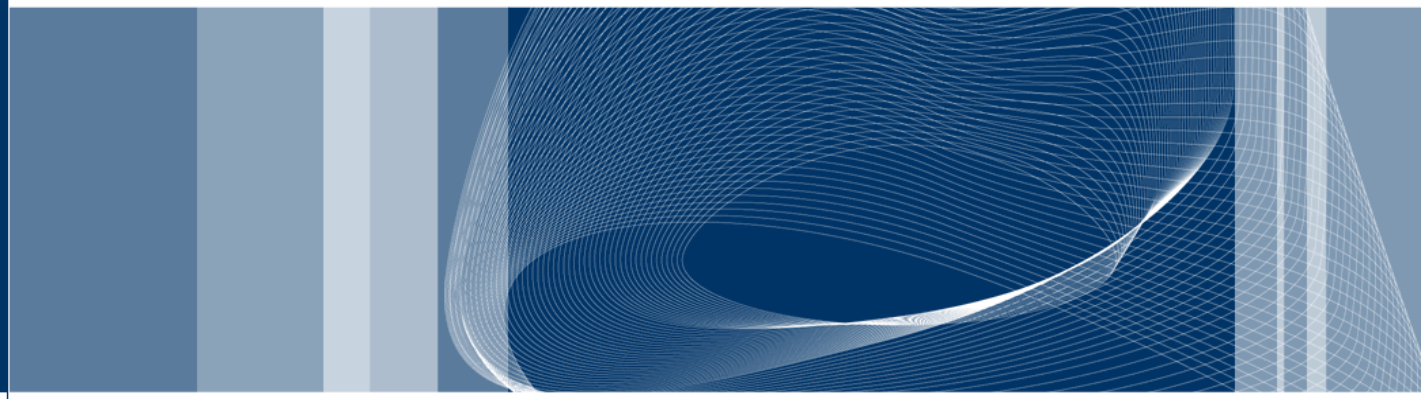
POLITECNICO DI MILANO



Reliability, Safety and Risk

Enrico Zio

QS World University Rankings 2026

*World | 98° (8%)
•Italia | 1°)

Engineering 2026

World | 21°
Italy | 1°

The team:

Laboratory of Analysis of Systems for the Assessment of Reliability, Risk and Resilience (LASAR3)

https://www.lasar.polimi.it/

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Laboratory of Analysis of Systems for the Assessment of Reliability, Risk and Resilience
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Professor

Google Scholar H-index =13

Stanford ranking:
Top 2% of the World scientists

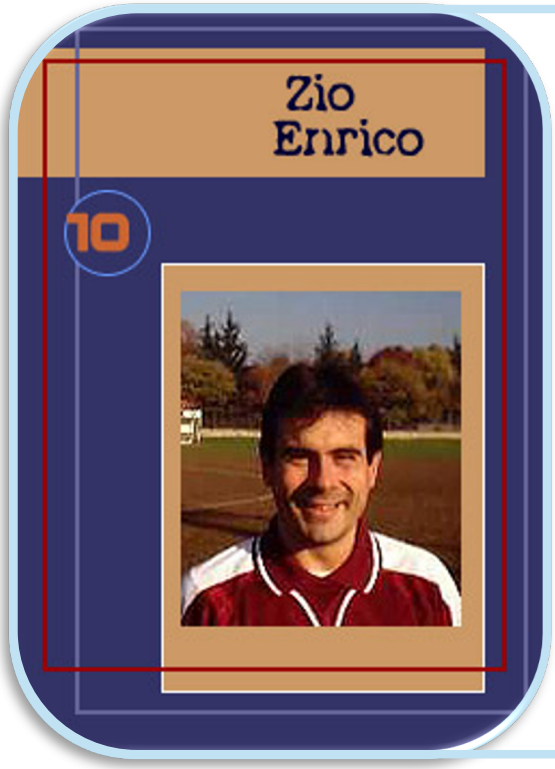
Enrico Zio

- Centre for research on Risks and Crises (CRC), Mines Paris PSL University
- Energy Department, Politecnico di Milano, Milan, Italy

- 2020 Humboldt Research Award of the Alexander von Humboldt Foundation
- IEEE fellow
- Asia-Pacific Artificial Intelligence Association fellow
- Academy of the Artificial Intelligence Industry fellow
- Lifetime achievement award of the Society for Reliability and Safety
- Alan O. Plait 2024 Award
- System Safety Society (ISSS) Educator of the Year Award (2024)
- Ayyub-Wiechel Risk Analysis Award of the American Society of Mechanical Engineers, ASME (2025).

- H-index = 114
- Top 2% of the World scientists, according to Stanford ranking
- Top 1% of Highly Cited Researchers, according to Clarivate Analytics

Professor



Signed for Panthers: July 1998

Better known "***Little knee***" for his ease in running.

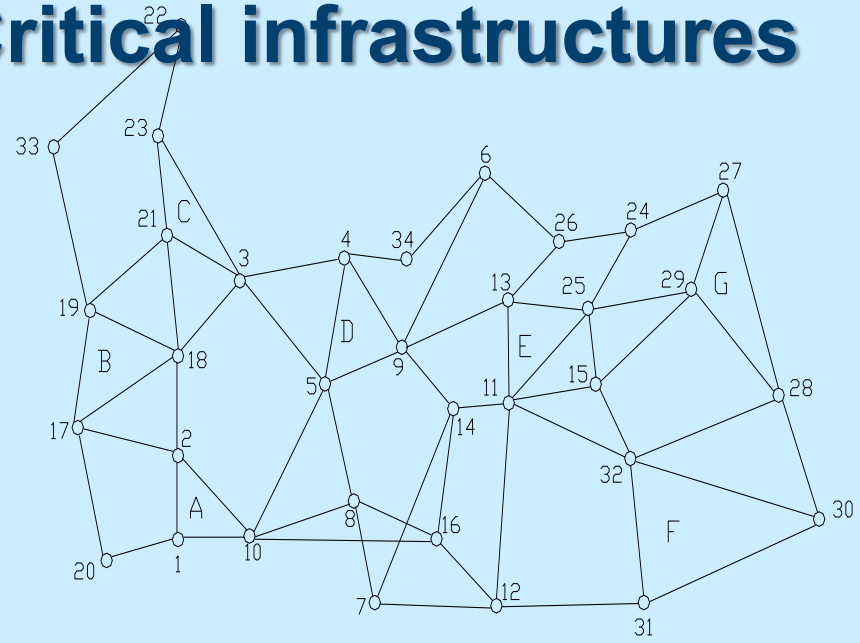
After the much talked retirement of the "*Divine Ponytail*" (Roberto Baggio), he stands as the last true and pure artist of the Italian soccer.

He remains a patrimony to be safeguarded, in spite of the " *tactical problem*" he represents for the Panthers team.

Fancy on the field and even brilliant off the field: meeting him disguised as Santa Claus at weddings or as deejay in popular Milano's bars, one would never realize that he is an internationally renowned luminary.

Technological systems

Critical infrastructures

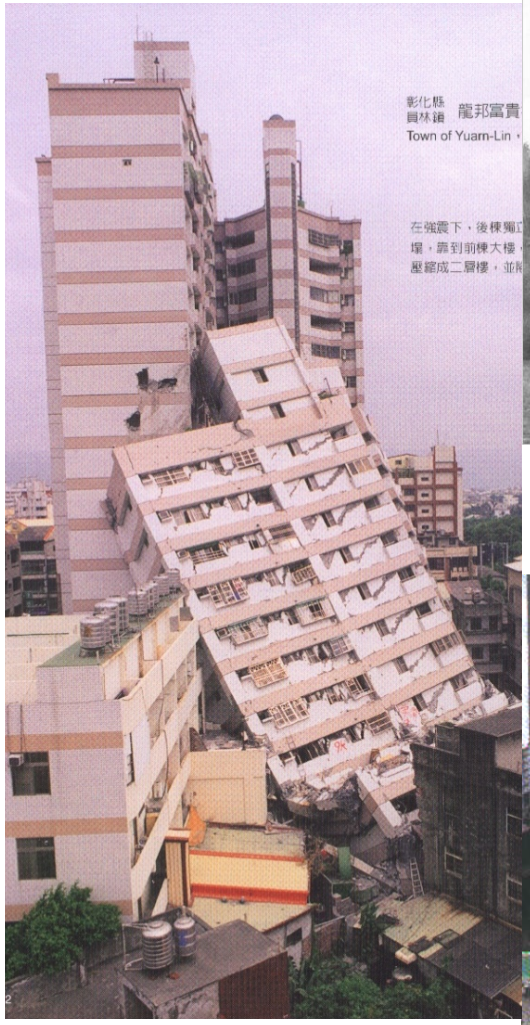


Water supply Systems

Electric Power Networks

Gas supply Systems

Failures



Failures

Failures (external events)

Taiwan News
台灣英文新聞
VOICE OF THE PEOPLE · BRIDGE TO THE WORLD
ESTABLISHED IN 1949

LANDSLIDE CUTS OFF TAIWAN FREEWAY, 2 TO 4 CARS FEARED BURIED.
25 APRIL 2010.

… LANDSLIDE BURIED A 300-M STRETCH OF NO. 3 FREEWAY BETWEEN TAIPEI AND KEELUNG

Failures (external events)

Kobe Earthquake (1995, Ms 7.3)

Chile Earthquake (2010, Ms 8.8)

Chi-Chi Earthquake (1999, Ms 7.6)

Gaoxiong Earthquake (2016, Ms 6.7)

Failures (external events)

Lifeline failures in Wenchuan Earthquake

In Dujiangyan City, the damaged pipelines length was 300km (more than 90%)

Failures (external events)

Extreme weather in January 2018

Failures and consequences

Loss of revenues

Unplanned shut-down,
D.C. Cook NPP

Fatalities and contaminations

Oil rig explosion in 2010,
Gulf of Mexico

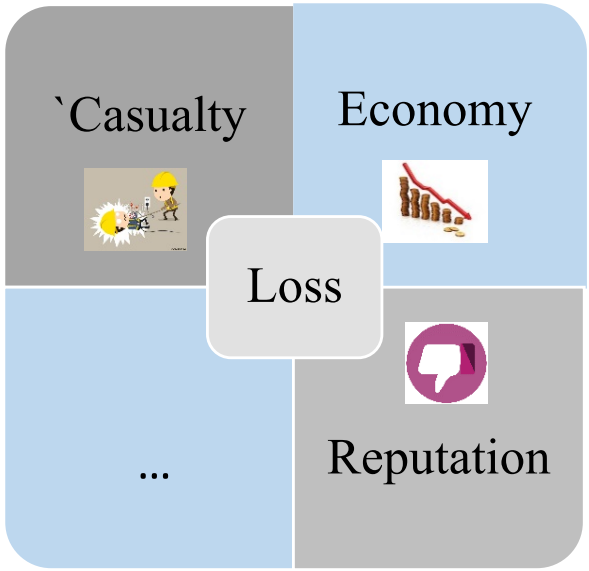
Failures and consequences

Crisis, service/business interruption, asset loss…

Failures and consequences: the problem

2018, Oklahoma Rig Explosion

2019, Nyonoksa radiation accident



Reduce

- Prevention
- Mitigation
- Emergency
- Recovery

Reliability

RELIABILITY: WHAT?

Reliability: an appreciable attribute of a person or artifact

Samuel T. Coleridge

"He inflicts none of those small pains and discomforts which irregular men scatter about them and which in the aggregate so often become formidable obstacles both to happiness and utility; while on the contrary he bestows all the pleasures, and inspires all that ease of mind on those around him or connected with him, with perfect consistency, and (if such a word might be framed) absolute reliability

Reliability: a pervasive concept…

Web of science (science citation) 9512

Library of congress 3253

Google 12,500,000

RELIABILITY: WHAT?

Reliability: ability to perform an assigned task for a given time

- Always present in human activities
- Increased importance with industrial revolution

From reasonable to rational solutions

Reliability Engineering

RELIABILITY ENGINEERING

An ensemble of formal methods to investigate the (uncertain) limits of systems

- *Why systems fail (reliability physics to discover causes and mechanisms of failure and to identify consequences)*
- *How to develop reliable systems*
- *How to measure/test* ***reliability*** *(in design, operation and management)*
- *How to maintain systems reliable (fault diagnosis and prognosis, maintainability)*

RELIABILITY ENGINEERING

- System representation and modeling
- System model quantification
- Uncertainty modeling & quantification

RELIABILITY: Uncertain limits

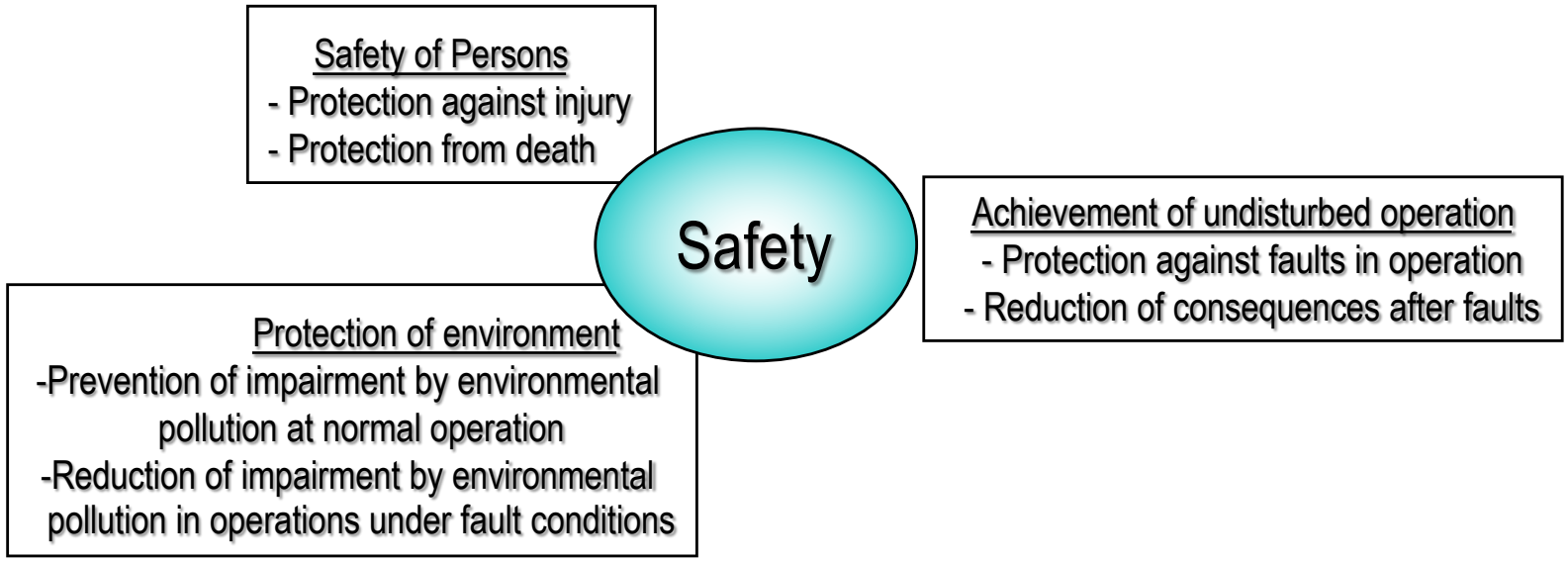
- *Uncertainty in system representation and modeling*
- *Uncertainty in components behavior and relationships*
- *Uncertainty on values of components parameters in time*

Safety

PROTECT LIVES & PROPERTY

PROTECT NATURE

Safety



Safety RAM

Reliability
Availability
Maintainability

Safety and accident analysis

SAFETY ≡ freedom from unaffordable harm

- **Explanatory (a posteriori, reactive)**

Accident analysis

Difficulty/challenges:

– When something has happened, we try to find the cause.

When the cause has been found, we try to eliminate it or reduce it.

How can we find out what went wrong in complex socio-technical systems living in an uncertain environment

We live in an uncertain world → **Coping with uncertainties**

Subject (decision maker) → lack of complete knowledge (epistemic)

Object (aleatory) → Bernoulli

Safety and risk assessment

SAFETY ≡ freedom from unaffordable harm

- **Anticipative (a priori, pro-active)**

Accident analysis ⇩ **Difficulty/challenges:**

How can we predict what may go wrong?

− Risk assessment: predicting what can happen ⇩ Elimination or prevention of potential risks

“Freedom from unaffordable harm”

⇩

Models, methods, concepts must be compatible and able to describe “reality” in an adequate fashion

RISK=(A,C,L(U)) **True Risk**
Risk=(a,c,l(u),k) **Modeled Risk**

Epistemic → Model of l(u) ⇩ PRA + epistemic model
Aleatory

Uncertainty

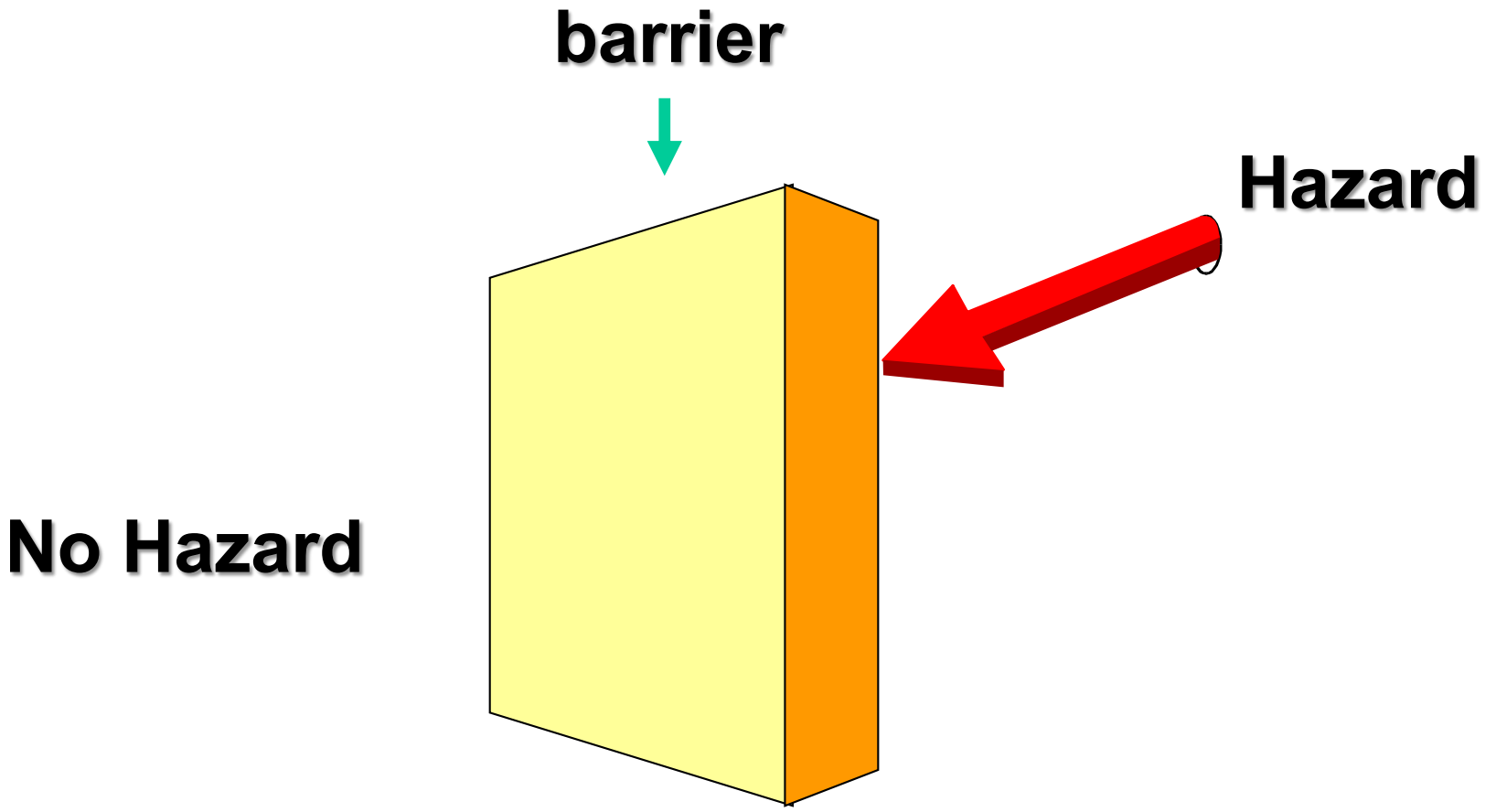
Aleatory Uncertainty

- irreducible uncertainty
- property of the system
- random fluctuations / variability / stochasticity

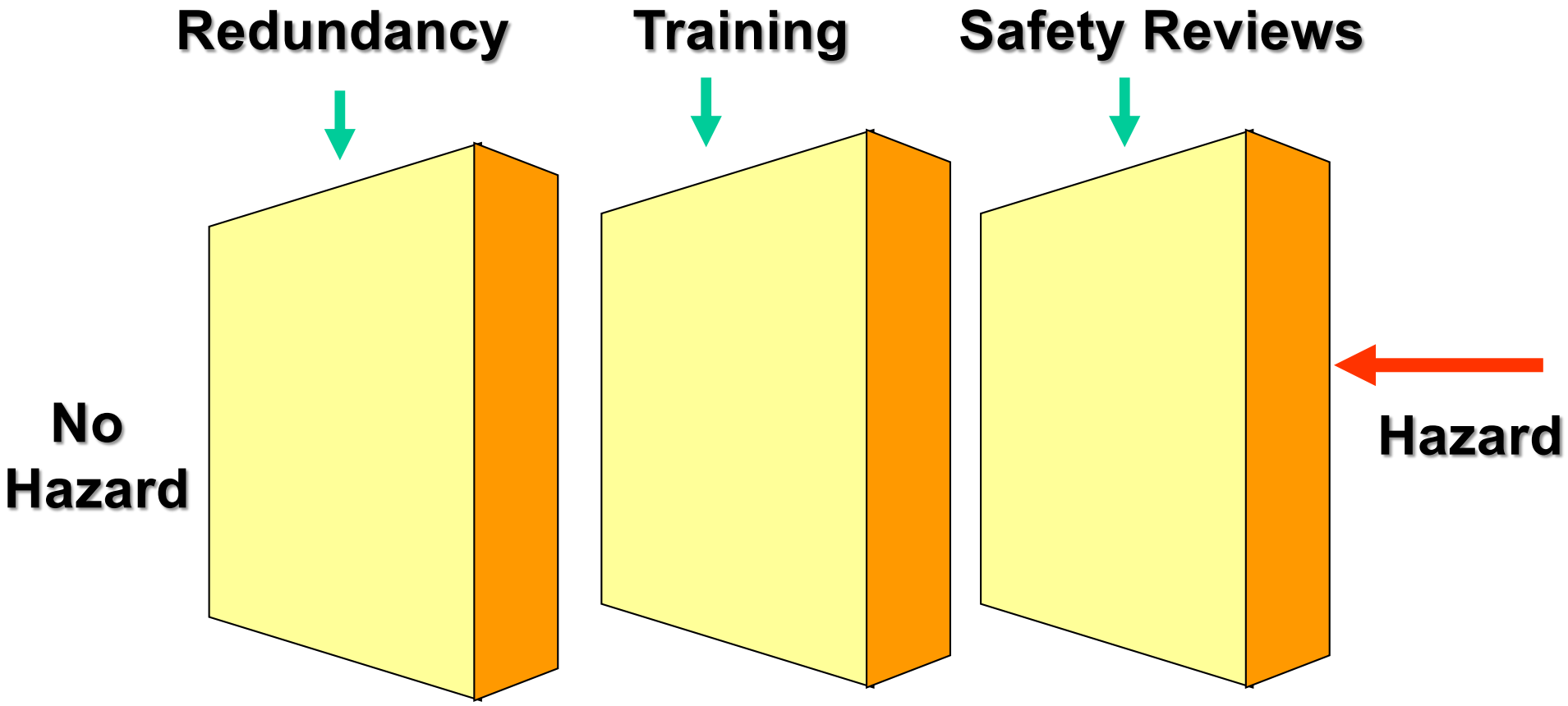
Epistemic Uncertainty

- reducible uncertainty
- property of the analyst
- lack of knowledge or perception

The ‘parmesan cheese’ model



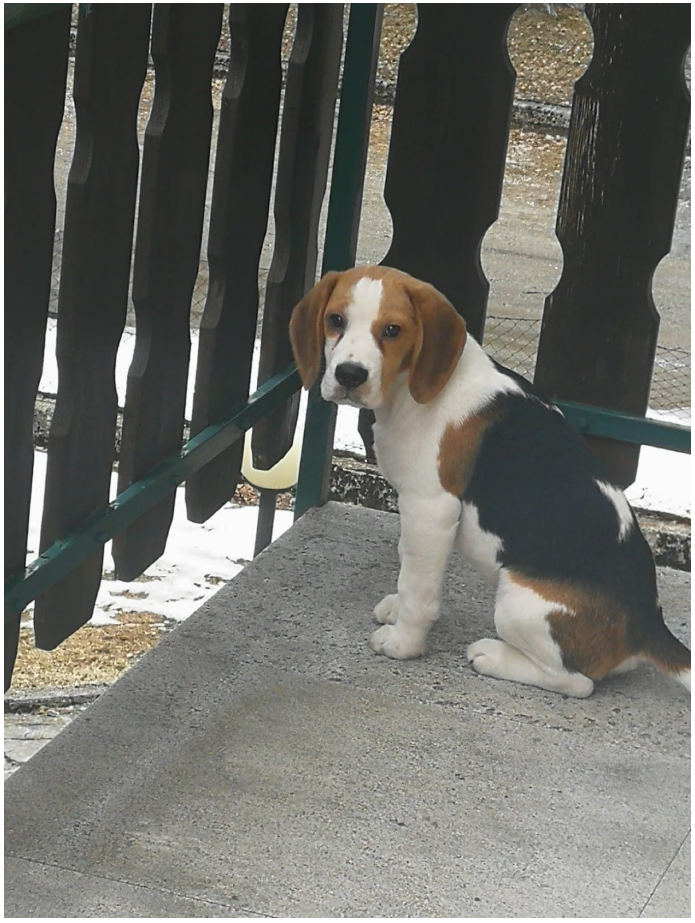
Multiple Barriers



Redundancy: Homogenous Components

Redundancy: Homogenous Components

Redundancy: Heterogenous Components



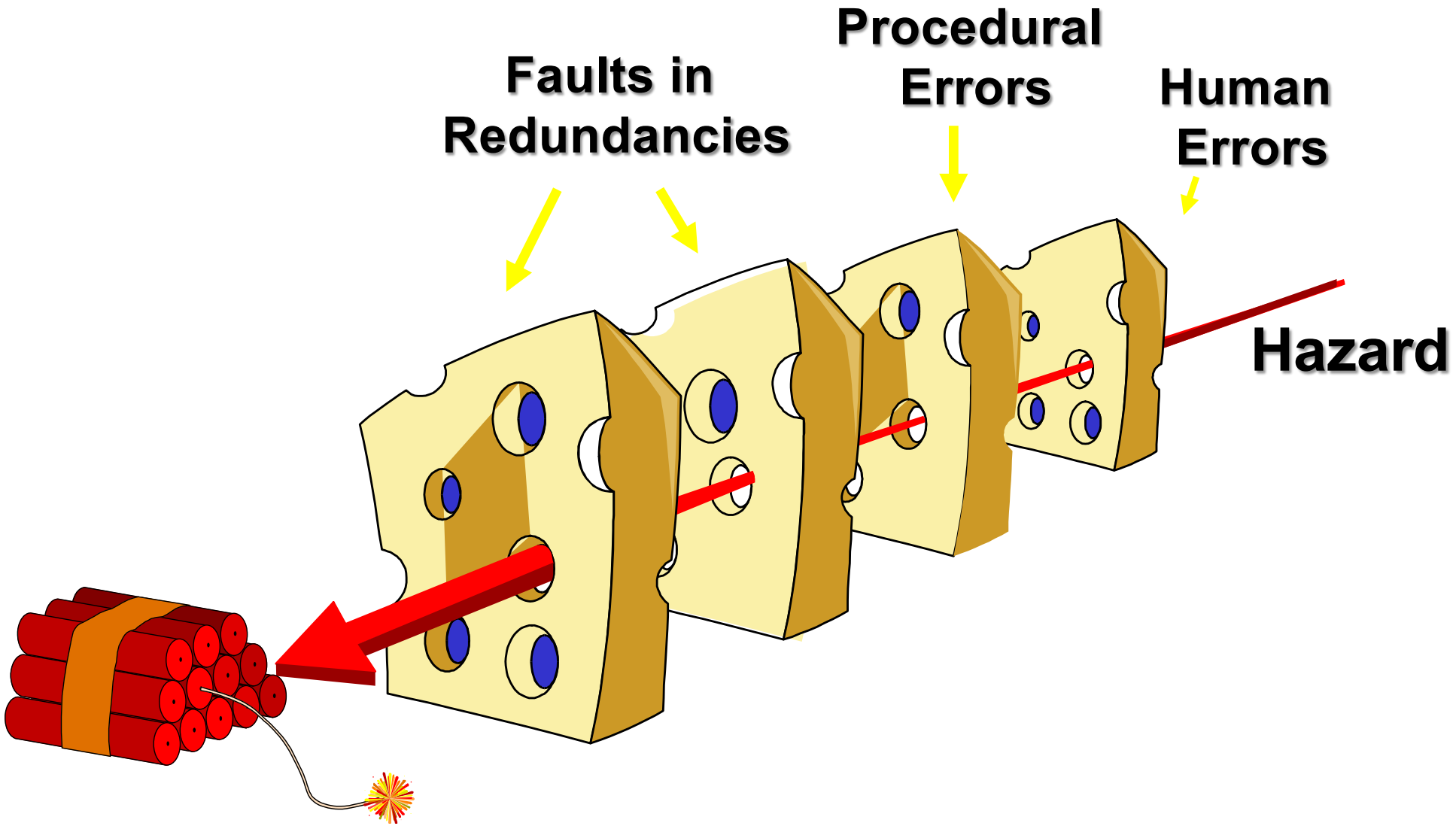
Risk

Reality: Disasters

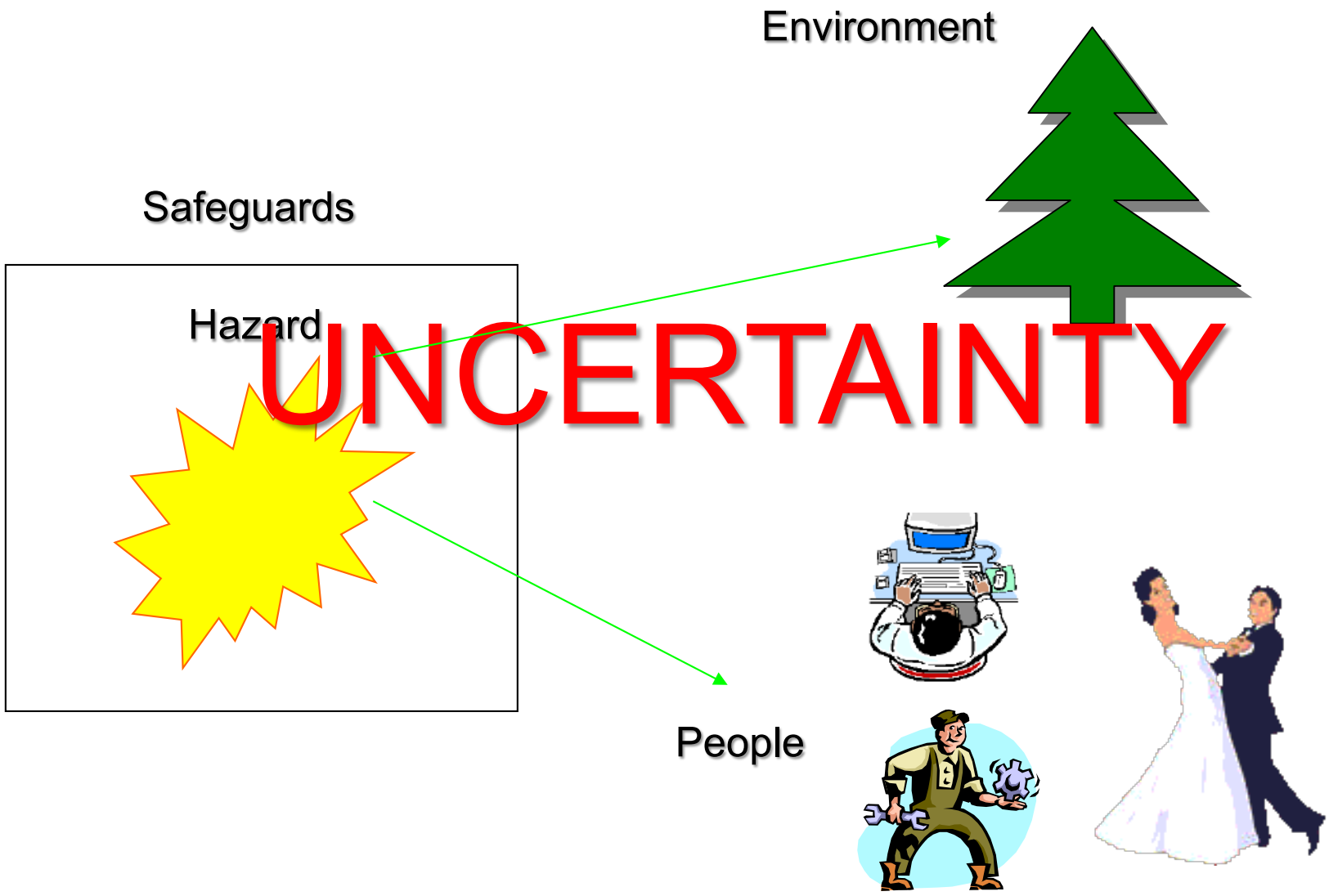
Reality: An example of a protection barrier

Not all safety barriers work...

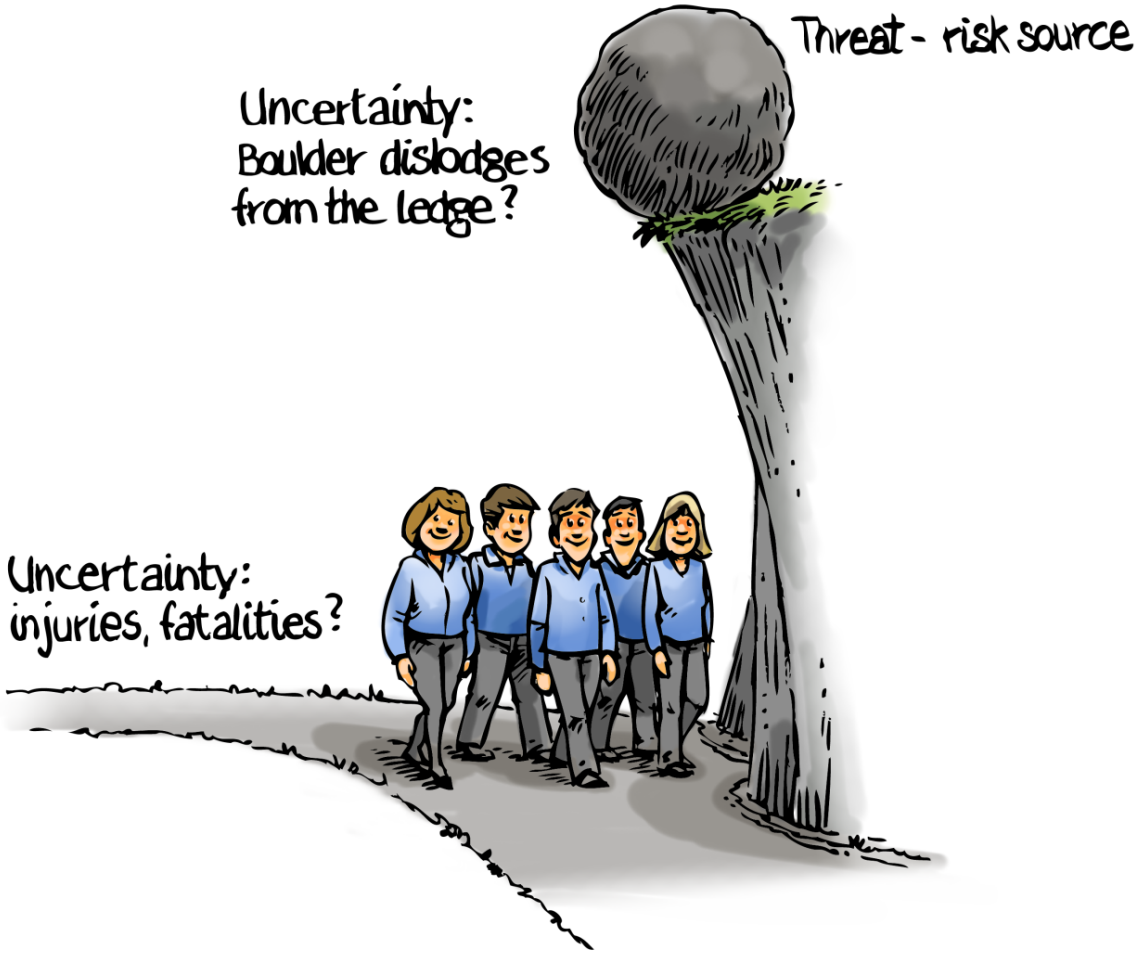
The ‘swiss cheese’ model



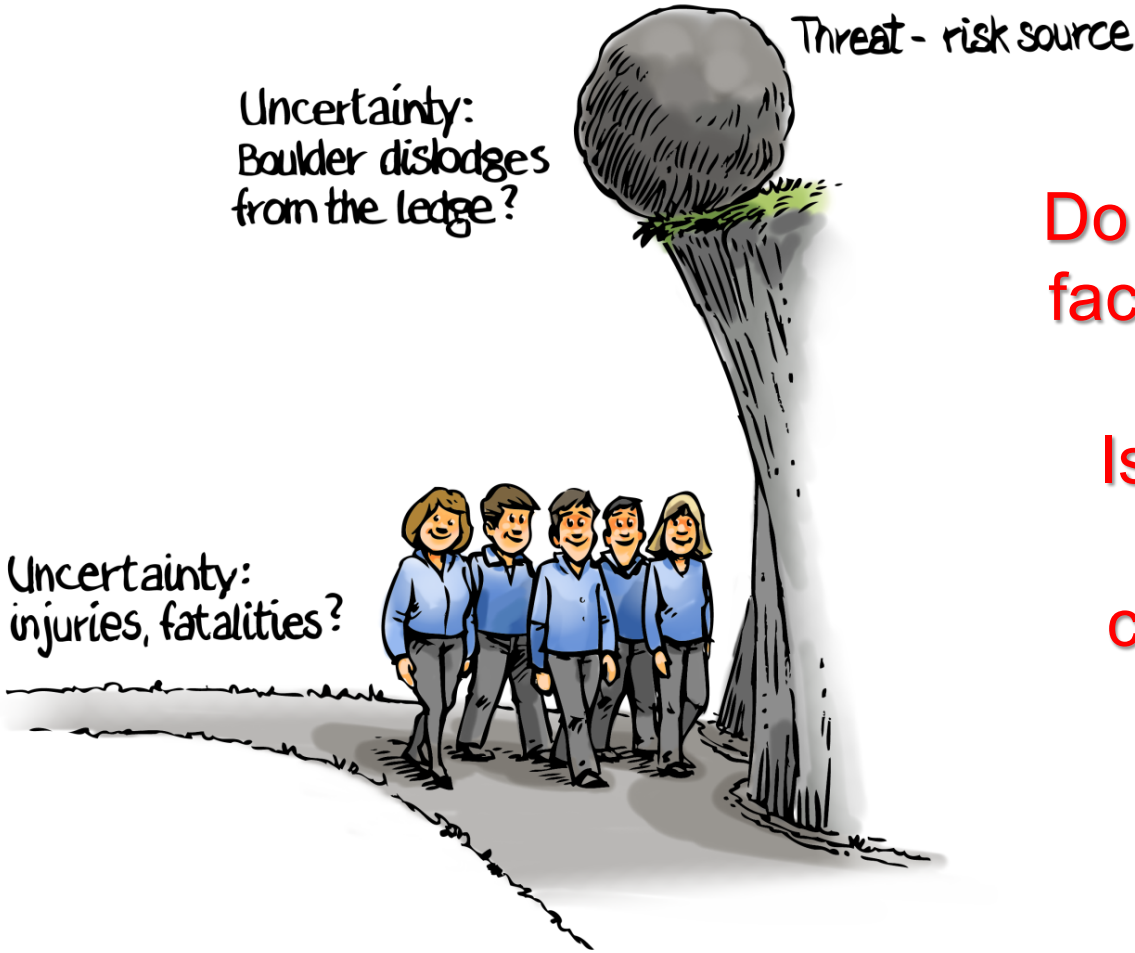
THE CONCEPT OF RISK:



The Risk Concept



The Risk Concept



Do these people face risk? Why?

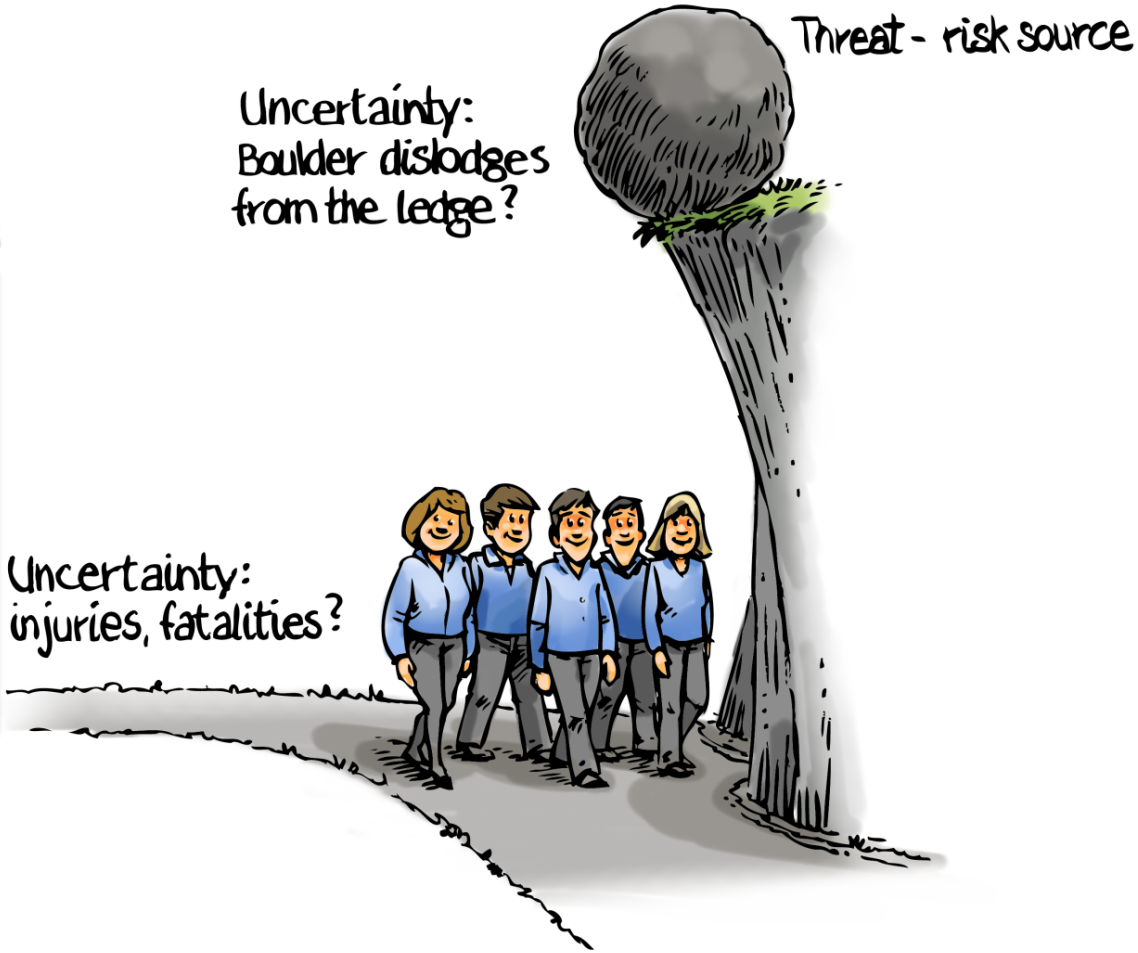
Is probability needed to conclude on this?

The Risk Concept

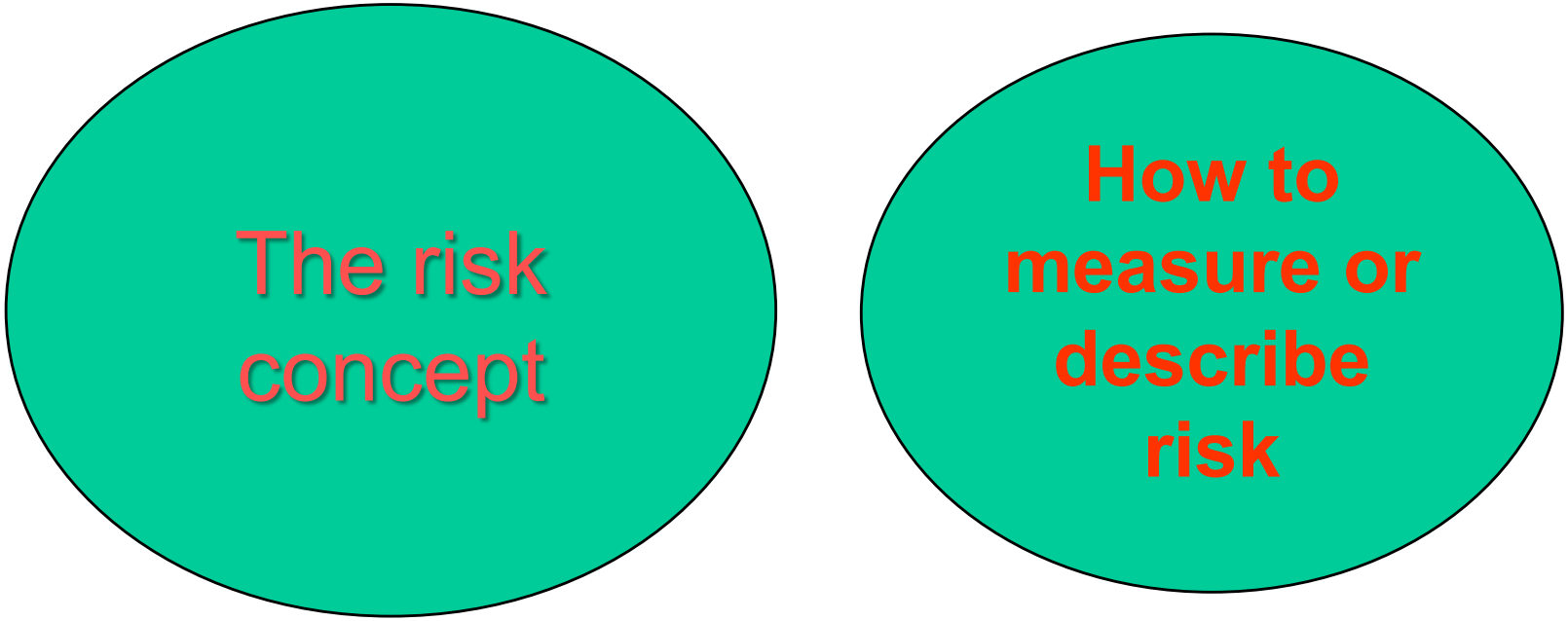
Consequences

Events with some effects

Some effects are undesirable



Uncertainty



Consequences & Uncertainty

Risk

RISK = POTENTIAL DAMAGE + UNCERTAINTY

Dictionary: RISK = possibility of damage or injury to people or things

1) What undesired conditions may occur? → Accident Scenario, S
2) With what probability do they occur? → Probability, p
3) What damage do they cause? → Consequence, x

$$RISK = \{S_i, p_i, x_i\}$$

S. Kaplan. B.J. Garrick, On the quantitative definition of risk, Risk Analysis, 1981

RISK ASSESSMENT

Risk

1) What undesired conditions may occur? → Accident Scenario, S
2) With what probability do they occur? → Probability, p
3) What damage do they cause? → Consequence, x

$$\text{RISK} = \{S_i, p_i, x_i\}$$

RISK ASSESSMENT:

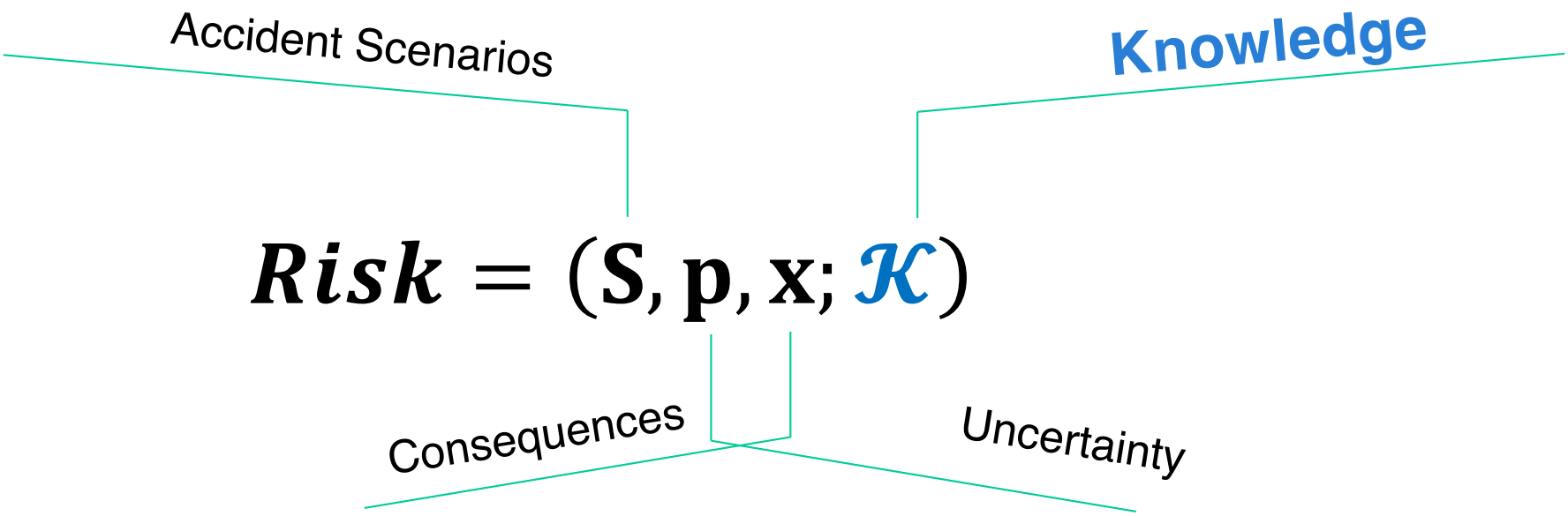
Systemic Analysis of system performance under undesired conditions (uncertain space)

System/Man/Environment interactions under uncertainty

PROBABILISTIC RISK ASSESSMENT

(QUANTITATIVE RISK ASSESSMENT)

Risk assessment – a knowledge "exercise"



Apostolakis G. The concept of probability in safety assessments of technological systems. Science. 1990
Aven T, Zio E, Knowledge in Risk Assessment and Management, Wiley; 2018.

Risk Assessment

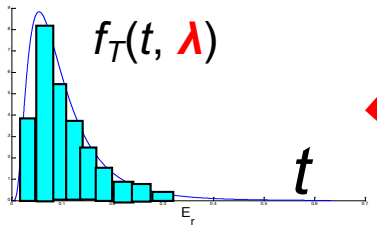
KNOWLEDGE K

valve 1

valve 2

...

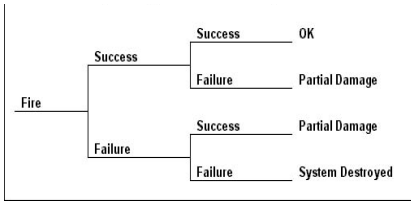
valve *N*

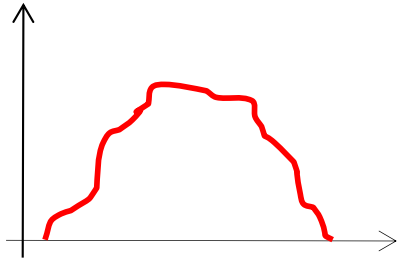


"λ is UNIFORM between 10^{-3} and 10^{-2} $[h^{-1}]$"

"λ is less than 10^{-2} $[h^{-1}]$ with probability 0.9"

SYSTEM RISK MODEL





(UNCERTAIN) RISK MEASURES (a,c,u,M,K)

REPRESENTATION OF UNCERTAINTY (M)

UNCERTAINTY PROPAGATION

Probabilistic Risk Assessment

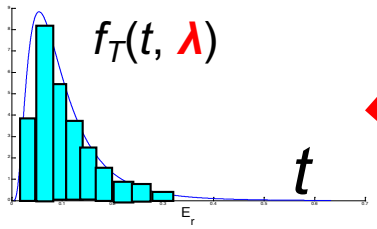
KNOWLEDGE K

valve 1

valve 2

...

valve *N*



"λ is UNIFORM between 10^{-3} and 10^{-2} $[h^{-1}]$"

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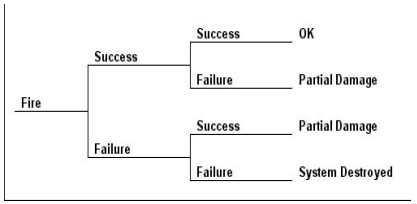
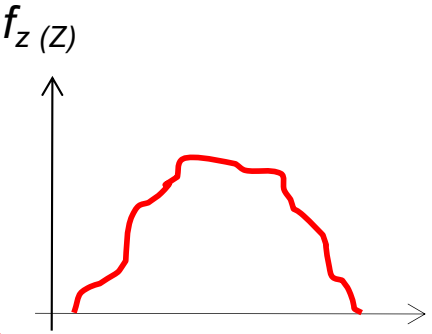
PROBABILISTIC REPRESENTATION OF UNCERTAINTY (M=P)

SYSTEM RISK MODEL

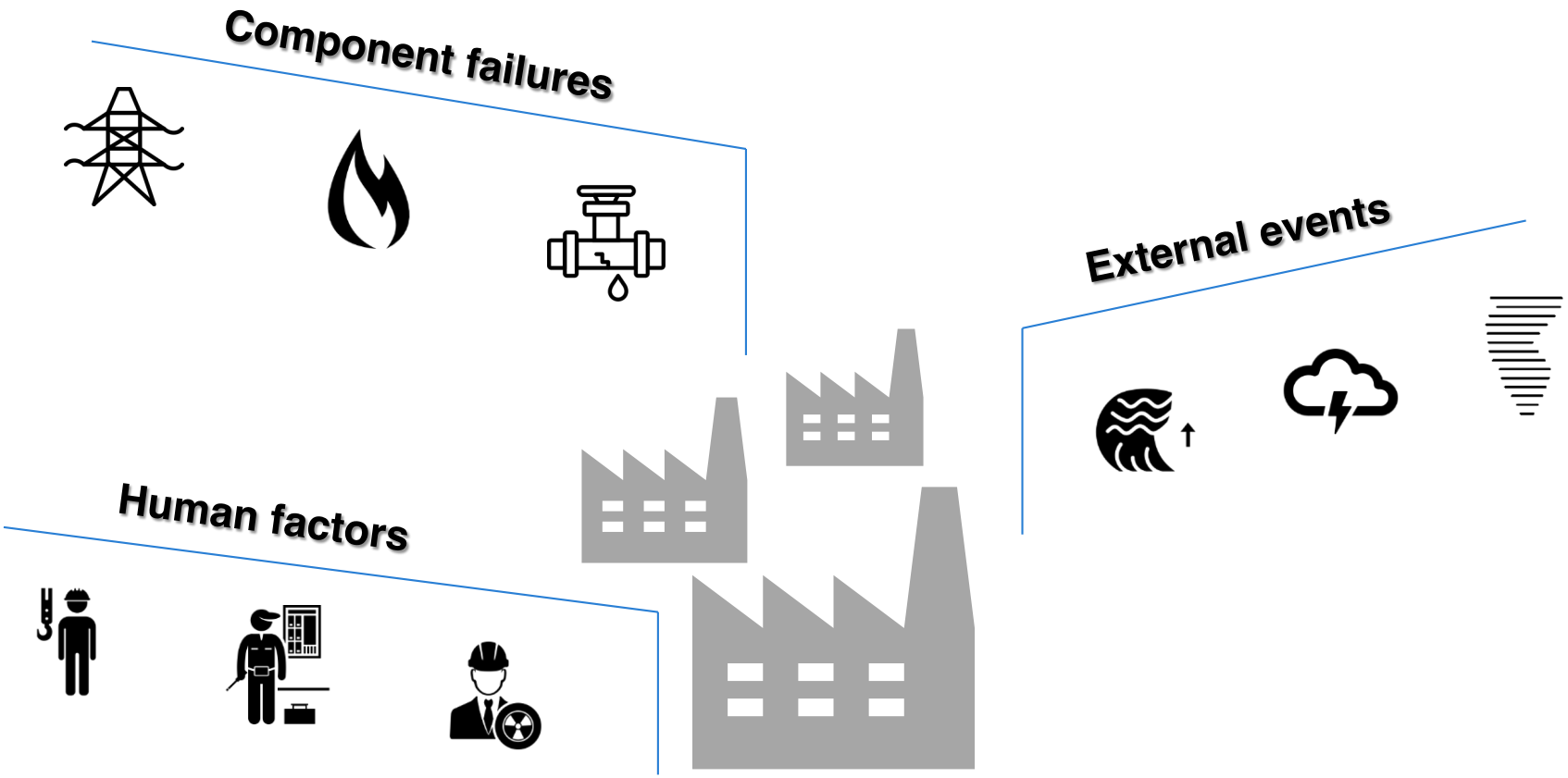


UNCERTAINTY PROPAGATION

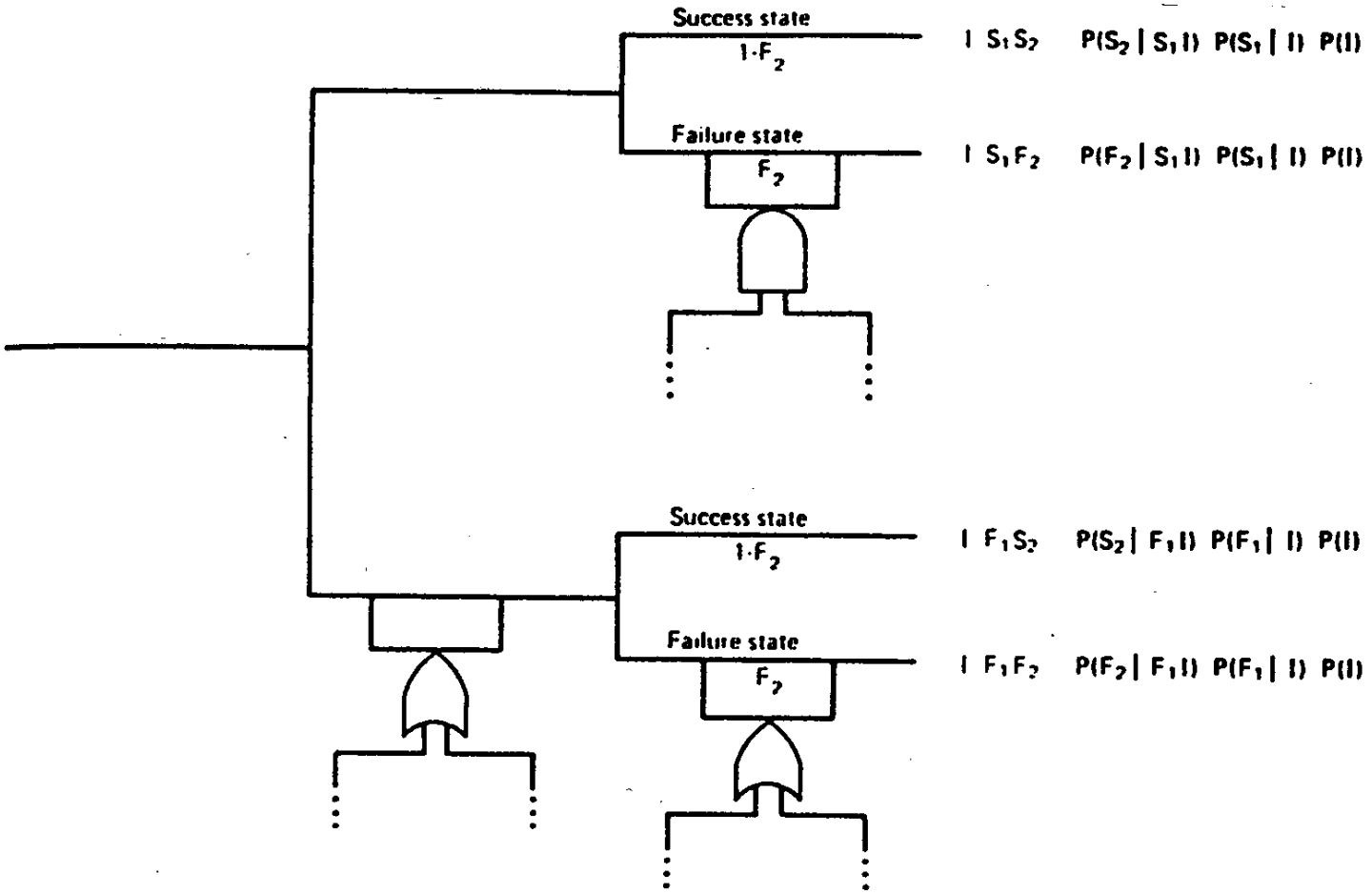


(PROBABILISTIC) RISK MEASURES (a,c,u,P,K)

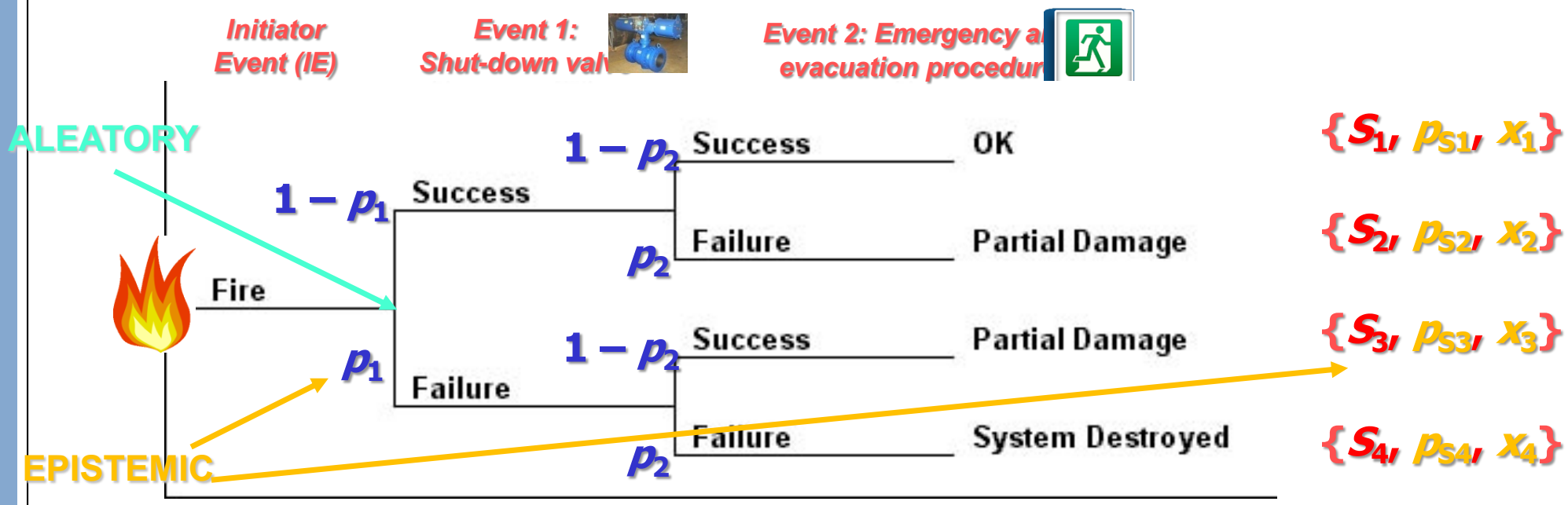
HAZARDS



Event Trees/Fault Trees



(aleatory and epistemic) Uncertainty



Aleatory: variability, randomness (in **occurrence** of the **events** in the **scenarios**)

Epistemic: lack of knowledge/information (**probability** and **consequence** models)

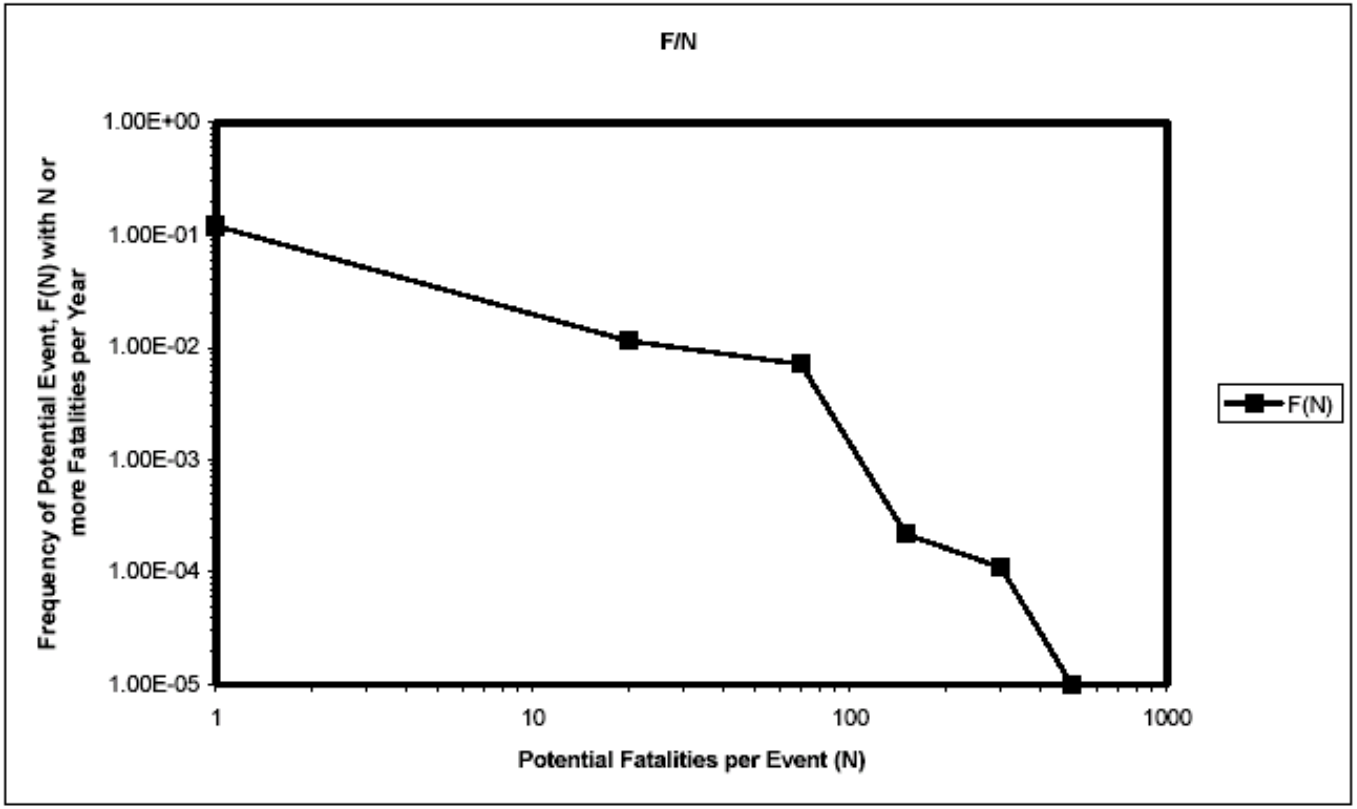
PRA results:

$$\{S_i, p_i, x_i\}$$

S	p	x
S_1	p_1	x_1
…	…	…
S_N	p_N	x_N

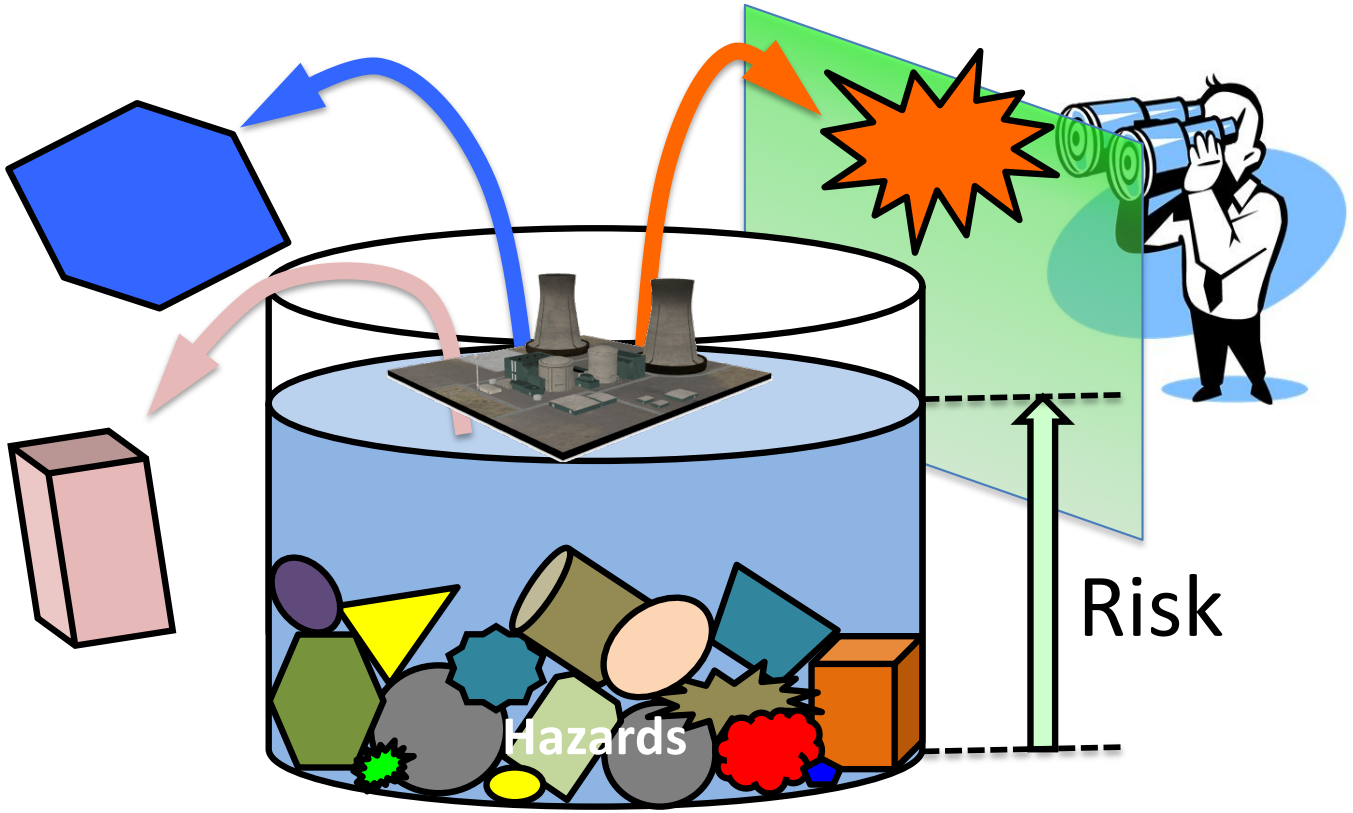
Example of F/N graph

Scenario	Number (N) of Potential Fatalities	Frequency of Scenario per Year	Frequency of Incidents with Potential (N) or more Fatalities per Year
1	1	0.1	0.12021
2	20	0.014	0.01141
3	70	0.0075	0.00713
4	150	0.00023	0.00022
5	300	0.00009	0.00011
6	500	0.00001	0.00001



Risk management

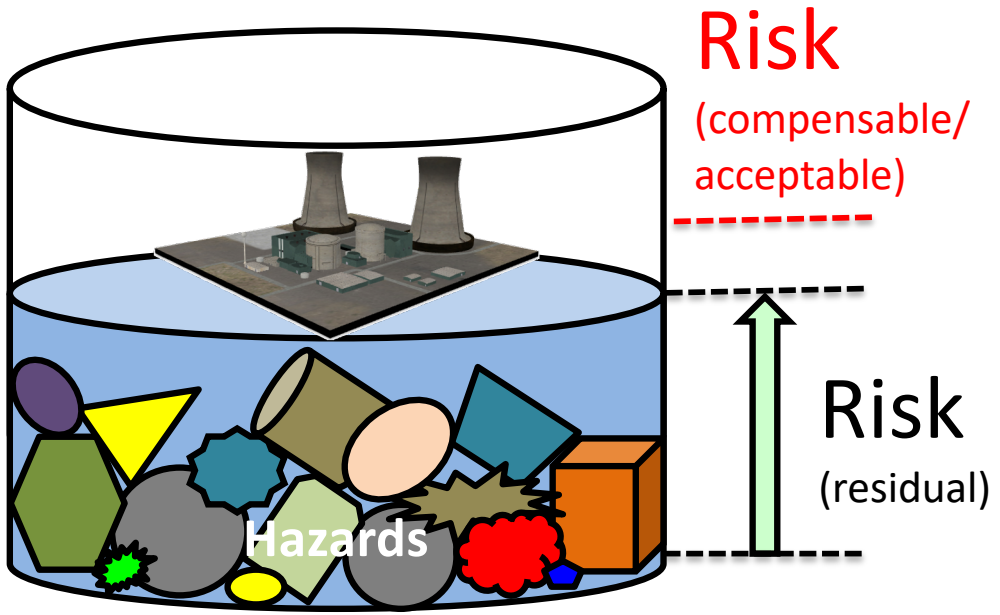
Risk management



A. Yamaguchi, PSAM 12, 2016

T. Aven and E. Zio, Foundational Issues in Risk Assessment and Risk Management, Risk Analysis, Vol. 34(7), 2014

Risk management



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Risk-Informed Decision Making (1)

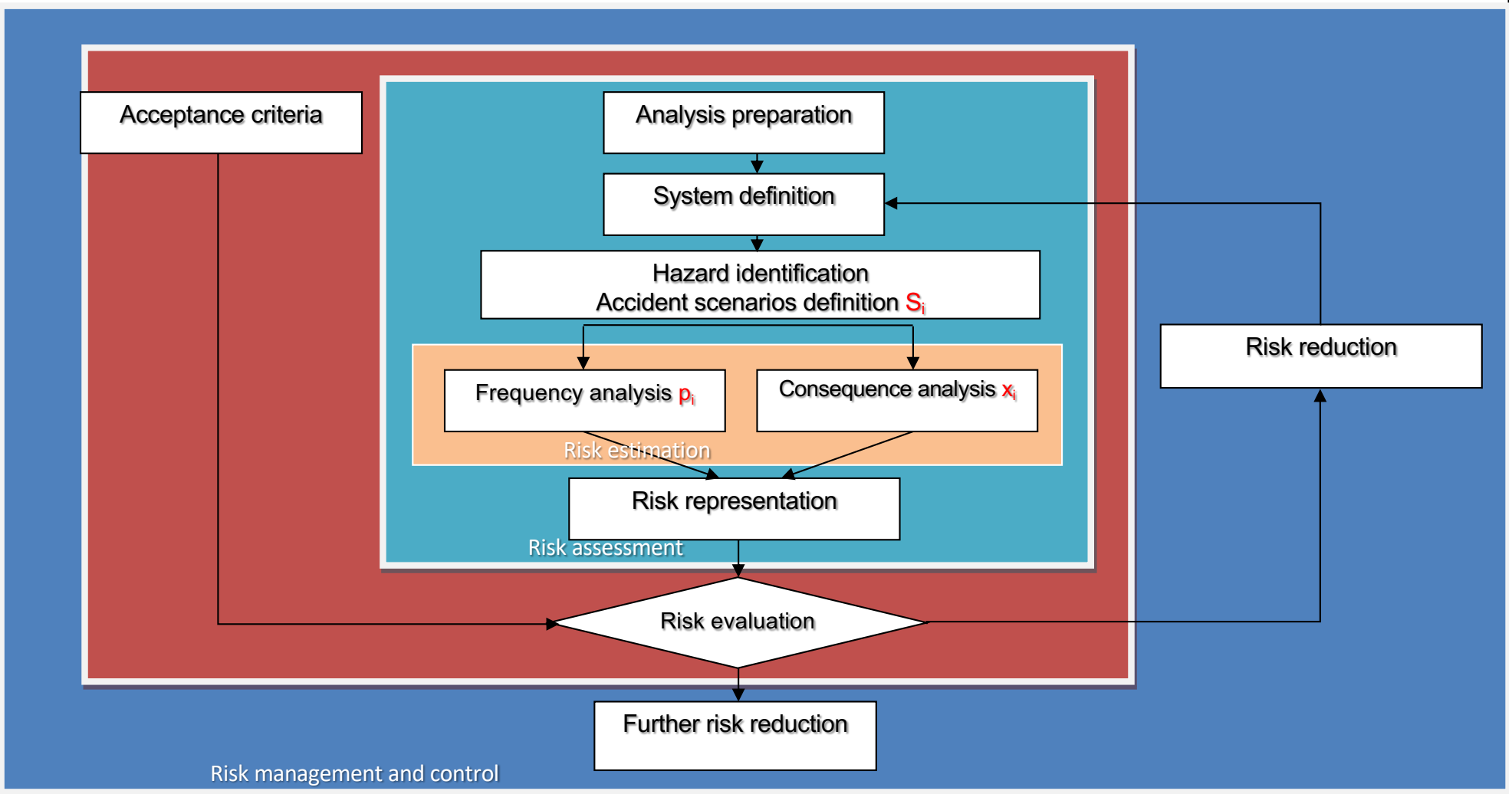
- Decision making must be based on the current state of knowledge of the decision maker (DM)
  - The current state of knowledge regarding design, operation, and regulation is key.
  - The current state of knowledge is informed by science, engineering and operating experience, including past incidents.
- What we know about plant behavior is not easily available to the DM
  - Accident sequences, human performance, risk significance of systems, structures, and components, etc

Risk-Informed Decision Making (2)

- **PRAs provide this information to the DM**
  - **PRAs do not predict the future**
  - **PRAs evaluate and assess potential accident scenarios to inform the decision makers' current state of knowledge.**

PRA = Probabilistic Risk Assessment

Risk Assessment and Management



Example of F/N graph

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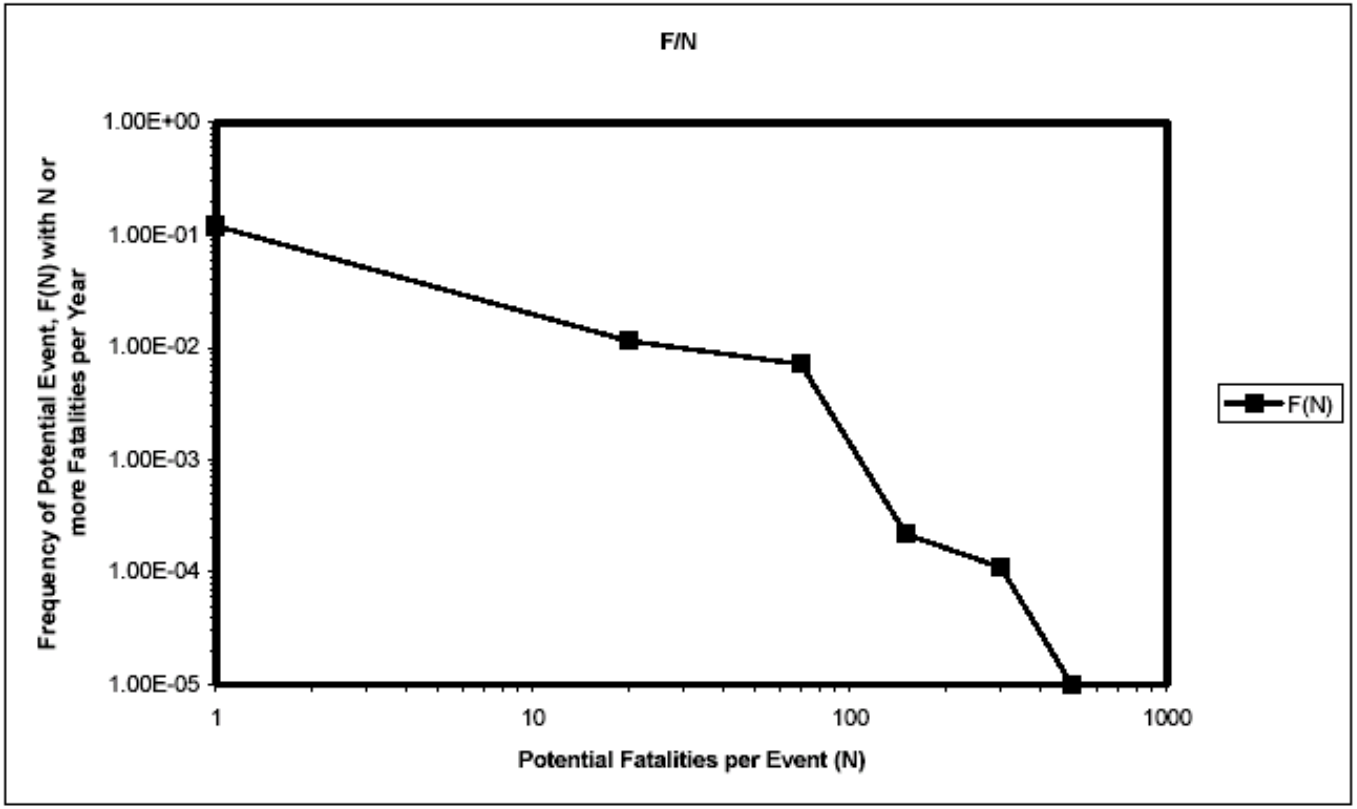
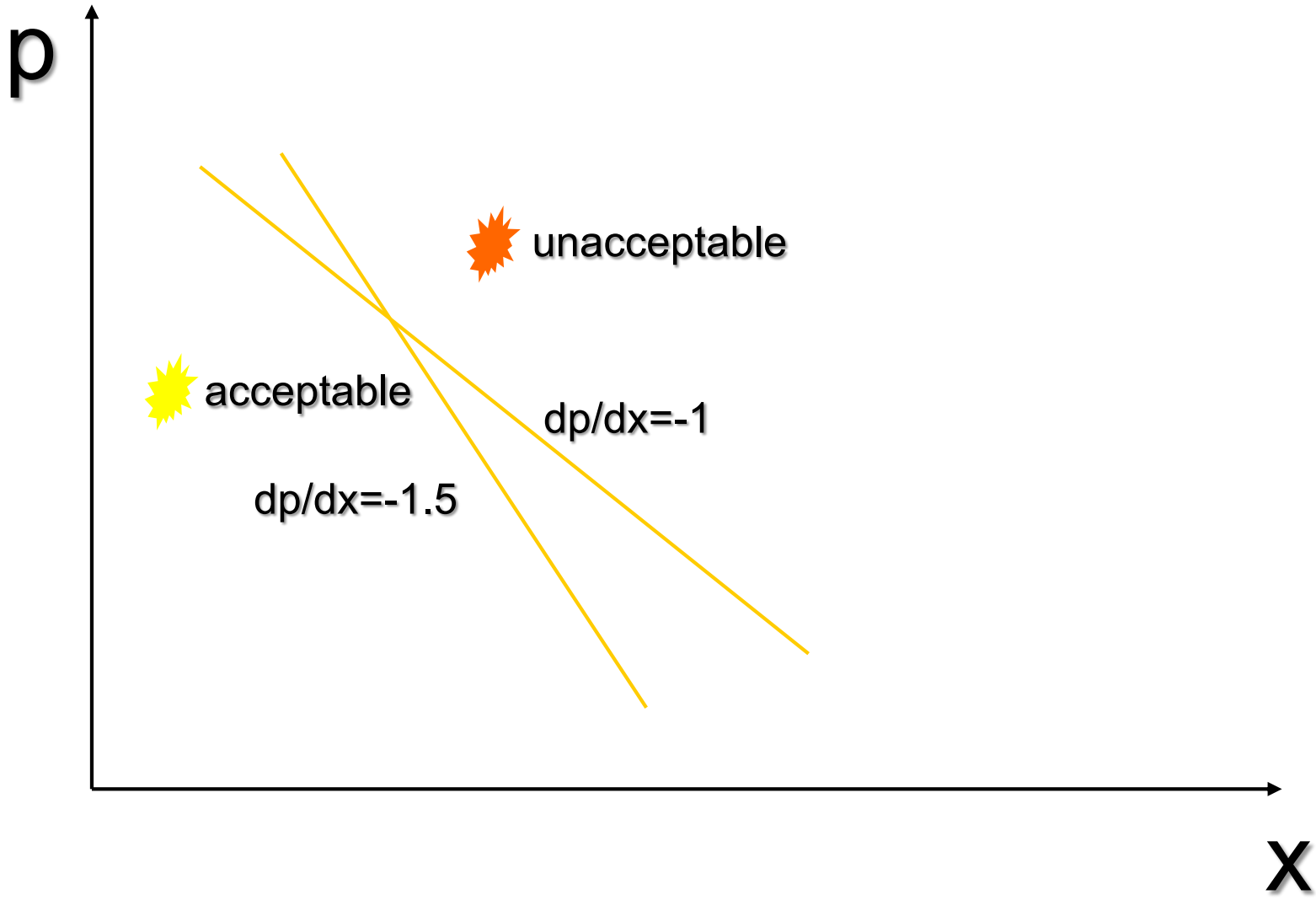


FARMER'S CURVE:



RISK MATRIX:

The level of risk is broadly acceptable and generic control measures are required aimed at avoiding deterioration.

Consequence					Increasing Annual Frequency					
Severity	People	Environ.	Assets	Reputation	0	A	B	C	D	E
					Practically non-credible occurrence	Rare occurrence	Unlikely occurrence	Credible occurrence	Probable occurrence	Likely/Frequent occurrence
					Could happen in E&P industry	Reported for E&P industry	Has occurred at least once in Company	Has occurred several times in Company	Happens several times/y in Company	Happens several times/y in one location
1	Slight health effect / injury	Slight effect	Slight damage	Slight impact	*Continuous Improvement*					
2	Minor health effect / injury	Minor effect	Minor damage	Minor impact		*Risk Reduction Measures*				
3	Major health effect / injury	Local effect	Local damage	Local impact						
4	PTD(*) or 1 fatality	Major effect	Major damage	National impact			*Intolerable Risk*			
5	Multiple fatalities	Extensive effect	Extensive damage	International impact						

The level of risk can be tolerable only once a structured review of risk-reduction measures has been carried out

The level of risk is not acceptable and risk control measures are required to move the risk figure to the previous regions.

Main strategies for handling risk

Codes and standards – simple problems

Risk assessment informed

Robustness, resilience-based strategies

Cautionary/ precautionary principles

Dialogue

Balancing other concerns

Balance

Development and protection

Develop, creating values

Take risk

Reduce the risks and uncertainties

Cost-benefit analyses

ALARP

cautionary-precautionary

Risk acceptance criteria

CLASSICAL TECHNIQUES OF RISK ASSESSMENT

Risk Assessment: main steps

1. System description and modeling
2. Historical analysis of past accidents
3. Hazard identification
4. Selection of most critical hazards and identification of Initiating Events (IEs)
5. Analysis of the accident sequences deriving from the IEs
6. Evaluation of risk → decision-making process

Classical Techniques for Risk Assessment

- Hazard identification: FMEA & HAZOP
- Accident Scenarios Identification: ETA, FTA
- System Failure Probabilty Assessment: ETA, FTA

FAILURE MODES AND EFFECTS ANALYSIS

FMEA

- Qualitative
- Inductive

AIM:

Identification of those component failure modes which could fail the system (reliability) and/or become accident initiators (safety)

FMEA: Procedure steps

component	Failure mode	Effects on other components	Effects on subsystem	Effects on plant	Probability*	Severity +	Criticality	Detection methods	Protection and mitigation
Description	Failure modes relevant for the operational mode indicated	Effects of failure mode on adjacent components and surrounding environment	Effects on the functionality of the subsystem	Effects on the functionality and availability of the entire plant	Probability of failure occurrence (sometimes qualitative)	Worst potential consequences (qualitative)	Criticality rank of the failure mode on the basis of its effects and probability (qualitative estimation of risk)	Methods of detection of the occurrence of the failure event	Protections and measures to avoid the failure occurrence

Failure mode: The manner by which a failure is observed. Generally, it describes the observable effect of the mechanism through which the failure occurs (e.g., short-circuit, open-circuit, fracture, excessive wear)

HAZARD OPERABILITY ANALYSIS

HAZOP

- Initially developed to analyze chemical process systems; later extended to complex operations and other types of systems (e.g., software)

- It is a qualitative, structured and systematic examination of a planned or existing process or operation in order to identify and evaluate problems that may represent risks to personnel or equipment, or prevent efficient operation

- Deductive (search for causes)

- Inductive (consequence analysis)

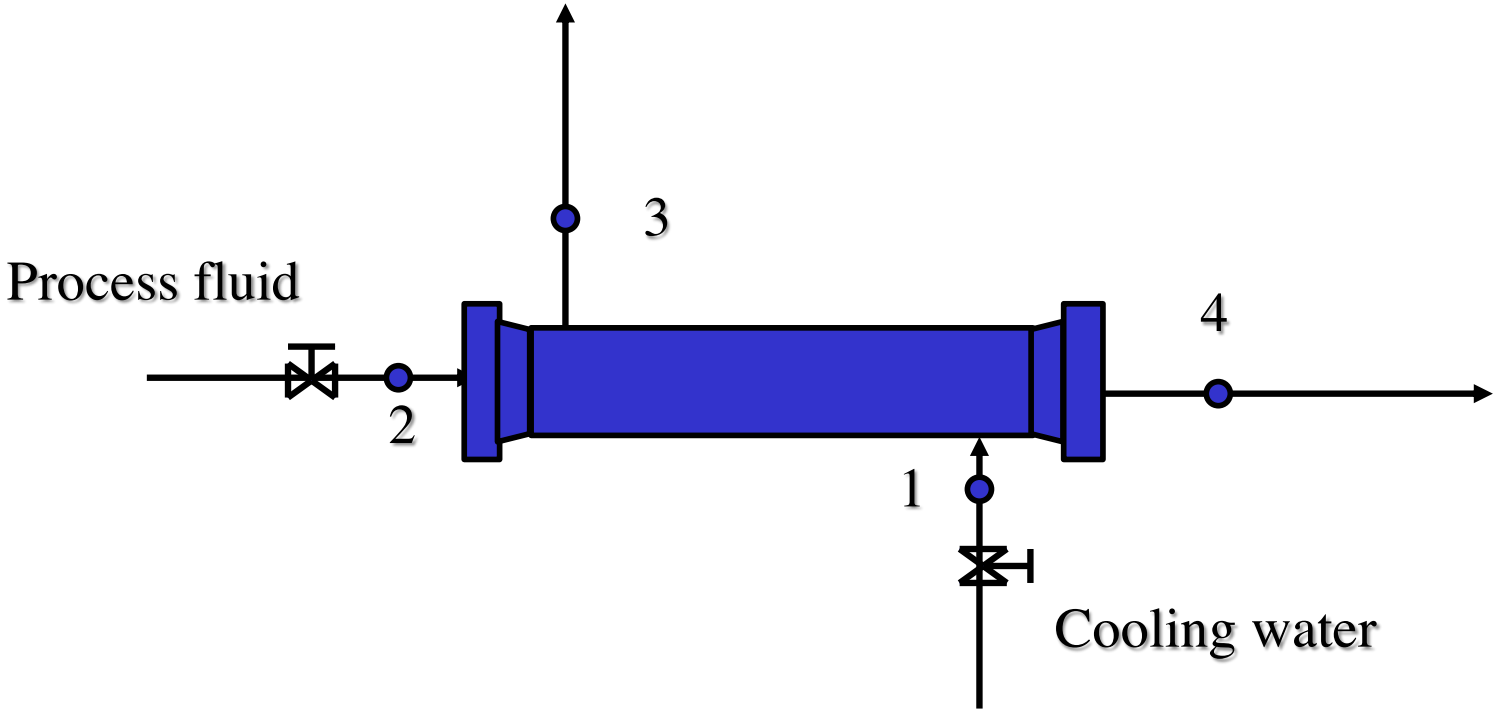
Hazop: example

SYSTEM: shell & tube heat exchanger

Study Node: 1

Operational Mode: Nominal Conditions

Design Intent: P= 2bar, T=20°C, Flow=1l/sec



HAZOP: Table

Study title:								Page: of	
Drawing no.:		Rev no.:						Date:	
HAZOP team:								Meeting date:	
Part considered:									
Design intent:		Material: Source:		Activity: Destination:					
No.	Guide Word	Element	Deviation	Possible Causes	Consequences	Safeguards	Comments	Actions Required	Actions Assigned to
Assign each entry a unique tracking number	Insert deviation guide word used	Describe what the guide word pertains to (material, process step, etc.)	Describe the deviation	Describe how the deviation may occur	Describe what may happen if the deviation occurs	List controls (preventive or reactive) that reduce deviation likelihood or severity	Capture key relevant rationale, assumptions, data, etc.	Identify any hazard mitigation or control actions required	Record who is responsible for actions

Source: IEC 61882

POLITECNICO DI MILANO

FAILURES

CentraleSupélec

ARAMIS reliable innovation

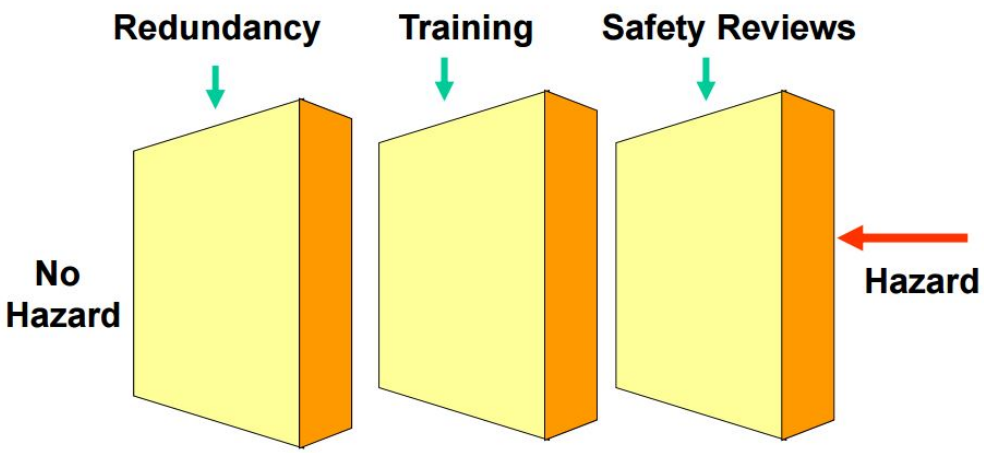
FONDATION EDF Science - Enseignement en partenariat avec l'Institut de France

Failures

Prevented by

Design for Reliability/Availability

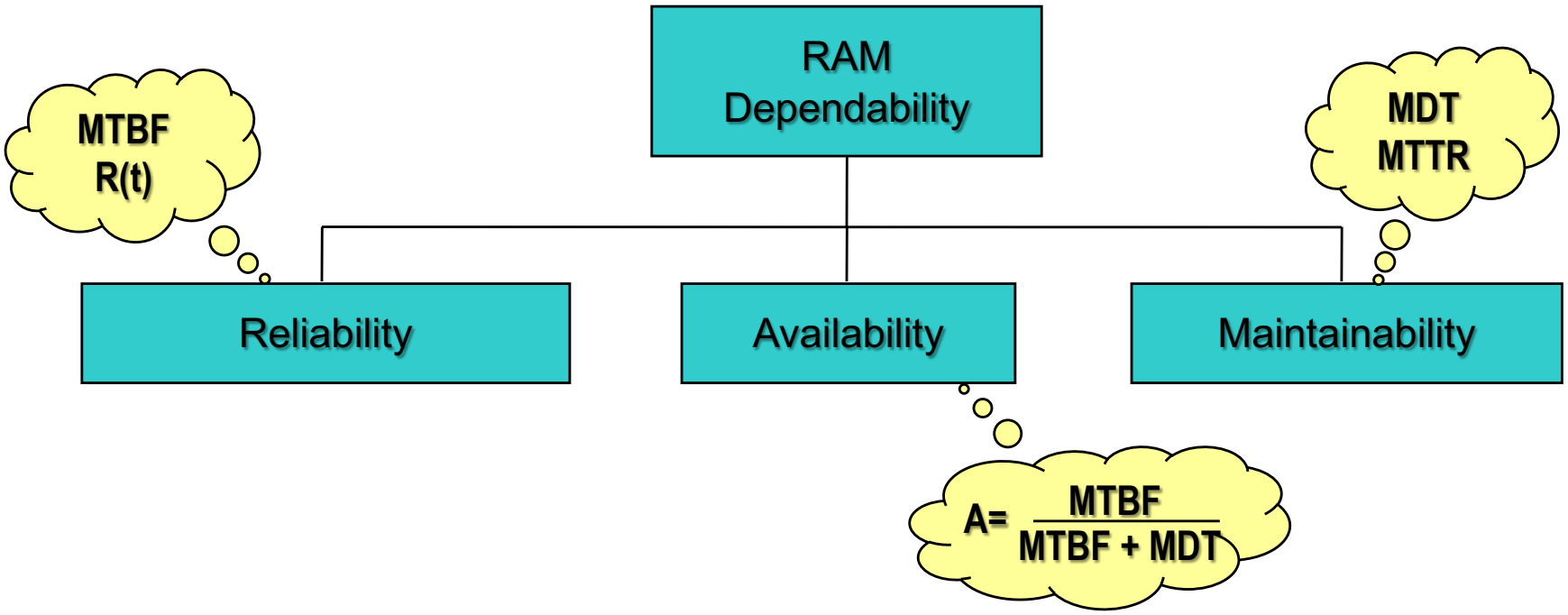
Maintenance



- RAM background:

RAM = Reliability, Availability, Maintainability

Background



- Definition under IEC 50 (191):
- Summarising expression to describe availability and its influencing factors, reliability and maintainability.
- *Note*: Dependability is only used for general descriptions of non-quantitative character.

- Broad definition:
- Dependability is the methodical approach of estimating, analysing and avoiding failures in the future.

Introduction: reliability and availability

- **Reliability** and **availability**: important performance parameters of a system, with respect to its ability to fulfill the required mission in a given period of time

- Two different system types:
  - Systems which must satisfy a specified mission within an assigned period of time: **reliability** quantifies the ability to achieve the desired objective without failures
  - Systems maintained: **availability** quantifies the ability to fulfill the assigned mission at **any** specific moment of the life time

Maintainablilty:

Ability of a unit, under given circumstances, to maintain or respectively to reset its actual state so that the desired requirements are met, provided that maintenance is carried out using the specified resources and stated procedures.

• RAM background:

Component reliability

Basic definitions (1)

Reliability **is the ability of an item to perform a required function under stated conditions for a stated period of time.**

Therefore….
the *failure* is an event
whereby a unit or component
under consideration is no longer
capable of fulfilling a required function
under stated conditions
for a stated the period of time.

Basic definitions (2)

The *required function* includes the specification of satisfactory operation as well as unsatisfactory operation. For a complex system, unsatisfactory operation may not be the same as failure.

The *stated conditions* are the total physical environmental including mechanical, thermal, and electrical conditions.

The *stated period of time* is the time during which satisfactory operation is desired, commonly referred to as service life.

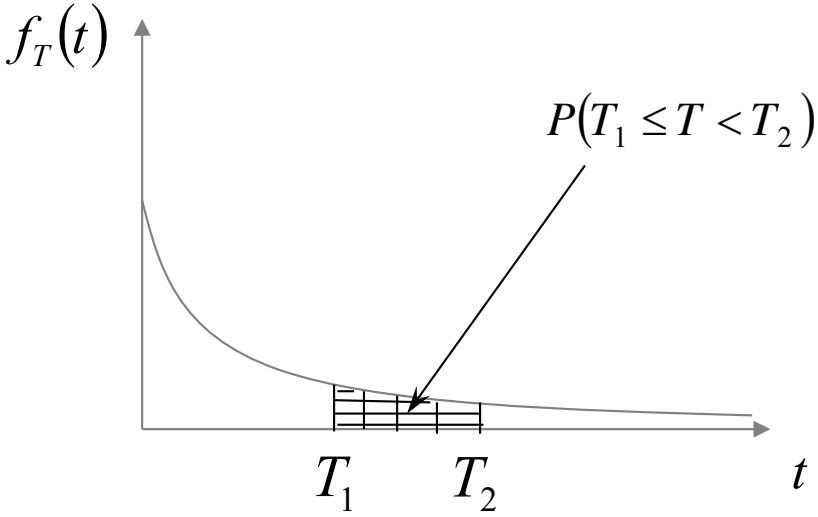
Basic definitions (3)

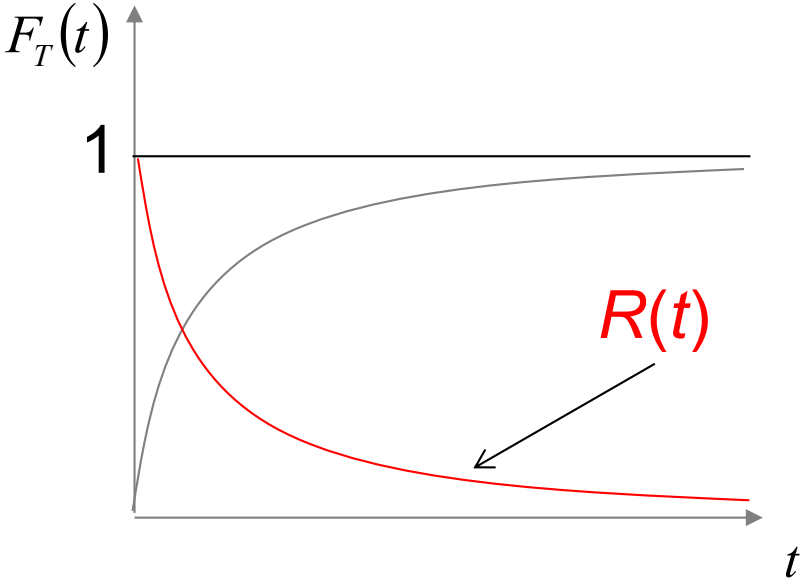
- T = Time to failure of a component (random variable)
  - cdf = $F_T(t)$ = probability of failure before time t: P($T<t$)
  - pdf = $f_T(t)$ = probability density function at time t:

    $f_T(t)dt$ = P($t<T<t+dt$)
  - ccdf = $R(t)$ = 1- $F_T(t)$ = reliability at time t: P($T>t$)
  - $h_T(t)$ = **hazard function** or failure rate at time t

$$h_T(t)dt = P(t < T \le t + dt \mid T > t) = \frac{P(t < T \le t + dt)}{P(T > t)} = \frac{f_T(t)dt}{R(t)}$$

Basic definitions (4)





Hazard function: the bath-tub curve

Three types of failures:

- **Early failures** (Infant mortality), caused by errors in design, defects in manufacturing, etc..

Characteristic: The failure rate is initially high, but rapidly decreases.

- **Wear-out failures**, caused by ageing.

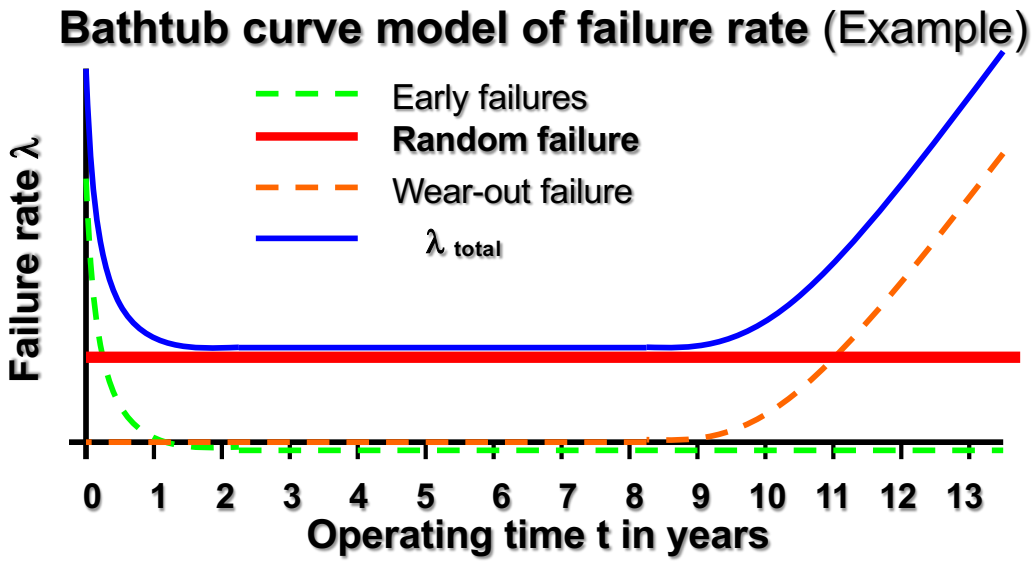
Characteristic: The failure rate increases monotonically.

(Both types are systematic failures and could be prevented by improvement in design, manufacturing, maintenance).

- **Random failure:** appear spontaneously and purely by chance.

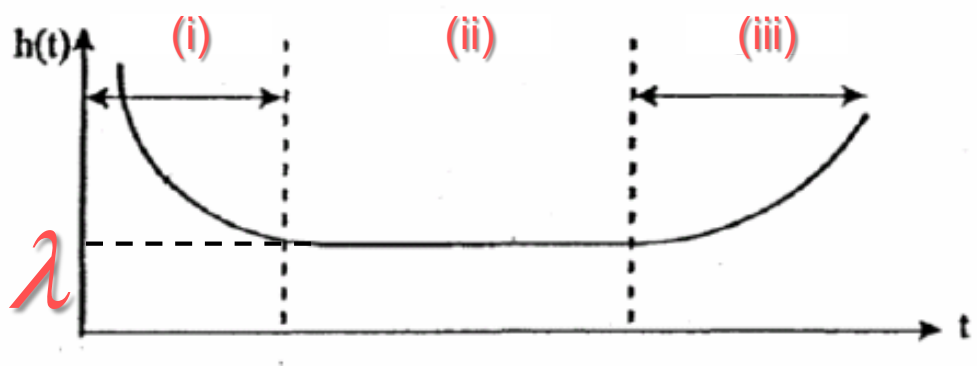
Characteristic: Constant failure rate during the whole lifetime of the units.

These types of failure rates result in the traditional bathtub curve



Hazard function: the bath-tub curve

- The hazard function shows three distinct phases:
  i. Decreasing - *infant mortality* or *burn in period*
  ii. Constant - *useful life*
  iii. Increasing - *ageing*



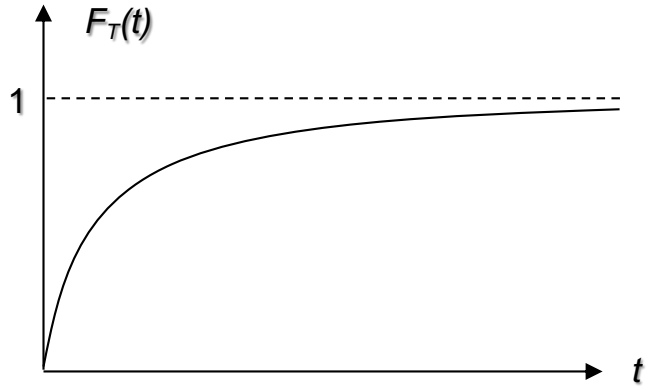
The unit of the failure rate λ is failure/time, often indicated as FIT (Failure in Time).
e.g. **1 FIT = 1 Failure per 10^9h in FRU**(Field Replaceable Unit) **employed in the railway industry**

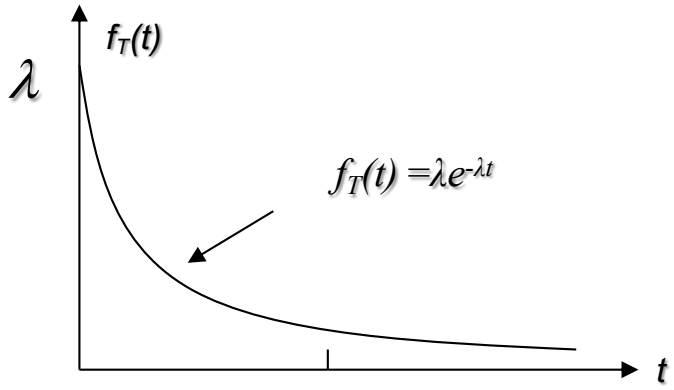
The exponential distribution (1)

- $h_T(t) = \lambda,\ t \geq 0$

$$F_T(t) = P(T \leq t) = 1 - e^{-\lambda t}$$

$$\begin{cases} f_T(t) = \lambda e^{-\lambda t} & t \geq 0 \\ = 0 & t < 0 \end{cases}$$





- Only distribution characterized by a constant hazard rate
- Widely used in reliability practice to describe the constant part of the bath-tub curve

The exponential distribution (2)

- The expected value and variance of the distribution are:

$$E[T] = \frac{1}{\lambda} = MTTF \qquad ; \qquad Var[T] = \frac{1}{\lambda^2}$$

- Failure process is **memoryless**

$$P(t_1 < T < t_2 \mid T > t_1) = \frac{P(t_1 < T < t_2)}{P(T > t_1)} = \frac{F_T(t_2) - F_T(t_1)}{1 - F_T(t_1)} =$$

$$= \frac{e^{-\lambda t_1} - e^{-\lambda t_2}}{e^{-\lambda t_1}} = 1 - e^{-\lambda (t_2 - t_1)}$$

The Weibull distribution

- In practice, the age of a component influences its failure process so that the hazard rate does not remain constant throughout the lifetime

$$F_T(t) = P(T \le t) = 1 - e^{-\lambda t^{\alpha}}$$

$$\begin{cases} f_T(t) = \lambda \alpha t^{\alpha-1} e^{-\lambda t^{\alpha}} & t \ge 0 \\ = 0 & t < 0 \end{cases}$$

$$E[T] = \frac{1}{\lambda}\Gamma\left(\frac{1}{\alpha}+1\right) \quad ; \quad Var[T] = \frac{1}{\lambda^2}\left(\Gamma\left(\frac{2}{\alpha}+1\right) - \Gamma\left(\frac{1}{\alpha}+1\right)\right)^2$$

$$\Gamma(k) = \int_0^{\infty} x^{k-1} e^{-x} dx \qquad k > 0$$

- RAM background:

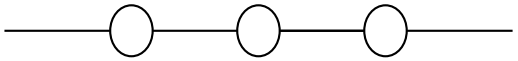
System reliability

(simple)

Definition of the problem

- **Objective**:
  - Computation of the system reliability *R(t)*
- **Hypotheses**:
  - *N* = number of system components
  - The components' reliabilities $R_i(t)$, i = 1, 2, …, *N* are known
  - The system **configuration** is known

Series system



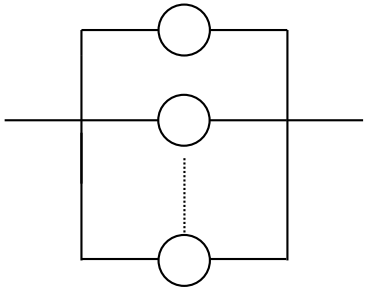
- All components must function for the system to function

$$R(t) = \prod_{i=1}^{N} R_i(t)$$

- For *N* **exponential** components:

$$R(t) = e^{-\lambda t} \longrightarrow \begin{cases} \lambda = \sum_{i=1}^{N} \lambda_i \longrightarrow \text{System failure rate} \\ E[T] = \frac{1}{\lambda} \longrightarrow MTTF \end{cases}$$

Parallel system



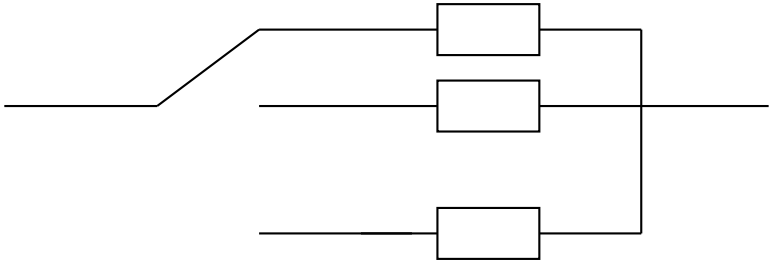
- All components must fail for the system to fail

$$R(t) = 1 - \prod_{i=1}^{N} [1 - R_i(t)]$$

- For *N* **exponential** components:

$$R(t) = 1 - \prod_{i=1}^{N} \left[1 - e^{-\lambda_i t}\right] \longrightarrow \begin{cases} MTTF = \sum_{i=1}^{N} \frac{1}{\lambda_i} - \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{1}{[\lambda_i + \lambda_j]} + \\ + \sum_{i=1}^{N-2} \sum_{j=i+1}^{N-1} \sum_{k=j+1}^{N} \frac{1}{[\lambda_i + \lambda_j + \lambda_k]} - \ldots + (-1)^{N-1} \frac{1}{\sum_{i=1}^{N} \lambda_i} \end{cases}$$

Standby system



- One component is functioning and when it fails it is replaced immediately by another component (sequential operation of one component at a time)
- The system configuration is **time-dependent** $\Rightarrow$ the story of the system from $t = 0$ must be considered
- Two types of standby:
  - **Cold**: the standby unit cannot fail until it is switched on
  - **Hot**: the standby unit can fail also while in standby

- RAM background:

System reliability and availability (complicated)

FAULT TREE ANALYSIS

Fault Tree Analysis (FTA)

- Systematic and quantitative
- Deductive

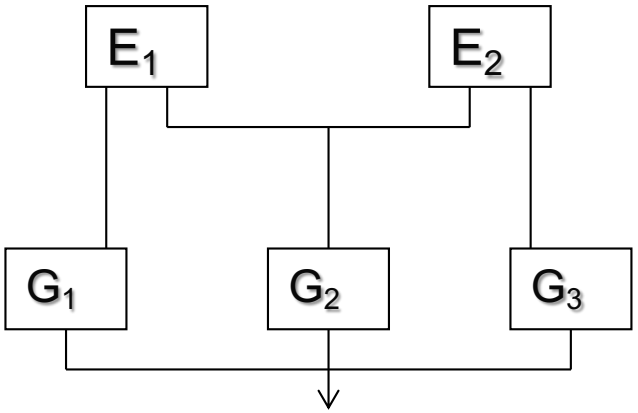
AIM:

1. Decompose the system failure in elementary failure events of constituent components
2. Computation of system failure probability, from component failure probabilities

FT construction: Procedure steps

1. Define top event (system failure)

Electrical generating system

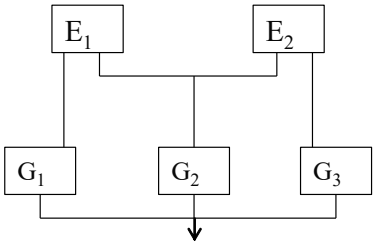


E1, E2 = engines

G1, G2, G3 = generators, each one is rated at 30 KVA

T = Failure to supply at least 60 kVA

FT Result



T = failure to supply at least 60 KVA

1

G_1, G_2 do not supply power

A

No output from G_1

E_1

G_1

B

No output from G_2

G_2

E_1

E_2

2

G_2, G_3 do not supply power

B

E_2

G_3

C

No output from G_3

3

G_3, G_1 do not supply power

C

E_1

A

FT qualitative analysis

FT qualitative analysis

Introducing:

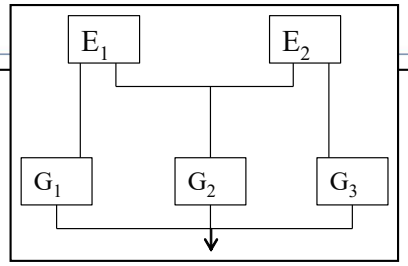
X_i : binomial indicator variable of i-th component state (basic event)

$$X_i = \begin{cases} 1 \text{ failure event } \underline{\text{true}} \\ 0 \text{ failure event } \underline{\text{false}} \end{cases}$$

- **FT = set of boolean algebraic equations (one for each gate) => structure (switching) function Φ:**

$$X_T = \Phi(X_1, X_2, \ldots, X_n)$$

FT mcs: Example



$$X_{T_1} = X_{E_1}X_{G_2} + X_{E_1}X_{E_2} + X_{G_1}X_{G_2} - X_{E_1}X_{E_2}X_{G_2} - X_{E_1}X_{G_1}X_{G_2}$$

$$= 1-[1-X_{E_1}X_{G_2} - X_{E_1}X_{E_2} - X_{G_1}X_{G_2} + X_{E_1}X_{E_2}X_{G_2} + X_{E_1}X_{G_1}X_{G_2}] =$$

$$= 1-[1-X_{E_1}X_{G_2} - X_{E_1}X_{E_2} - X_{G_1}X_{G_2} + X_{E_1}X_{E_2}X_{G_2} + X_{E_1}X_{G_1}X_{G_2} + X_{E_1}X_{E_2}X_{G_1}X_{G_2} - X_{E_1}X_{E_2}X_{G_1}X_{G_2}] =$$

$$= 1-[1-X_{E_1}X_{E_2} - X_{G_1}X_{G_2} + X_{E_1}X_{E_2}X_{G_1}X_{G_2} - X_{E_1}X_{G_2} + X_{E_1}X_{E_2}X_{G_2} + X_{E_1}X_{G_1}X_{G_2} - X_{E_1}X_{E_2}X_{G_1}X_{G_2}] =$$

$$= 1-[1-X_{E_1}X_{E_2} - X_{G_1}X_{G_2} + X_{E_1}X_{E_2}X_{G_1}X_{G_2} - X_{E_1}X_{G_2}(1-X_{E_1}X_{E_2} - X_{G_1}X_{G_2} + X_{E_1}X_{E_2}X_{G_1}X_{G_2})] =$$

$$= 1-[(1-X_{E_1}X_{G_2})(1-X_{E_1}X_{E_2} - X_{G_1}X_{G_2} + X_{E_1}X_{E_2}X_{G_1}X_{G_2})] =$$

$$= 1-[(1-X_{E_1}X_{G_2})(1-X_{E_1}X_{E_2})(1-X_{G_1}X_{G_2})]$$

3 minimal cut sets:

$$M_1 = \{E_1G_2\}$$
$$M_2 = \{E_1E_2\}$$
$$M_3 = \{G_1G_2\}$$

FT quantitative Analysis

FT quantitative analysis

Compute system failure probability from primary events probabilities by:

1. **using the laws of probability theory at the fault tree gate**
2. **using the mcs found from the qualitative analysis**

$$P[\Phi(\underline{X})=1]=\sum_{j=1}^{mcs}P[M_j]-\sum_{i=1}^{mcs-1}\sum_{j=i+1}^{mcs}P[M_iM_j]+\cdots+(-1)^{mcs+1}P[\prod_{j=1}^{mcs}M_j]$$

It can be shown that:

$$\sum_{j=1}^{mcs}P[M_j]-\sum_{i=1}^{mcs-1}\sum_{j=i+1}^{mcs}P[M_iM_j]\le P[\Phi(\underline{X})=1]\le\sum_{j=1}^{mcs}P[M_j]$$

EVENT TREE ANALYSIS

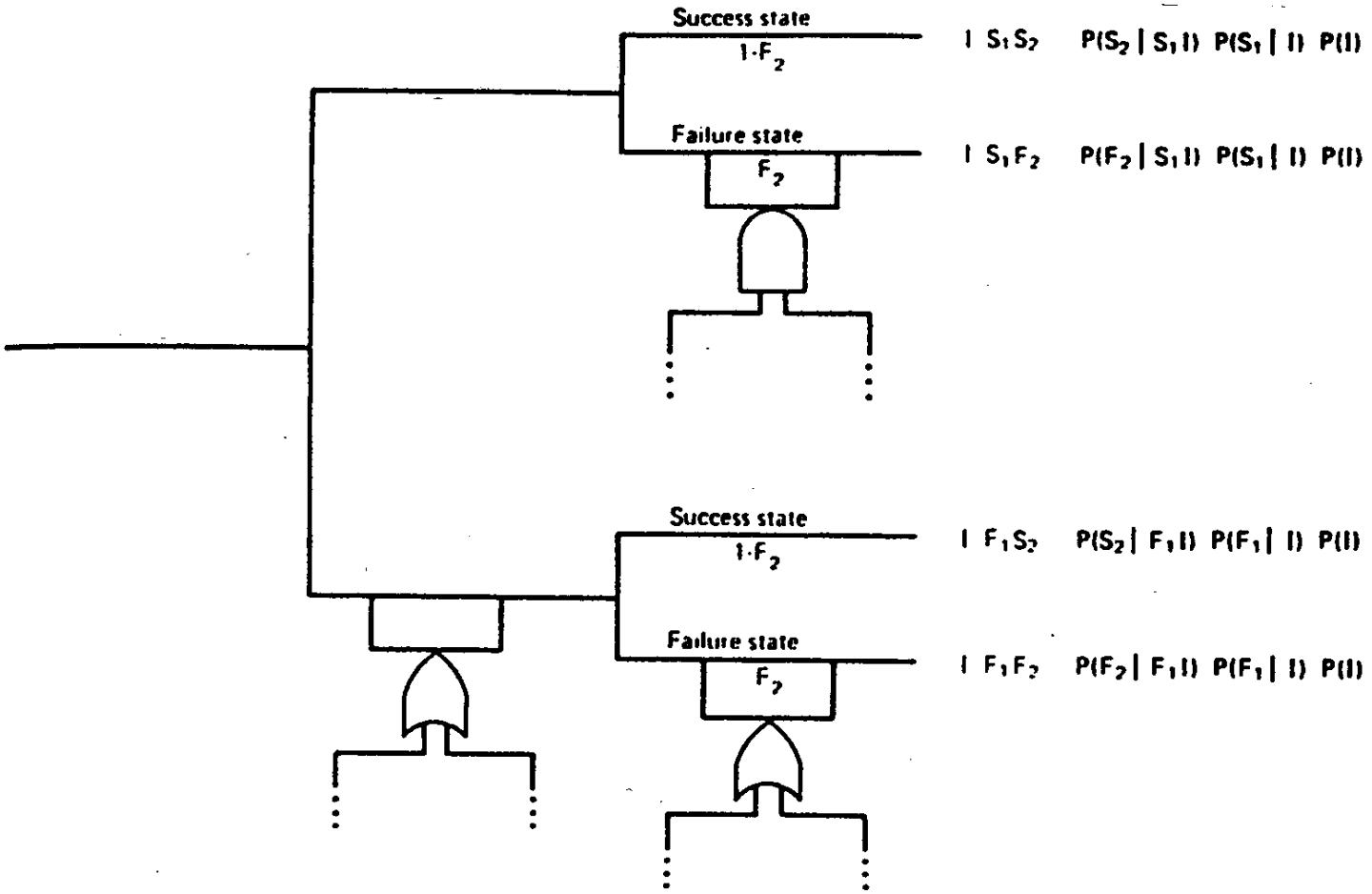
Event Tree Analysis (ETA)

- Systematic and quantitative
- Inductive

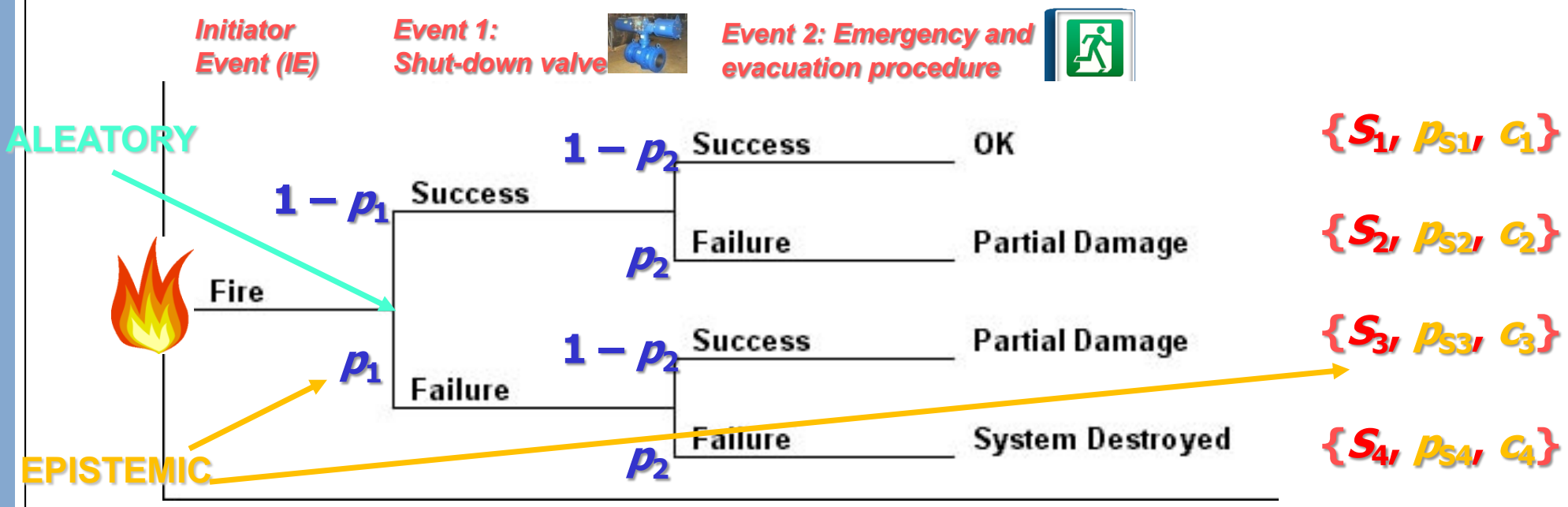
AIM:

1. Identification of possible scenarios (accident sequences), developing from a given accident initiator
2. Computation of accident sequence probability

ETA+FTA


Success state
$1\text{-}F_2$
Failure state
F_2
$I\ S_1S_2$ $P(S_2 | S_1 I)\ P(S_1 | I)\ P(I)$
$I\ S_1F_2$ $P(F_2 | S_1 I)\ P(S_1 | I)\ P(I)$
Success state
$1\text{-}F_2$
Failure state
F_2
$I\ F_1S_2$ $P(S_2 | F_1 I)\ P(F_1 | I)\ P(I)$
$I\ F_1F_2$ $P(F_2 | F_1 I)\ P(F_1 | I)\ P(I)$

(aleatory and epistemic) Uncertainty



Aleatory: variability, randomness (in occurrence of the events in the scenarios)

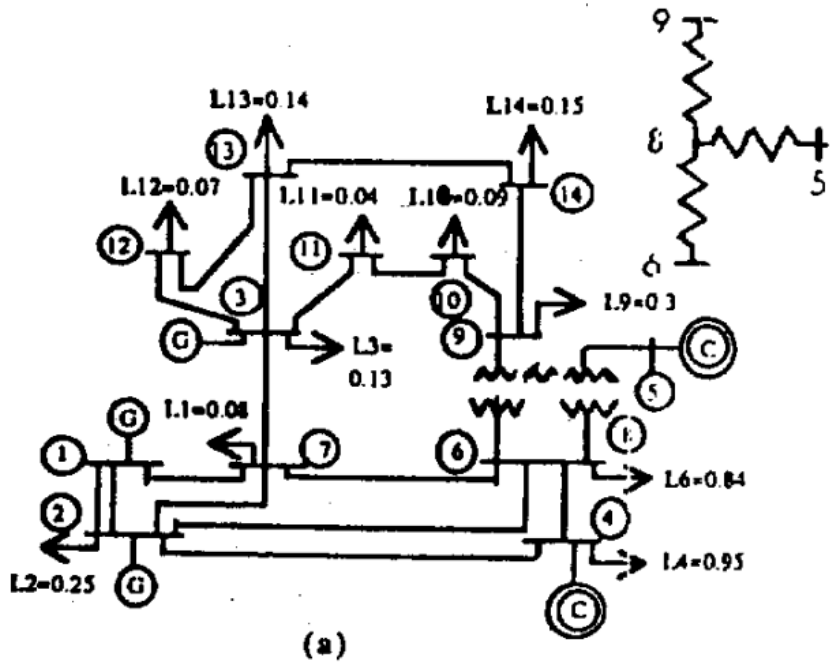
Epistemic: lack of knowledge/information (on the values of the parameters of the probability and consequence models)

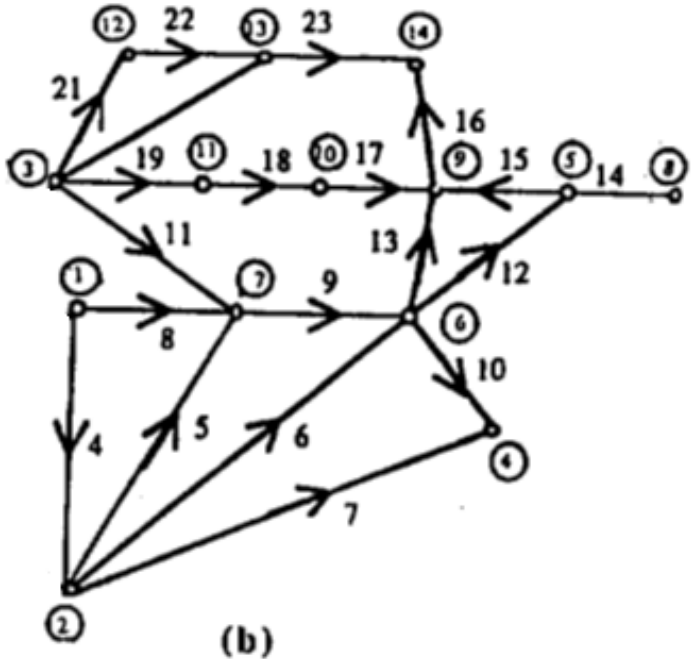
- RAM background:

System reliability and availability (complex)

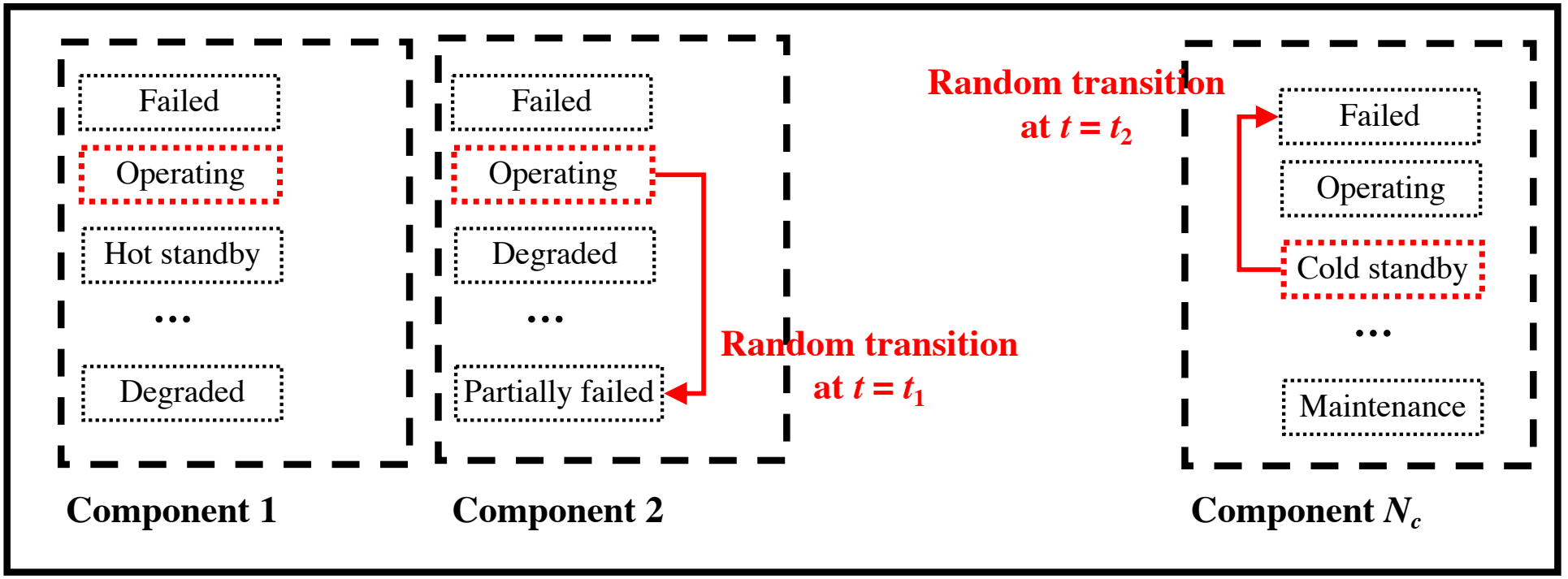
Complex System (IEEE 14)

Generators (G1, G2 , G3)
Loads (2, 3, 4, 6, 7, 9, 10, 11, 12, 13, 14)
Power delivery paths: lines (L) and buses (B).





SYSTEM



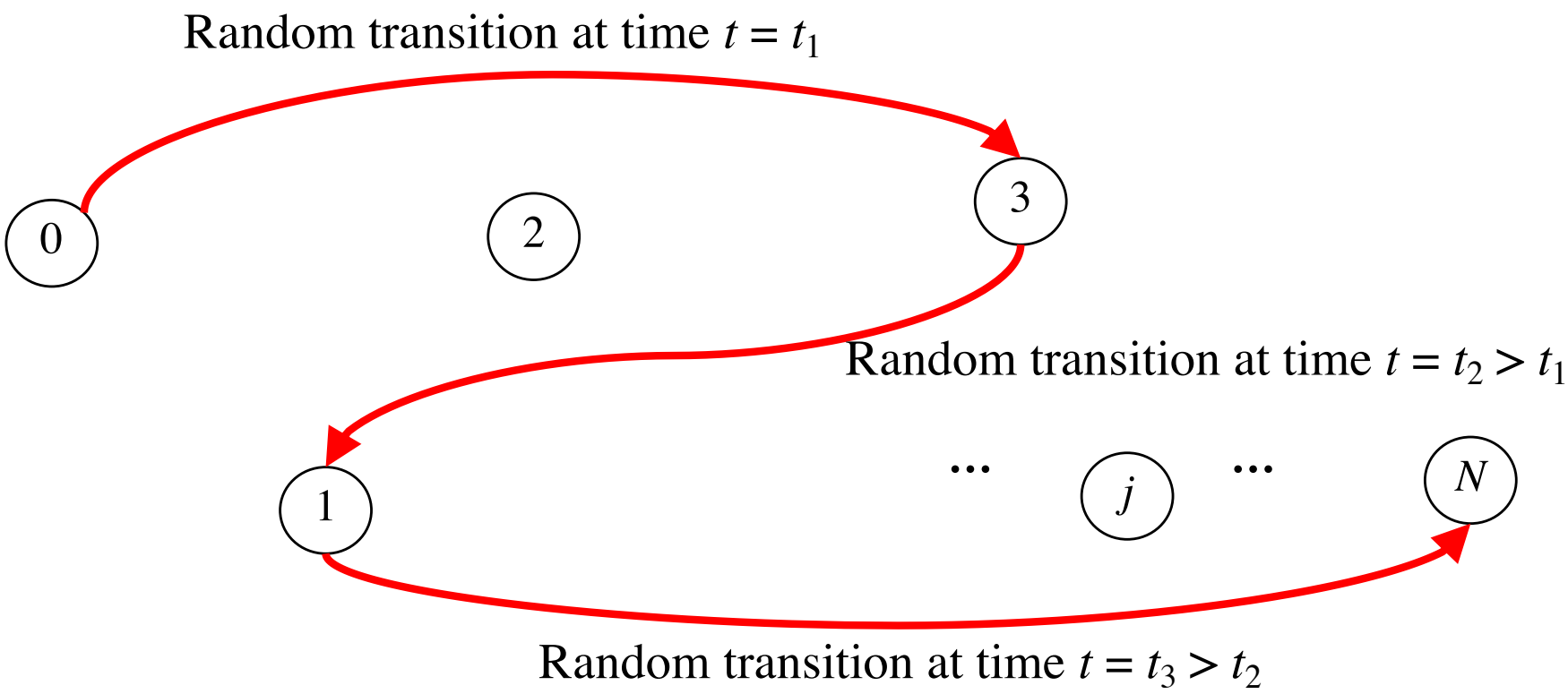
Under specified conditions:

Stochastic process of system evolution

=

MARKOV PROCESS

- **Transitions** from one state to another occur **stochastically** (i.e., **randomly in time**)



- Extending to the other equations:

$$\frac{d\underline{P}}{dt} = \underline{P}(t)\cdot\underline{\underline{A}}\ ,\ \underline{\underline{A}} = \begin{pmatrix} -\sum_{j=1}^{N}\alpha_{0j} & \alpha_{01} & \dots & \alpha_{0N} \\ \alpha_{10} & -\sum_{\substack{j=0\\ j\neq 1}}\alpha_{1j} & \dots & \alpha_{1N} \\ \dots & \dots & \dots & \dots \end{pmatrix}$$

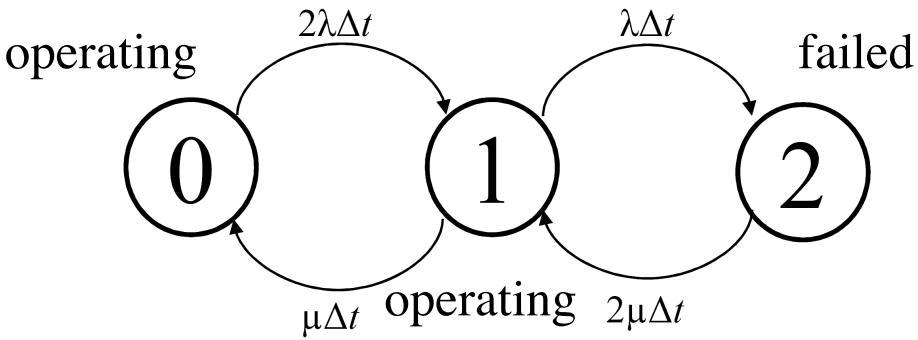
α_{00} α_{11}

TRANSITION RATE MATRIX

System of **linear**, **first-order differential equations** in the unknown state probabilities

$$P_j(t), j = 0,1,2,...,N,\ t \geq 0$$

1. Exclude all the failed states $j \in F$ from the transition rate matrix $\underline{\underline{A}}$



$$S = \{0,1\}$$
$$F = \{2\}$$

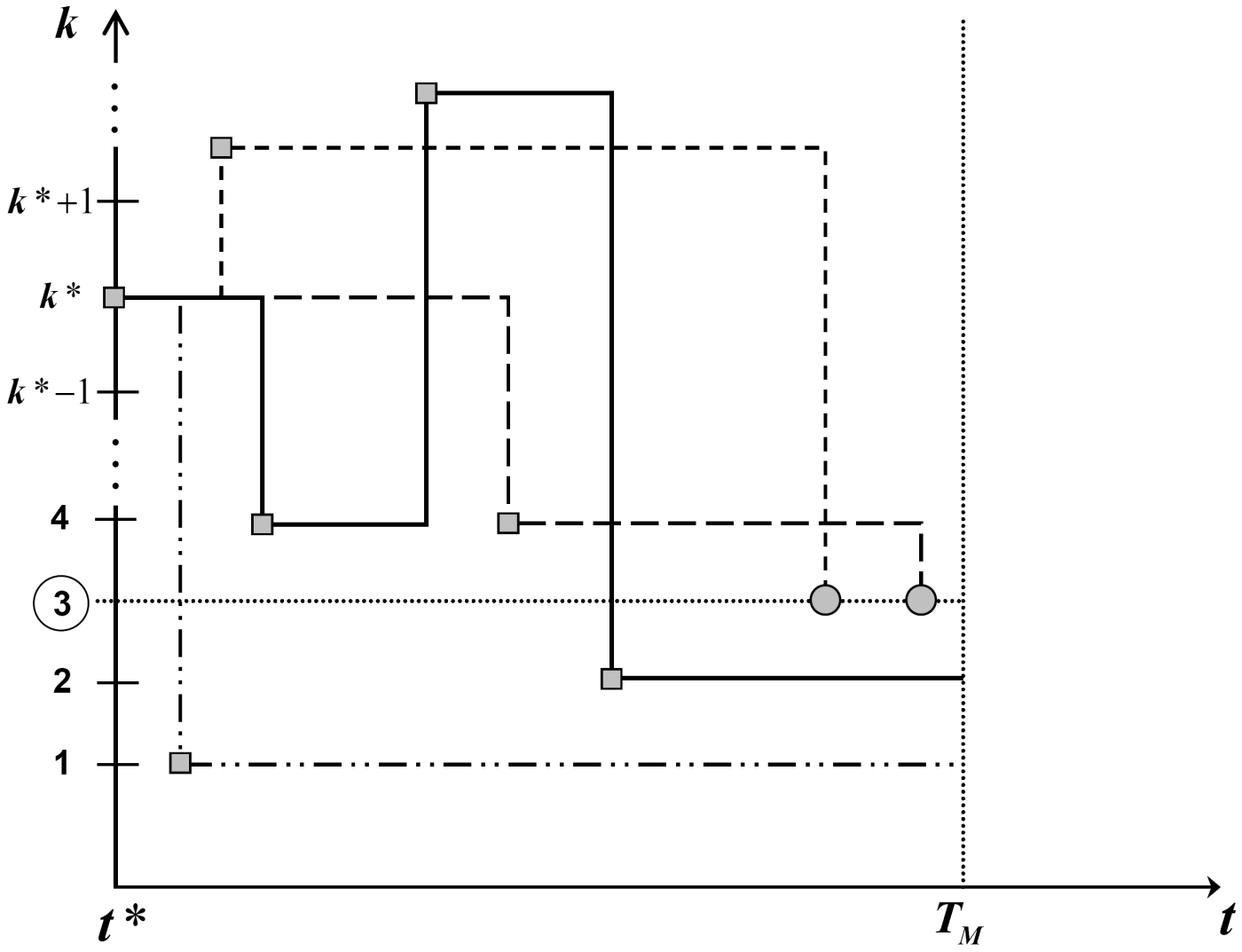
$$\underline{\underline{A}} = \begin{pmatrix} -2\lambda & 2\lambda & 0 \\ \mu & \mu+\lambda & \lambda \\ 0 & 2\mu & -2\mu \end{pmatrix}$$

$$\underline{\underline{A}} = \left(\begin{array}{cc|c} -2\lambda & 2\lambda & 0 \\ \mu & -(\mu+\lambda) & \lambda \\ \hline 0 & 2\mu & -2\mu \end{array}\right) \Rightarrow \underline{\underline{A}}' = \begin{pmatrix} -2\lambda & 2\lambda \\ \mu & -(\mu+\lambda) \end{pmatrix}$$

The new matrix $\underline{\underline{A}}'$ contains the transition rates for transitions **only among the success states** $i \in S$

(the "reduced" system is virtually functioning continuously with no interruptions)

Monte Carlo Simulation

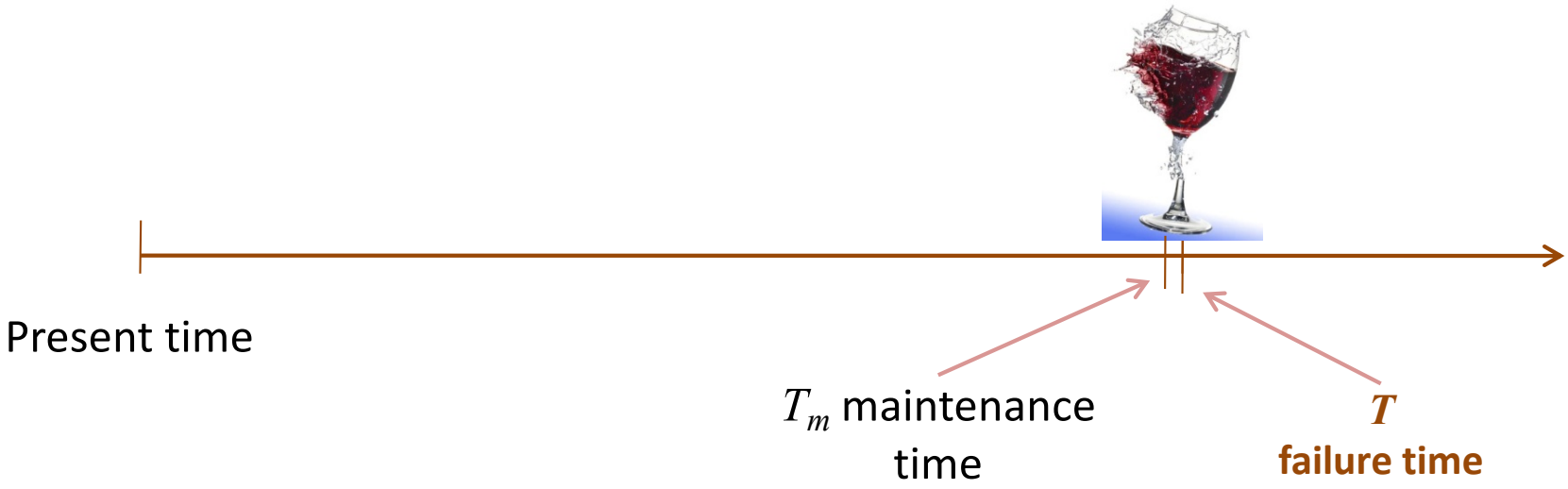


Maintenance

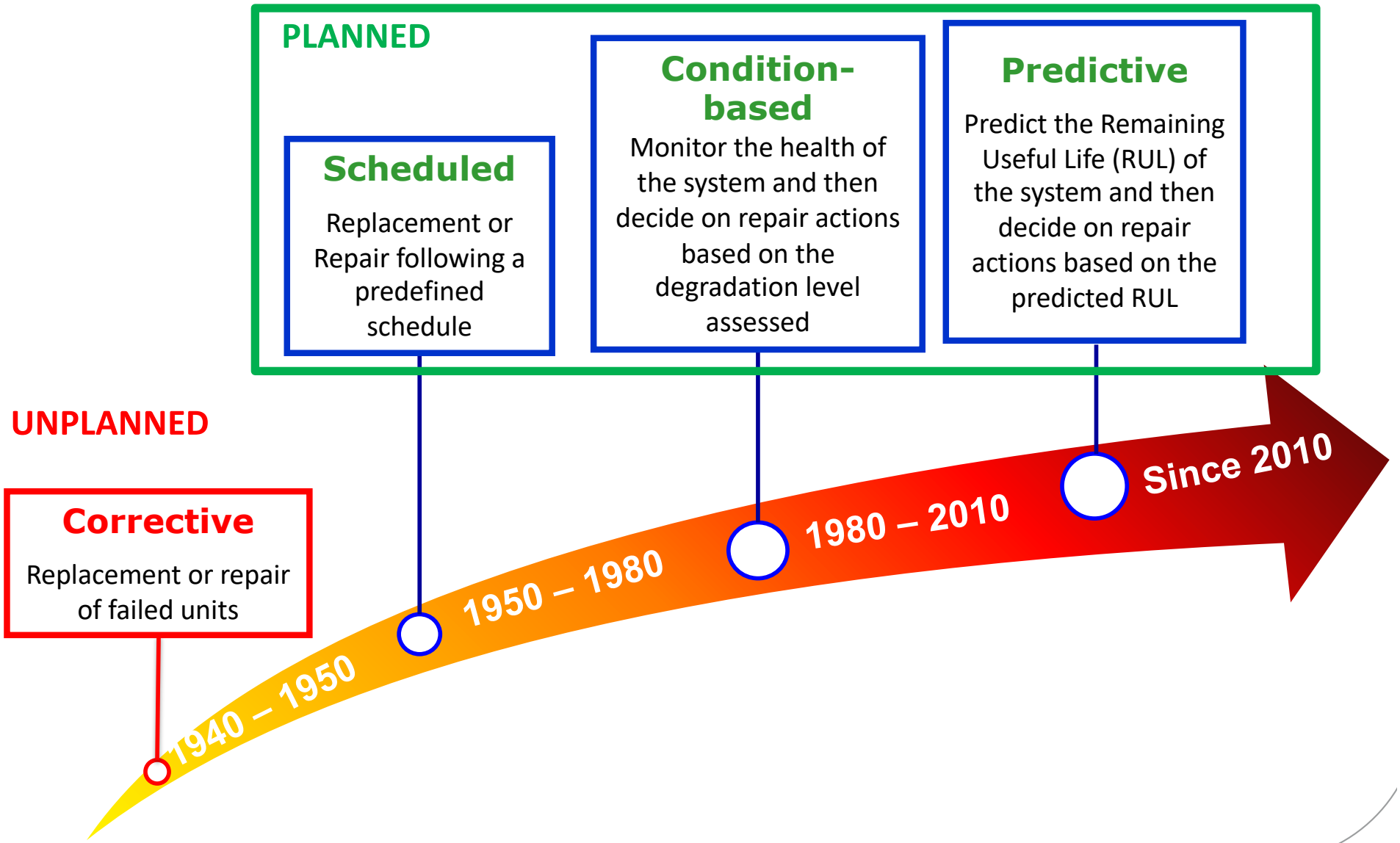
Ideal Maintenance: When?

$$T_m = T - dt$$

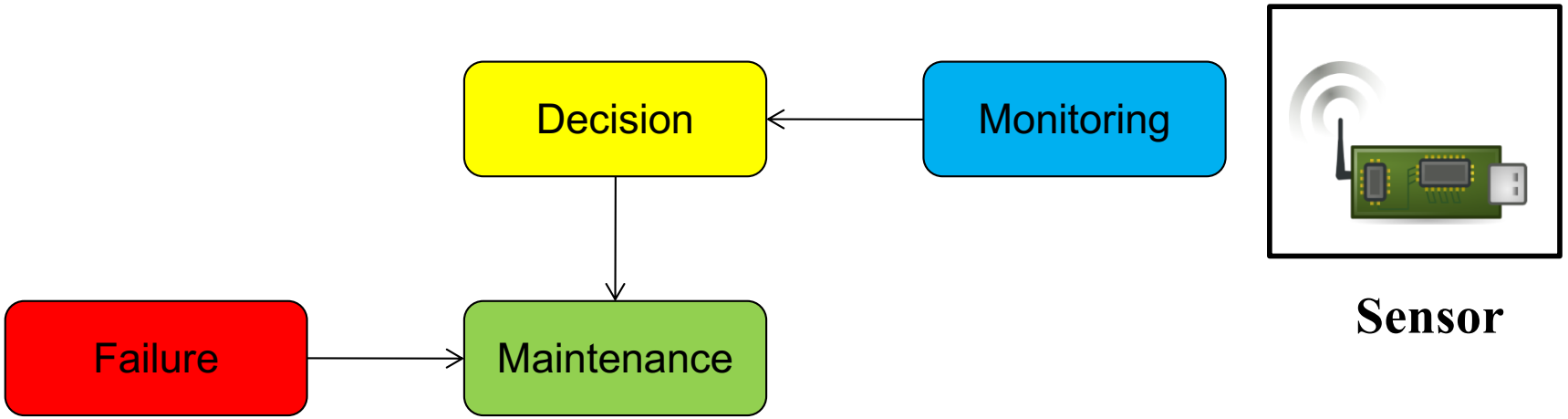
- Component's life fully exploited
- Unavailability due to maintenance actions are avoided



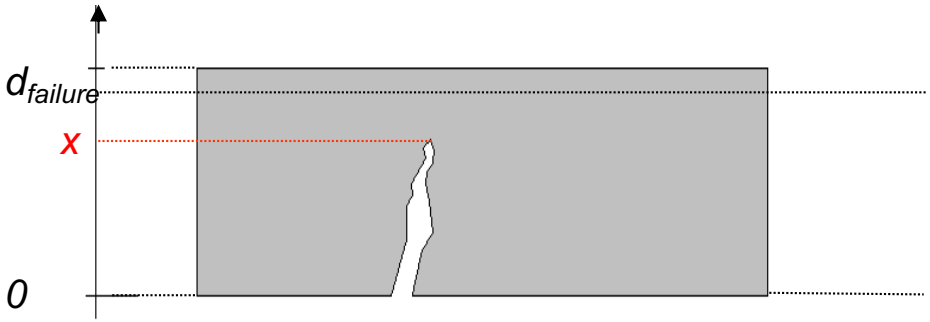
Maintenance Intervention Approaches

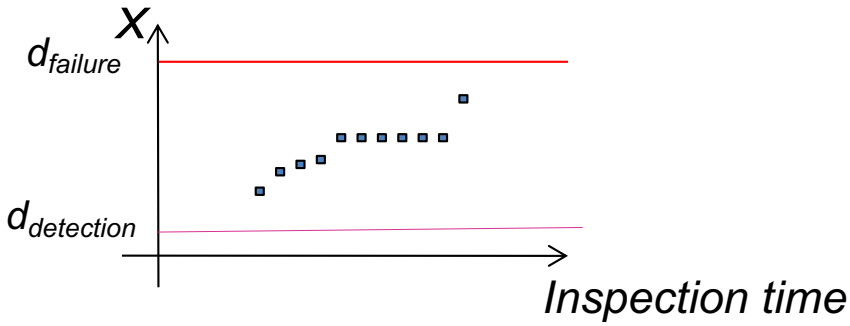


Condition-based Maintenance

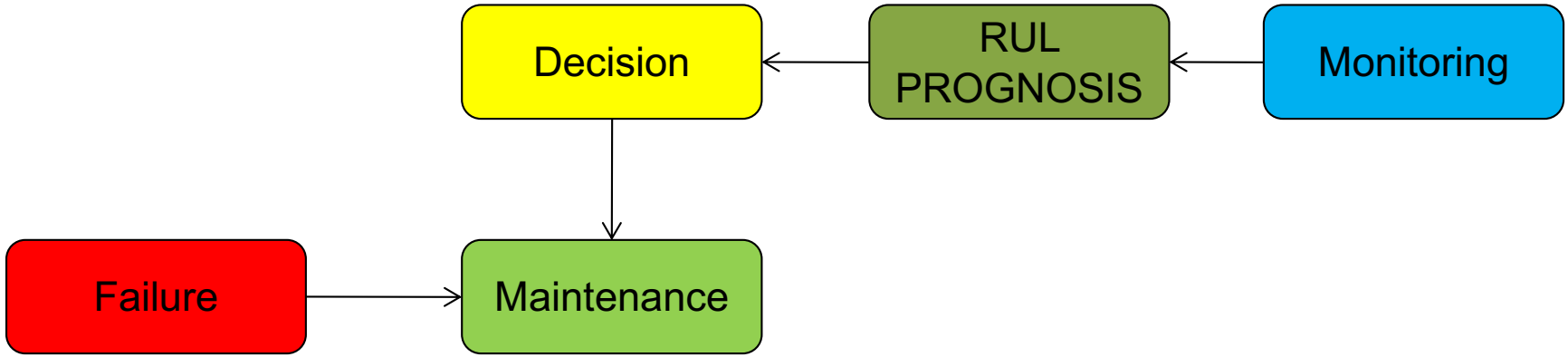


- Equipment degradation monitoring:
  - Periodic inspection by manual or automatic systems

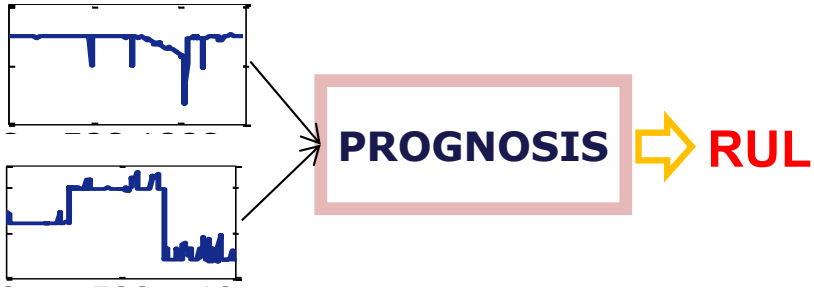




Predictive Maintenance

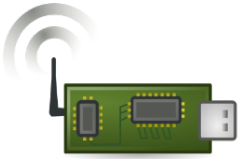


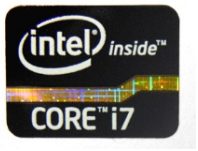
- Equipment degradation monitoring:
- Remaining Useful Life (RUL) prediction
- Maintenance Decision



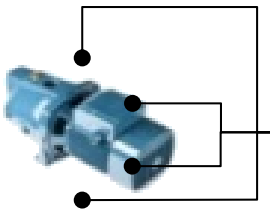
Prognostics and Health Management (PHM) for Predictive (PrM) and Condition-based (CBM) Maintenance

PHM in support to CBM and PrM

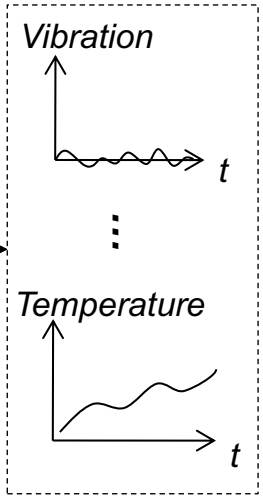




Artificial Intelligence-based



Equipment



Sensors measurements

Fault Detection

- Normal Conditions
- Abnormal Conditions

Fault Diagnostics

- Anomaly of Type 1
- Anomaly of Type 2
- Anomaly of Type 3

Fault Prognostics

- Remaining Useful Life (RUL)

- No Maintenance
- Maintenance

Decision Maker

Maintenance Decision

The lectures

Introduction - Definition of Safety, Risk; Structure of Risk Analysis of Complex Engineering Systems Method of Hazard Identification
Analytical calculations of simple system reliability
Analytical calculations of system availability
Fault Tree Analysis
Event Tree Analysis
Markov Models
Prognostics and Health Management
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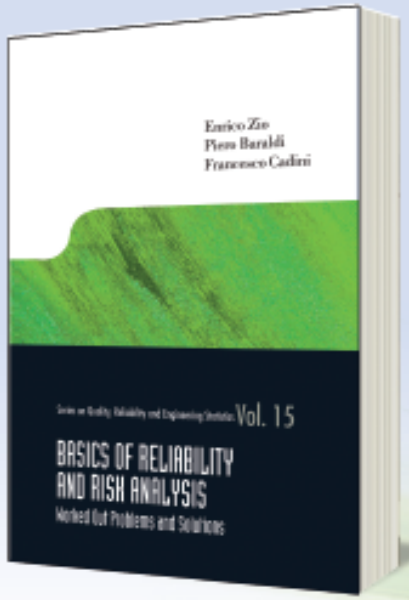

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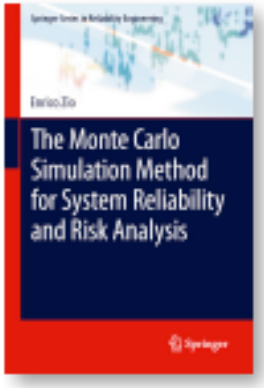

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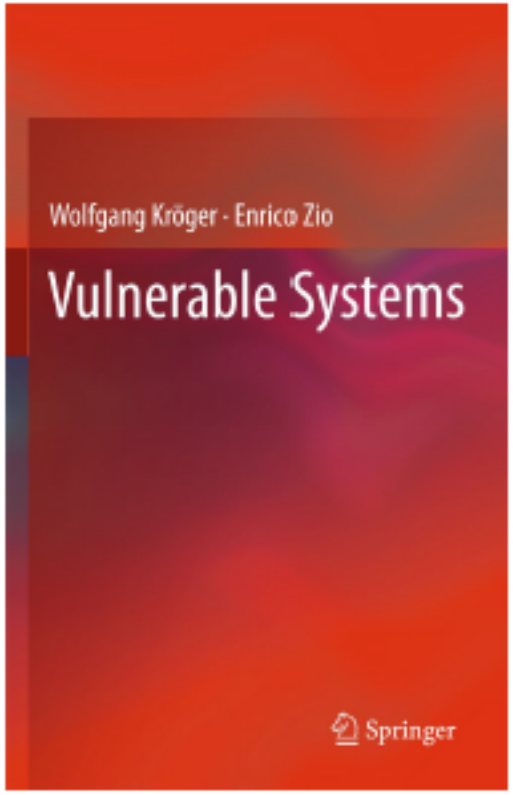

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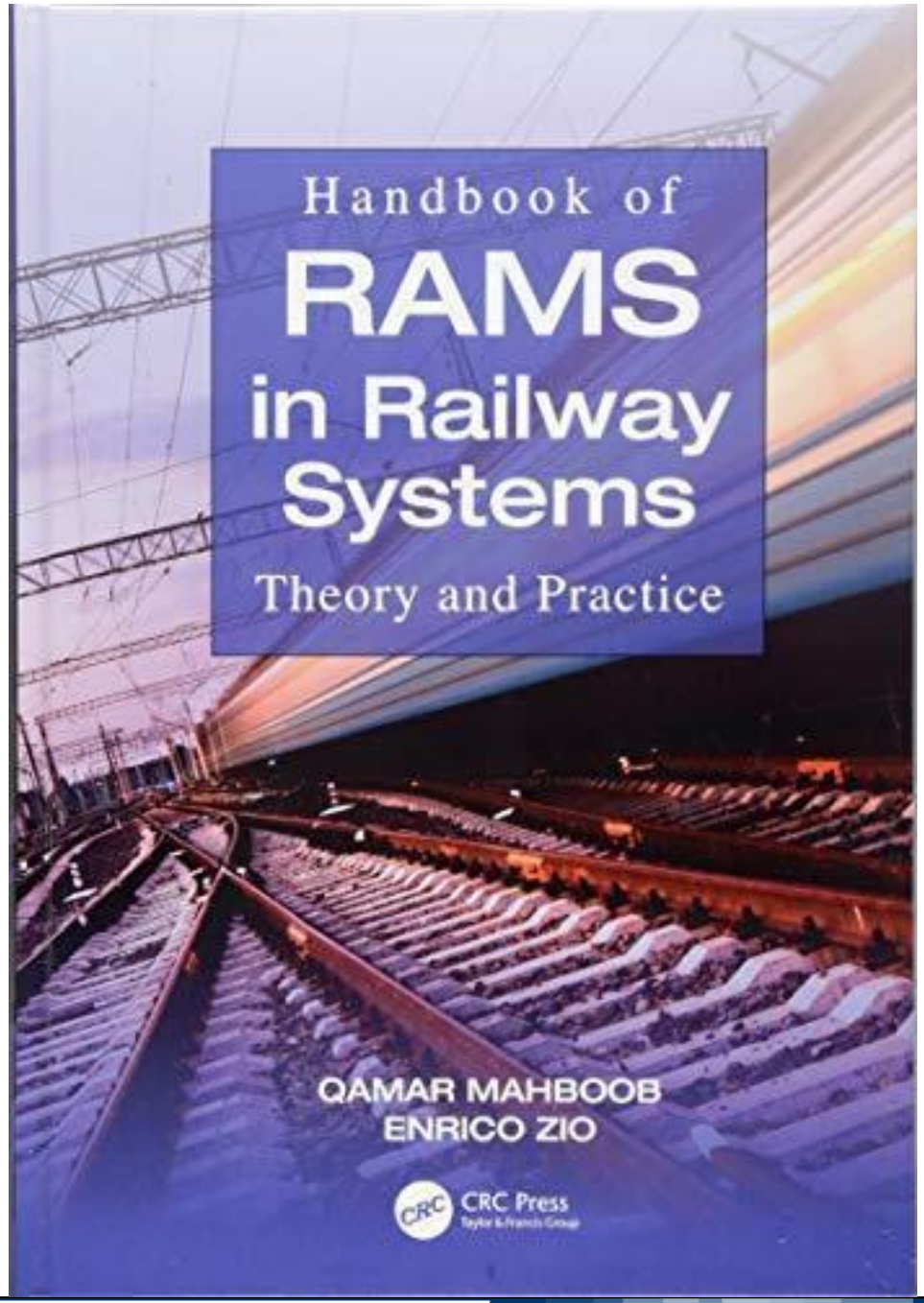
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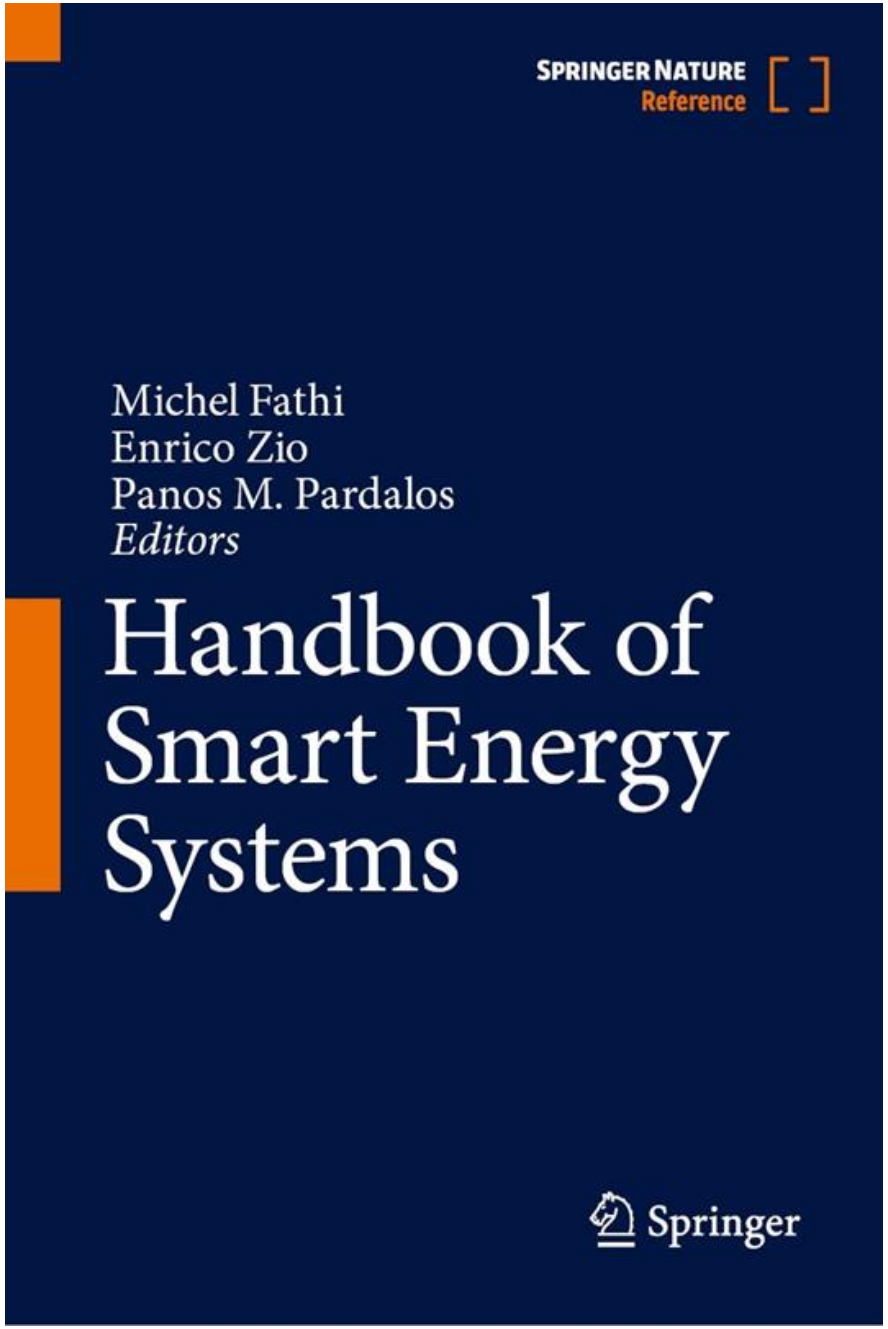
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