DTU Civil Engineering
Department of Civil Engineering

Co-funded by the Erasmus+ Programme of the European Union

METHODS SUPPORTING FIRE RISK ASSESSMENT AND MANAGEMENT

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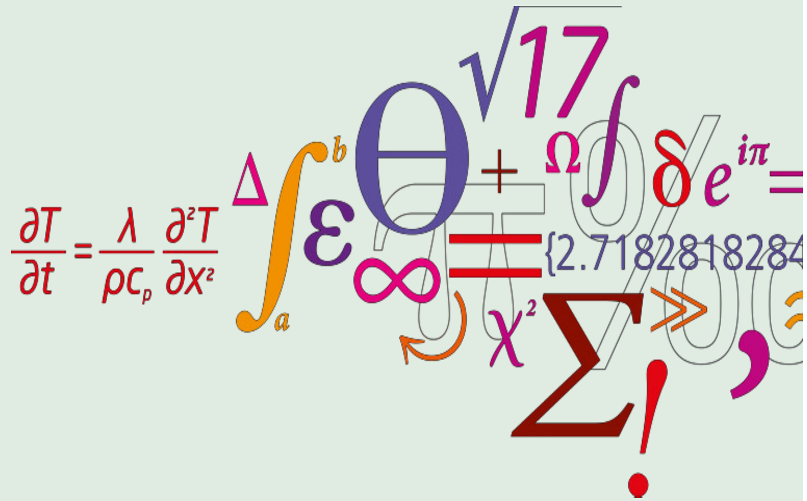
Fire Group



outline

- General accident model
- System safety
- QRA methodology
- Uncertainty
- Performance based building regulation and codes
- ASET / RSET calculation

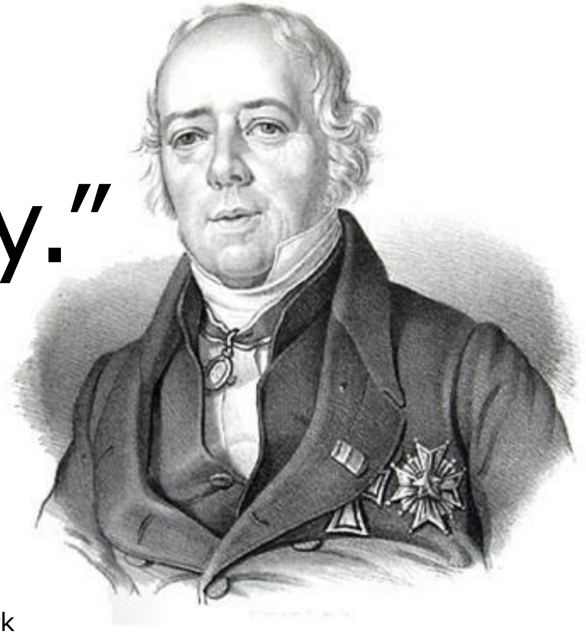
But first…

I like to give a short presentation on my university and background

Our mission

”DTU will develop and create value using the natural sciences and the technical sciences to benefit society.”

H.C. Ørsted
Founder of DTU



Education

Innovation

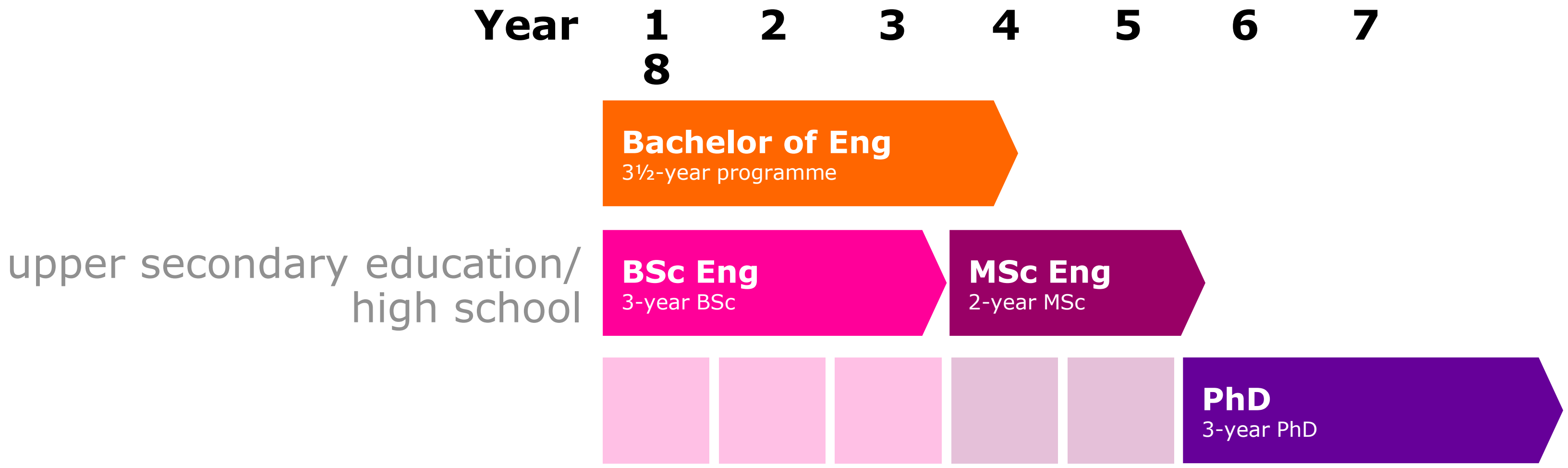
Scientific advice

Research

Locations


GREENLAND
Sisimiut
DENMARK
Hirtshals
Østerild
Mors
Høvsøre
JUTLAND
Silkeborg
campuses
research facilities
test facilities
Lyngby
Ballerup
Risø
Frederiksberg
ZEALAND
FUNEN
Lindholm
BORNHOLM

Education



BEng

17

Programmes

BSc Eng

18

Programmes

MSc Eng

29 + 30

Programmes

joint international MSc programmes in collaboration with partner universities

Education
- in figures 2016

11,031 **students**

From
99
countries

28%
Women
in our BEng, BSc
and MSc programmes

Total enrolment

4,127	**BEng** *(Bachelor of Engineering)*
3,070	**BSc Eng** *(Bachelor of Science)*
3,834	**MSc Eng** *(Master of Science)*
1,528	International*

* *International students are defined as students with an entry-level degree from abroad*

Test Facilities, Laboratories and Workshops

DTU Civil Engineering has a number of test facilities:

- Large experimental halls for testing full-scale building structures
- Fire laboratory for reaction-to-fire testing of materials
- Small laboratories with electron microscopes for materials studies
- Outdoor test stands for testing of solar panels, etc.

Construction materials laboratory

The facilities are widely used for experimental studies and PhD projects, but also for teaching and research purposes.

Strategic research areas

Development Areas

- Focus: To address major challenges currently faced by society with sustainable development as the overall theme.
- Aim: To enhance activities in the area of innovation and research-based public sector consultancy.

Current Development Areas:

Danish Building Academy

Aims to create a platform that strengthens the innovation between companies, teaching and research.

ZeroWaste Byg

Aims at an innovative and untraditional approach to redesigning structures and construction materials towards a zero waste society.

Sustainable Light Concrete Structures

Aims at a cross-disciplinary rethinking of building structures in a context of application where the relevant functional requirements are considered simultaneously.

Research

DTU Civil Engineering conducts research within a defined number of academic focus areas of key importance to construction processes, buildings and structures.

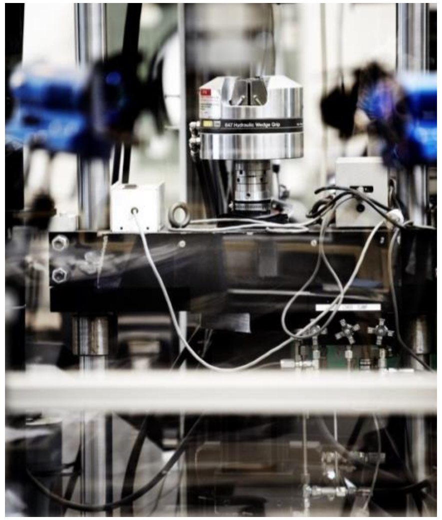
The department produces 12-17 PhD graduates a year within a wide range of focus areas.

Focus areas

Structural Engineering
Bridge Structures, Structural Design, Stability and Fatigue, Safety and Risk Analysis, Wind Technology, Glass and Glass Structures

Building Energy
Sustainable buildings, Solar heating systems, Building energy Simulations programs (CDIO), Smart cities, Hydrothermal building physics, Energy renovation

Indoor Climate and Building Physics
Indoor Environment and its Impact on Human Comfort, Health and Performance, Ventilation and Air Conditioning, Hospital Ventilation, Aircraft Cabin Environment, Thermal Comfort



Research

Geotechnics and Geology

Oil Extraction, Hydro Power, Wind Turbine Foundations, Geotechnics, Deep Excavations and Tunnels

Building Design and Materials

Fire Safety Engineering

Building Information Modelling (BIM)

Building Design in Greenland

Sustainable Light Concrete Structures

Construction Materials:

- Concrete
- General Physical and Chemical Properties,
- Moisture Transfer and Moisture Fixation.
- **Fire safety** of bio-composit materials, polymers, wood, a.o.

Pr.1.1.2018 arctic technology is part of building design and materials:

Arctic Technology, Construction in Greenlandic Permafrost Areas, Arctic Waste Management, Building Design in Greenland, Renewable Energy Sources in the Arctic, Social and Educational Conditions in Greenland, Raw Materials and Mining in the Arctic, Redesigned sustainable materials

System safety

A Case from daily life – is it probable?

A shopkeeper regularly threw packing waste by the back door of his shop as he quickly stocked the shelves after a delivery.

His workers sometimes opened the back door to have a cigarette break outside.

One week he'd left the pile of rubbish for several days and a discarded cigarette butt caused it to catch fire.

By the time the fire was spotted and put out, it had caused substantial damage to his back door and his shelving units.

There was a significant cost in damaged stock and repairs.

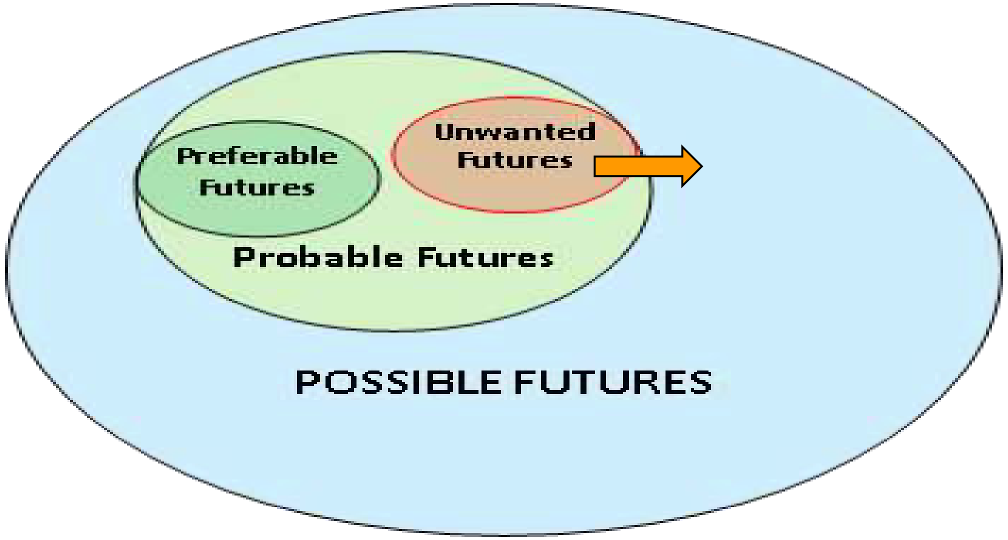
How the fire could have been prevented ?

This fire could have been easily prevented if the shopkeeper had completed his risk assessment and taken simple steps to control the risks.

From Fire safety guide HSL: <http://www.hse.gov.uk/toolbox/fire.htm>

What is risk management?

Risk management scans the uncertain future ahead of us, trying to pick out the main features, both good and bad. In this way we can steer away from things that might harm us (threats), and aim towards things that might help us (opportunities).



Alternative futures relevant for risk management

The **role of risk management** is to ensure that **Preferable Futures are possible** and are among Probable Futures while Unwanted Futures are moved from the Probable zone into the Possible Futures zone.

Risk is everywhere

The world we inhabit is unpredictable, strange, incomprehensible, surprising, mysterious, awesome, different, other.

We neither know nor understand everything, and we cannot control everything.

View: Risk is a social construct

(Slovic, 1999)

There is no such thing as a ”real risk” or ”objective risk”.

Risk is a social construct insofar that *’human beings have invented the concept risk to help them **understand and cope** with **dangers** and **uncertainties** of life*’

Uncertainty

The nature of uncertainties

Aleatory uncertainty	Epistemic uncertainty
It describes **the inherent variation associated with the physical system or the environment** under consideration.	It derives from some **level of ignorance, or incomplete information** about the system / the surrounding environment.
stochastic uncertainty (variability) irreducible uncertainty inherent uncertainty	subjective uncertainty reducible uncertainty model form uncertainty.

Estimation of Aleatory uncertainties

Aleatory uncertainties **are accessible by mathematical procedures :**

- Characterized by probability distributions or other probability measures.

- Models for deriving probability distributions and measures are available within the mathematics of probability

Estimation of Epistemic uncertainties

The mathematical representation of epistemic uncertainty has proven to be challenging.

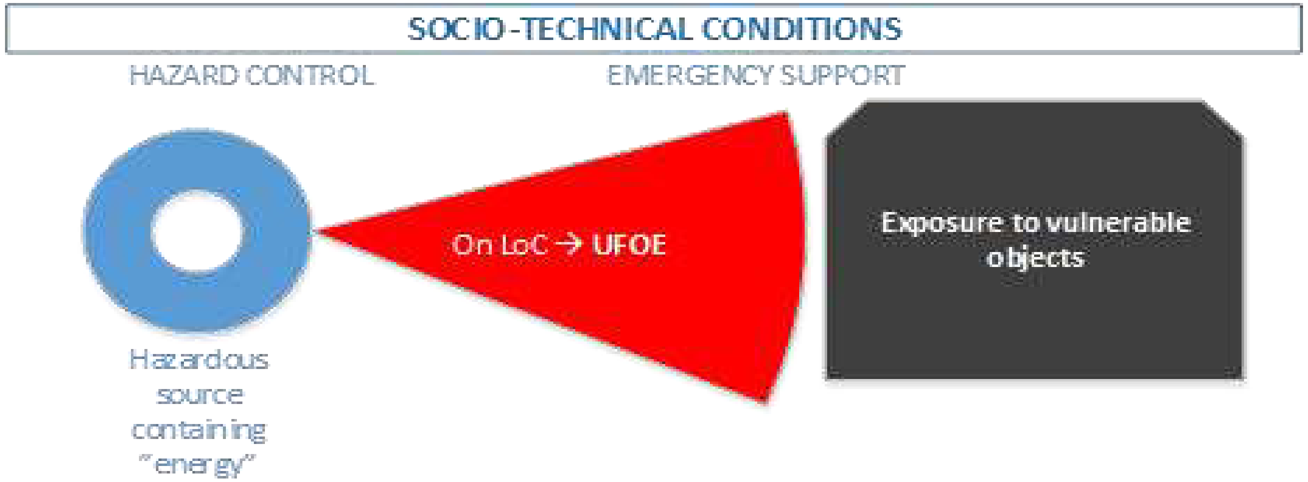
A number of newer theories that capture (parts of) epistemic uncertainty are available. For example:

- possibility theory,
- fuzzy set theory,
- evidence theory and
- the theory of imprecise probabilities.

Real risk assessment problems typically present a mixture of the both types of uncertainty.

A general (fire) accident model

A general accident model

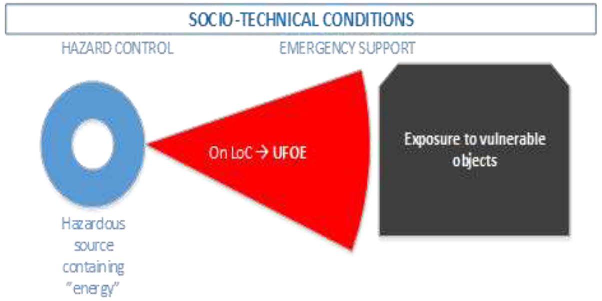


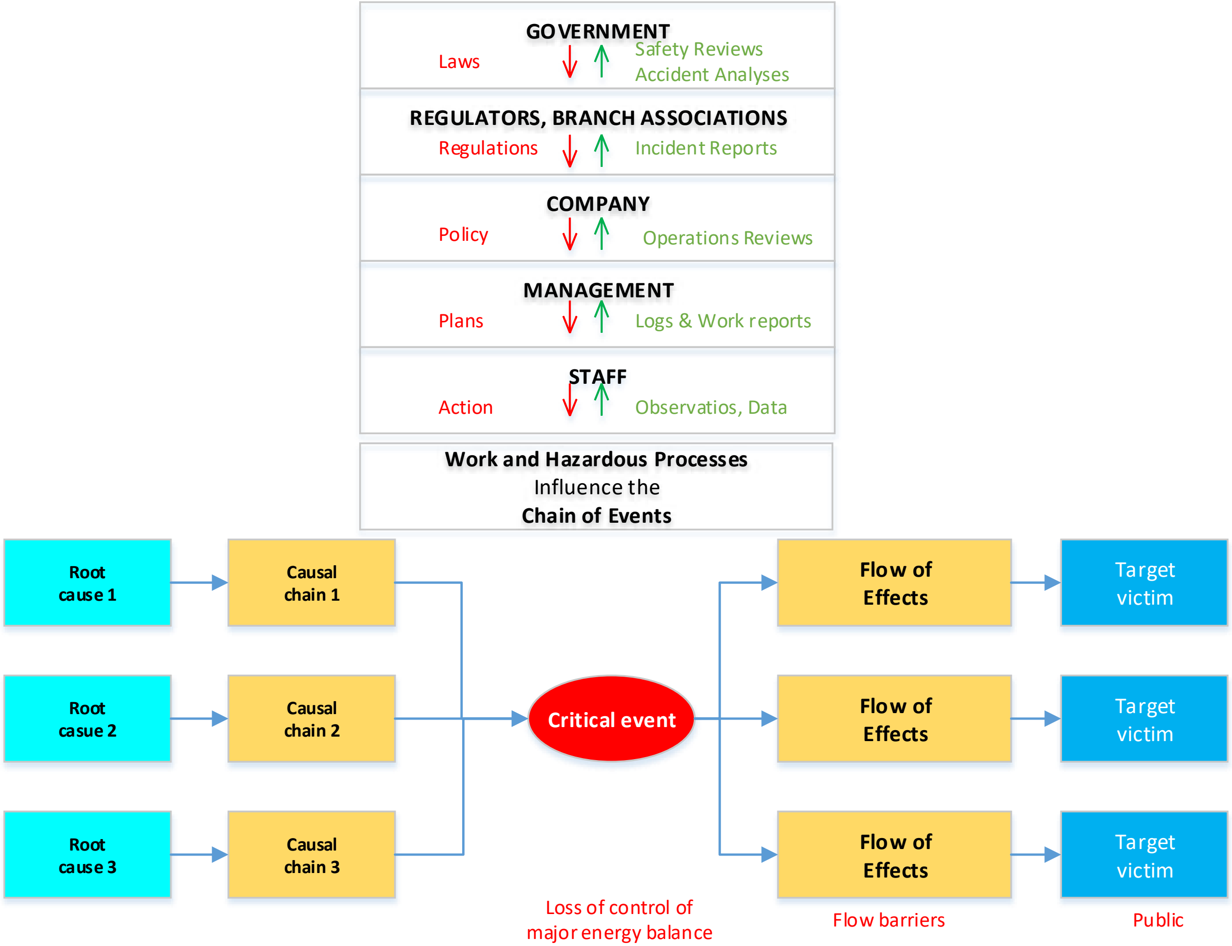
Mitigation in emergency situations

Under a UFOE situation emergency support is needed. The model regards six universal emergency measures to prevent or mitigate exposures of the vulnerable objects. These are:

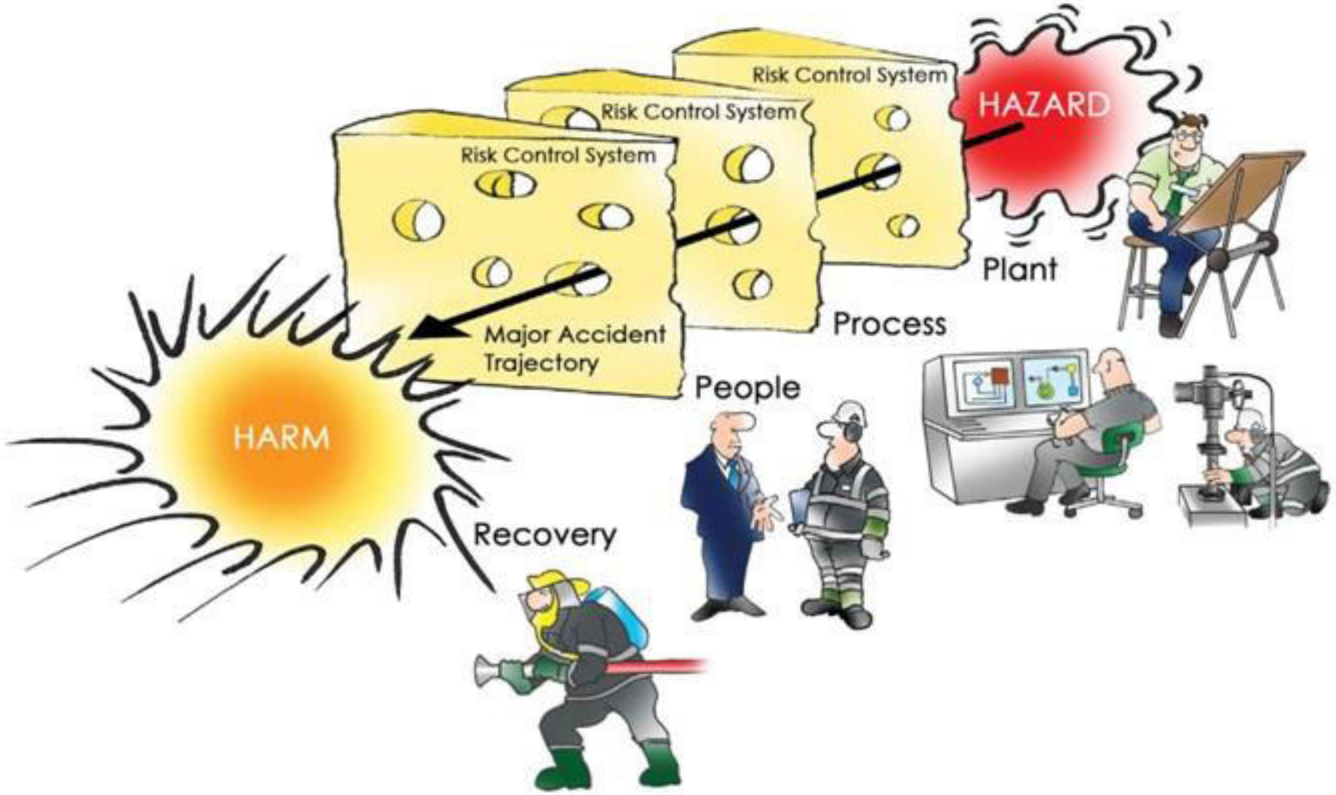
- **move vulnerable objects:**
  - evacuate plant stuff, evacuate neighbors, stop traffic to areas, remove valuable objects
- **modify energy:**
  - water curtain, sprinkling
- **redirect flow:**
  - lead water form fire fighting away from sensitive areas, collect water from fire fighting (portable spill basins), build interimistic dams
- **control source:**
  - extinguish fire, cover leak
- **encapsulate moving energy:**
  - cover with foam
- **establish negative source:**
  - lead spill to sewer, add chemical agents to bind dangerous substances

Human & organisational factors

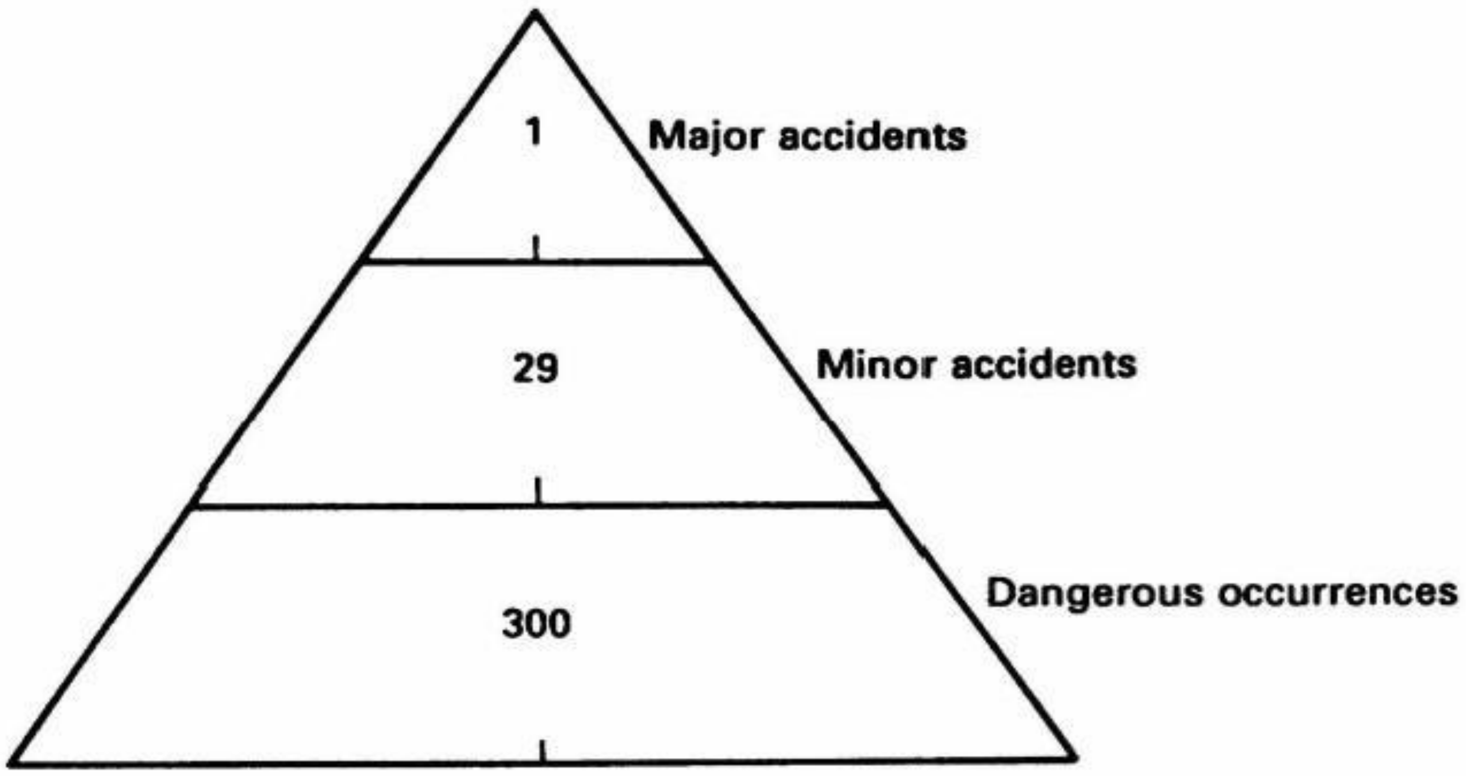




Swiss cheese model



Heinrich Triangle



Statistics are important

From Heinrich Triangle and various other reasons it is obvious that statistics are needed!

Statistics - where to get the numbers?

- Incident Data
  - Tables, reports, Statistical Bureau, Insurance companies
- Field Inspection Data
- Laboratory Data and Simulation Data

Statistics are meaningless at the time of a critical event

It is important to be critical to the values and sources.

Accidents vs Risk

Accidents

- Past
- Source of knowledge and experience

Risk

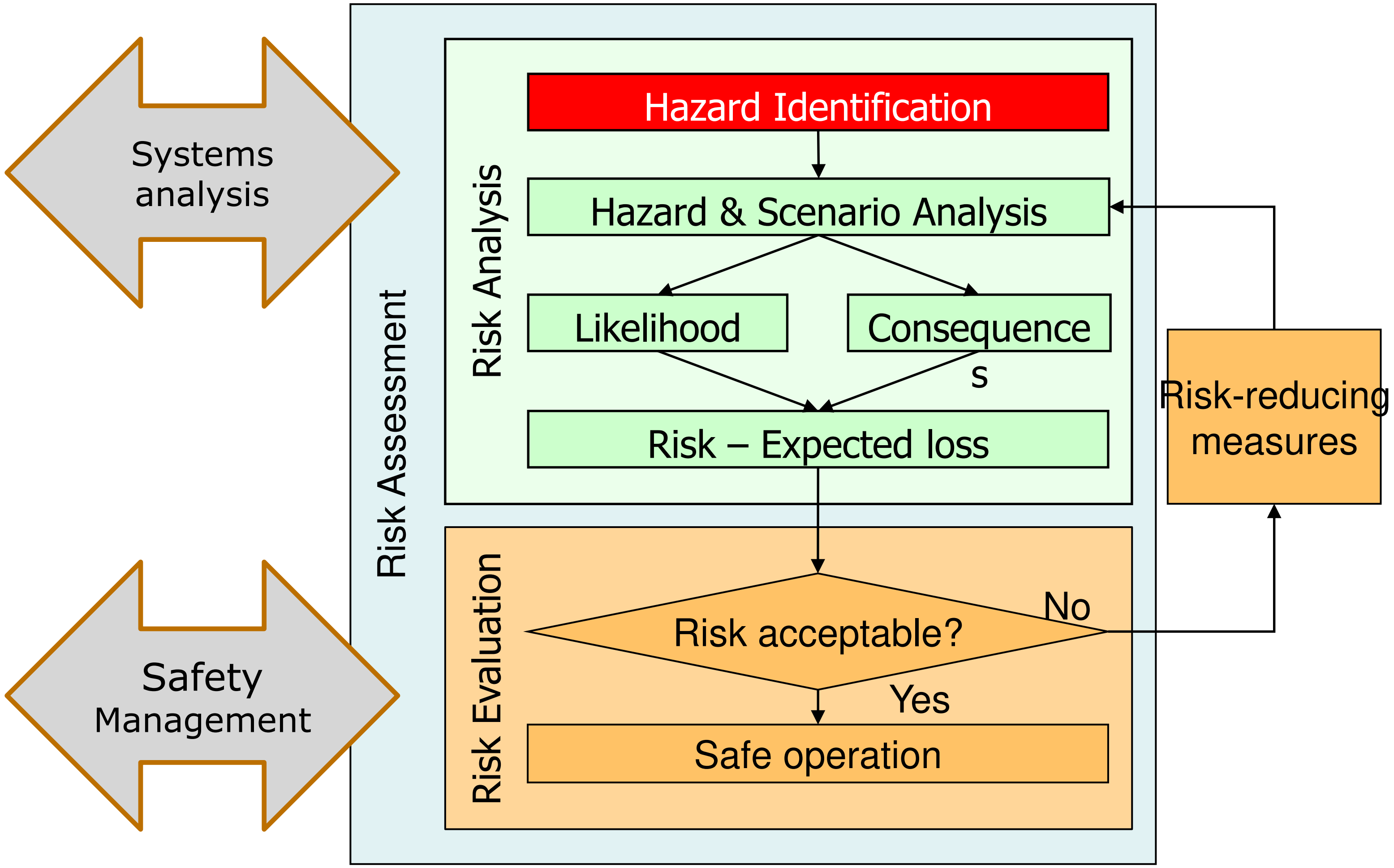
- A statement about the possible future states
- synthesis of all available knowledge (including, but not limited to, knowledge from past accidents)

1. Data from the past may not be applicable (new technology, new hazards)
2. A single accident can neither validate nor invalidate a risk analysis

Quantitative Risk Assessment

- Originally developed for nuclear industries
- With great success applied in chemical industries
- Over time all or parts are applied to many other situtions in our society
  - Air traffic
  - Health sector
  - Rail traffic
  - Maritime industries
  - Many other industries
- Fire risk assessment fit natural into this framework

Fire Risk Assessment



Hazard identification

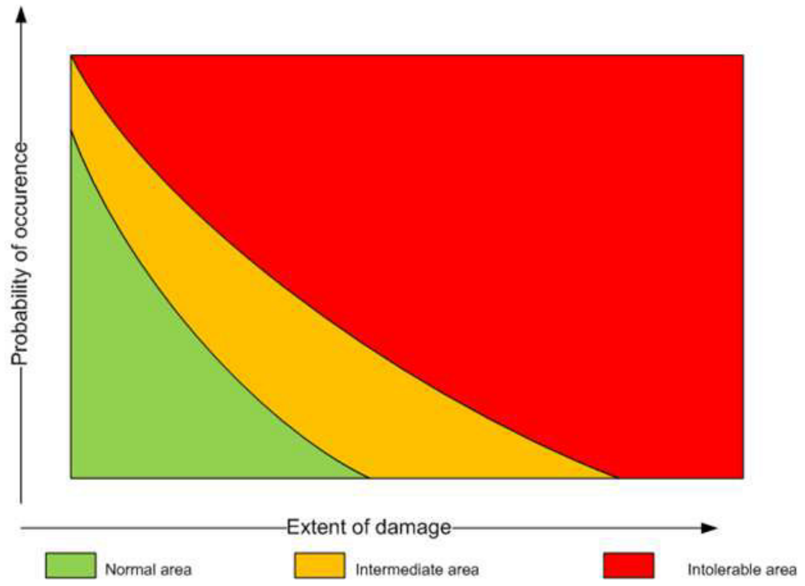
- Checklists - good for well defined systems
- HAZOP - Hazard and Operability Study : good to find hazards in a flow system
- FMEA - Failure Modes and Effects Analysis: good to find hazards by components
- FTA - Fault Tree Analysis : good to analyse for the root cause of failures
- ETA - Event Tree Analysis : good to analyse the progression of events
- Bow-tie - Combination of FTA and ETA
- SBD - Safety Barrier diagrams: good to analyse the appropriateness of safety barriers

Semi –qualitative ranking: Criticality

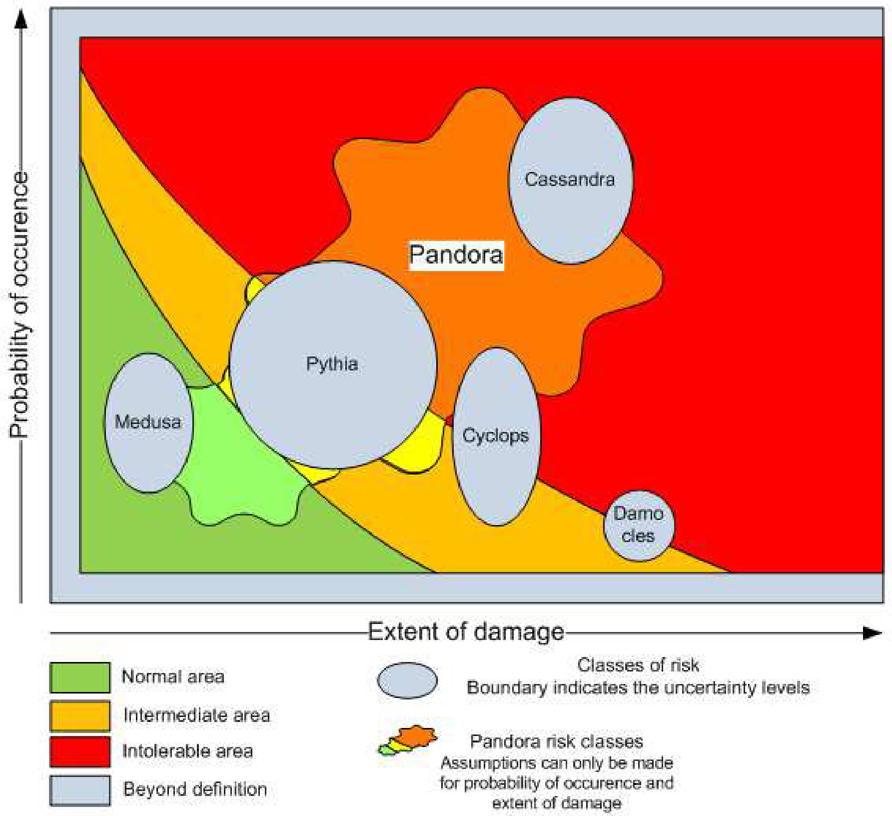
- Risk Priority Number RPN = S x O x D
  - S: Severity
  - O: Probability
  - D: likelihood of detection (low number→high likelihood)

Probability Class					
	Frequent, probability of occurrence: $Pi > 0,2$				
	Probable, probability of occurrence: $0,1 \leq Pi < 0,2$		Failure mode 1		
	Occasional, probability of occurrence: $0,01 \leq Pi < 0,1$				
	Remote, probability of occurrence: $0,001 \leq Pi < 0,01$			Failure Mode 2	
	Improbable, probability of occurrence: $0 \leq Pi < 0,001$				
		I	II	III	IV
		Severity Class			

Traffic light diagram



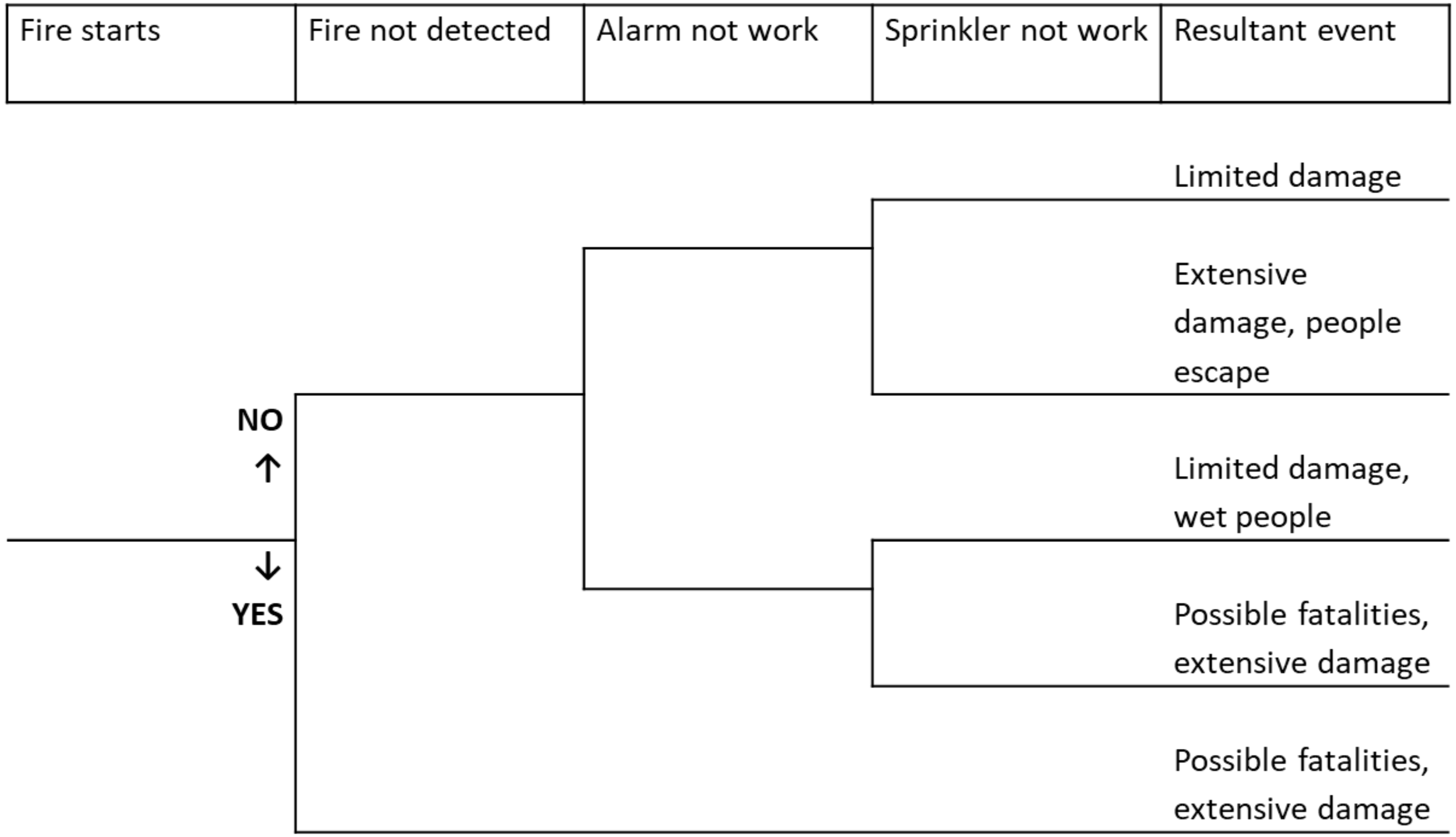
Traffic light diagram considering uncertainty



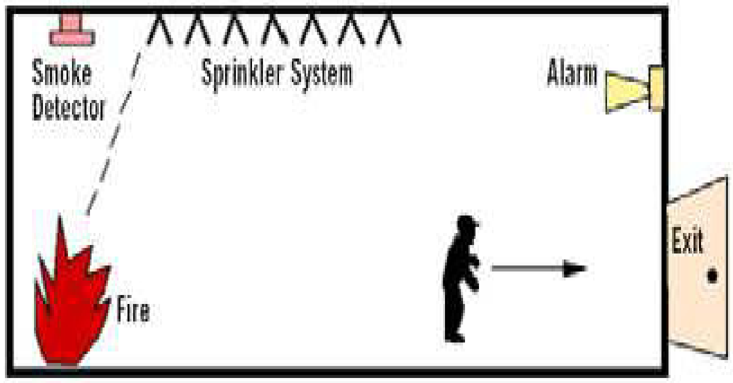
Redrawn from Renn, Klinke, European Molecular Biology Organization EMBO reports 5 special issue 2004

Management	Risk class	Extent of damage	Probability of occurrence	Strategies for action
Science-based	Damocles Cyclops	High High	Low Uncertain	•Reducing disaster potential •Ascertaining probability •Increasing resilience •Preventing surprises •Emergency management
Precautionary	Pythia Pandora	Uncertain Uncertain	Uncertain Uncertain	•Implementing precautionary principle •Developing substitutes •Improving knowledge •Reduction and containment •Emergency management
Discursive	Cassandra Medusa	High Low	High Low	•Consciousness building •Confidence building •Public participation •Risk communication •Contingency management

Event tree



Fire starts
Fire not detected
Alarm not work
Sprinkler not work
Resultant event
NO
YES
Limited damage
Extensive damage, people escape
Limited damage, wet people
Possible fatalities, extensive damage
Possible fatalities, extensive damage



Smoke Detector
Sprinkler System
Alarm
Fire
Exit

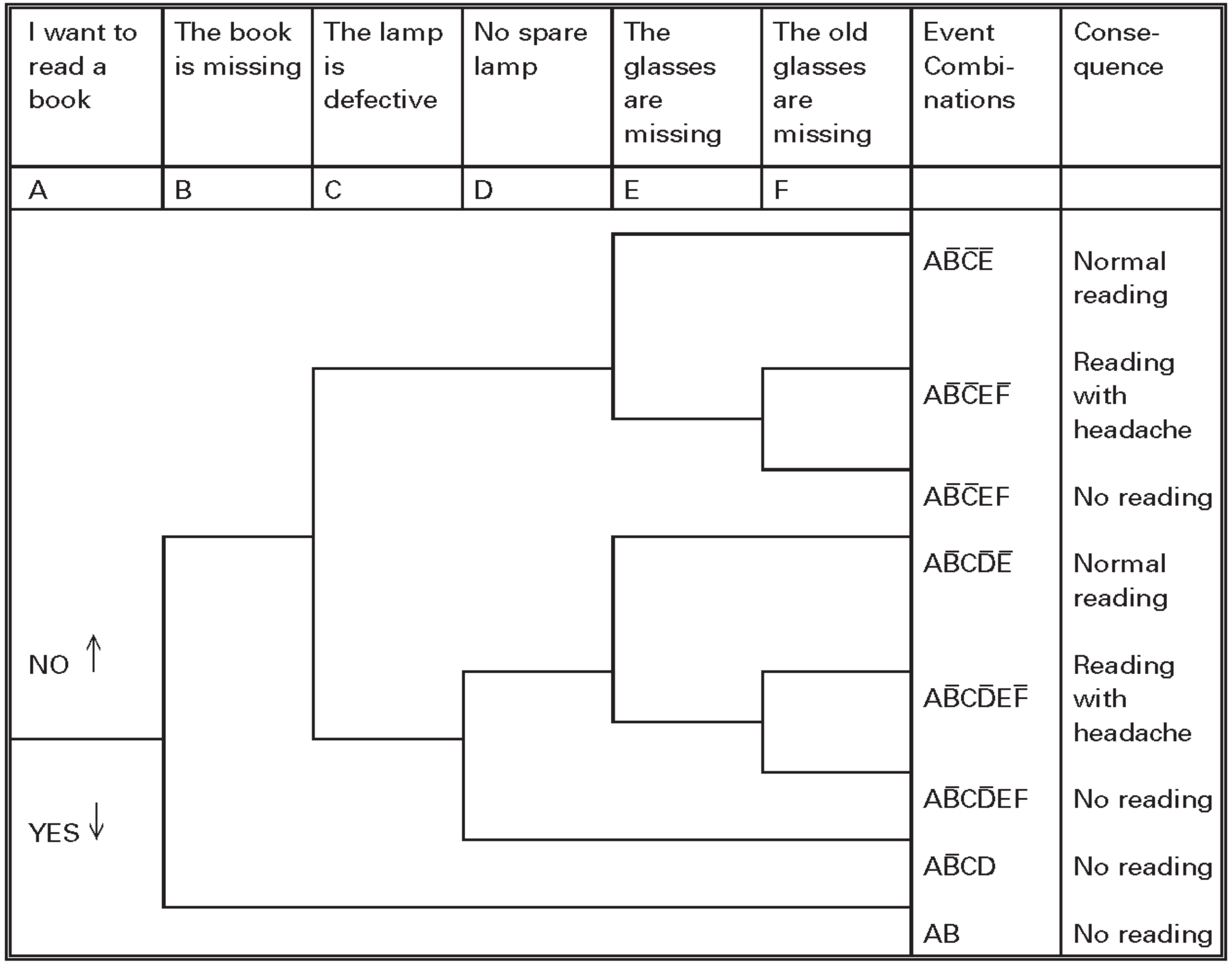
Construction of event trees

starts with the defining the initiating event and the collection of all relevant heading events. The next step is to put the heading events in the right order

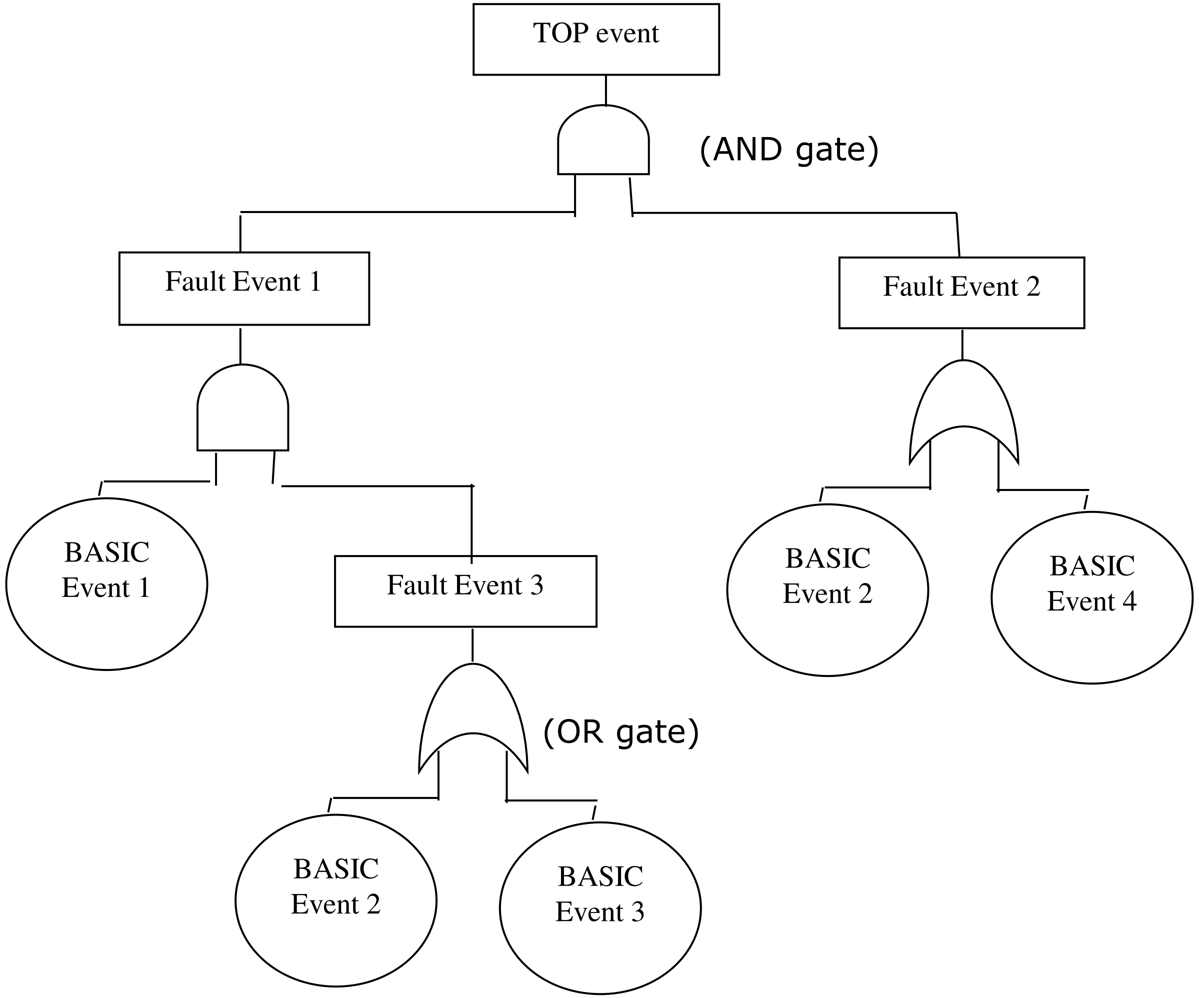
Example. Suppose you want to read a book (initiating event is “I want to read a book”) for which you need a reading lamp and your reading glasses. A spare lamp and one more pair of old glasses can also be available. So the events can be put in the following order:

I want to read a book	The book is missing	The lamp is defective	No spare lamp	Glasses are missing	Old glasses missing
A	B	C	D	E	F

Example: “I want to read a book”

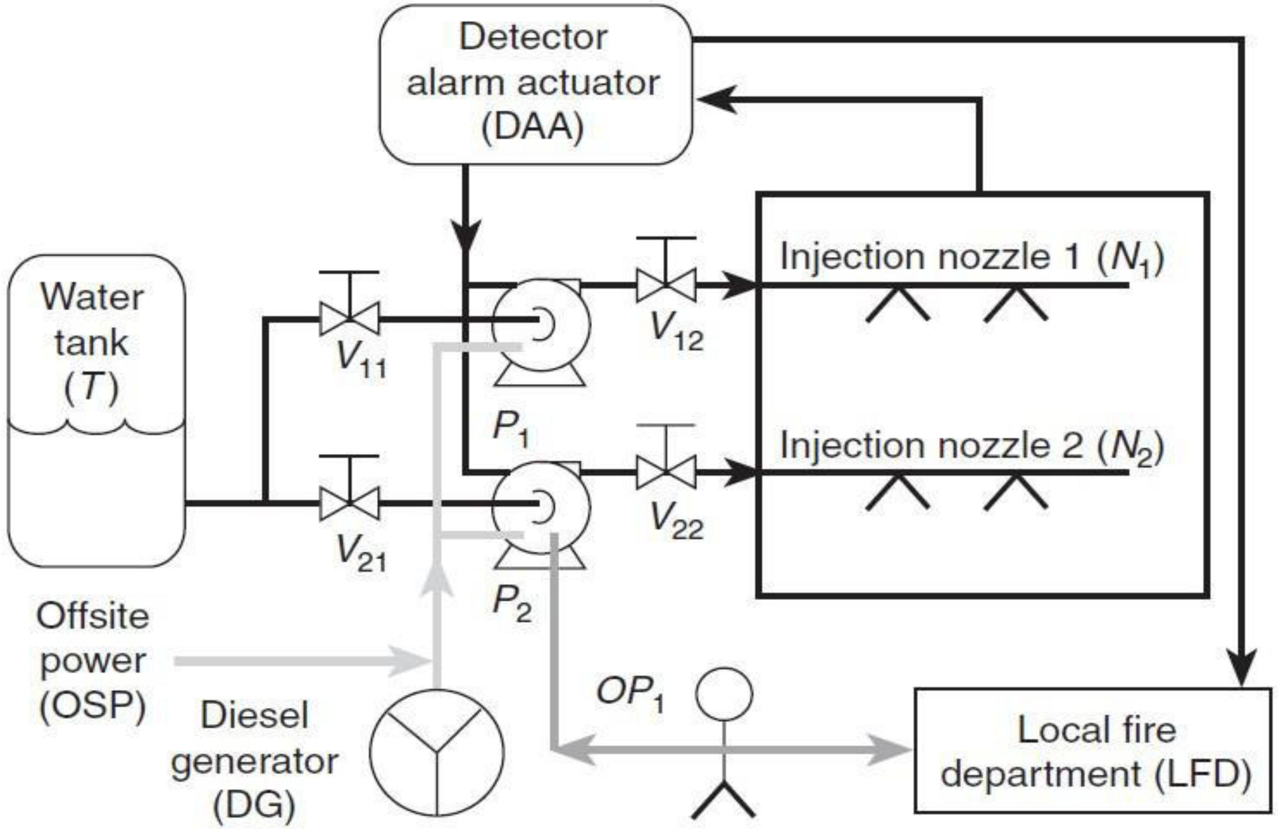


Fault tree

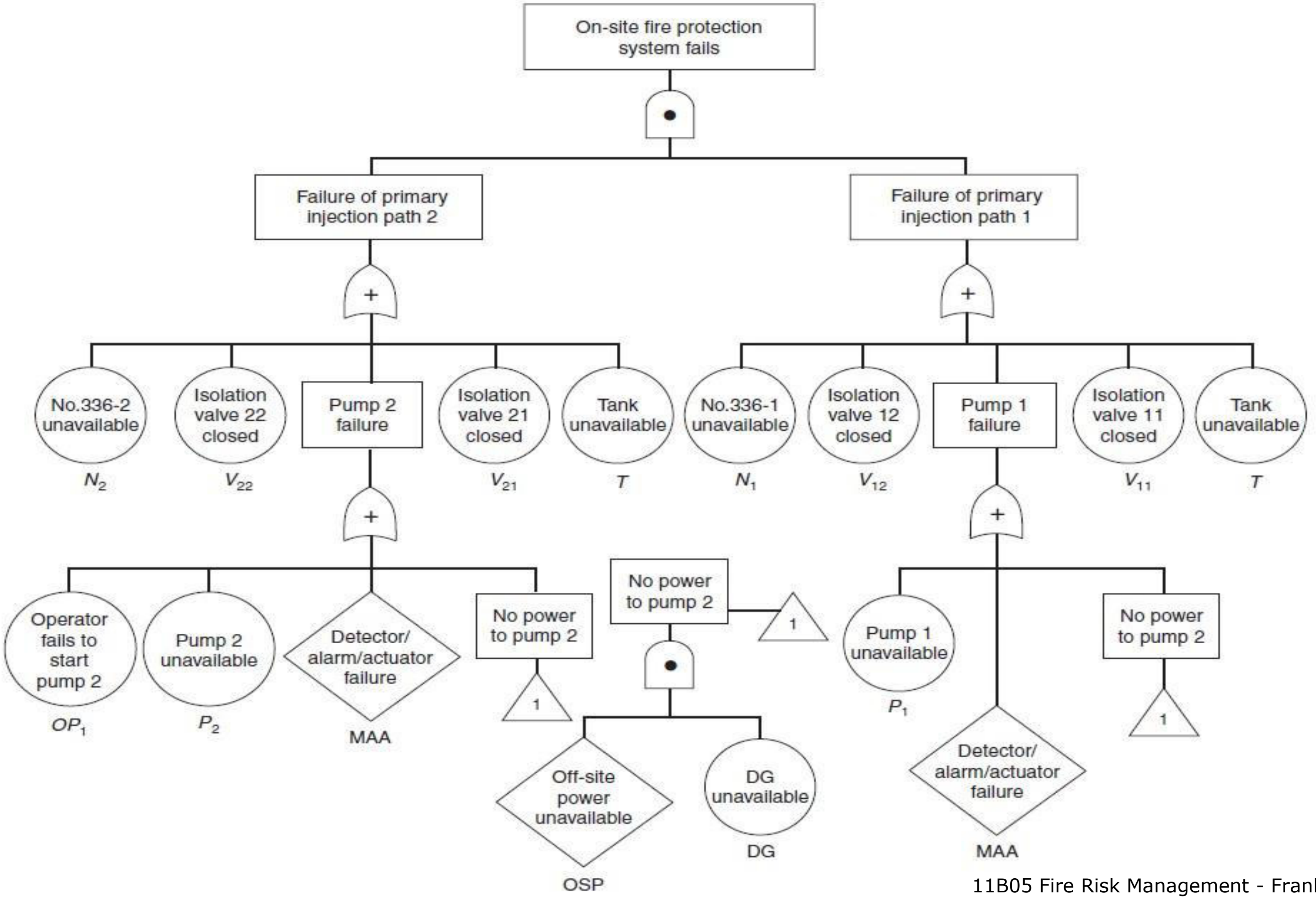


- Four combinations or sets of BASIC events that can lead to the TOP event:
  - Set 1 : 1,2
  - Set 2 : 1,2,4
  - Set 3 : 1,2,3
  - Set 4 : 1,3,4
- Both Set 2 and Set 3 are supersets of Set 1; that is, Sets 2 and 3 each contain Set 1 as a subset. Once these supersets are deleted, the remaining sets are the minimal cut sets for our example fault tree:
  - Minimal Cut Set 1 : 1,2
  - Minimal Cut Set 2 : 1,3,4

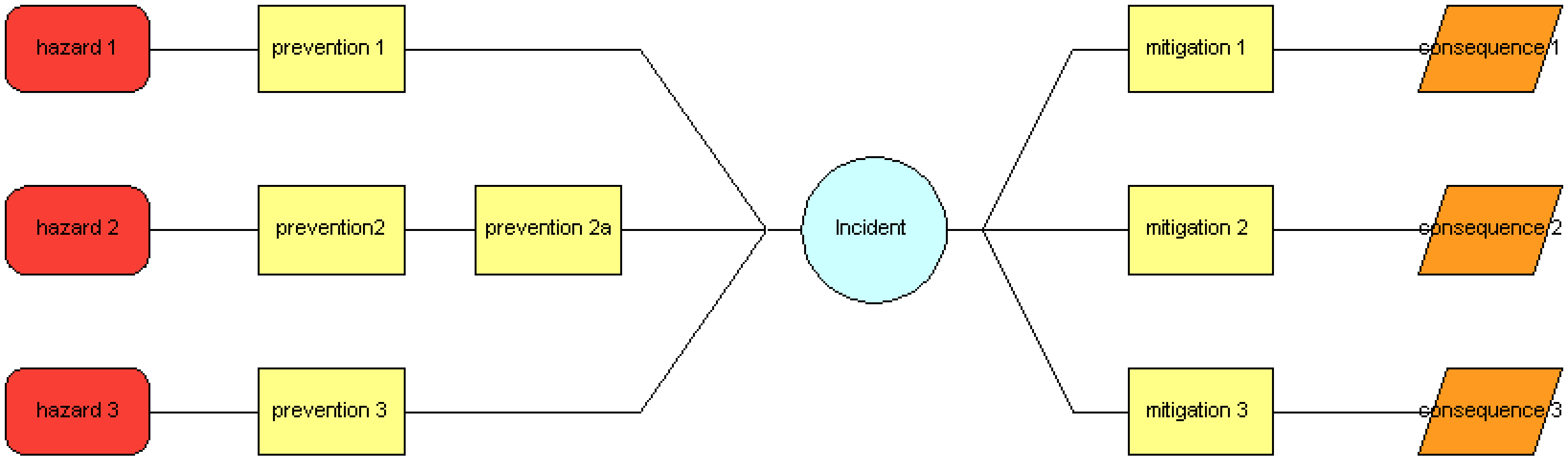
Example - Fire Protection System



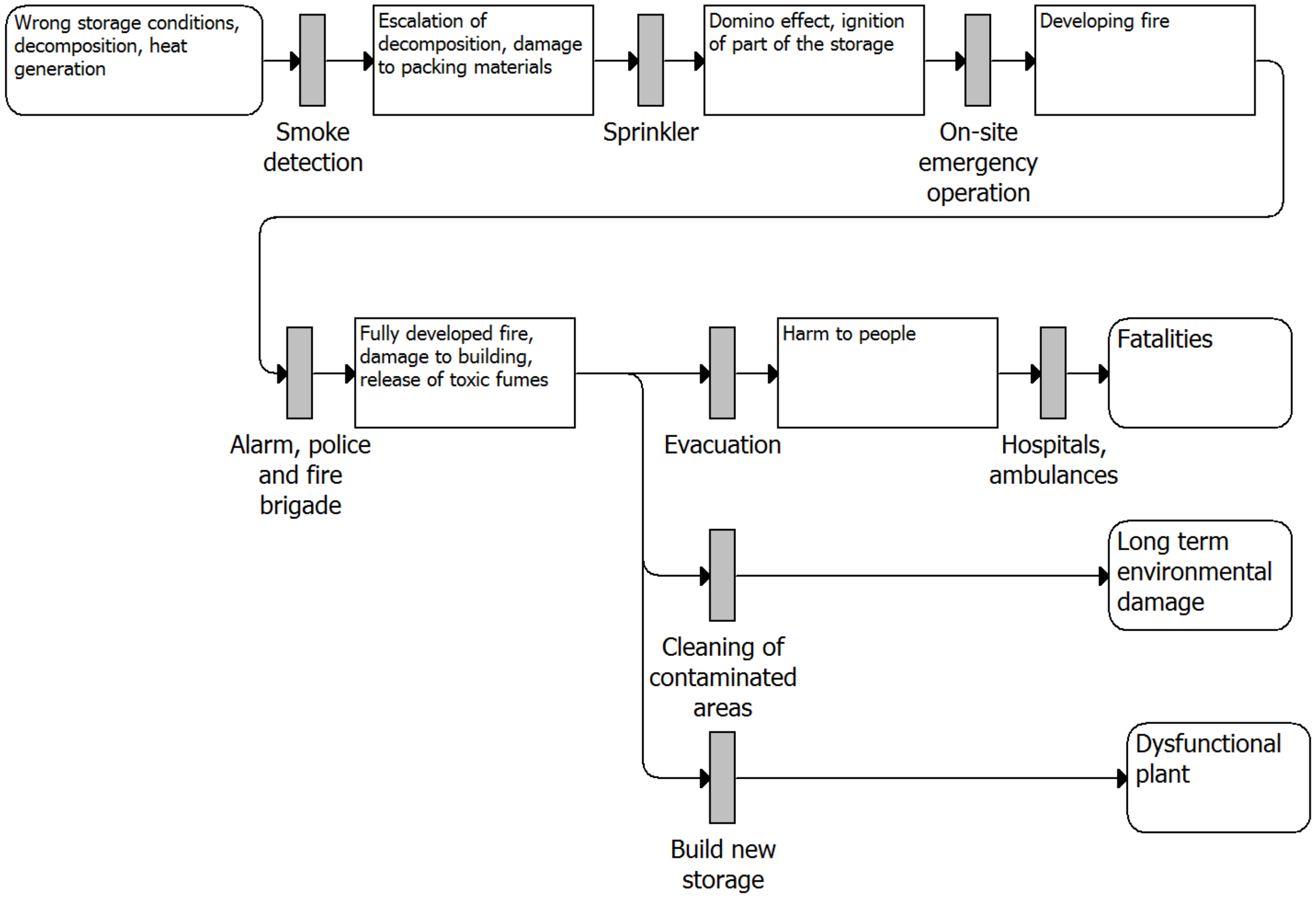
Example - Fire Protection System -



Bowtie principle

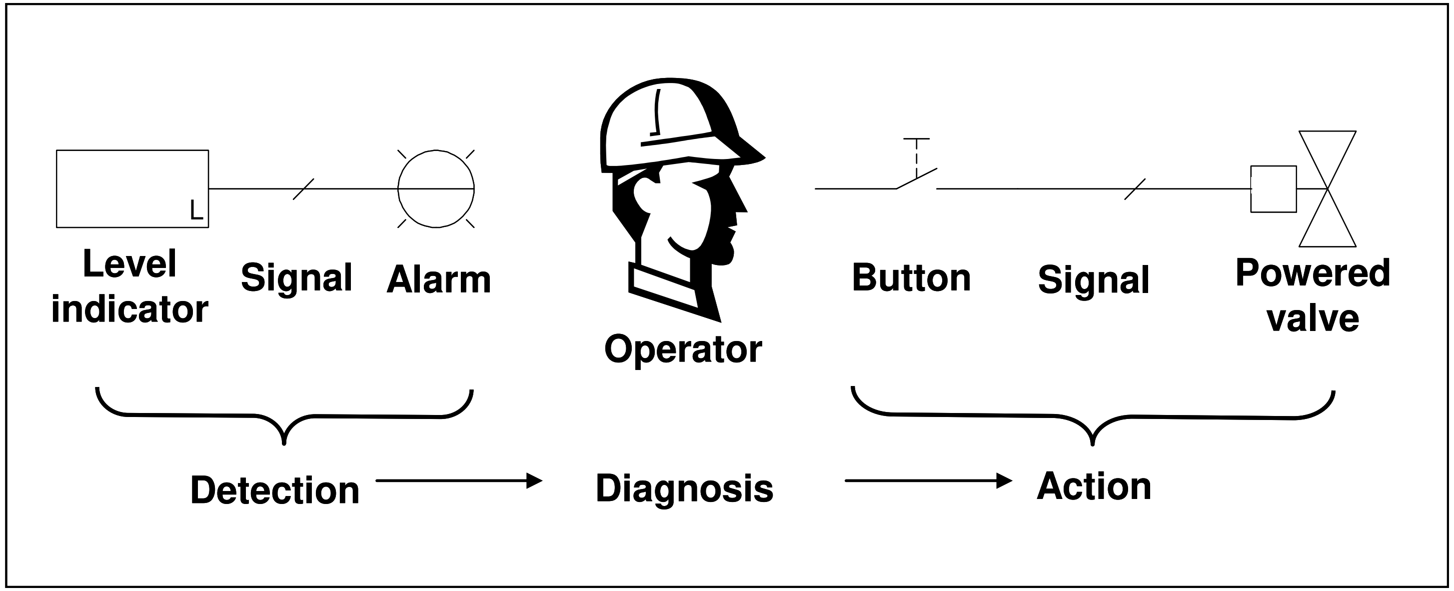


Safety Barrier diagram warehouse fire scenario



Complete safety barriers

Detect – Diagnose – Act



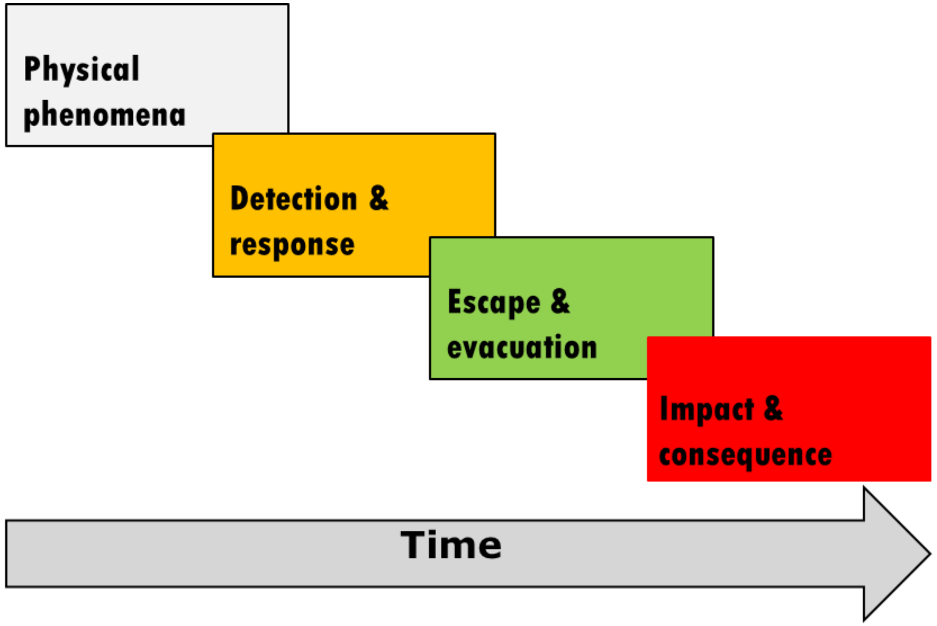
Classification of safety barriers

Safety Barrier Types

- Permanent Barriers
  - Overly conservative design
  - Passive barriers
  - Temporary barriers
  - Barriers requiring energy supply
- Preventive Barriers
  - Respect for safety zones
  - Preparative actions
- Interventions (Active barriers)
  - Hardware intervention
  - intervention from E/E/PE systems
  - Human intervention following alarm (procedural)
  - Situational human intervention (procedural)
  - Knowledge based human intervention (ad hoc)

How many barriers?

Dynamic approach



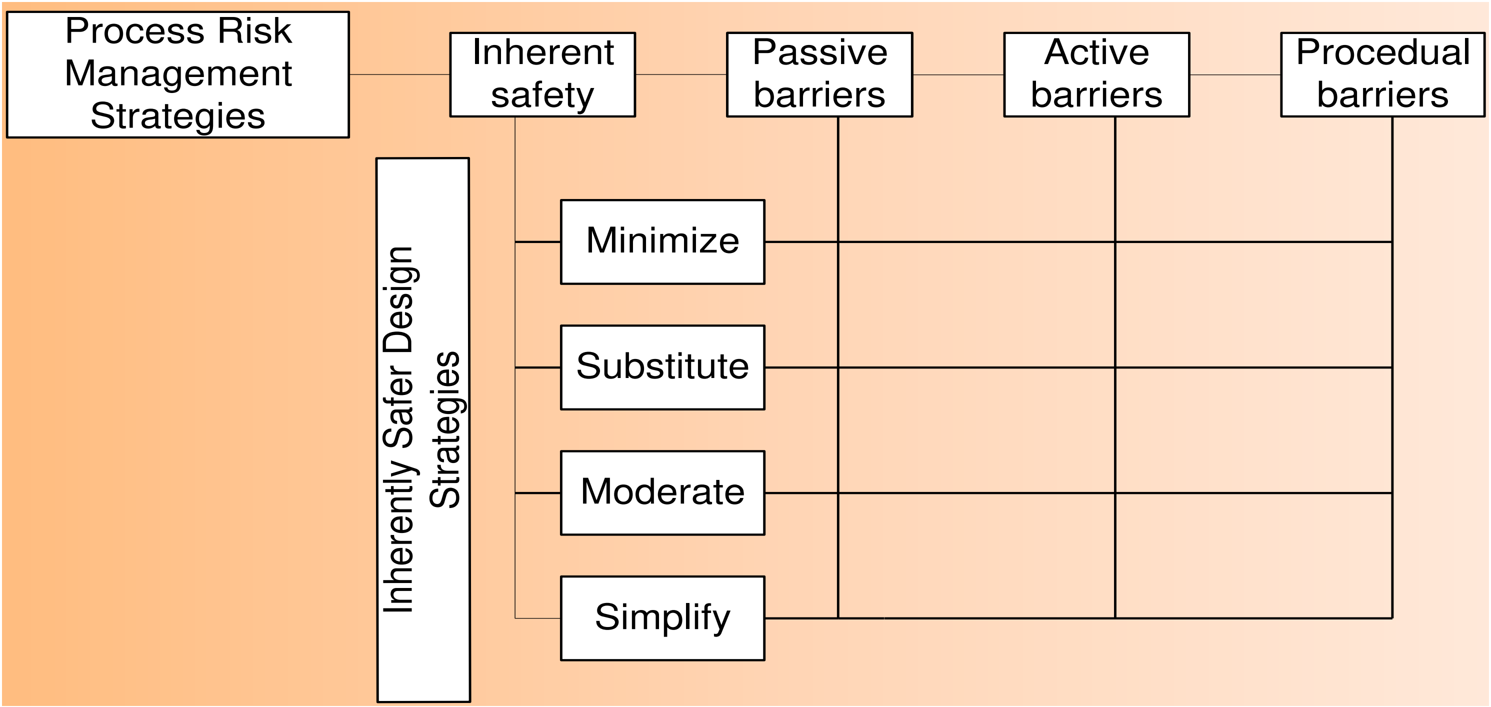
The term "dynamic risk assessment", is interpreted differently ((Hakobyan et al. 2008):

- Methods for periodic updates of an Probabilistic Risk Analysis (PRA) to address any changes in a plant configuration
- Updates to account for the ageing of equipment
- Approaches that include explicit deterministic modelling of dynamic processes combined with stochastic modelling to describe a systems evolution.

Approaches to prevent /mitigate accidents

- Seveso directive –named after the accident near the Italien town Seveso → dioxine release
- Atex directive – regulation /standard to prevent ignition in work places. (fuel – oxygen – ignition source)

- Theoretical models : inherently safer systems and Haddons principles



Haddon: *Energy Damage and the Ten Counter-Measure Strategies*

Inherent Safety

Safety functions

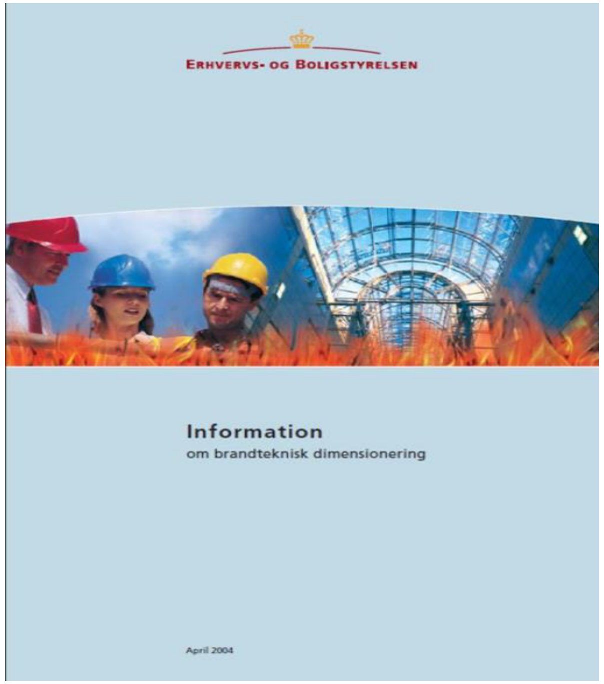
Planning

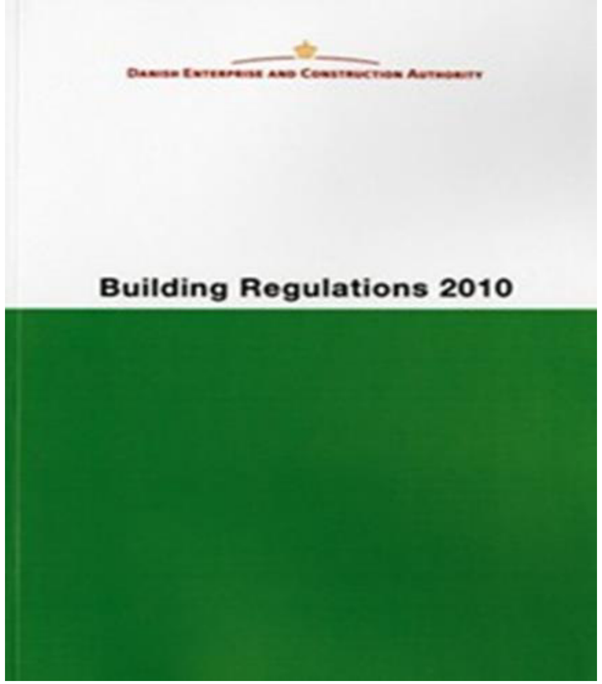
Emergency response

1. Prevent marshalling (build-up) of energy
2. Reduce the amount of energy marshalled
3. Prevent the release of this energy
4. Modify the rate of spatial distribution of the energy from its source
5. Separate the susceptible structure in space or in time
6. Use separation by interposition of a "barrier"
7. Modify the contact surface between source and susceptible structure
8. Strengthen the susceptible structure
9. Mitigate or stop the damage process when it is occurring
10. Fast recovery to the pre-event status, or at least to some stabilised but structurally modified status

Building regulations

Danish Regulation & Guidelines: BR10 and supporting documents





ISO- performance based approach

"The application of engineering principles, rules and expert judgement based on a scientific appreciation of the fire phenomena, of the effects of fire, and the reaction and behaviour of people, in order to:

- *save life, protect property and preserve the environment and heritage;*
- *quantify the hazards and risk of fire and its effects;*
- *evaluate analytically the optimum protective and preventative measures necessary to limit, within prescribed levels, the consequences of fire"*

Inter-jurisdictional Regulatory Collaboration Committee (IRCC)

- *a group comprising lead building regulatory agencies of more than 13 countries (see www.irccbuildingregulations.org), has been exploring this for a number of years and has proposed a structure for how risk concepts might be more explicitly reflected within performance-based building regulations*

  (Meacham et al. 2005).

- Many of the concepts in the IRCC approach were contemplated by the International Code Council (ICC) in the USA during the drafting of their model building code, the *ICC Performance Code (ICCPC) for Buildings and Facilities* (*ICC 2001; Meacham 2001*).

- Since then, the Australian Building Codes Board (ABCB) and the Department of Building and Housing (DBH) in New Zealand have considered the concepts embodied in these approaches and have explored these and other approaches to better linking 'tolerable risk' to 'tolerable performance' in their respective building codes.

Performance-based vs. prescriptive

(*"…the term 'performance-based' is used to reflect a focus on the intended function or outcome of a regulatory requirement*

rather than on

how that function or outcome is to be achieved, which is described as 'prescriptive' or 'descriptive'.")

Suggestion:

Building design uses risk-informed criteria → create risk-informed performance based building codes

(Meacham, Journal of Risk Research, Vol. 13, No. 7, October 2010, 877–893)

IRCC-hierachy

Tier-1	**Goal (Safety)**	➢ Provide an environment reasonably free from injury and death
Tier-2	**Functional Statement (Fire / Life Safety)**	➢ Provide suitable measures to reasonably protect building occupants from the effects of fire.
Tier-3	**Operative Requirements (Egress)**	➢ Means of egress shall be designed with adequate *capacity and protection* ➢ Provide *time* to reach a place of safety without being unreasonably exposed to untenable conditions.
Tier-4	**Performance/Risk Groups**	➢ Primary uses of the building and its general characteristics, etc. ➢ Importance of the building ➢ Occupant risk characteristics associated with the primary uses of the building ➢ Types of Hazard event and their impacts the building and occupants are expected to withstand (design loads)
Tier-5	**Performance Levels**	➢ Levels of Tolerable Impact and Protection.
Tier-6	**Performance Criteria**	➢ Tenability (Heat Flux, Temperature, Radiation, Visibility, Toxicity) ➢ Structural Stability Safety Systems
Tier-7a	**Deemed to Satisfy Prescriptive Solutions**	
Tier-7b	**Performance-Based Solutions**	
Tier-8	**Verification Methods**	➢ Tests, Standards, Models

Lit.: Meacham; Journal for Risk Research (2010) http://www.tandfonline.com.proxy.findit.dtu.dk/doi/pdf/10.1080/13669871003703260

IRCC – hierachy: detailed approach

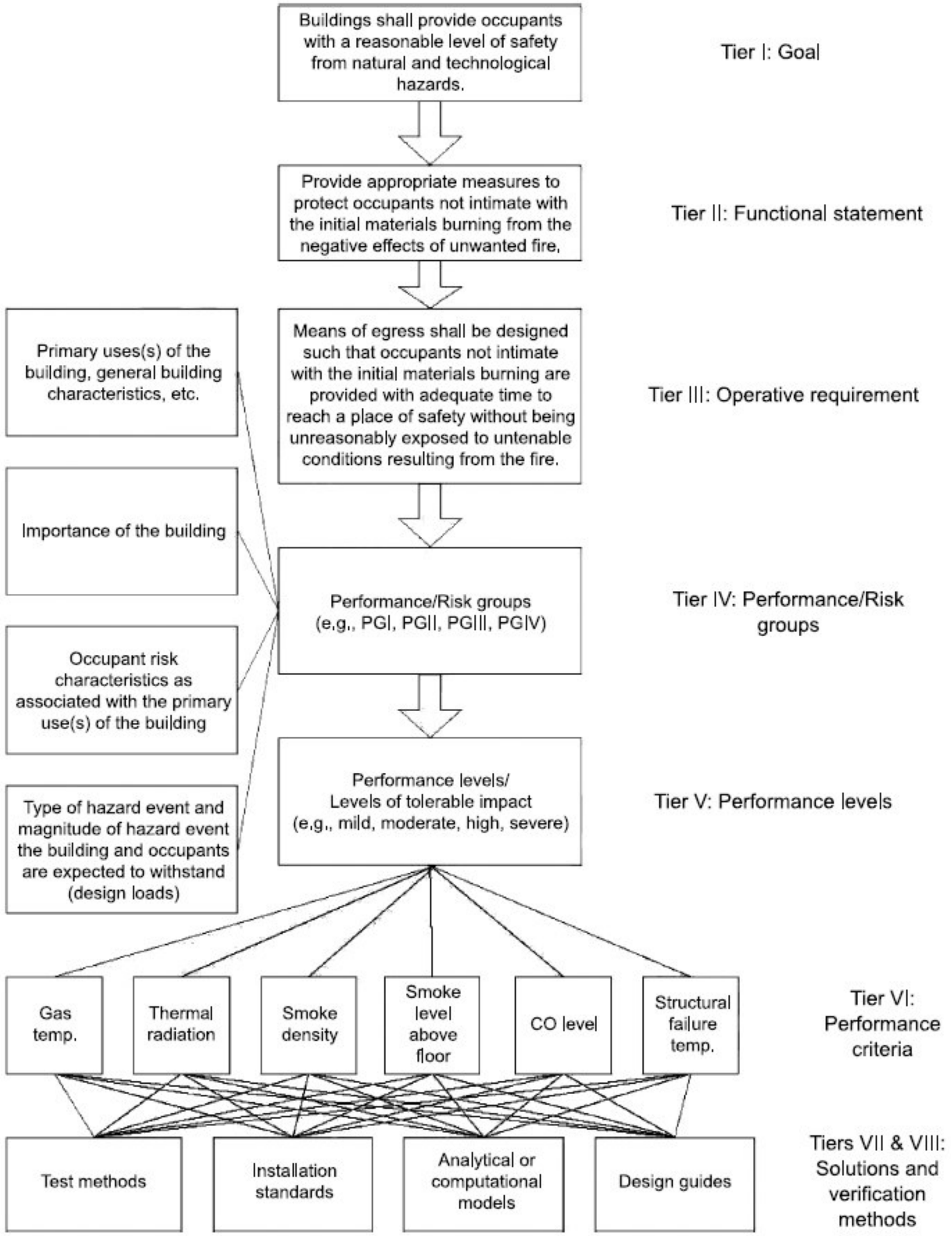
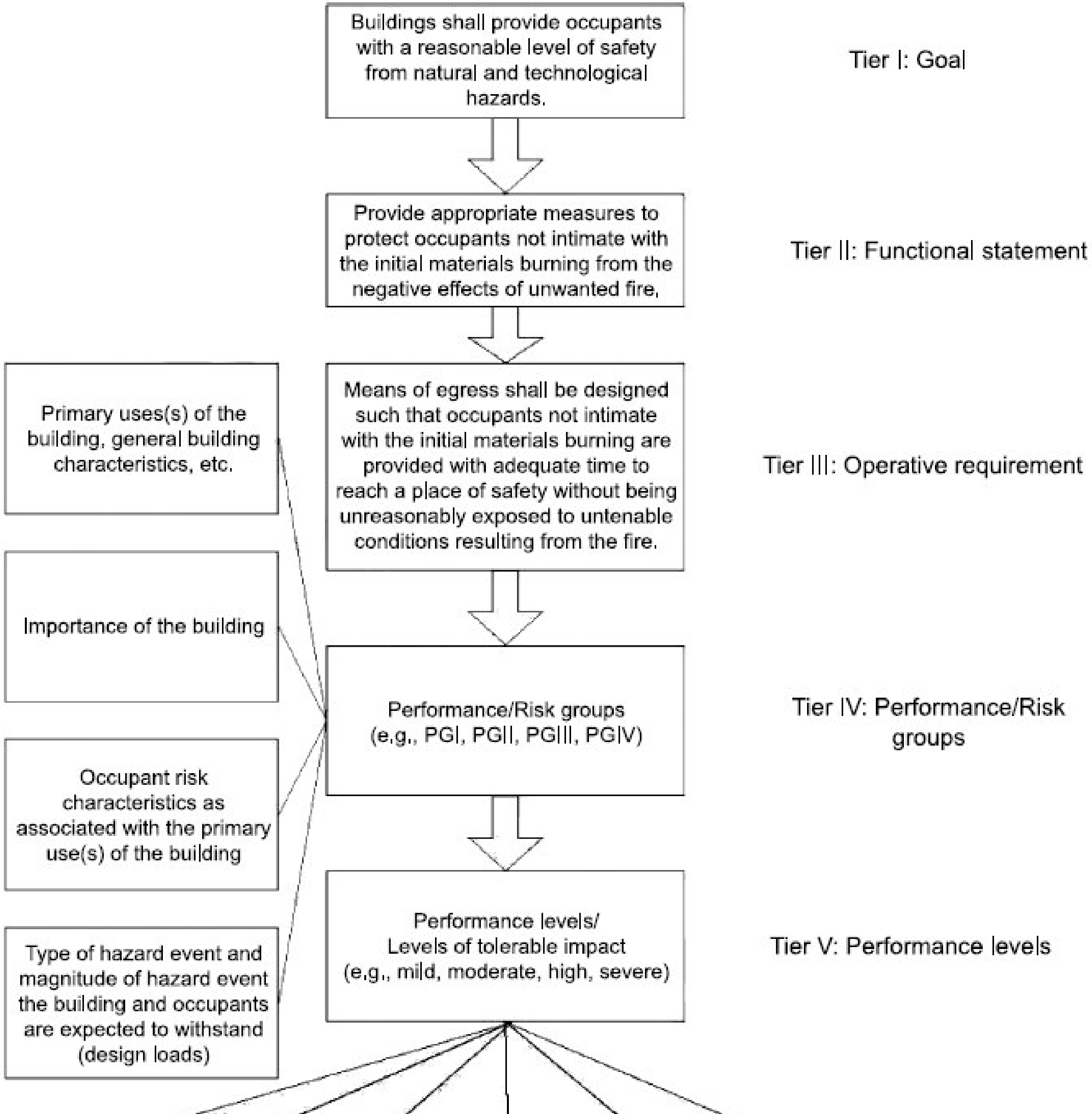


Figure 3. IRCC hierarchy with linkages (adapted from Meacham 2008).

IRCC – hierachy: detailed approach



IRCC – hierachy: detailed approach

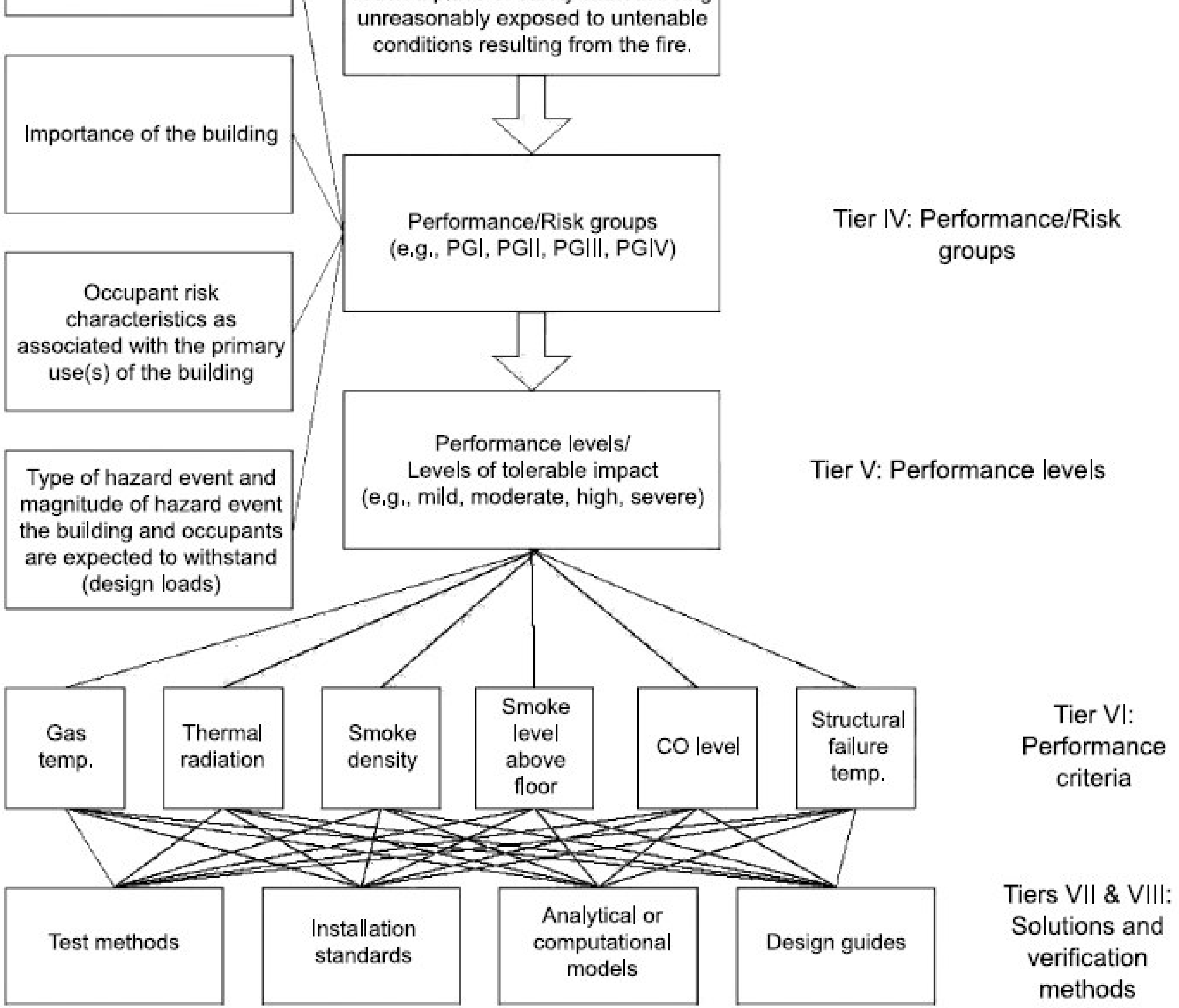


Figure 3. IRCC hierarchy with linkages (adapted from Meacham 2008).

Key risk factors to address

- Number of persons using the building
  - occupying, visiting, employed,…
- The amount of time people are in the building
- People sleep in the building
- Are the building occupants expected to be familiar with the building layout (egress paths)?
- Are a significant percentage of the building occupants members of vulnerable population groups? (disabled, elderly, patients,…)?
- Have the people in the building close social relations (family, job hierarchy,…)?

- Expected fire loads in the building
- Building is of great importance

Risk factors lead to performance groups for buildings

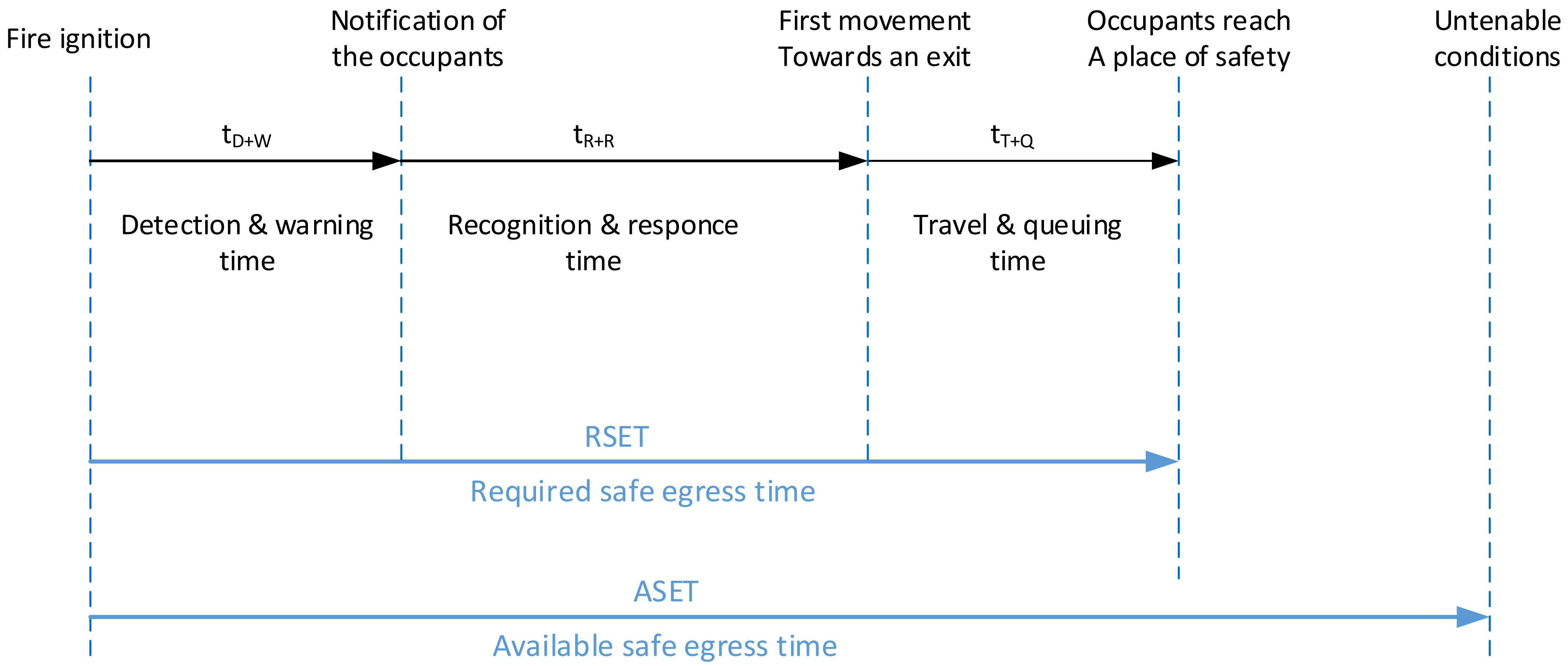
	Performance groups			
Magnitude of design events	PG I	PG II	PG III	PG IV
Very large (very rare)	SEVERE			MODERATE
Large (rare)				
Medium (less frequent)	HIGH			MILD
Small (frequent)				

Priority: safe evacuation of people

- Well designed egress paths

- Assuming that the fire resistance of fire walls etc. is not compromised during evacuation

Evacuation time

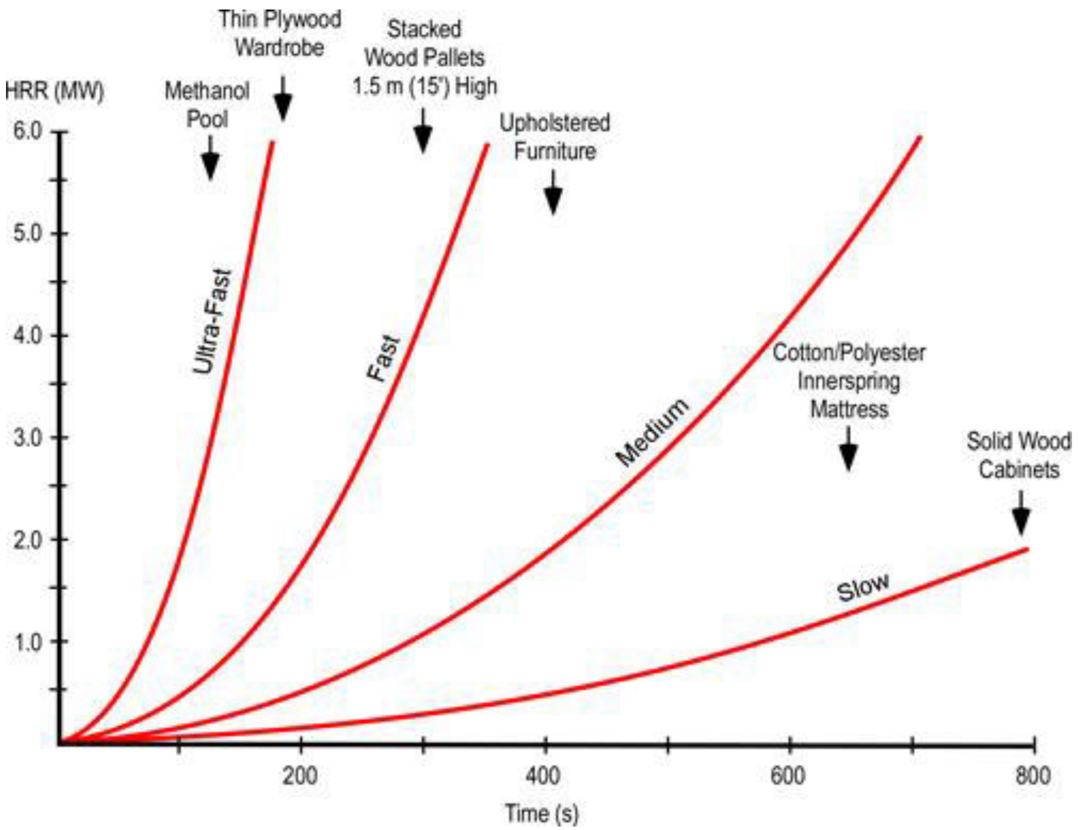


Egress time RSET

- The required safe egress time may be calculated from simple flow models. In case of many people (sports event) more complex models should be used.

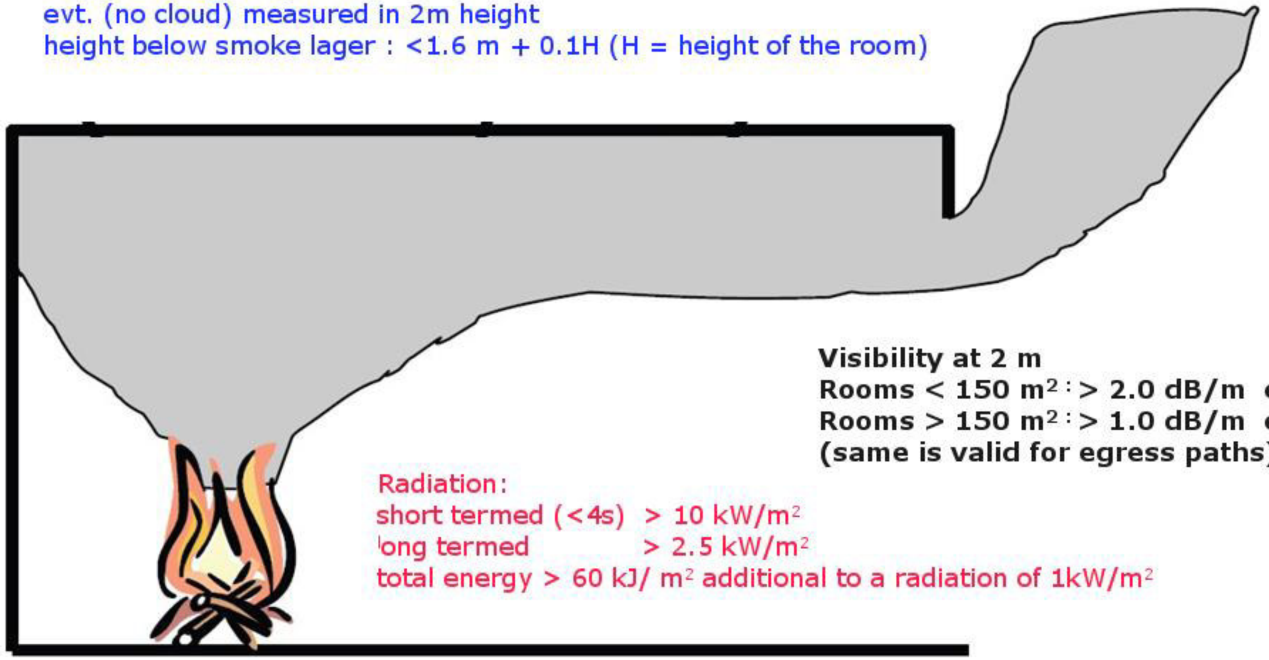
- RSET provides the normal time to reach an safe area in side or outside the building

Fire growth rates – ASET determination



Tenability limits – ASET determination

Available safe egression time- time until the first tenability limit is reached.



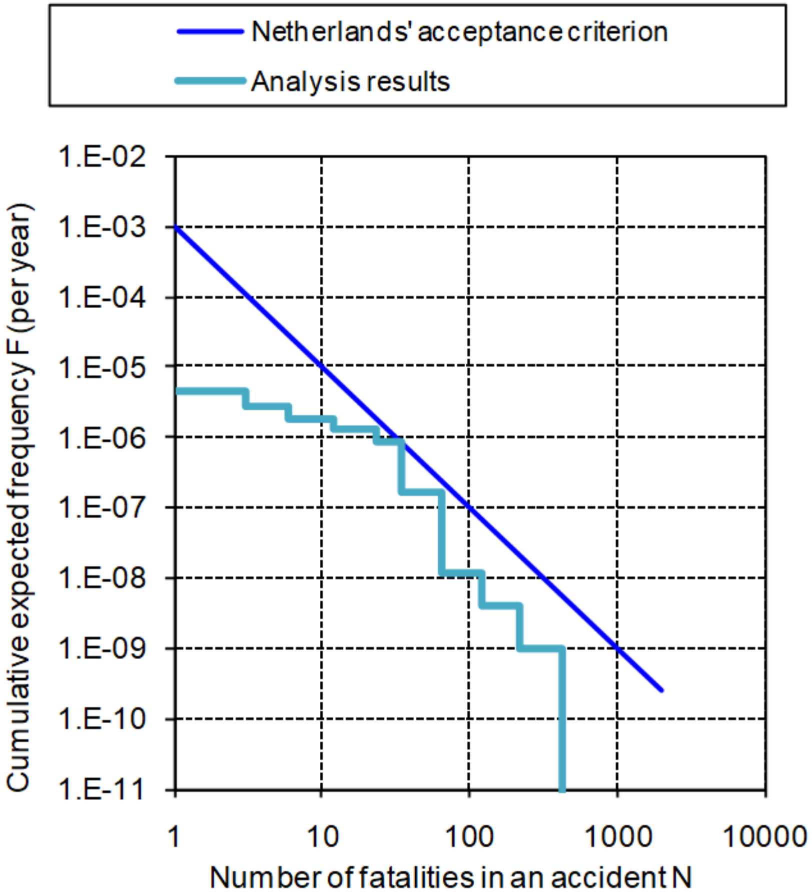
FN-curve

IF ASET is smaller than RSET:

Evacuation not complete→ fire victims may occur

FN curve shows the number of fatalities vs. probability, e.g. 100 victims or more are expected with a probability of 1e-8 pr. Year

Acceptance criterion based on risk aversion – accidents with many fatalities should have a much lower probability



Second priority - resistance to fires of structures

- Evacuation /egress in early stages of fire development
  - Fire location still confined within e.g. single room (fire compartment)

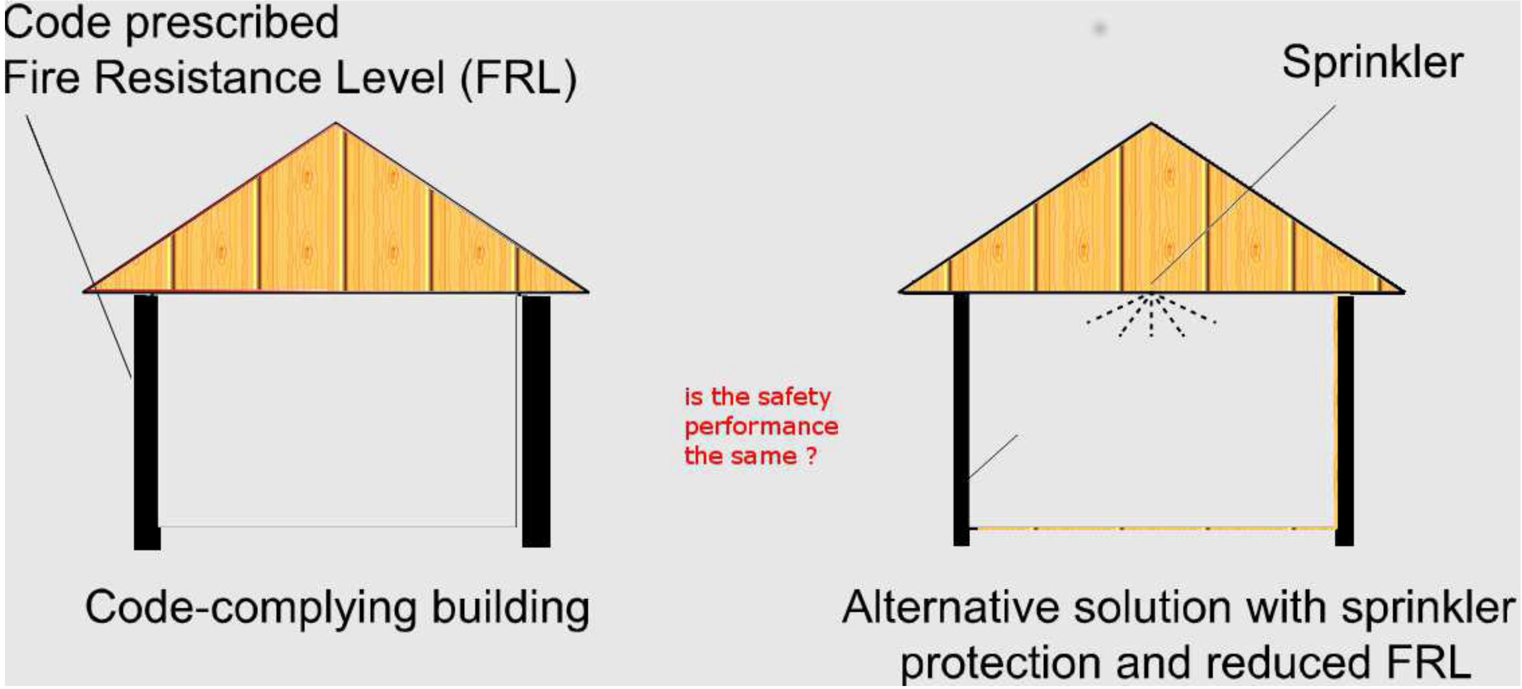
- The structures are designed to resist the fire to enable the firefighters to extinguish the fire

- On emergency response it is likely that the fire has reached flash over
  - Maximum fire impact on structures (walls, fire doors, windows, etc.)
  - Fire load is an important factor → duration of impact to structures

How to predict structural resistense to fire?

- Especially important for emergency response to secure fire fighters

- But how can this be estimated?
- How can the safety performance be compared for different fire engineering solutions?

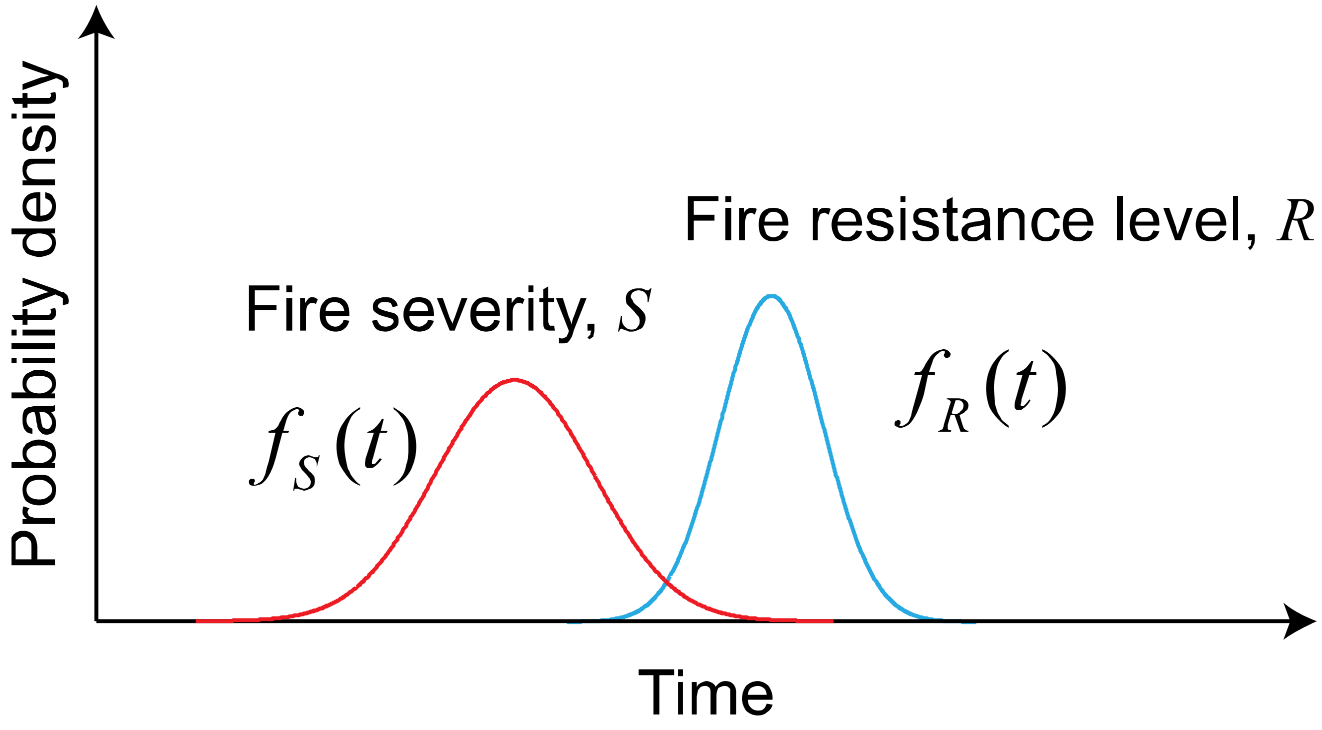


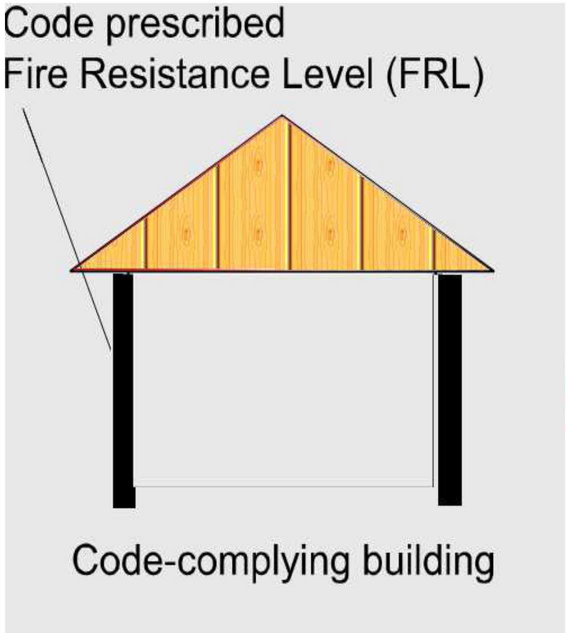
Example after He, Y. and Grubits, S. (2010).

Probabilistic analysis using the structural reliability theory

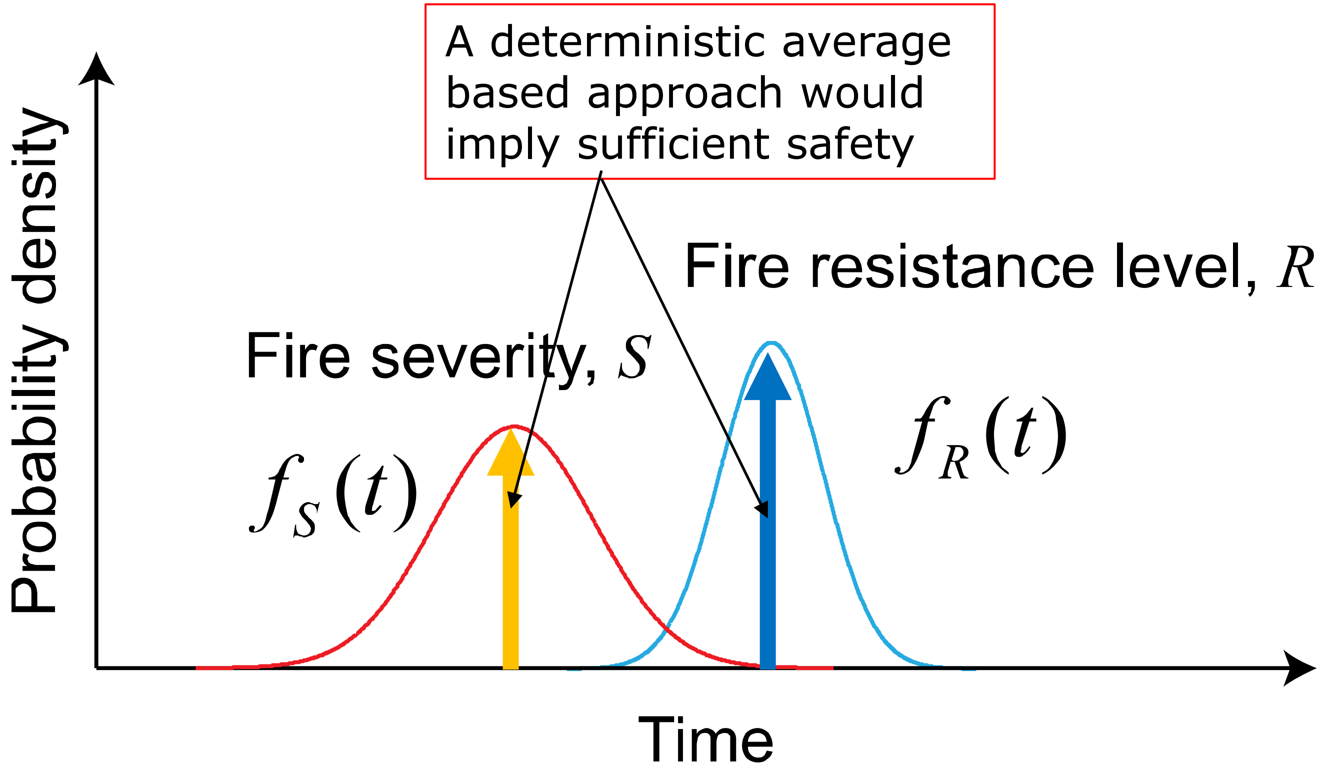
Fire severity S

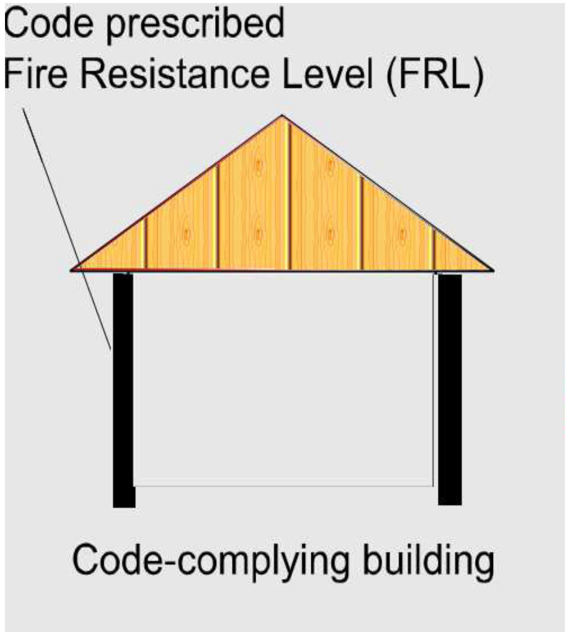
the structure will be exposed to different fire loads giving different fire curves and fire durations





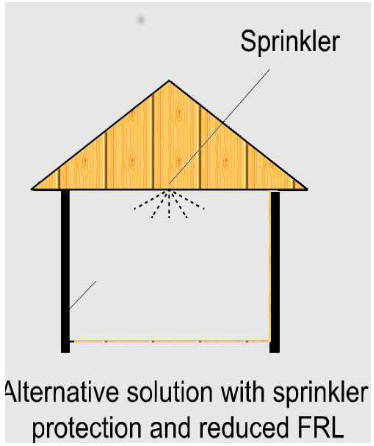
Probabilistic analysis using the structural reliability theory

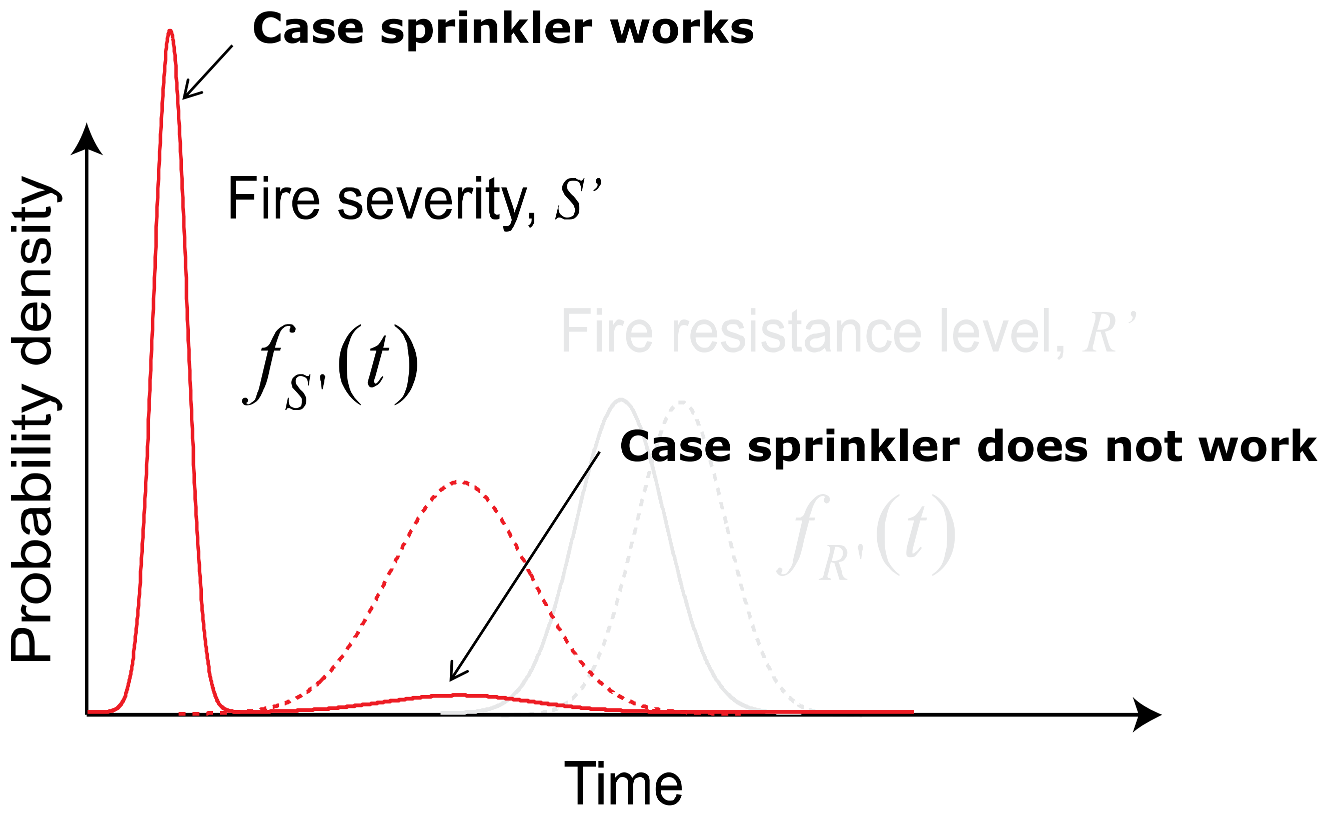




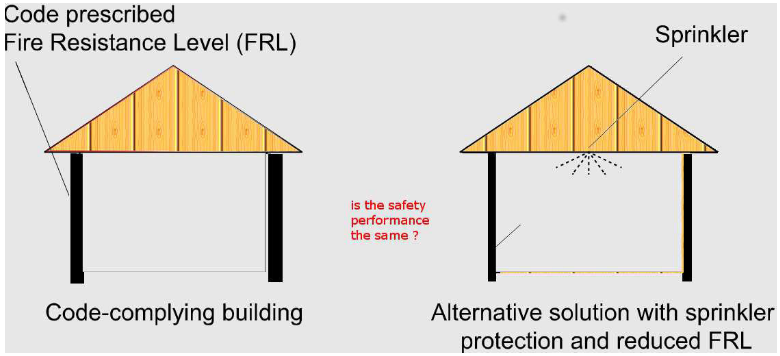
Modeling of *R'* and *S'*

Changing of the probability density function by sprinkler protection.





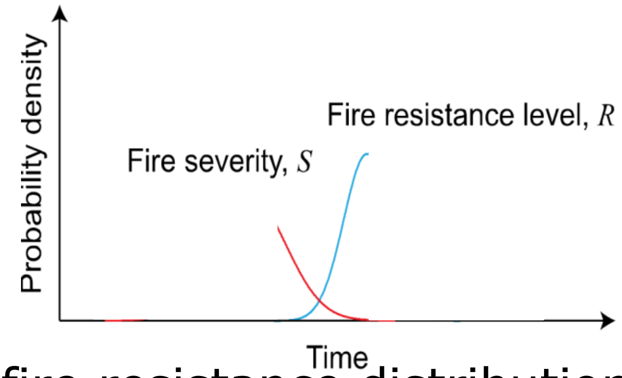
How to compare the safety levels?



Comparing in terms of *probability of failure*

- *The structural reliability theory* provides methods to assess the probability of failure, e.g.:
  - a building element does not resist fire if:

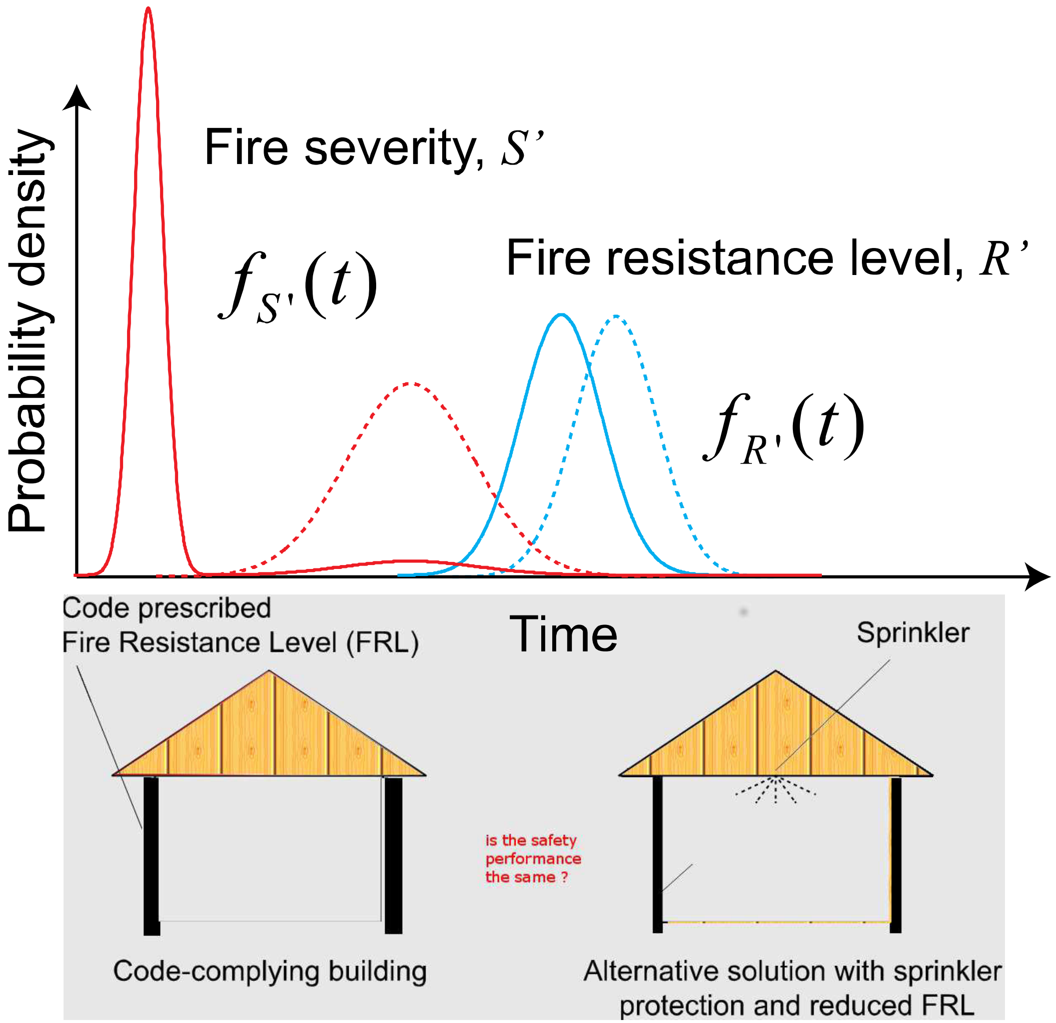
$$f_{duration,fire} \geq f_{duration,resistens}$$



→ The result is the overlapping area for the fire severity and the fire resistance distribution

The comparison for both cases

- Code complying solution vs. alternative solution with sprinkler protection and reduced FRL.



Thank you for listening