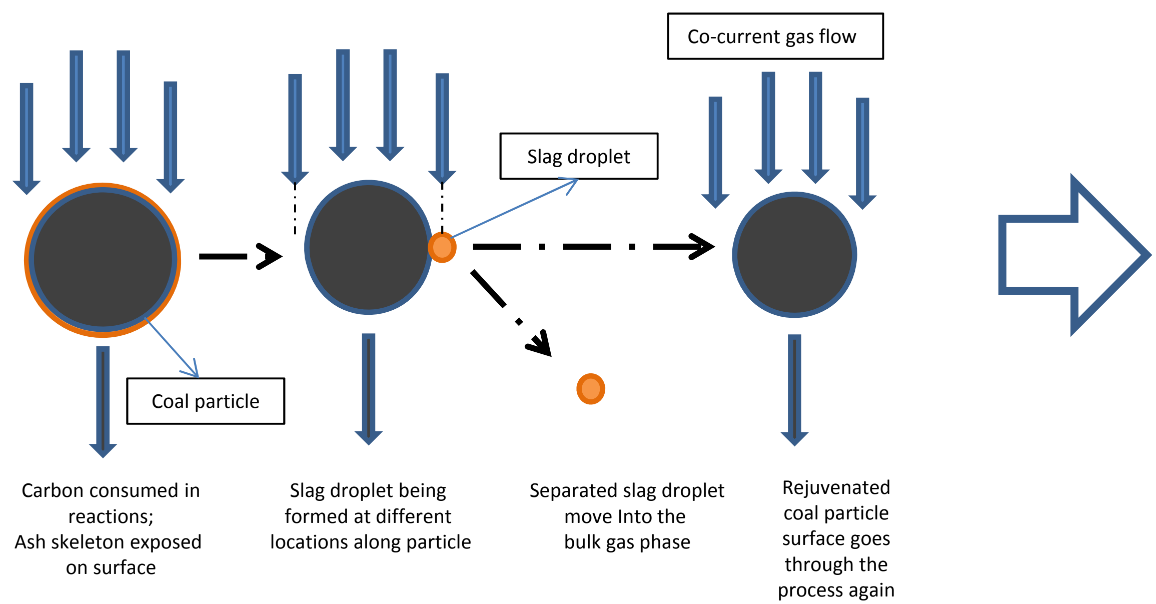
- Gasifier operates at temperatures of about 1200-1600°C
- Liquid slag flows on walls and is collected at bottom
- Gasifier model developed at WVU does not consider slagging phenomenon
- Slag penetration mainly responsible for refractory degradation

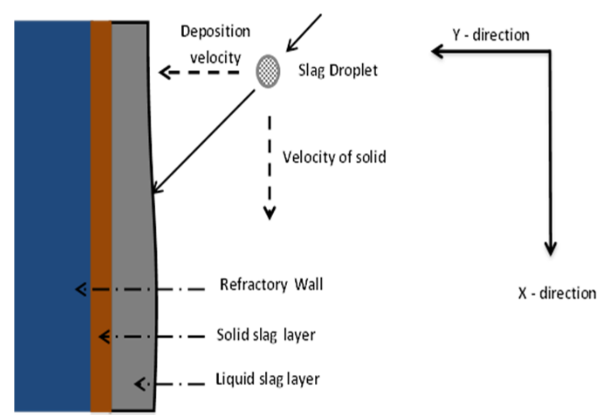
Two-stage model for slag deposition

1. Slag formation and detachment

2. Slag deposition and flow

Model Development

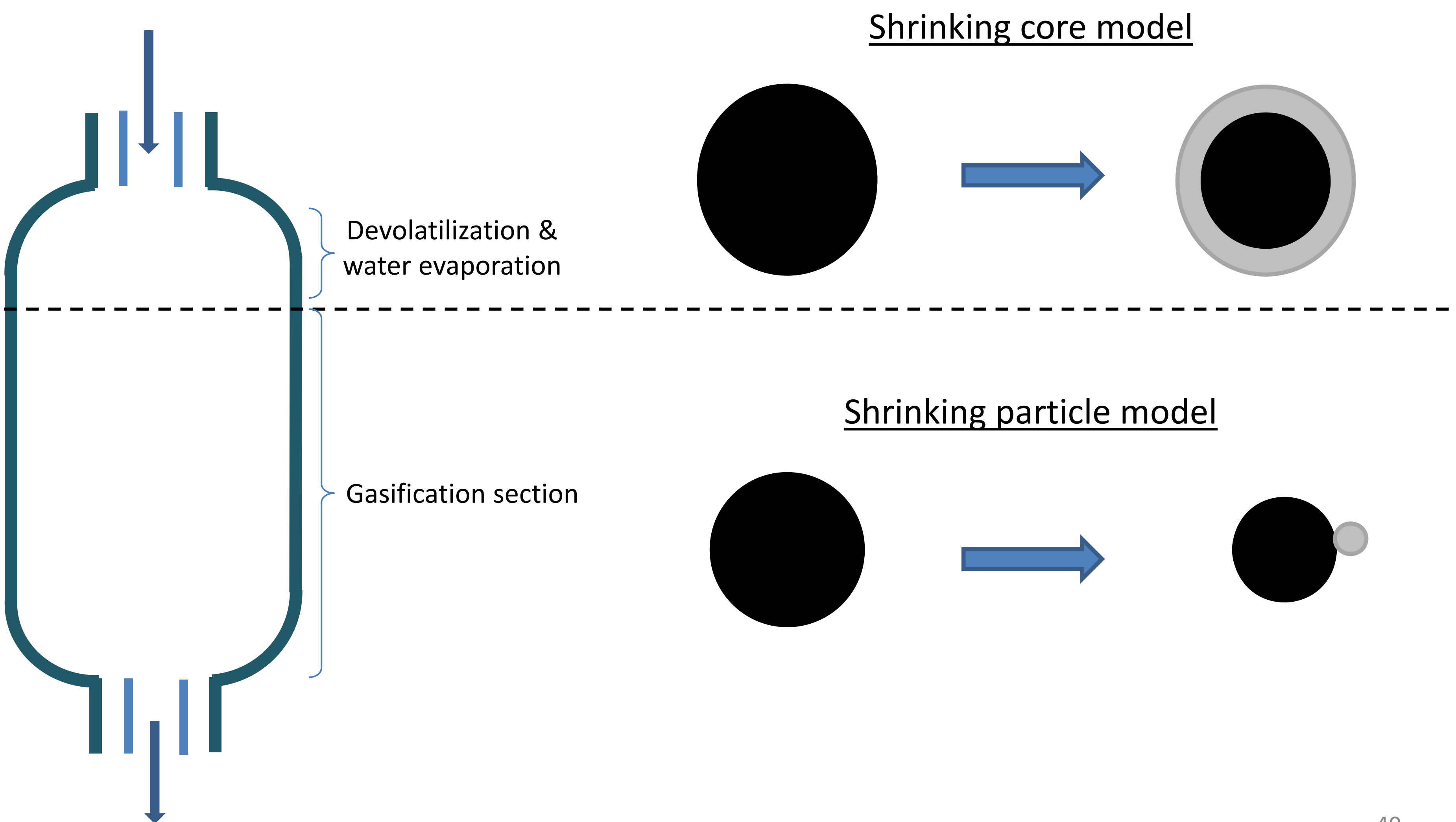




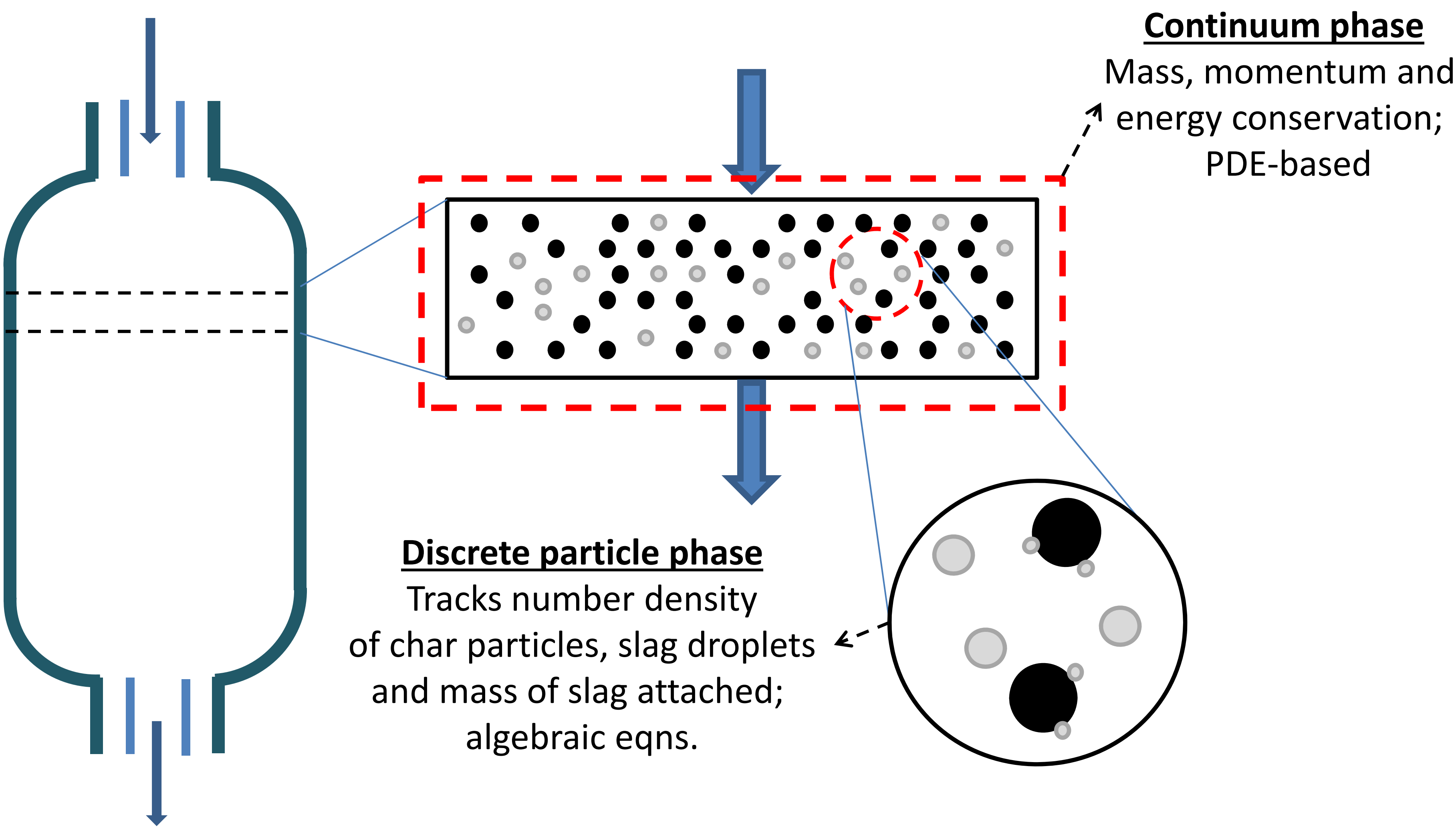
Slag formation on char particle

Slag deposition

Reaction Models Used in Non-Slagging and Slagging Gasifier Section

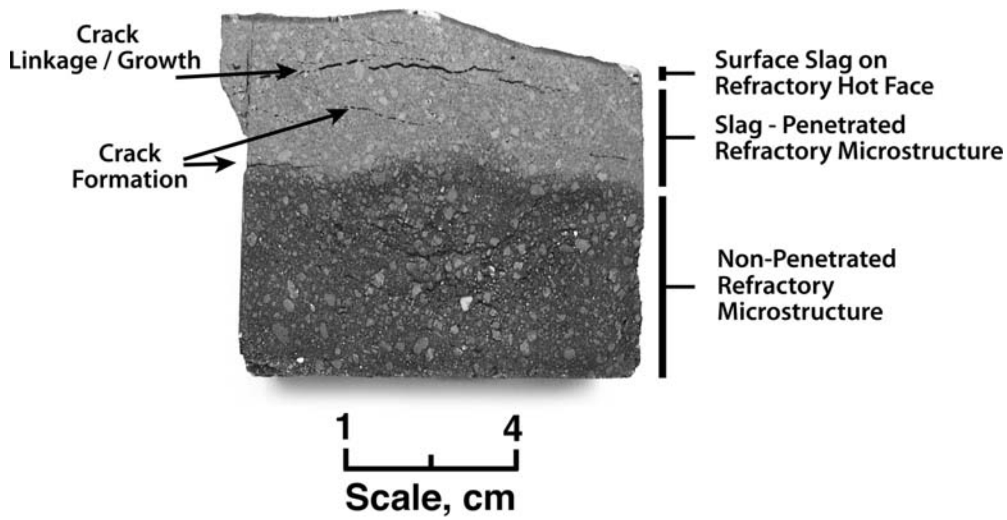


Integration of Continuum and Discrete Particle Phase



Gasifier Fault - Refractory Degradation

- ❑ Slag penetration



Bennett, J. “Failure Mechanisms in High Chrome Oxide Gasifier Refractories”; Metallurgical and Materials Transactions; 2011, 42, 4, pp. 888 - 904

- ❑ Spalling
  - ❑ Tensile Spalling
  - ❑ Compressive Spalling

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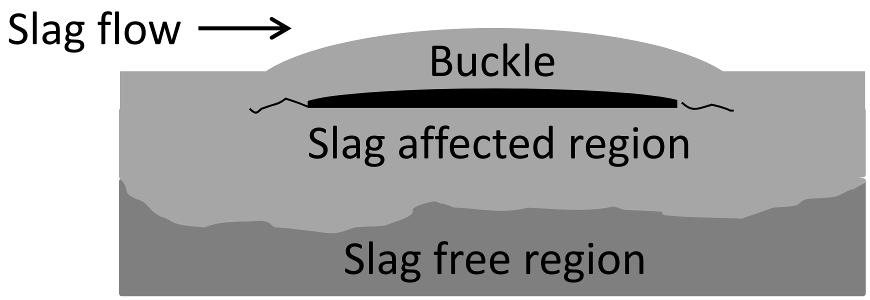
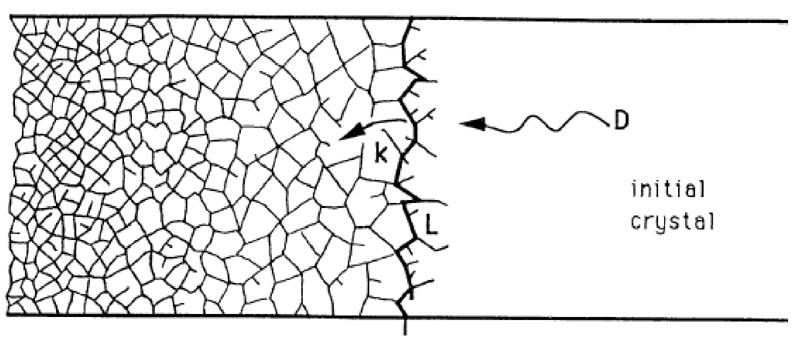
Compressive Spalling



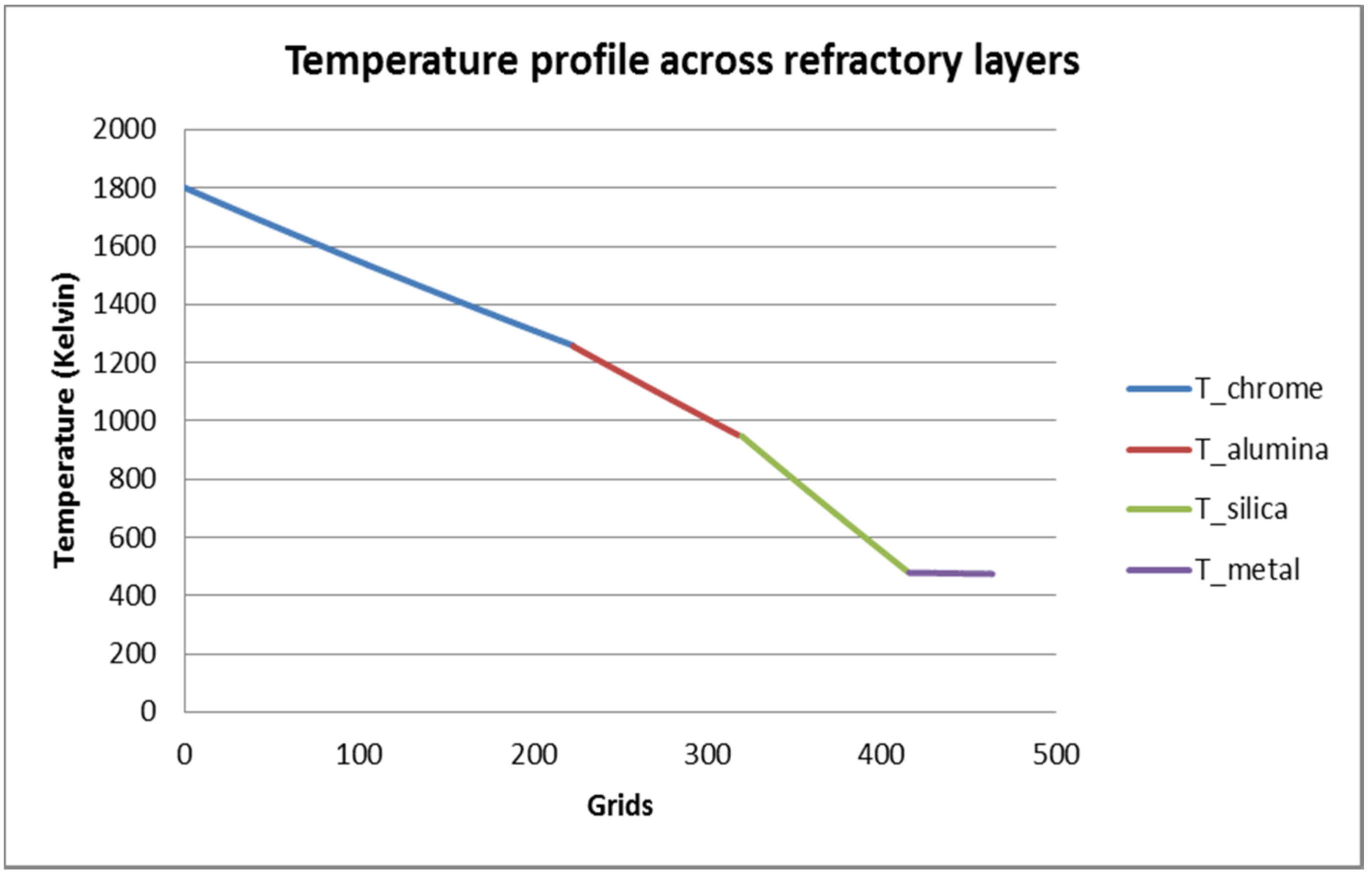
- Fe^{3+}/Cr^{3+} substitution
- Results in Buckling

Tensile Spalling

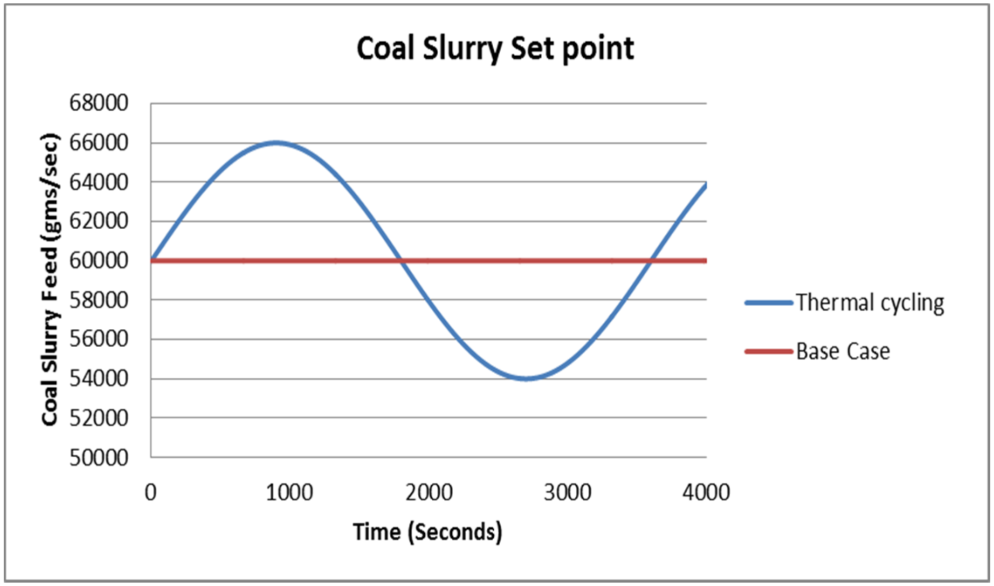


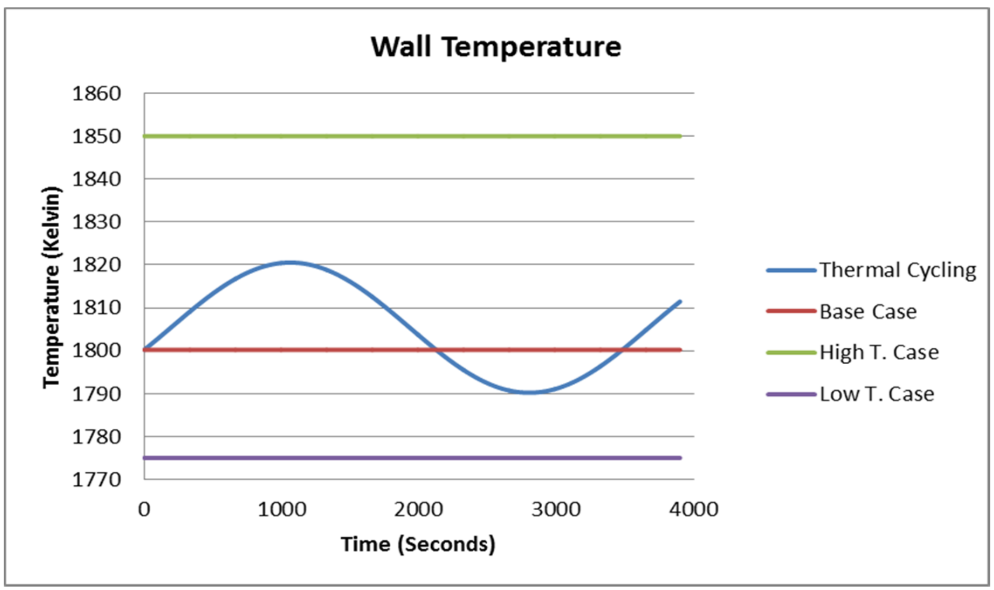
- Cr^{3+} migration
- Cracked structure

Results : Gasifier
Steady state temperature profile



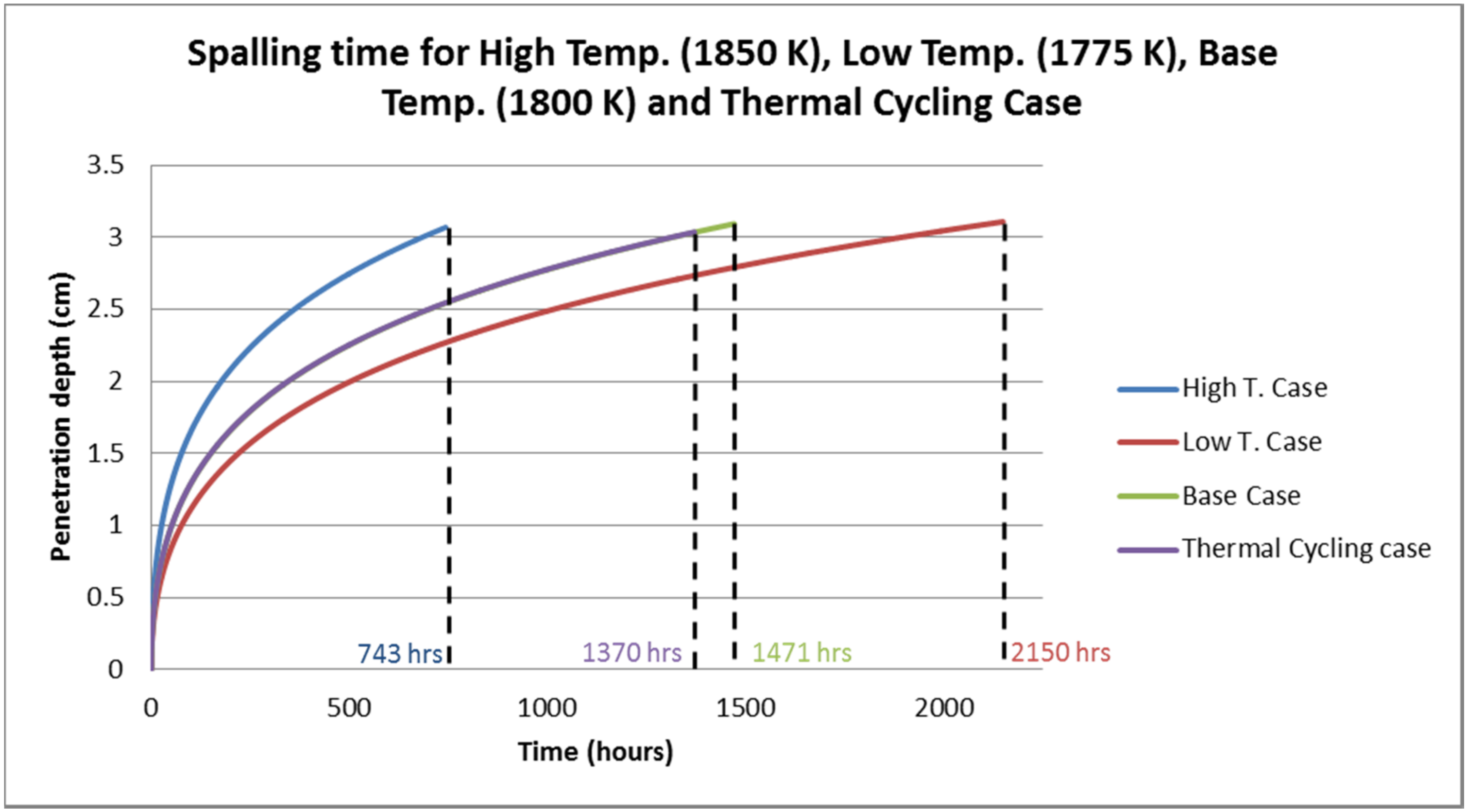
Testing: Base, Thermal Cycling, High and Low Case





- Coal slurry SP was oscillated using sinusoidal function with period of 1 hour
- Slag model wall temperature was found for this input and fit
- Wall temperature was used as boundary condition for Refractory Degradation model
- Gasifier model and Degradation model operate at different time scales

Results : Refractory Spalling time



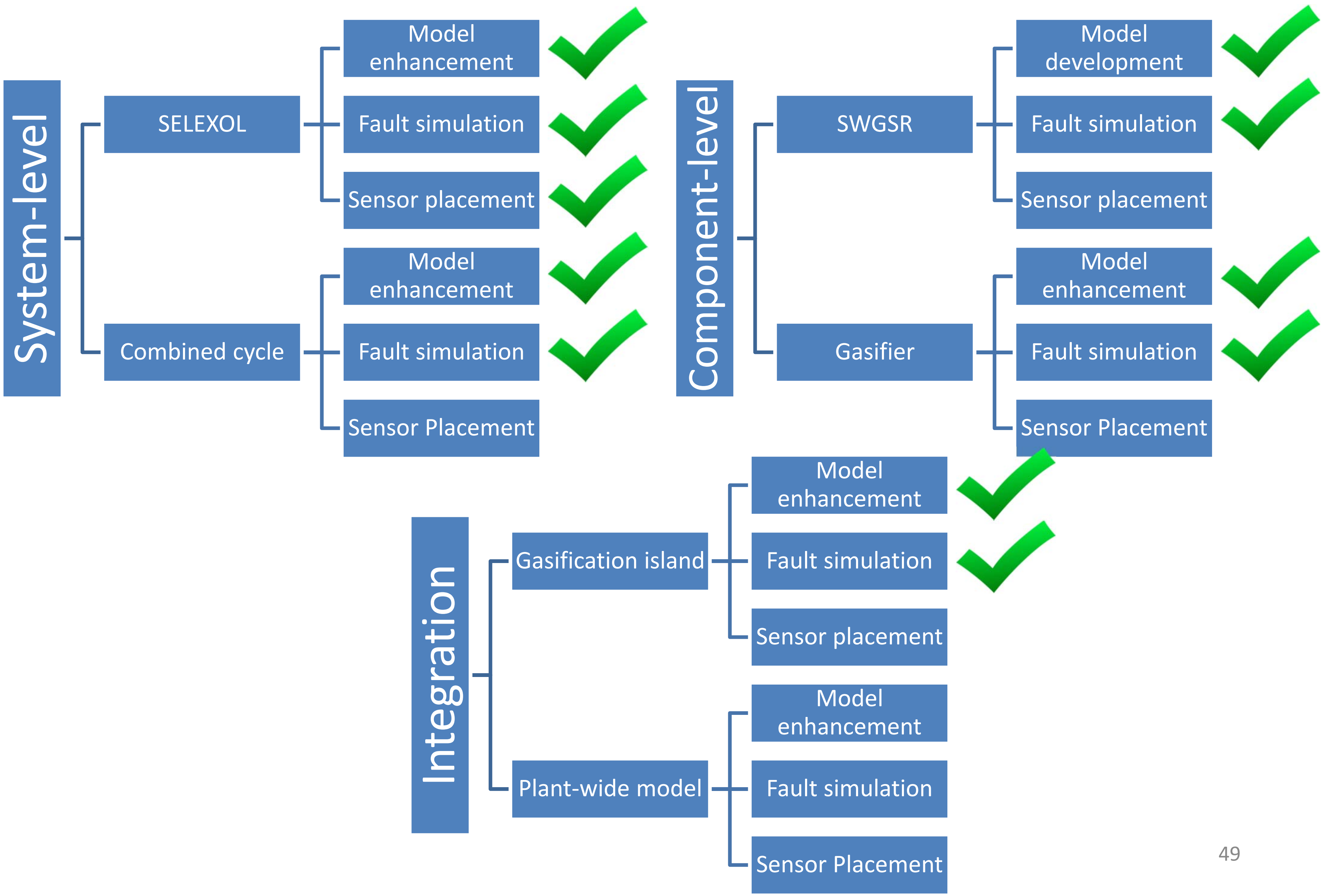
Future work

- Develop a reduced order gasifier model for estimation
- Implement distributed sensor placement algorithms on the gasifier
- Integrating the gasifier model into the gasification Island
- Perform two tier sensor placement algorithm

Current status

- System-level
  - SELEXOL
    - Model enhancement
    - Fault simulation
    - Sensor placement
  - Combined cycle
    - Model enhancement
    - Fault simulation
    - Sensor Placement
- Component-level
  - SWGSR
    - Model development
    - Fault simulation
    - Sensor placement
  - Gasifier
    - Model enhancement
    - Fault simulation
    - Sensor Placement
- Integration
  - Gasification island
    - Model enhancement
    - Fault simulation
    - Sensor placement
  - Plant-wide model
    - Model enhancement
    - Fault simulation
    - Sensor Placement

Current status



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