

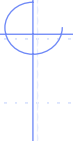


Criticality Analysis of Process Systems

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Paper: **AR&MS 2004RM-127**



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 - ▶ 4.b Combined flexibility-reliability criticality index, *FRC*
- ▶ 5. Implications for condition-based and preventive maintenance
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 - ▶ System Aggregation
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INTRODUCTION

Systematic methodology for formal criticality analysis of process systems which properly accounts for:

- **Process interactions,**
- **Equipment failure,**
- **Stochastic process variations**
- **Events related to process safety.**

Development of appropriate metrics for measuring:

- **System efficiency**
- **Relative criticality of the process equipment / events**

Important extensions are presented of the use of such a criticality analysis tools towards

- **Condition based maintenance**
(which fulfill certain efficiency and safety targets)

Use of the developed metrics for quantifying maintenance benefits

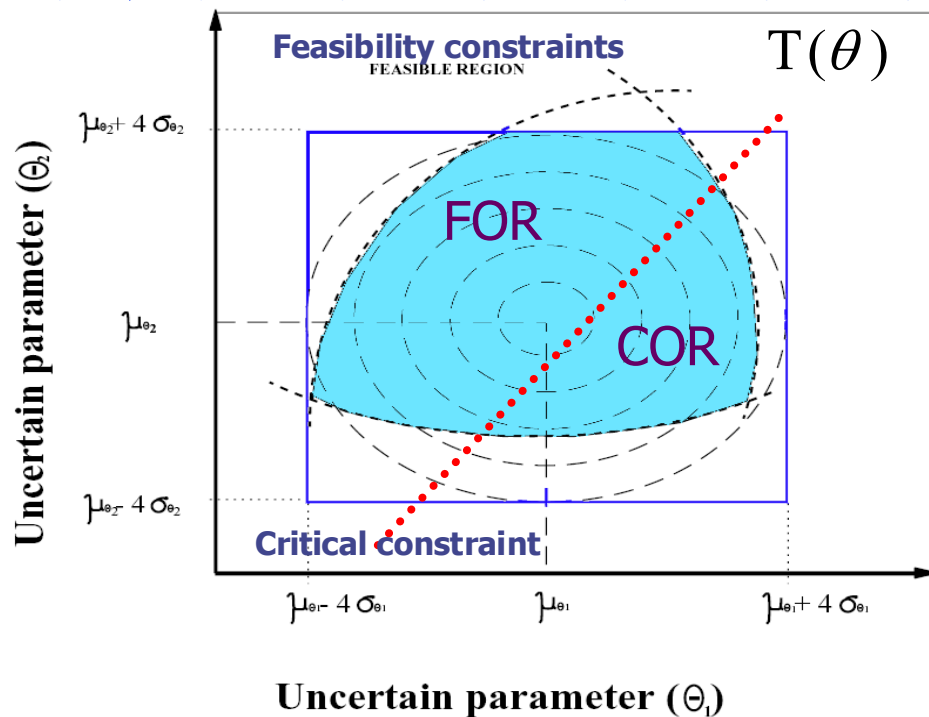
METHODOLOGY FOR CRITICALITY ANALYSIS OF PROCESS SYSTEMS

- Aggregation of parts of equipment into subsystems to reduce state space
- Transformation of the aggregated process flow-sheet into
Directed Logic Functional AND/OR Digraphs (DFLD)
- Automatic translation of **DFLD** into corresponding Fault-Tree
(Degraded operating modes for equipment are also considered)
- Estimation of state probabilities over time and system's efficiency:
 - **Stochastic Flexibility Index SF**
 - **Combined Flexibility-Reliability Index FR(t)**
 - **Criticality Index of states CI**
 - **System Criticality Index CRI(t)**
- Criticality Ranking for all equipment - events
 - **Flexibility Reliability Criticality Index CFRI**
- Criticality based maintenance

PERFORMANCE METRICS

(Stochastic Flexibility Index & Criticality Index)

- ◆ Stochastic Flexibility – SF: The expected probability of the system to fulfill process requirements and process constraints
- ◆ Criticality Index - CR: The expected probability of the system to fulfill process requirements and criticality constraints



$$SF = \Pr\{\psi(d, \theta) \leq 0\} = \int \dots \int P_D(\theta) d\theta$$

$$CR = \Pr\{\psi(d, \theta) \leq 0\}_{critical} = \int \dots \int_{\{\theta: \psi(d, \theta) \leq 0\}_{critical}} P_D(\theta) d\theta$$

$$\psi(d, \theta) = \min u \text{ / s.t. } f(d, z, \theta) \leq u$$

d : Design Variables

z : Control Variables

θ : Uncertain parameters

ψ : **Feasibility function** and **criticality constraints**

$$P(\theta) = \int_{\theta \in T} jpdf(\theta) d\theta$$

$$T(\theta) : \{\theta \mid \mu - 4\sigma \leq \theta \leq \mu + 4\sigma\}$$

RELATIONS BETWEEN DIFFERENT PERFORMANCE METRICS

- ◆ Stochastic Flexibility explicitly accounts for continuous process uncertain parameters and process model (continuous uncertainty)
- ◆ Criticality index explicitly accounts for the variations of continuous process uncertain parameters at the presence of critical constraints (continuous uncertainty- critical constraints)
- ◆ The reliability-availability models consider for equipment availability (discrete uncertainty)

However, a combined metric is required for considering **interactions between process models and reliability-availability models**

SYSTEMs PERFORMANCE METRICS

◆ The combined metric of Stochastic Flexibility Reliability Index

$$FR(t) = \sum_{k \in K_{OP}} P_k(t) SF_k(d, \theta) = \sum_{k \in K_{OP}} P_k(t) \int \dots \int_{\{\theta: \psi(d, \theta) \leq 0\}} P_D(\theta) d\theta$$

◆ The combined metric of System Criticality Index

$$CRI(t) = \sum_{k \in K_{OP}} P_k(t) CR_k(d, \theta) = \sum_{k \in K_{OP}} P_k(t) \int \dots \int_{\{\theta: \psi(d, \theta) \leq 0, \psi_{Critical}(d, \theta) \leq 0\}} P_D(\theta) d\theta$$

$$\psi(d, \theta) = \min u / s.t. f(d, z, \theta) \leq u$$

$$\psi_{Critical}(d, \theta) = \min u / s.t. f_{critical}(d, z, \theta) \leq u$$

$$T(\theta) : \{\theta / \mu - 4\sigma \leq \theta \leq \mu + 4\sigma\}$$

$$P_k(t) : \text{State probabilities (reliability models)}$$

CRITICALITY ANALYSIS

◆ The combined Flexibility Reliability Criticality Index - FRC

$$FRC_{i^*}(t) = \frac{\partial FR(t)}{\partial r_{i^*}} = \sum_{k \in K} \left\{ SF_k \frac{\partial P_k(t)}{\partial r_{i^*}} \right\}$$

Provides a measure of the relative importance (sensitivity) of a **system** wrt **subsystems, equipment** or **events** from an overall operability perspective.

For comparison purposes, a scaled

$rFRC_{i^*}(t)$ can be defined:

$$rFRC_{i^*}(t) = \frac{FRC_{i^*}(t)}{\max_i \{FRC_{i^*}(t)\}} \quad 0 \leq rFRC_{i^*}(t) \leq 1$$

Based on which the ranking of equipment/events/subsystems can be performed

Condition Based – Preventive Maintenance Algorithm

ASSUMPTIONS

1. Equipment is classified in maintainable and non-maintenanble;
2. Scheduling and ordering of maintenance tasks is based on the equipment - subsystems with the highest *criticality index* given enough maintenance resources
3. Maintenance tasks cannot be interrupted (unless maintenance resources for its completion are not available)
4. After maintenance, an equipment is considered As Good As New (AGAN)
5. Continuous plant operations are considered.

Assumption 1 prevents unnecessary plant shutdowns due to maintenance activities

Assumption 2 allows for a relative rating of the significance of execution maintenance

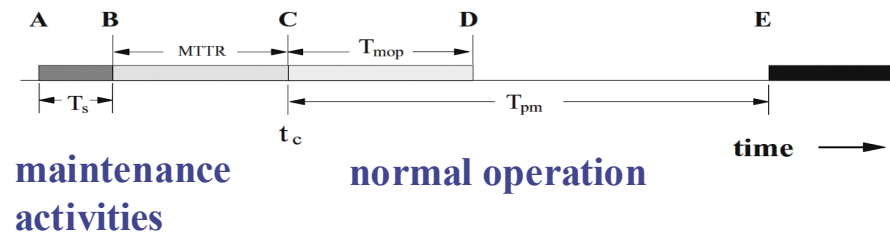
Assumption 3 prevents unnecessary swaps between maintenance tasks

Assumption 4 is used for convenience; As Good As Old (AGAO) can also he used

Assumption 5 is only imposed for computational reasons

Condition Based – Preventive Maintenance Algorithm

Equipment Operating Cycle



Time Periods

Maintenance activity period:

A-B maintenance task may be suspended

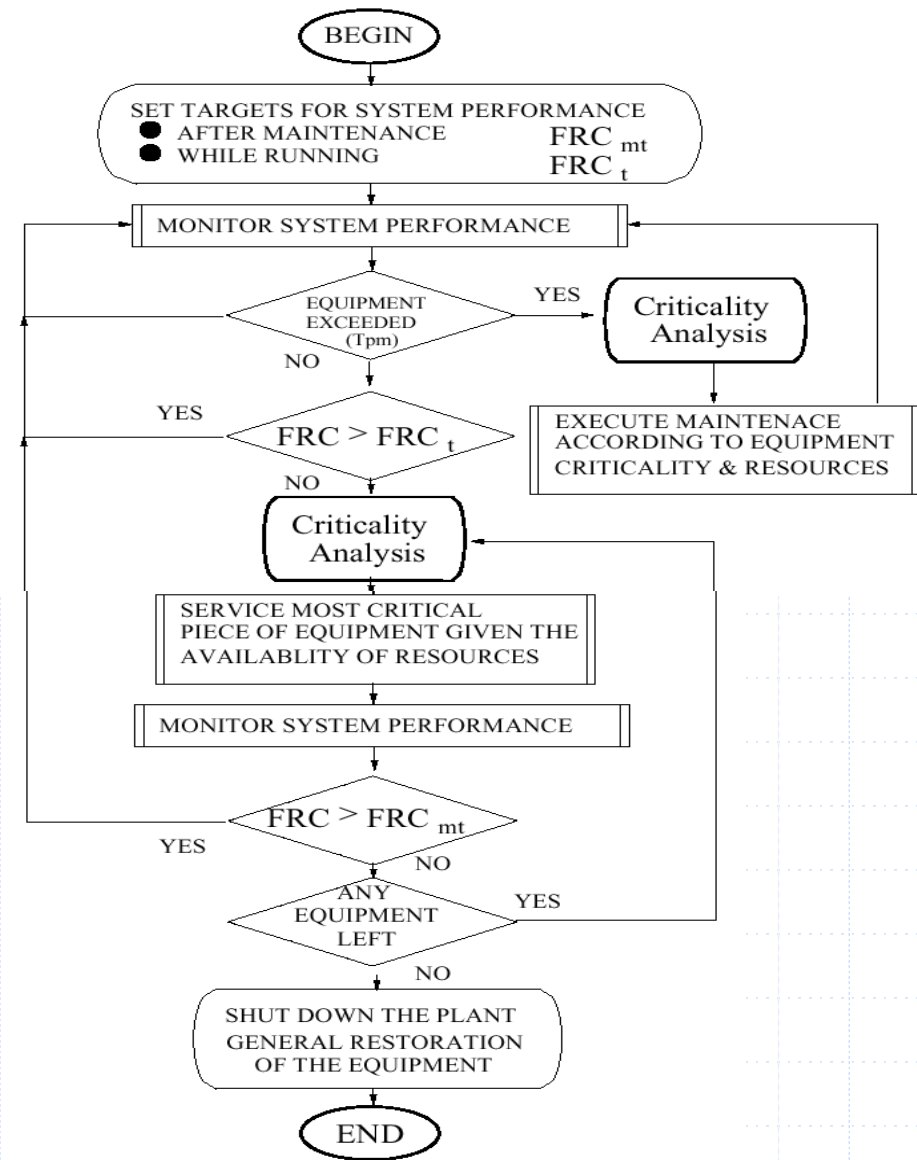
B-C corresponding duration = MTTR

Normal operation period:

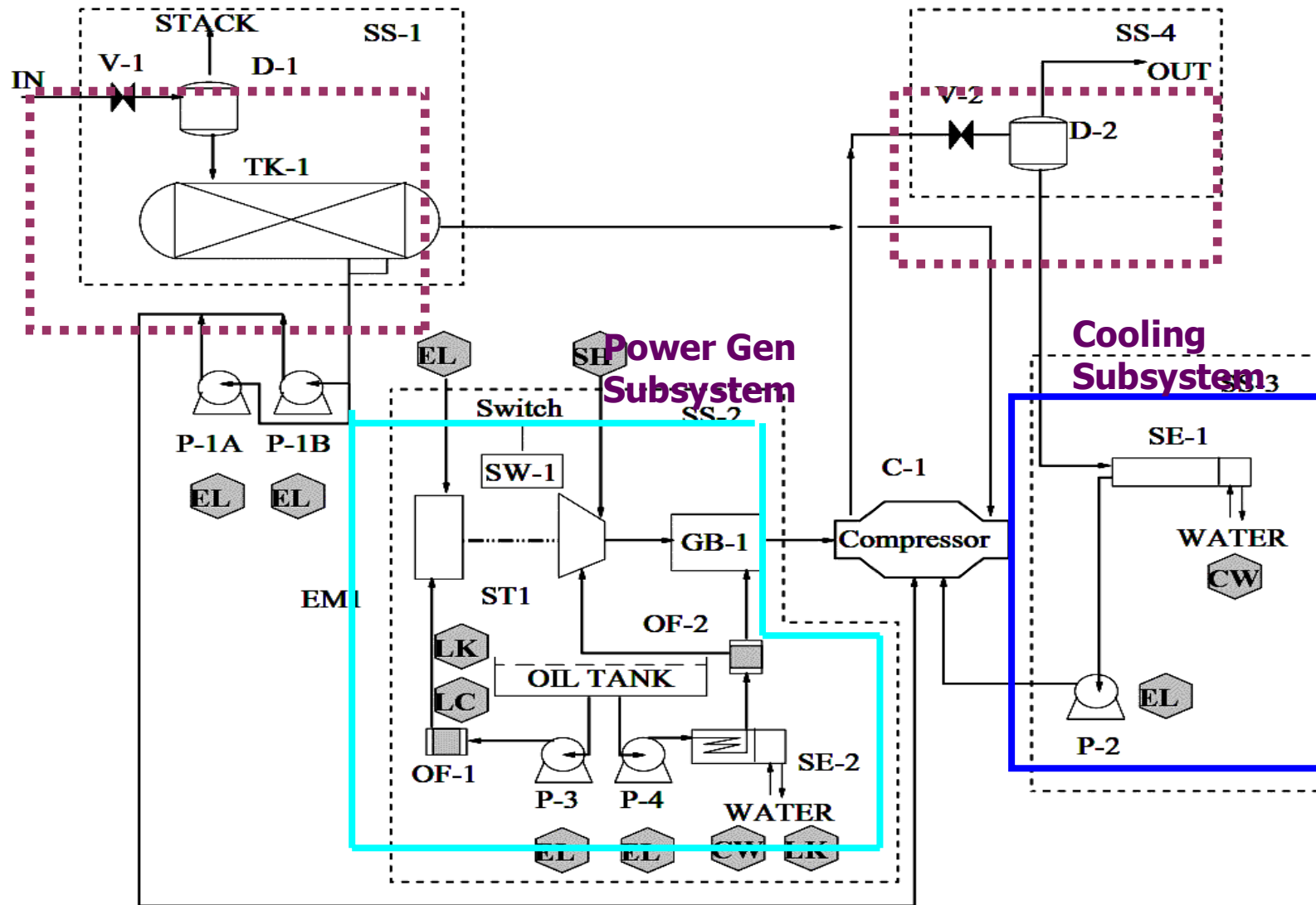
C-D minimum operational time (no maintenance)

D-E condition-based maintenance may be performed

This representation also allows for extra operational time (E+), if the operation of the equipment is pushed beyond the nominal operational window.



COMPRESSOR SYTEM (Process Configuration)



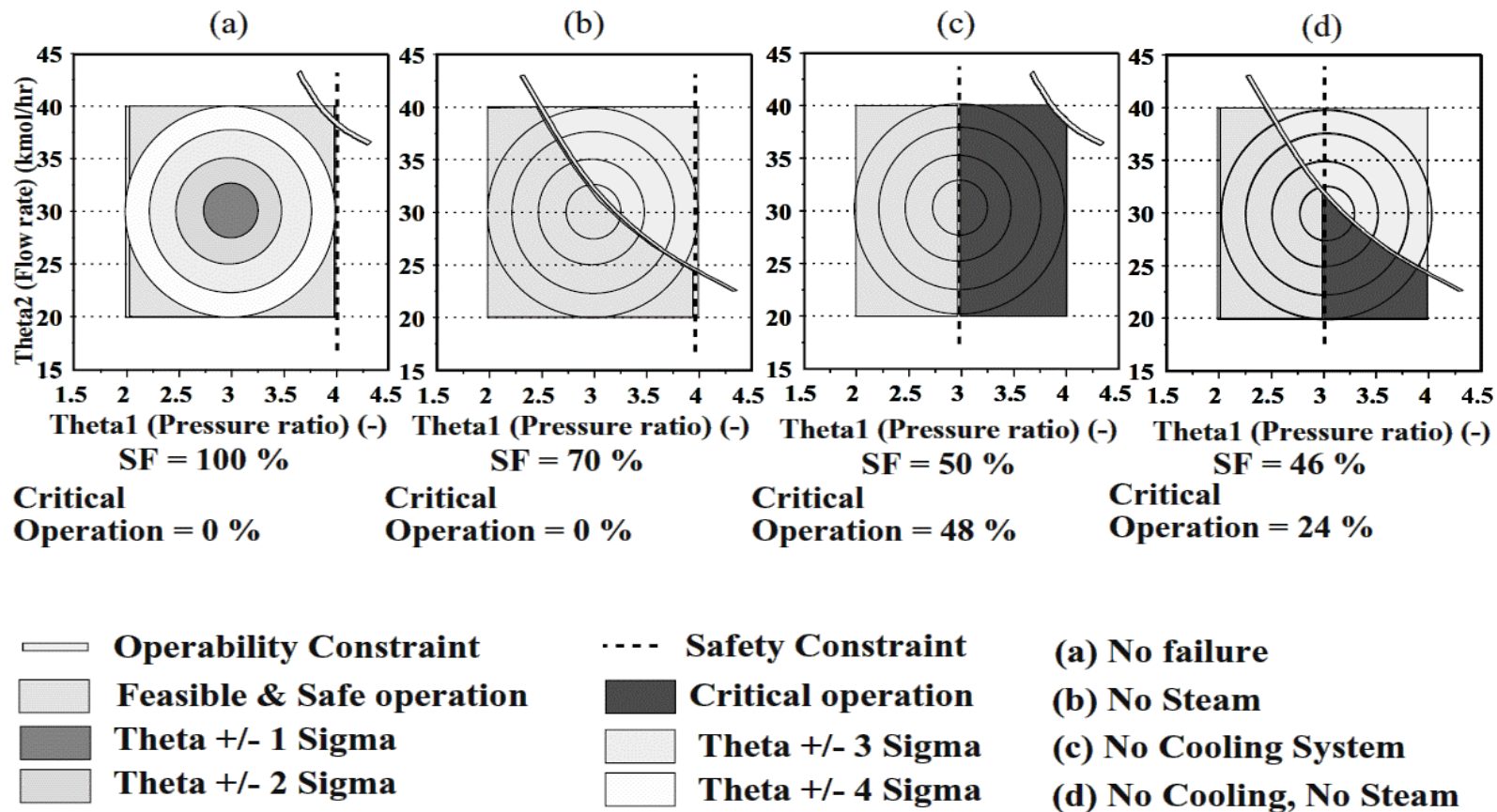
COMPRESSOR SYTEM (Process Model)

Adiabatic model

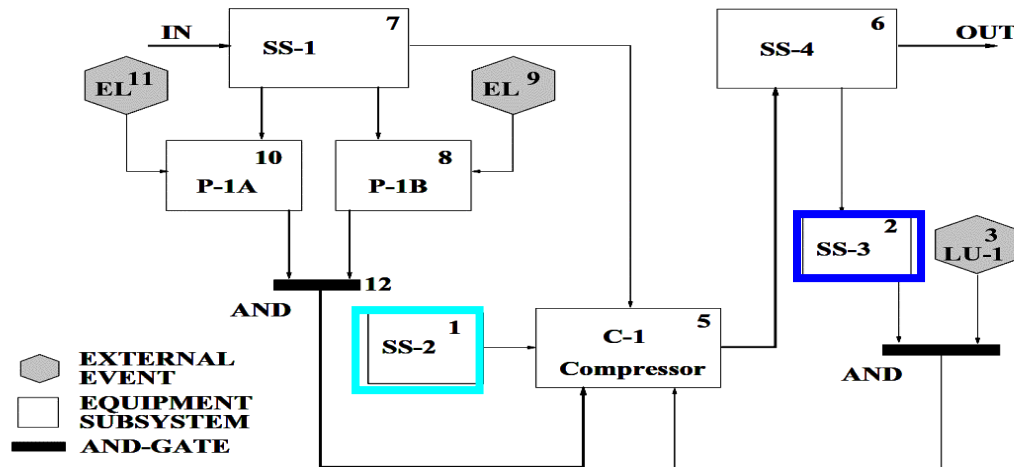
$$W_s^c = \frac{k \cdot R \cdot T_{in}}{(k-1) \cdot 3600} F_{in} \left[\left(\frac{P_{out}}{P_{in}} \right)^{\frac{n-1}{n}} - 1 \right] \quad T_{out} \leq T_{in} \left(\frac{P_{out}}{P_{in}} \right)^{\frac{n-1}{n}}$$

$W_s^c \leq W_{el} \cdot n_m$			$W_s^c \leq W_{st} \cdot n_m$		$T_{min} \leq T_{out} \leq T_{max}$
Parameter	Value	Description	Parameter	Value	Description
T_{in}	300 K	Inlet compressor temperature	k	1.29	Cp / Cv
n	1.398	Pressure Ratio (constant)	n_m	0.85	Mechanical Efficiency
Process constraints					
Maximum available horsepower			Allowed outlet temperatures		
Steam turbine 60 Kwatt			SS-3 = 440 K		T_{max}
Electric Motor 36 Kwatt			SS-3 = 410 K		T_{min}
Uncertain parameters			μ	σ	range ($\mu \pm 4\sigma$)
$\left(\frac{P_{out}}{P_{in}} \right)$	Compression ratio		3	0.25	1 to 5
F_{in}	Flow in rate		30	2.50	25 to 35

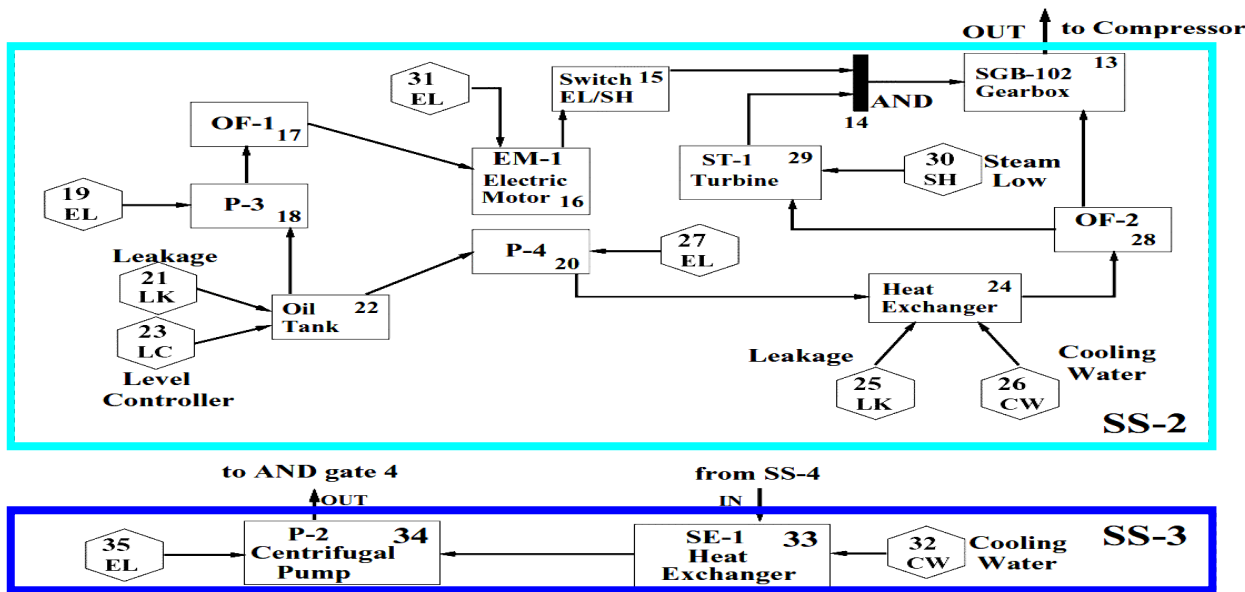
COMPRESSOR SYTEM (Feasible & Critical Regions of Operation)



COMPRESSOR SYTEM (DFLD Representation)



DFLD for the Aggregated System

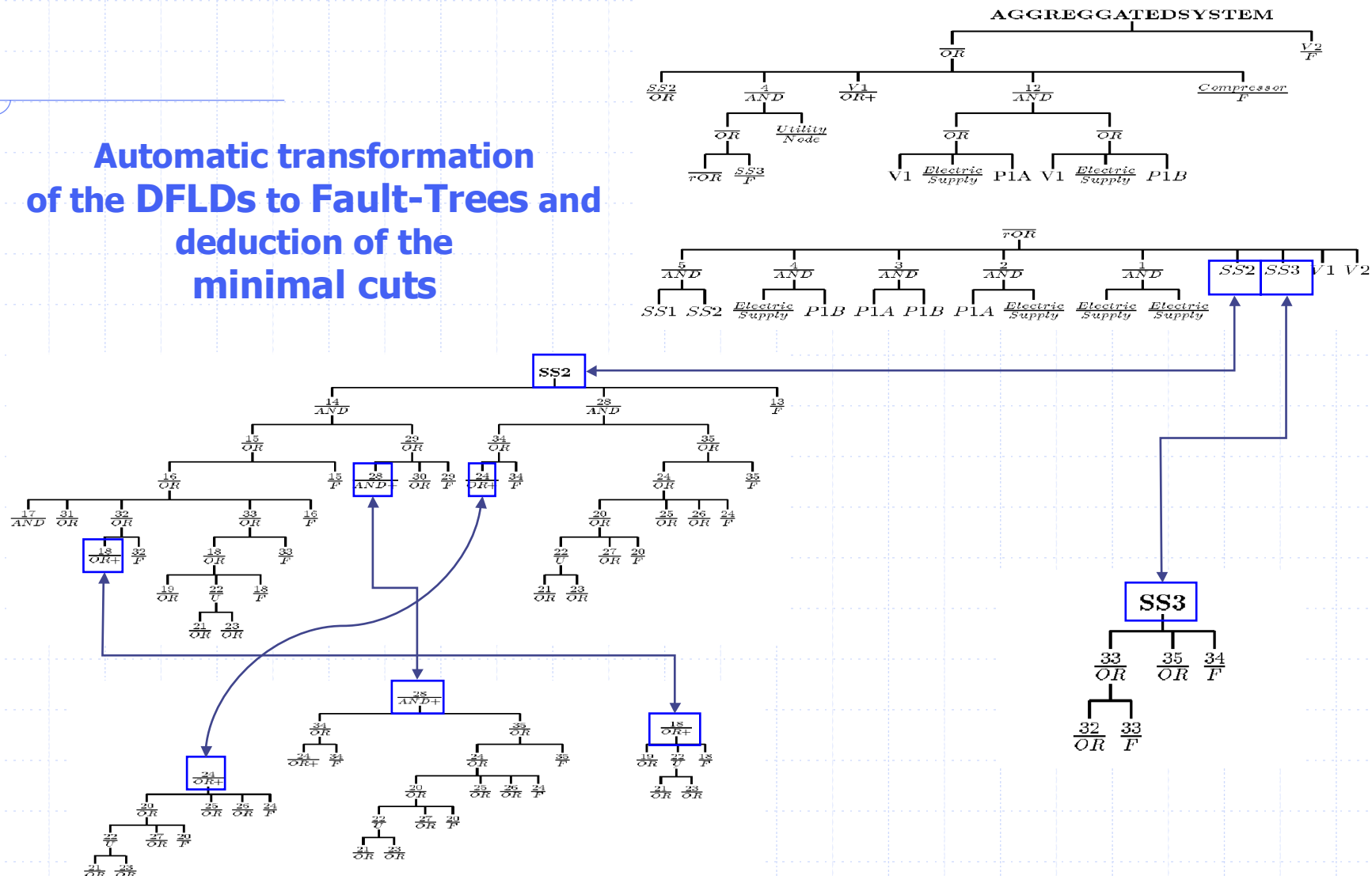


DFLD for Power Generation Subsystem SS-2

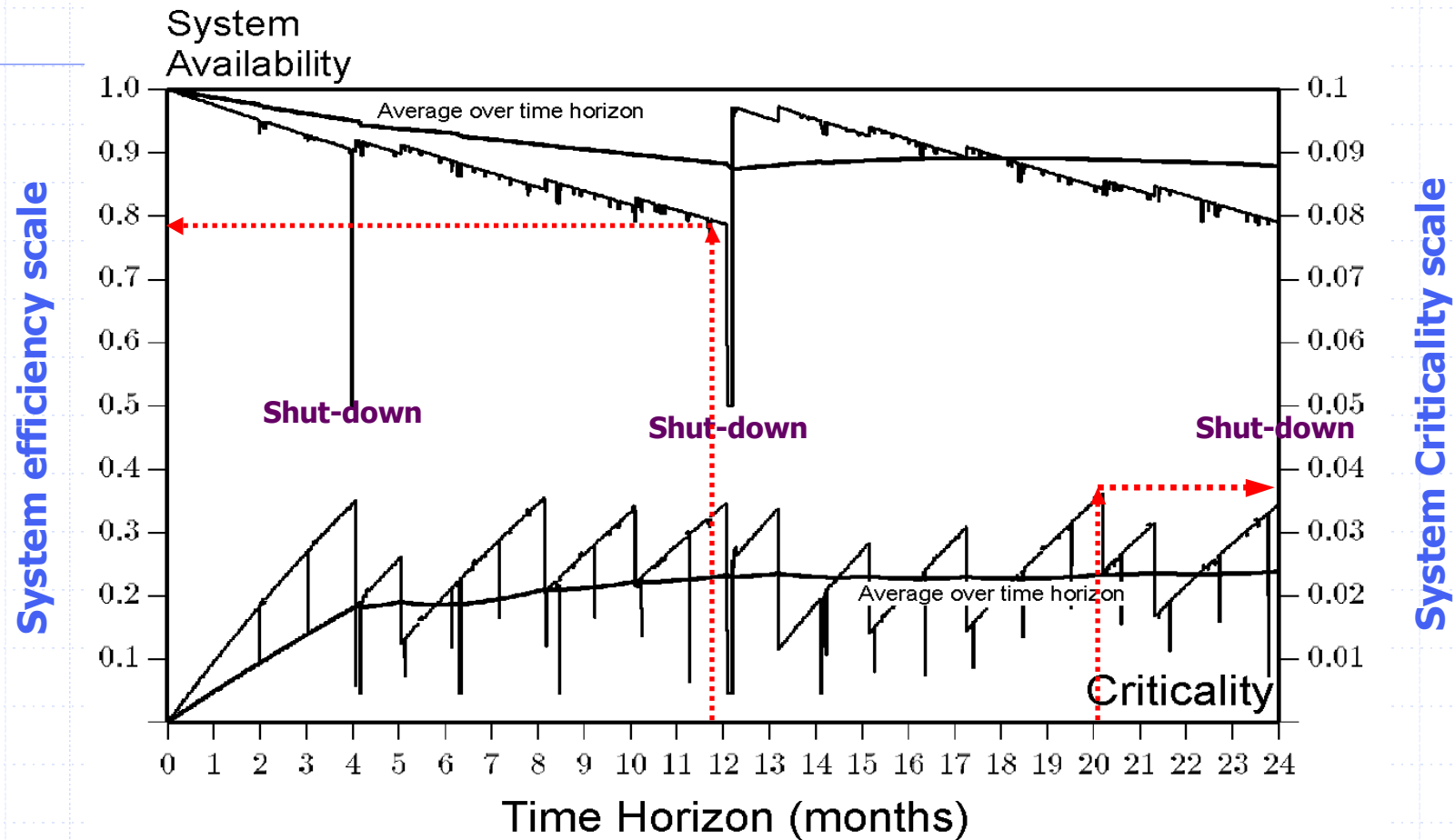
DFLS for Cooling Subsystem SS-2

COMPRESSOR SYTEM (from DFLD to FAULT TREES)

Automatic transformation
of the DFLDs to Fault-Trees and
deduction of the
minimal cuts



COMPRESSOR SYTEM (RESULTS)



System Flexibility-Availability & Criticality responses over a 24 months period

CONCLUSIONS

- ◆ While the criticality analysis methodology developed in this work predicts variable information regarding the overall system expected critical operations,
- ◆ the relative importance of the equipment to the process and identification of process and/or reliability bottlenecks,
- ◆ its link to the design optimization algorithm has not been formally established.
- ◆ However, as it is shown via the case study, the proposed methodology could be an efficient tool for the proper balance of preventive and condition based maintenance activities and the prediction of their impact to process operational decisions.