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Sensor Network Design for State Awareness: An Overview and Recent Results

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Outline

- Introduction
- Design of sensor network for fault diagnosis
- The problem of integrating sensor networks
- Value formulation for integrating sensor networks
- Examples
- Conclusions

Introduction

- What to measure, where to measure ??
- Identify critical measurements, prevent data overload

Introduction

- Sensor network design (SND) problem - Selection of variables to be measured and type of instruments to be used
- Selection of variables to be measured usually decided during design of P&ID for plant
- Decisions usually based on past experience & technical feasibility
- Cost of instrumentation ~ 15% of the total plant cost

Impact of Sensor Network

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Sensor Network Design Criteria

- Observability / redundancy
  - Ability to estimate variables using measurements
- Reliability
  - Ability to estimate variables under sensor failures
- Estimation accuracy
  - Ability to obtain accurate estimates
- Fault diagnosis
  - Ability to diagnose faults
  - Observability of Faults
  - Resolution of Faults
- Controllability Analysis
  - Inferential Measurements
  - Actuator Placement

Optimization approach for SND

- Objective Types
  - Single Objective
  - Multiple objectives (Cost and a primary objective within a problem domain)

- Solution approaches
  - Graph Theory
  - MILP
  - MINLP
  - GA
  - Goal Programming
  - Lexicographic Formulations
  - Uncertainty Formulations

Previous Techniques -Models

- Graph theory (Process Graph)
  - Single Objective (Cost, Observability or Reliability)
- Graph theory (Signed Directed Graph)
  - Fault Diagnostic Observability/Resolution
  - Controllability Analysis
- Linear Algebra
  - Single Objective (Cost, Observability or Reliability)
- State-Space
  - Estimation Accuracy
  - Diagnosability
  - Controllability

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Sensor Network Design for Fault Diagnosis

Sensor Location: Observability of Faults

- Observability requirement
  - Atleast one sensor should show deviation when a fault occurs
- Root (Fault) nodes
  - Nodes with only output arcs
- Key nodes
  - Variables with only input arcs

Sensor Location: Cause-Effect Modeling

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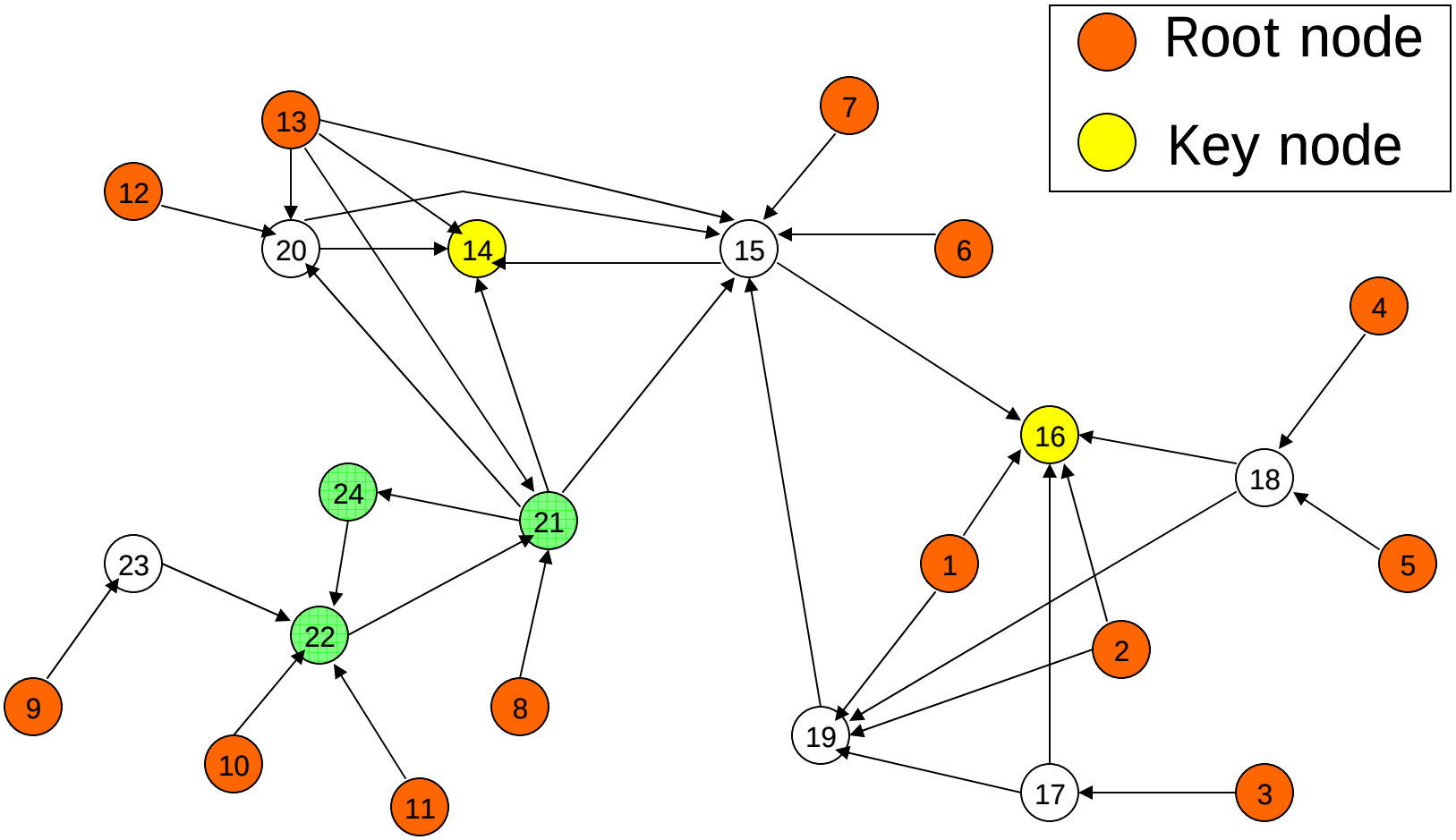
- Based on process digraph
  - Cause-effect relationships between process variables
  - Nodes: Process variables,faults
  - Arcs: Effect between nodes
- Process signed digraph (SDG)
  - Arcs: Have direction of effect (+,-)
- SDG variations: SDG with gains
  - Arcs: Have gains, along with signs
- Generated from process model equations

Sensor Location: Observability of Faults



Sensor Location: Observability of Faults

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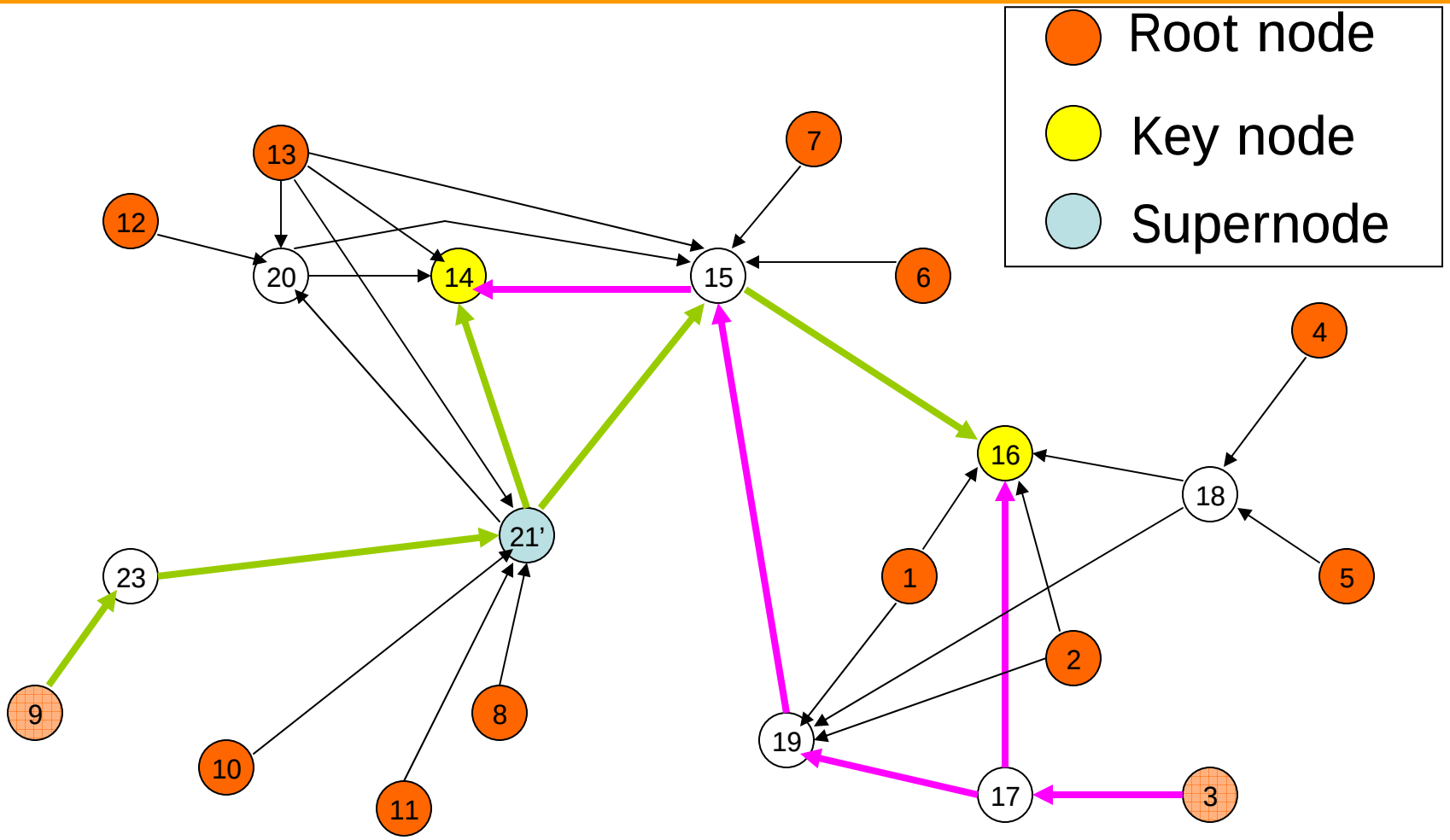
Lemma 1: In a directed graph which is weakly connected (the corresponding undirected graph is strongly connected) with no loops, there is atleast one directed path from a root node to a key node

- In the DG, replace the loops by supernodes
- Selection of all key nodes in this DG would ensure observability of all faults

Sensor Location: Observability of Faults



Sensor Location: Observability of Faults

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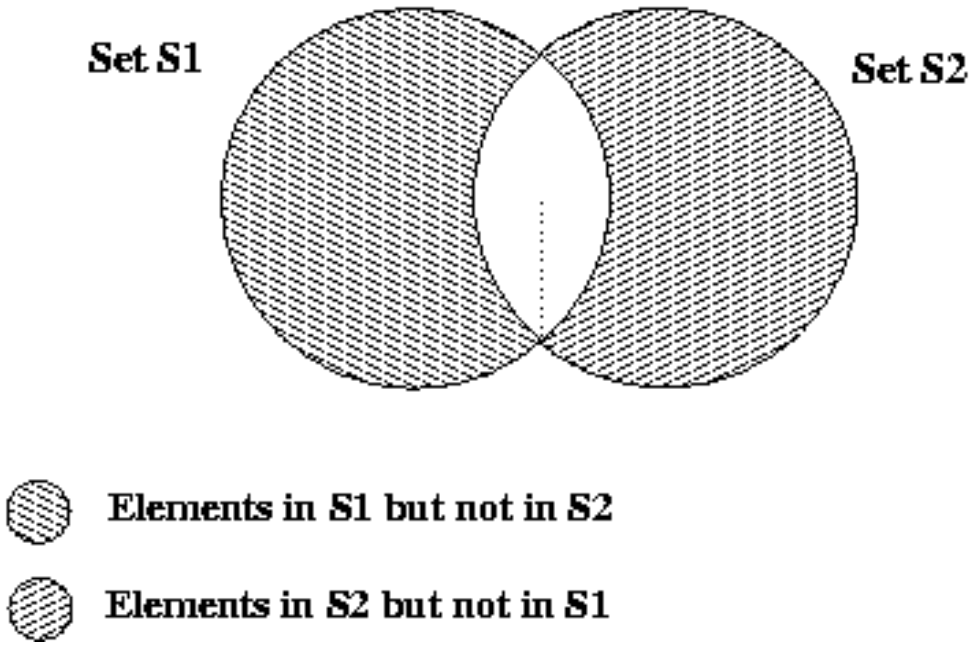
- Selection of all key nodes
  - Not necessarily the minimum set
- Choose the minimum set of sensors from the key nodes while ensuring observability of all faults
- F1={s1,s2,s3}, F2={s1,s4}
  - Choose s1
- Set cover problem
  - The selected sensors should contain atleast one sensor from each set
- Hard problem to solve exactly
  - Greedy search heuristics

Sensor Location: Resolution of Faults



- A sensor in the shaded region can distinguish between faults F1 and F2

Sensor Location: Resolution of Faults

- Differentiate between faults
- Single fault assumption
- Form new, pseudo faults corresponding to being able to resolve between original faults
  - F1={A1}={s1,s2,s3}, F2={A2}={s1,s2,s4}
  - All measurable nodes (and not just key nodes) considered
  - B_{12}= A1Δ A2 = {s3,s4} = set of sensors which can distinguish between F1 and F2
  - B_{12} covered => Faults F1 and F2 can be distinguished
- Form and cover all such B_{ij}: Total of ${}^{n}C_{2}$ such new faults
- Sufficient to resolve all faults

Sensor Location: Multiple Fault Scenario

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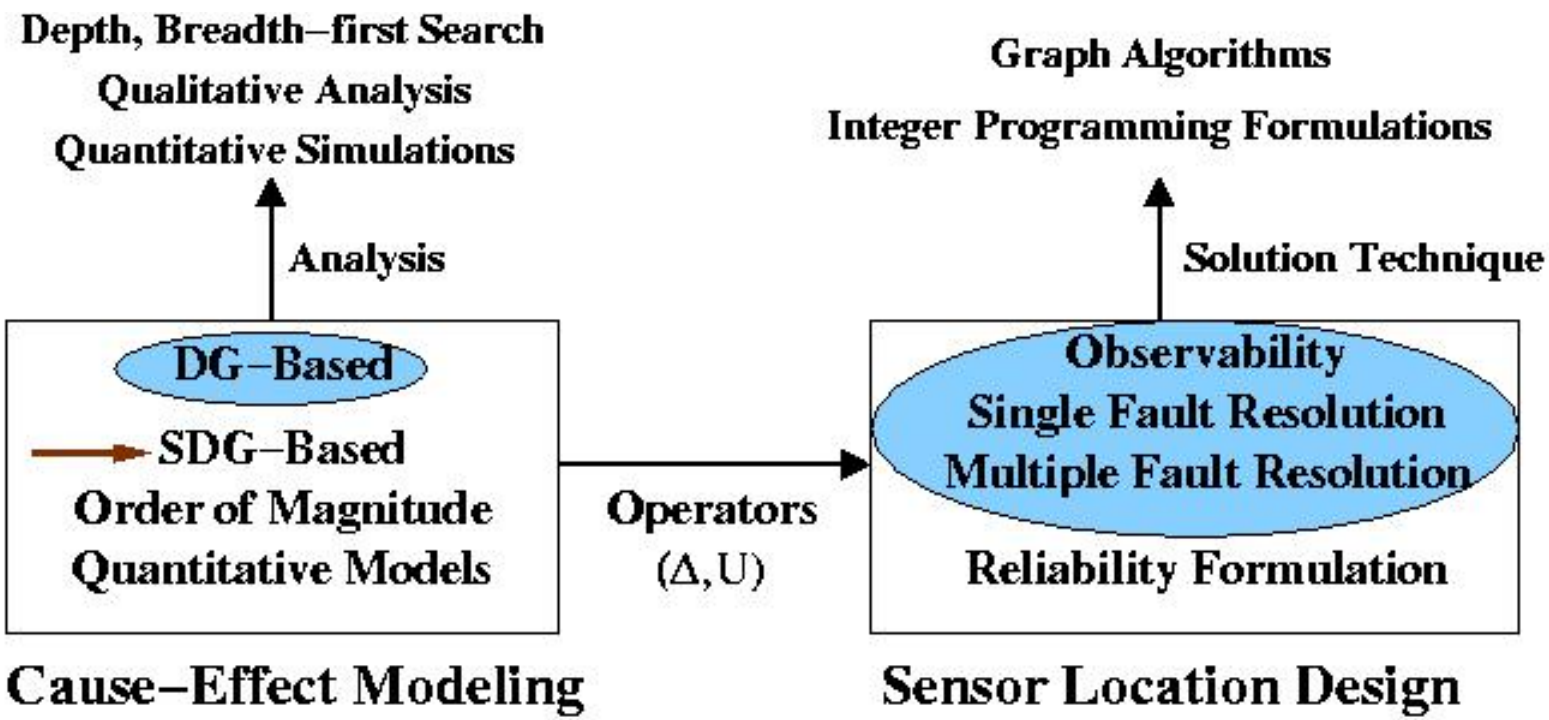
- Methodology extended to multiple fault occurrence scenario
- Create appropriate, pseudo faults
- Consider the specific case of upto two faults at a time
- F1={A1}={s1,s2}, F2={A2}={s2,s3}
- Take union: F_{12}=A1$\cup$A2 = {s1,s2,s3} = set of sensors affected when both faults F1 and F2 occur simultaneously
- Add to original set of faults
- Resolution problem for extended system
- Again an observability problem

Sensor Location: General Strategy



Integrated Sensor Network Design

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- What is the state of the art?
  - Design algorithms exist for individual objectives
    - Process Observability, Diagnostics
  - No integrated approach
- Key Driver
  - Single network has to cater to all process management objectives
  - Piece-meal solution not applicable
- Design approaches need to be developed for this integrated sensor network design problem

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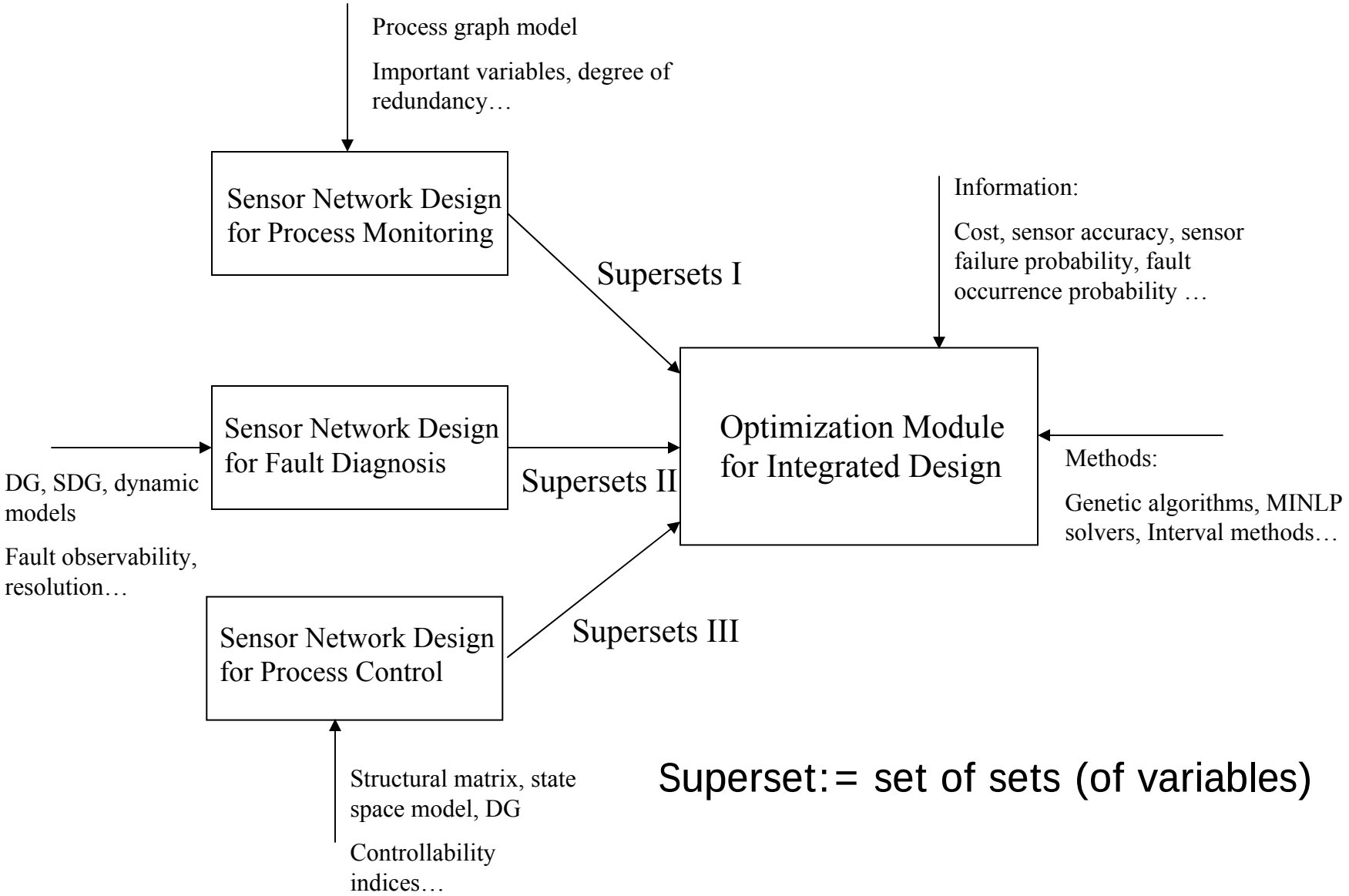
Superset Formulation for Integrated SND

Integrated Sensor Network Design



Superset:= set of sets (of variables)

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Value Formulation for Integrated SND

Joint Work With

Prof. Miguel Bagajewicz, University of Oklahoma

Prof. Donald Chmielewski, IIT Chicago

SND Perspectives

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Material Accounting:

Goal: Precise measurement/estimation of production rates.

Impact: Inventory costs and amount of lost product.

Control Systems:

Goal: Reduce variations around set operating points.

Impact: Product quality and throughput capabilities.

Fault Diagnosis:

Goal: Quickly and accurately identify equipment failures.

Impact: Downtime losses and safety issues.

The Upgrade Problem

Let SN_0 be an existing network, then an upgrade to network SN has a Value defined as:

$$\text{Value}\ (SN) = \text{Profit}\ (SN) - \text{Profit}\ (SN_0)$$

Then the upgrade SND problem is defined as:

$$\textbf{Maximize}\ \{\ \text{Value}\ (SN) - \text{Cost}\ (SN)\ \}$$

Integrated Maximum Profit Problem

$$\textbf{Maximize} \quad \{ \sum_{i=1}^{3} \{ V_i (SN) \} - \text{Cost}(SN) \}$$

where $V_i (SN)$ are the Value functions from the three perspectives

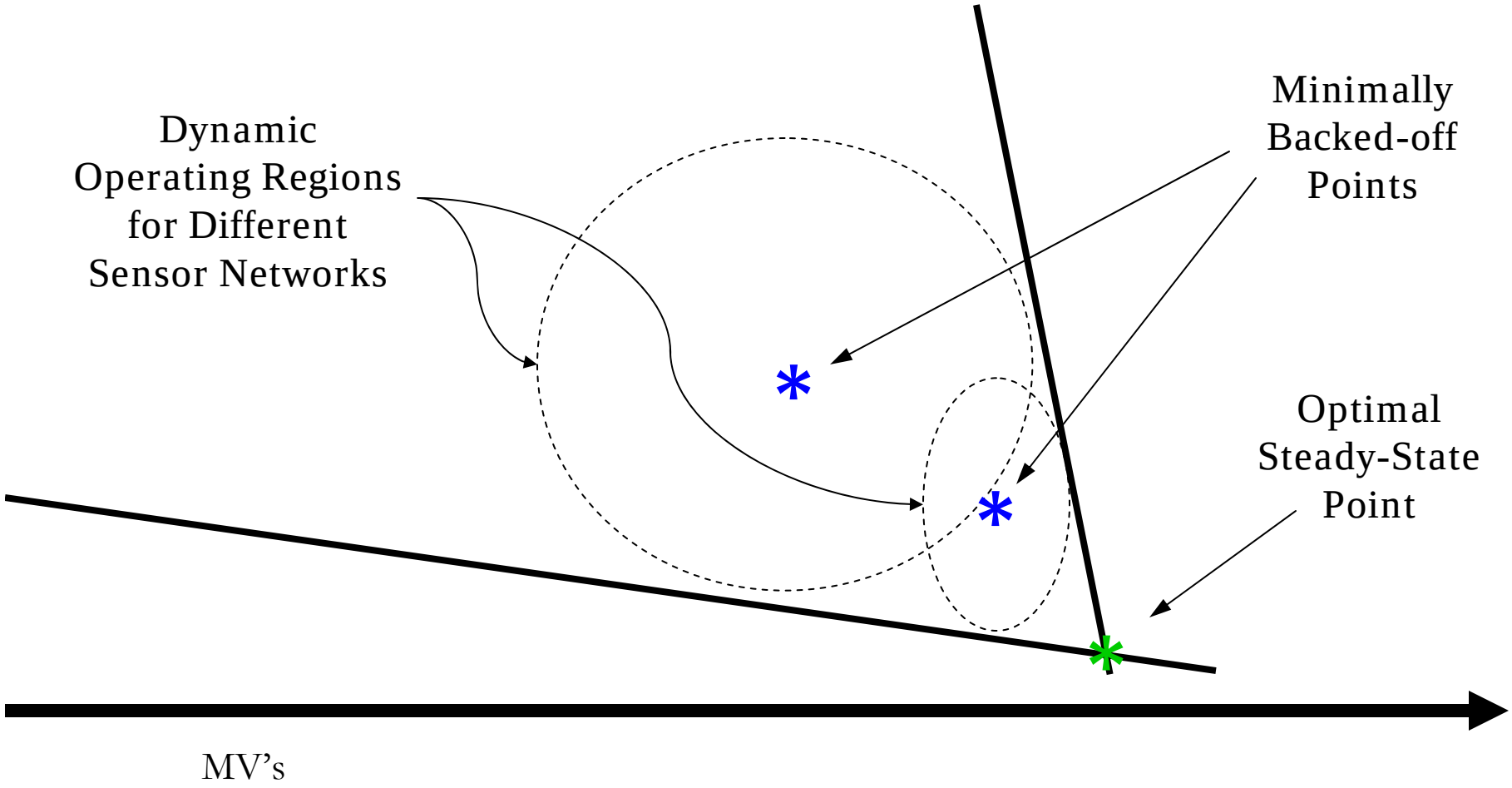
i=1 Control Systems

i=2 Material Accounting

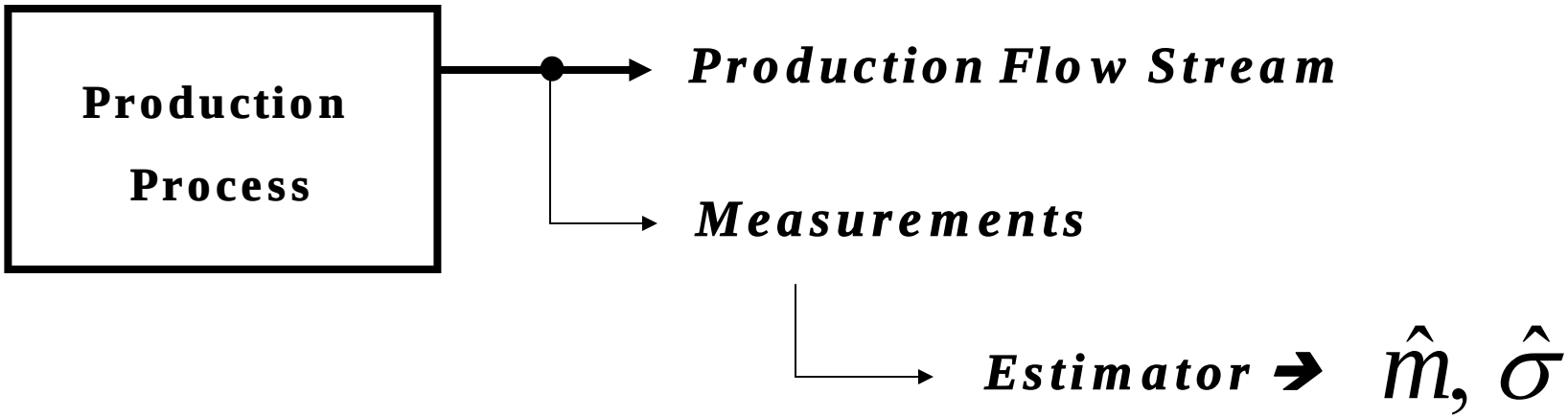
i=3 Fault Diagnosis

Maximum Profit Sensor Selection

(control system perspective)



The Material Accounting Perspective



where $\hat{m}$ is the estimated production rate of p

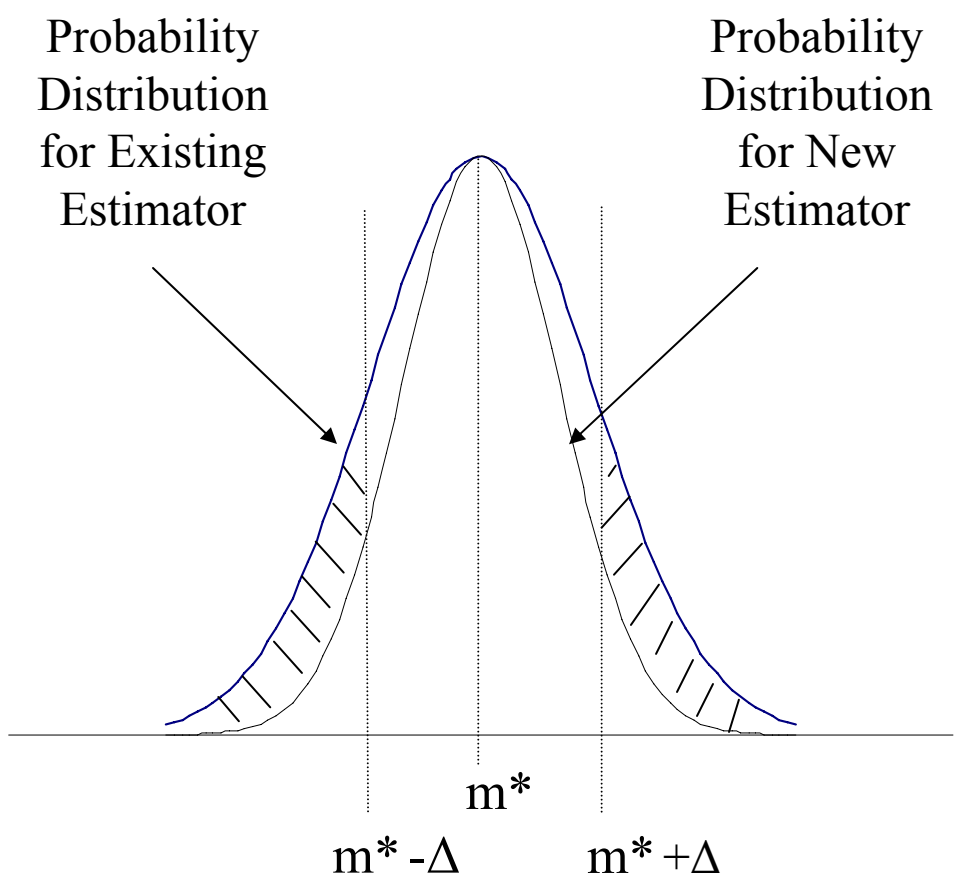
and $\hat{\sigma}$ is the precision of the estimator

Distribution of Estimates

Consider production stream *p*.

Assume the target production rate is m*.

Let $g(\xi, \hat{\sigma}_{p,m})$ be the estimate distribution function for the existing network, and $g(\xi, \tilde{\sigma}_{p,m})$ be for the new network



The Economic Value of an Upgrade

(material accounting perspective)

If a new network SN replaces SN_0 , which has a distribution

$g\left(\xi, \tilde{\sigma}_{p,m}(SN)\right)$ then upgrade value is defined as:

$$V(SN) = K_S\left[DEPL\left(\hat{\sigma}_{p,m}(SN_o)\right) - DEPL\left(\tilde{\sigma}_{p,m}(SN)\right)\right]$$
$$\cong K_S\gamma\left(\hat{\sigma}_{p,m}(SN_o) - \tilde{\sigma}_{p,m}(SN)\right)$$

where K_s is the product value (or the cost of inventory) and γ is a constant.

The Fault Perspective

(Detection Formulation)

- Consider a set $\boldsymbol{F}$ of possible faults $\boldsymbol{F}=\{ \boldsymbol{f_i} \}$.

Define a set $\boldsymbol{A_i}(SN)$ as the set of sensors in SN that can observe fault $\boldsymbol{f_i}$.

If $\boldsymbol{A_i}(SN)$ is not empty then $\boldsymbol{f_i}$ can be detected.

Assume immediate correction occurs for detected faults.

If all faults in $\boldsymbol{F}$ can be detected, then no production losses or safety incidents will be expected.

The Value of an Upgrade

- Let $\boldsymbol{F_u}(SN)$ be the set of un-diagnosable (or undetectable) faults (from $\boldsymbol{F}$) for a given configuration SN.

The Expected Economic Loss due to $\boldsymbol{F_u}(SN)$ is denoted:

$$\text{EEL}\ (\boldsymbol{F_u}(SN))$$

If $\boldsymbol{F_u}(SN)$ is empty then

$$\text{EEL}\ (\boldsymbol{F_u}(SN)) = \mathbf{0}$$

The Value of an upgrade from SN_0 to SN is

$$V(SN) = \text{EEL}\ (\boldsymbol{F_u}(SN_0)) - \text{EEL}\ (\boldsymbol{F_u}(SN))$$

CSTR Example

Upgrade Data:

- New 1% precision sensors can replace 2% sensors.
- Replacement cost is $1000/yr (includes purchase, installation, maintenance and replacement costs).
- 1% sensor available for other locations ($1000/yr)

Profit Function ($/yr):

$$p(C_A, F, F_c, F_{vg}) = M_{an}\,[\alpha_1(C_{Ai} - C_A)F - \alpha_2 F_c - \alpha_3 F_{vg}]$$

Motivating Example
(control system perspective)

	No	New Sensors	Value ($/yr)	Sensor Costs ($/yr)	Value - Sensor Costs ($/yr)
○	1	C_A, P	7,060	2,000	5,060
	2	C_A, T_c, P	7,630	3,000	4,630
	3	P	4,500	1,000	3,500
	4	T, P	5,420	2,000	3,420
□	5	C_A, T, T_c, V, P	8,090	5,000	3,080
	6	T, T_c, V, P	6,150	4,000	2,140
△	7	none	0	0	0

Motivating Example
(material accounting perspective)

No	New Sensors	Value ($/yr)	Sensor Costs ($/yr)	Value - Sensor Costs ($/yr)
1	C_{Ai}	131	1000	-868
2	F_{vg}	127	1000	-872
3	F_2	77	1000	-922
4	All sensors	355	13,000	-12,644

In all cases the cost of adding sensors far exceeds the profit returned in the form of Upgrade Value.

Motivating Example
(fault diagnosis perspective)

No	New Sensors	Value ($/yr)	Sensor Costs ($/yr)	Value - Sensor Costs ($/yr)
1	T_{ci}, T_i	7,810	2,000	5,810
2	F_c, T_c, T_i	7,810	3,000	4,810
3	T_c, T_{ci}	4,720	2,000	2,720
4	F_c, T_c	4,720	2,000	2,720

Integrated Perspective
(CSTR Example)

No	New Sensors	Value ($/yr)	Sensor Costs ($/yr)	Value - Sensor Costs ($/yr)
1	C_A, P, T_{ci}, T_i	14,930	4,000	10,930
2	C_A, P, F_c, T_c, T_i	15,525	5,000	10,525

Case 1: union of best networks from individual perspectives.

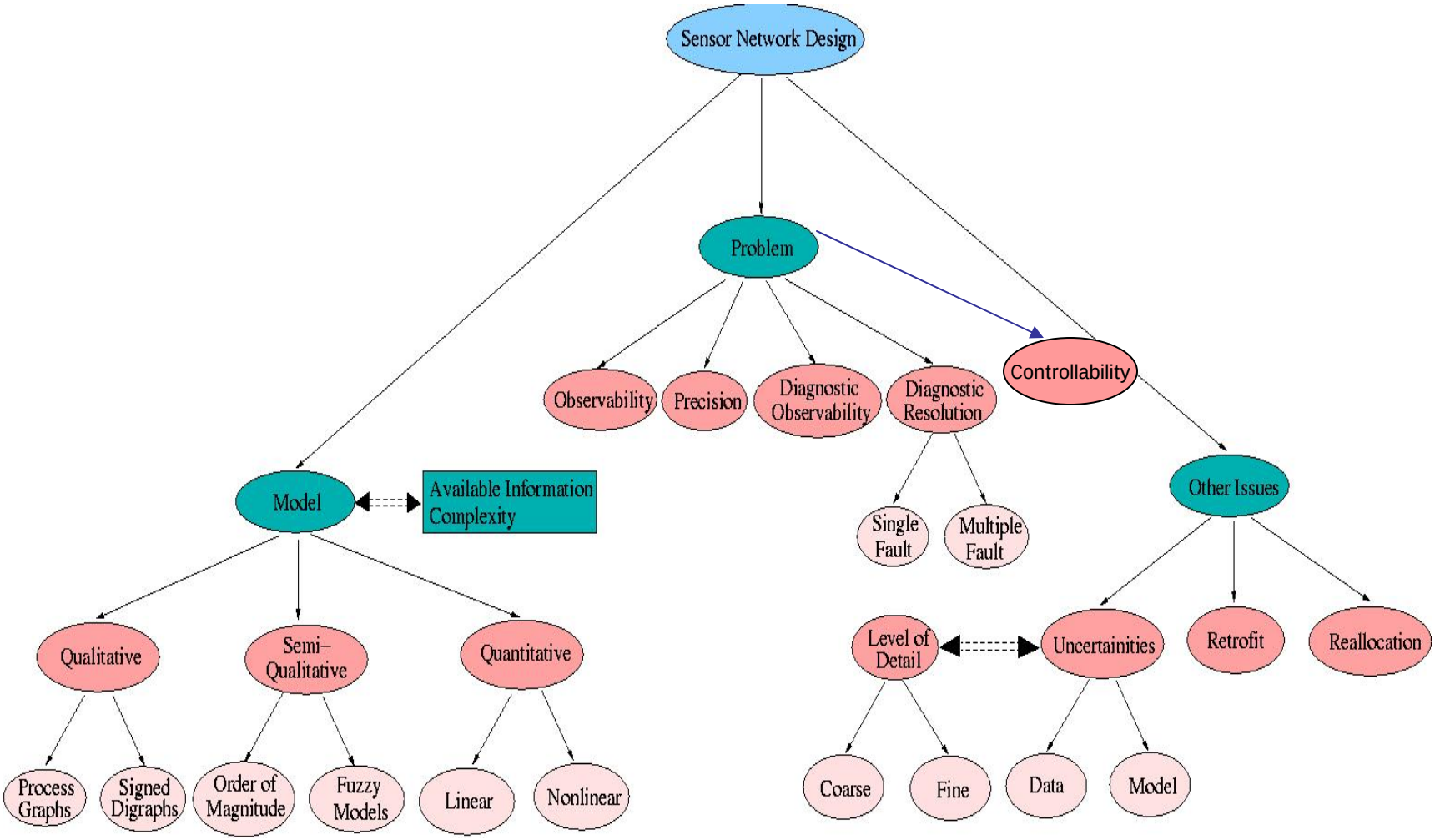
Case 2: union of second best networks.

- These are the best combinations given the tables presented.
- Exhaustive enumeration search is underway.

Conclusions

- Review of sensor network design
- Sensor network design for diagnosis
- Need for integrated sensor network design
- Value formulation for integrated sensor network design

Summary of Sensor Network Design Issues



Sensor Location: SDG Based Modeling

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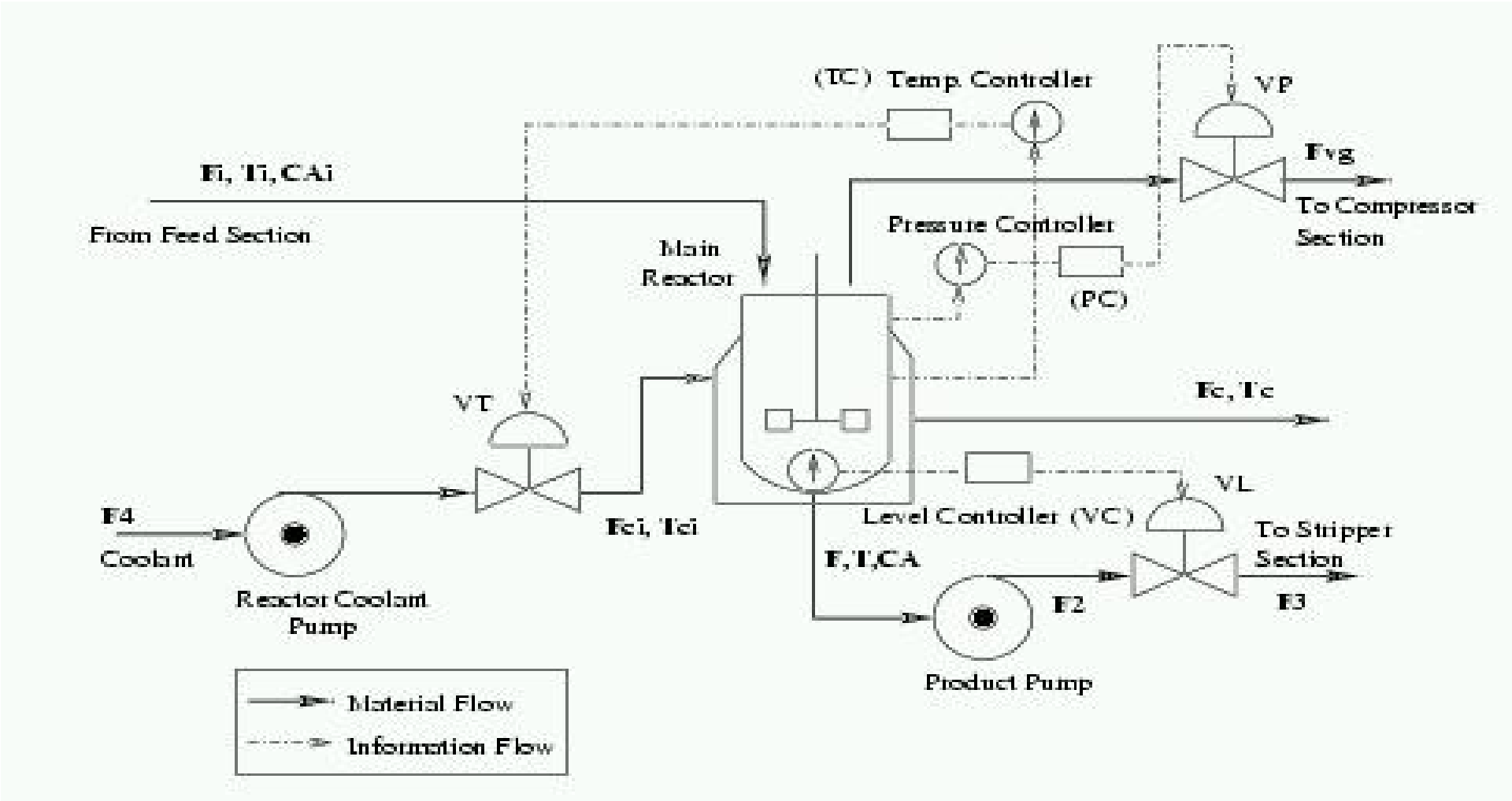
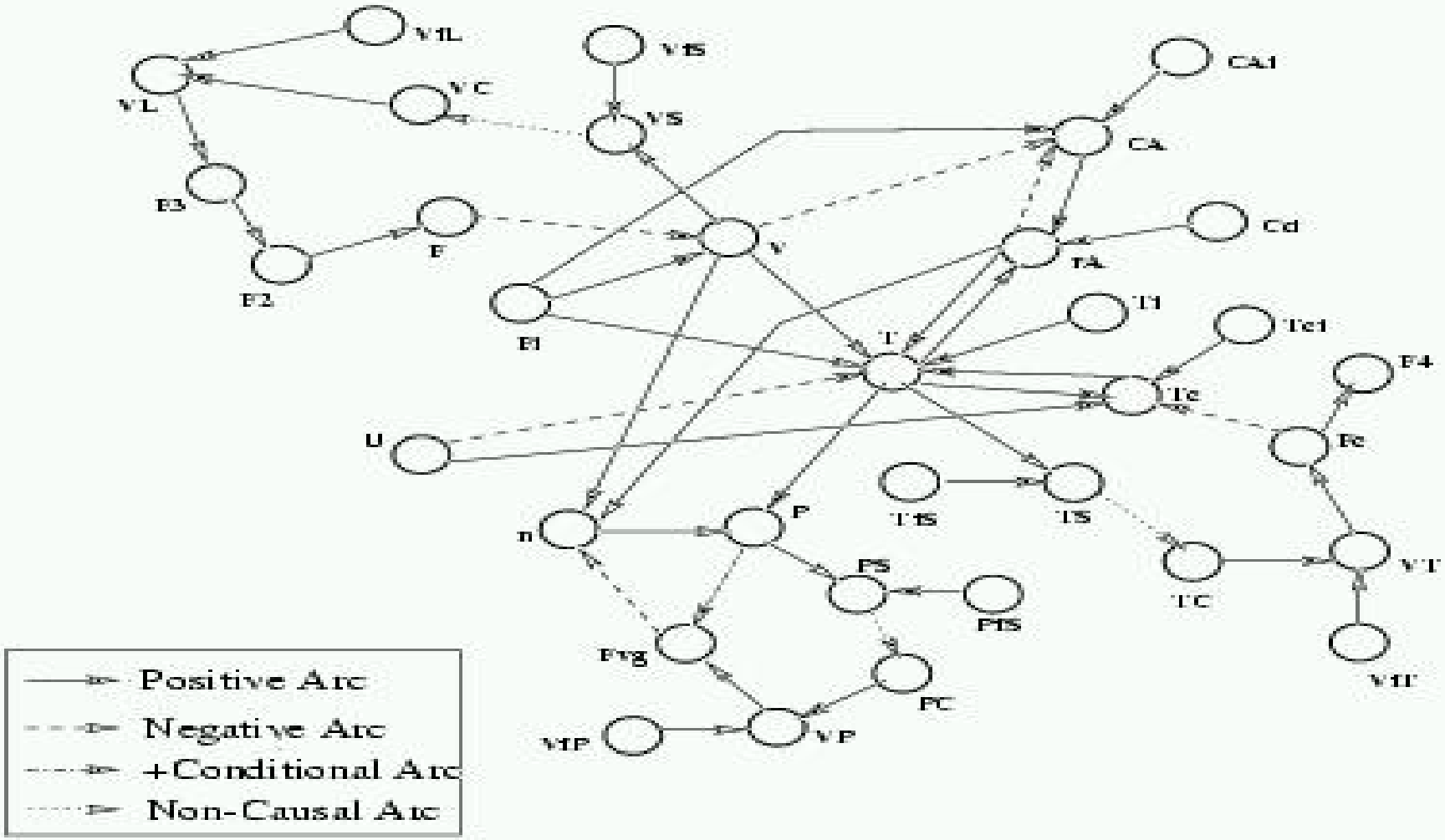
- SDG: DG + arc signs
- Advantages:
  - Better resolution of existing faults
  - Incorporation of details about faults, such as flow-rate increases, flow-rate decreases
- Fault-modeling issues
  - Multiple paths with opposing signs
  - Negative, positive feedback loops
  - Control loops with the potential of masking disturbances
  - Multiple faults with opposing effects
- Appropriate ($\Delta, \cup$) Operators for generation of pseudo faults
- Different sensor location obtained

CSTR Case Study



CSTR Case Study



CSTR Case Study

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Sensor location for CSTR Case Study

	Single-Fault Resolution	Double-Fault Resolution
SDG	[VS,PS,TS,CA,Tc, Fc,F]	[VS,PS,TS,CA,F,Fc, Tc,PC]
DG	[VS,PS,TS,CA,Tc, Fc,F]	[VS,PS,TS,CA,F,Fc, Tc,PC]

Indistinguishable Sets (including control loop failures)

Single fault: SDG model leads to 50% reduction

Double fault: 75 % increase for the DG case

Integrated Design Objectives

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- Introduce a new
  Profit Based Paradigm for SND.

- Propose an
  Integrated Perspective for SND.

Minimum Capital Cost Formulation

(single objective perspective)

Minimize Sensor Network Cost (SN)

s.t. Performance Metrics (SN) > Performance Targets

where

SN is the candidate sensor network, and

Targets must be selected by the plant engineer

Minimum Capital Cost Formulation

(integrated perspective)

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Minimize Sensor Network Cost (SN)

s.t. Accounting Metrics (SN) > Precision Targets

Detection Metrics (SN) > Fault Targets

Control Metrics (SN) > Control Targets

Unfortunately,

- Targets still need to be selected.
- Still no quantification of upgrade benefits.

Maximum Profit Formulation

(single objective perspective)

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Maximize { Profit (Targets) - Cost (SN) }

s.t. Performance Metrics (SN) $\geq$ Targets

$\Leftrightarrow$

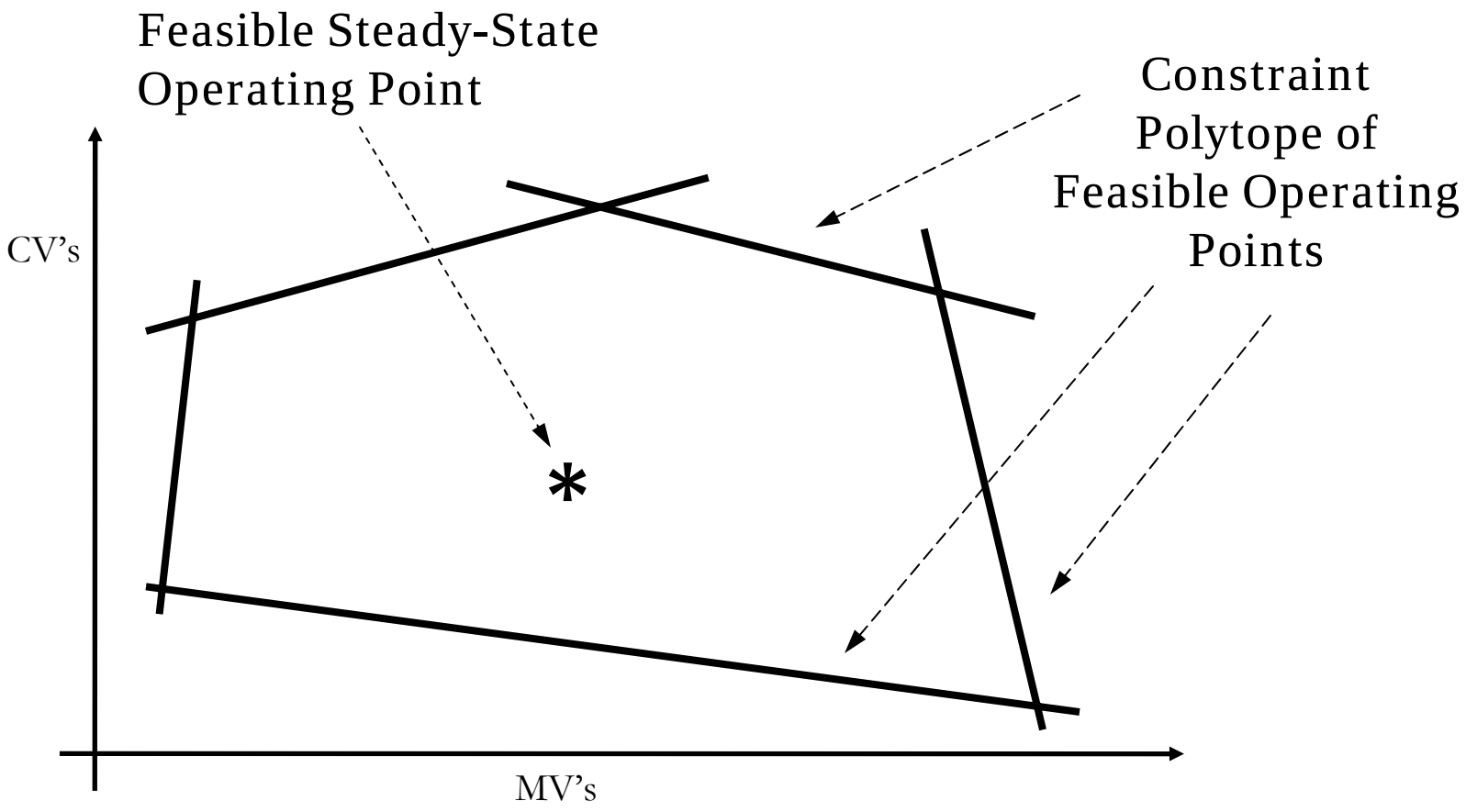
Maximize { Profit (Targets) - Cost (SN) }

s.t. Performance Metrics (SN) = Targets

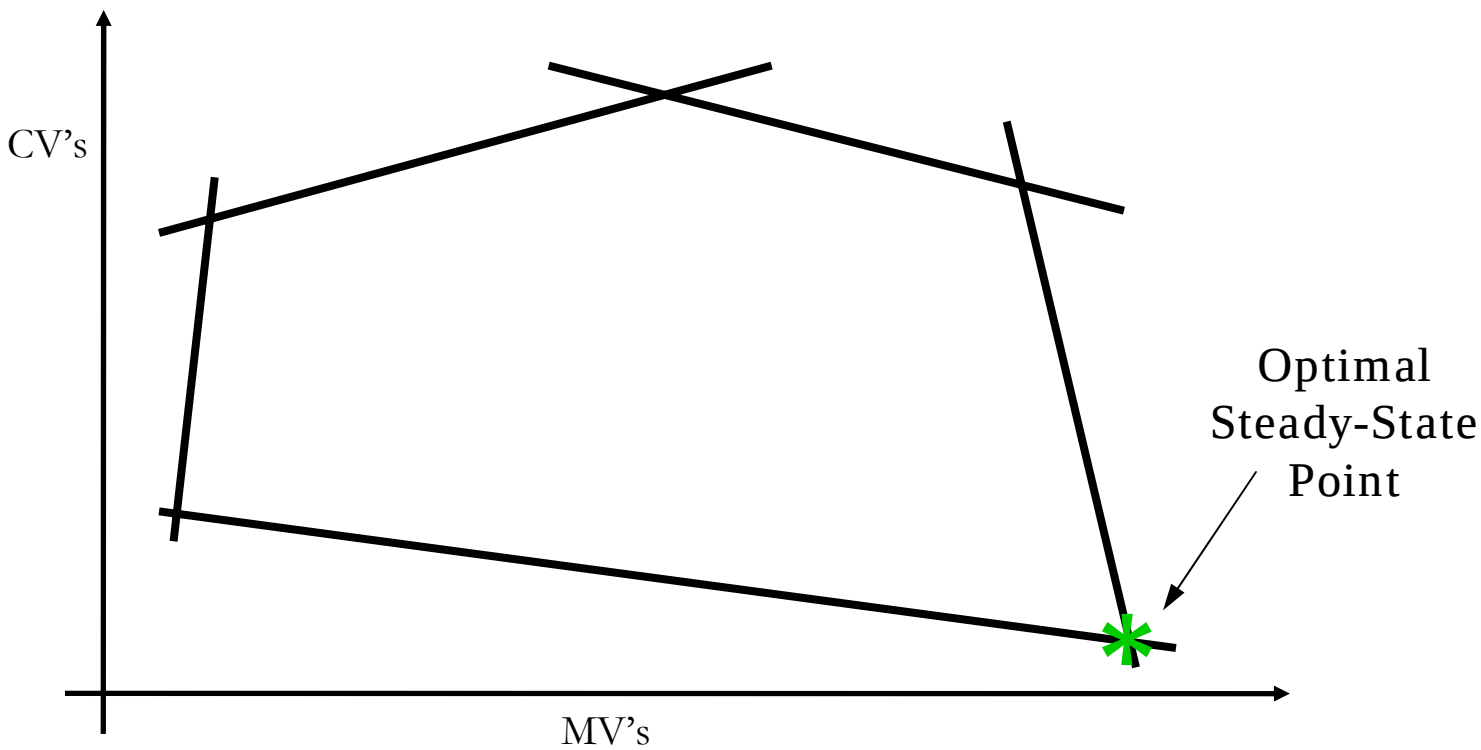
$\Leftrightarrow$

Maximize { Profit (SN) - Cost (SN) }

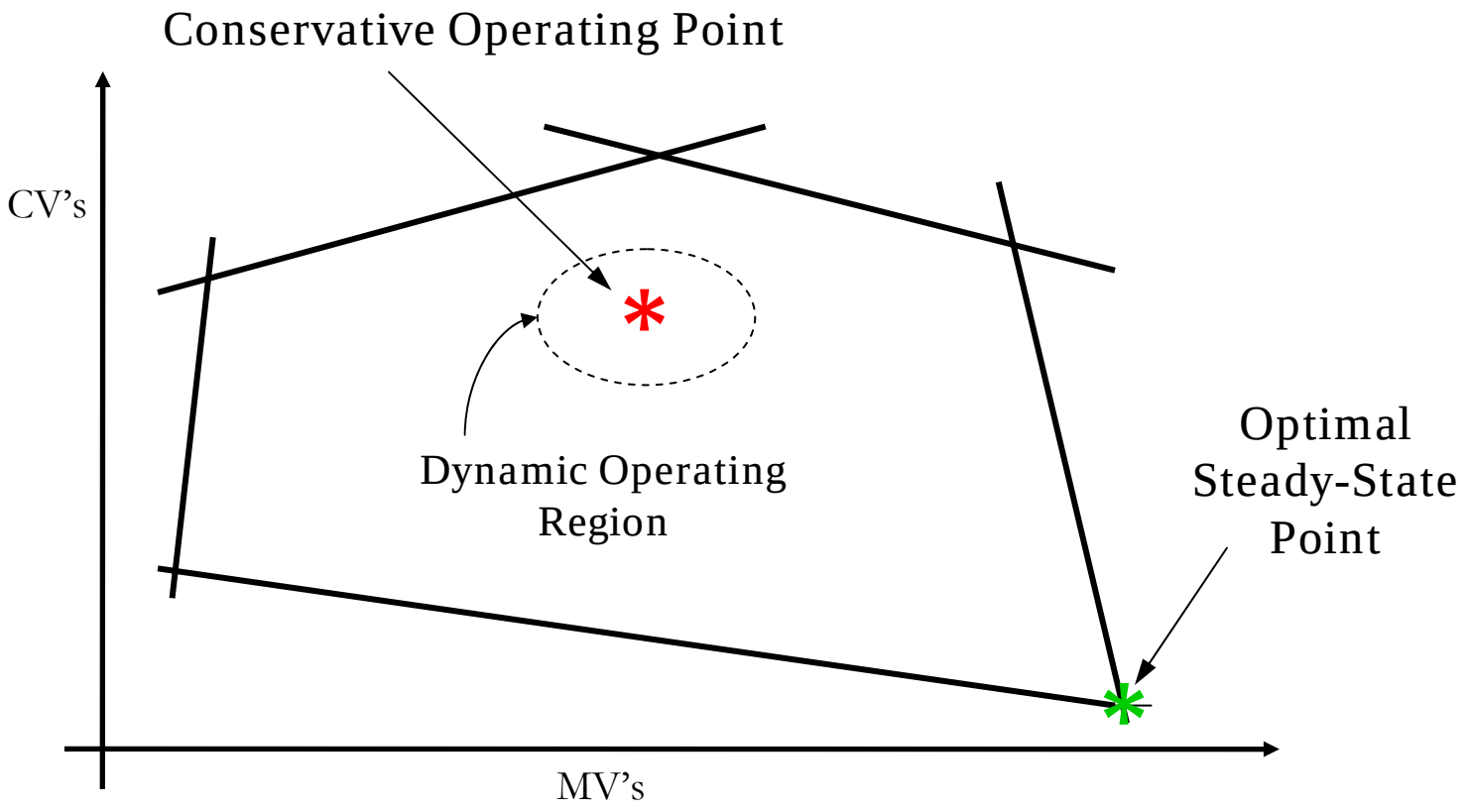
The Control System Perspective



Real-Time Optimization



Impact of Disturbances and Dynamics



Downside Expected Production Loss

Given an distribution $g\left(\xi, \hat{\sigma}_{p,m}(SN_0)\right)$ one can calculate the probability that target production is not met.

This is quantified as the Downside Expected Production Loss:

$$DEPL(\hat{\sigma}_{p,m}) =$$

$$T\int_{-\infty}^{m^*}(m^* - \xi)g(\xi, \hat{\sigma}_{p,m})d\xi \approx 0.2T\hat{\sigma}_{p,m}$$

Diagnosis Formulation

- Define $\boldsymbol{A_{ik}}(SN)$ as the set of sensors in SN that can resolve fault $\boldsymbol{f_i}$ aginst $\boldsymbol{f_k}$.

  $\boldsymbol{A_{ik}}(SN)$ is the symmetric difference between $\boldsymbol{A_i}$ and $\boldsymbol{A_k}$:

$$A_{ik} = A_i \cup A_k - A_i \cap A_k$$

- $\boldsymbol{A_{ik}}(SN)$ not empty for all $\boldsymbol{k}$ then $\boldsymbol{f_i}$ can be diagnosed.

  If all faults in $\boldsymbol{F}$ can be diagnosed, then no production losses or safety incidents will be expected.