Quantitative risk assessment in process safety studies: an overview

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Introduction (1)

Process industry
Examples: chemical and petrochemical sector, Oil and Gas (O&G), explosives, fertilizers, etc.

Process safety
Dealing with major accident hazard and induced risk – LOSS PREVENTION

Major accidents definition (“Seveso” Directive (art. 3))

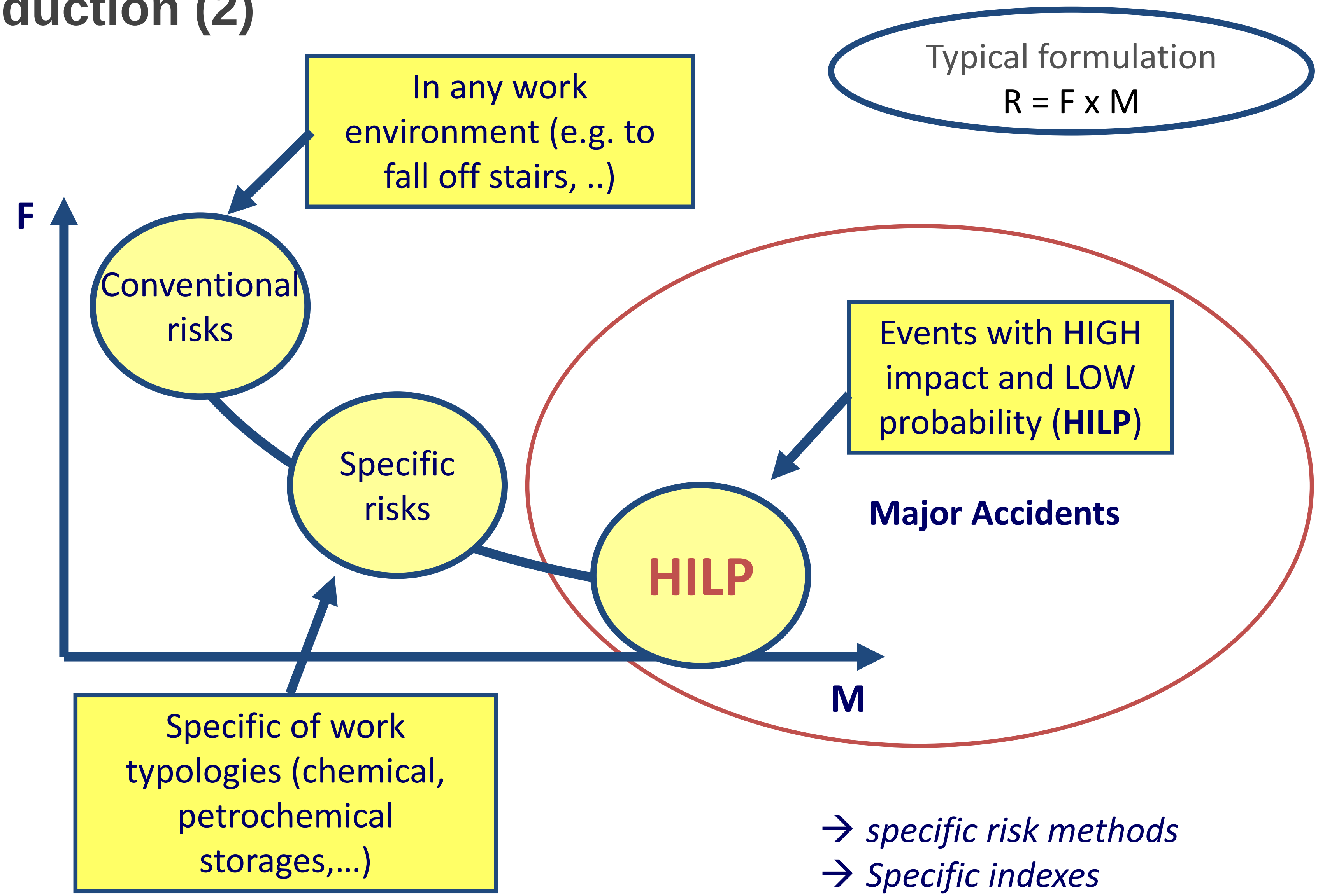
“Occurrence such as a major emission*, fire, or explosion resulting from uncontrolled developments in the course of the operation of any establishment, and leading to serious danger to human health and/or the environment, immediate or delayed, **inside or outside the establishment**, and **involving one or more dangerous substances**”;

** for instance a toxic cloud*

(Inherent) hazardous properties

Specific conditions (handling and storage)
high or low pressure, high or low temperature

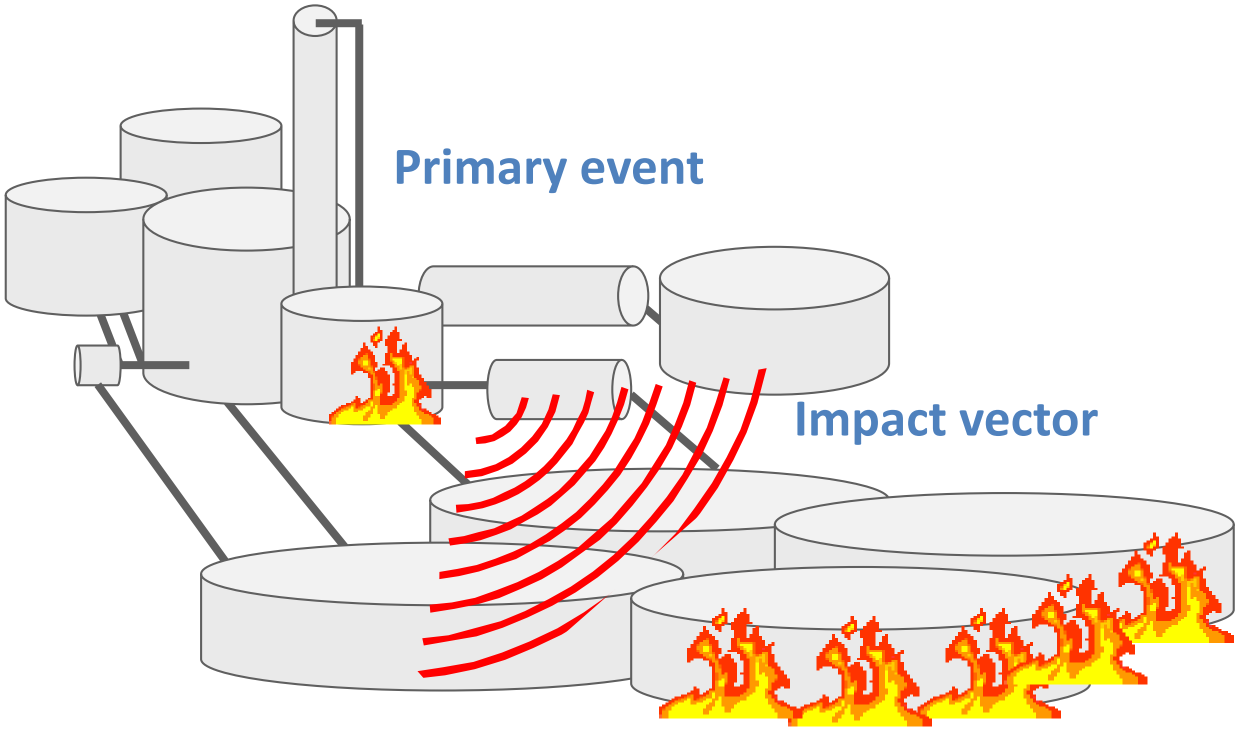
Introduction (2)



→ *specific risk methods*
→ *Specific indexes*
→ *Specific acceptance criteria*

Introduction (3)

DOMINO EFFECT and related risks



- Domino effect was responsible of several catastrophic accidents that took place in the chemical and process industry
- Seveso Directive requires that all the possible accidental scenarios caused by domino effect are taken into account.
- No well accepted approach exists for the analysis of domino hazards.

Outline and aims of the presentation

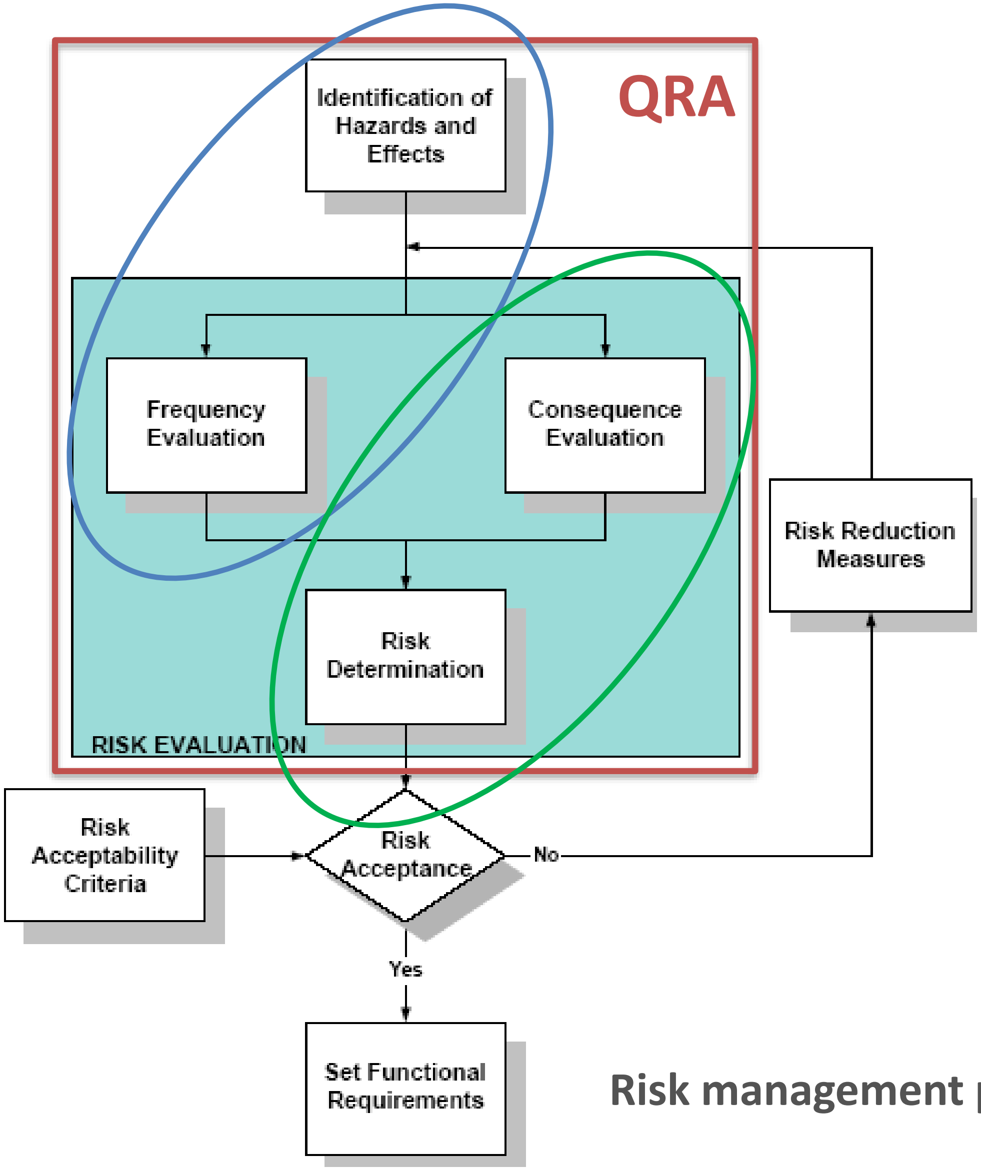
- Presentation of **Quantitative Risk Assessment** (QRA) in the process industry

- QRA methodology: description of main steps and specific studies for domino effect

- QRA and risk indexes: definition of specific risk indexes and related risk acceptance criteria

- Example of application for land use planning and domino effect analysis

Quantitative Risk Assessment in process safety (1)



- The generic procedure for risk evaluation is well-established
- Each box requires the application of specific tools to the analysis of the project/installation
  - **General and common-use tools are available**
  - **Different available approaches and disagreement in the use of results**

Complex events: domino effect
Need of extension

Risk management process

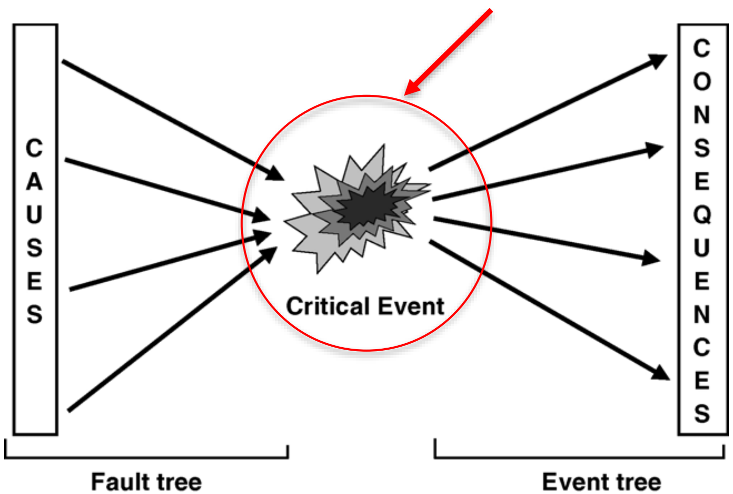
Quantitative Risk Assessment in process safety (2)

Hazard identification

Past accident accidents data analysis is a useful support. However, structured *techniques* are needed, containing both experience based and predictive elements

Based on brainstorming assessment

Focusing on Consequences → ***HAZID***
Focusing on the process → ***HAZOP***



- Safety Review
- Relative Ranking Methods (F&EI, Mond Index, CEI, etc.)
- Check-list Analysis
- Preliminary Hazard Analysis
- **HAZID (Hazard Identification) Analysis**
- What-if Analysis
- FMEA (Failure Modes and Effects Analysis)
- **HAZOP (Hazard and Operability) Analysis**
- Fault Tree Analysis
- Event Tree Analysis
- Human Reliability Analysis

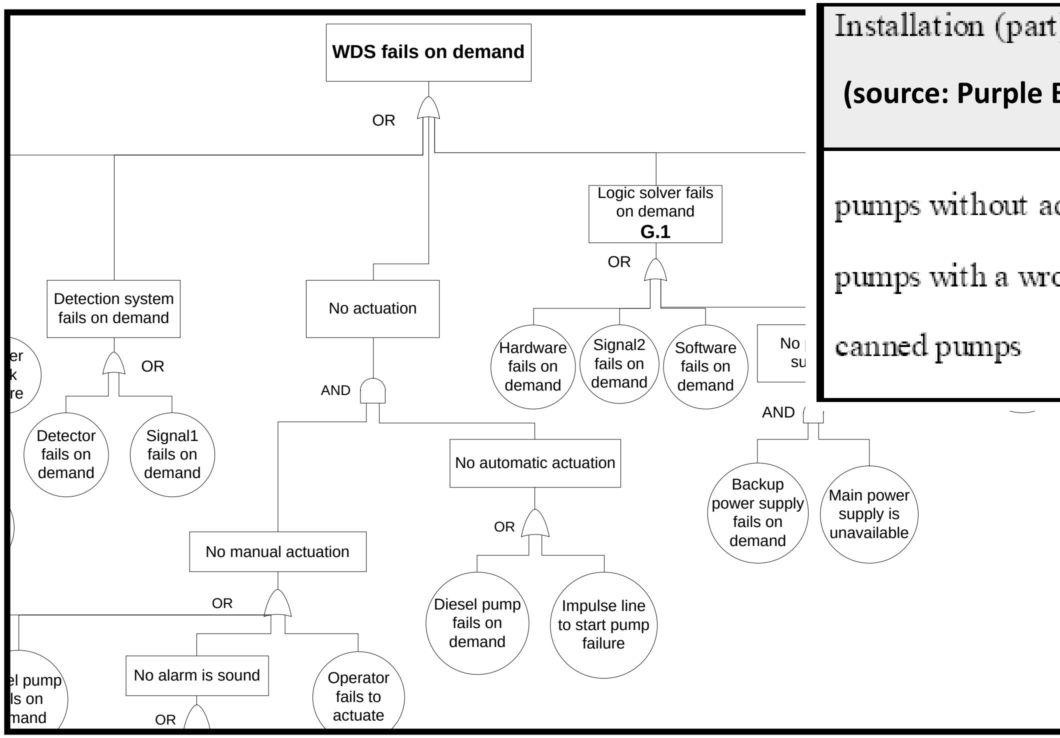
….. and many others

Quantitative Risk Assessment in process safety (3)

Frequency evaluation

Open issues: “static”analysis, dynamic approach is missing

Fault tree analysis
Only for complex accident chains



Generic frequencies data for the critical events for random failures (frequency in 1/y)

Installation (part) (source: Purple Book)	G.1 Catastrophic failure	G.2 Leak
pumps without additional provisions	$1 \times 10^{-4}\ y^{-1}$	$5 \times 10^{-4}\ y^{-1}$
pumps with a wrought steel containment	$5 \times 10^{-5}\ y^{-1}$	$2.5 \times 10^{-4}\ y^{-1}$
canned pumps	$1 \times 10^{-5}\ y^{-1}$	$5 \times 10^{-5}\ y^{-1}$

Quantitative Risk Assessment in process safety (3)

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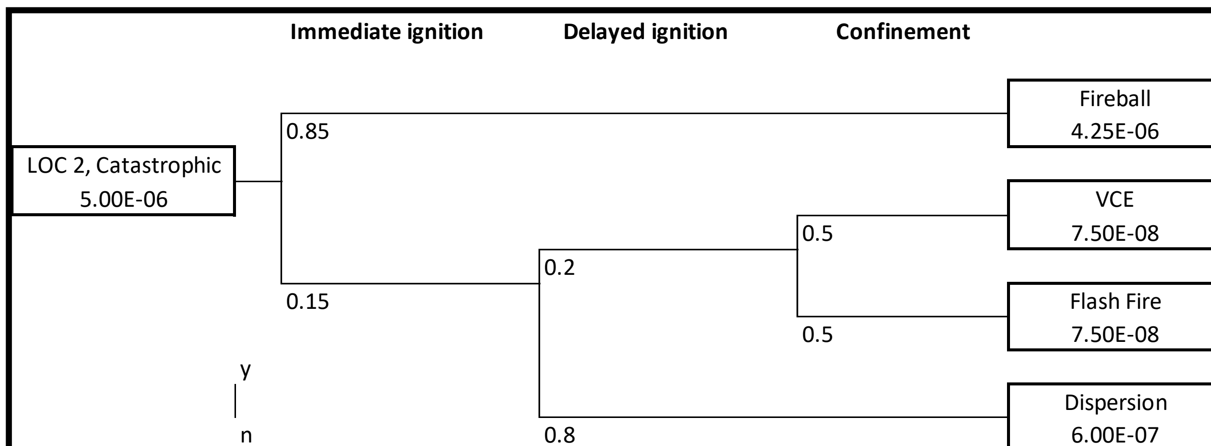


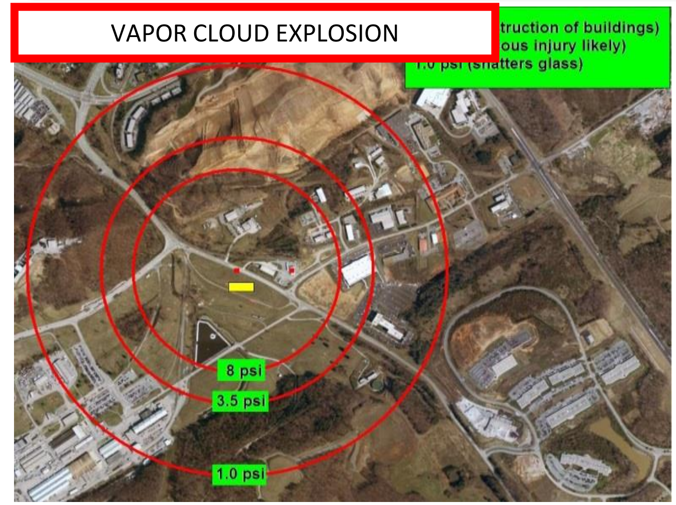
Event tree analysis
Identification of final outcomes

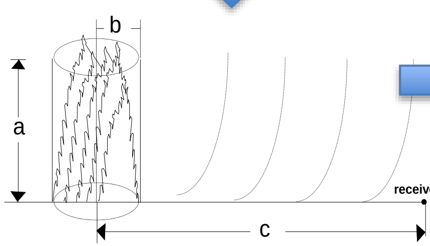
Quantitative Risk Assessment in process safety (4)

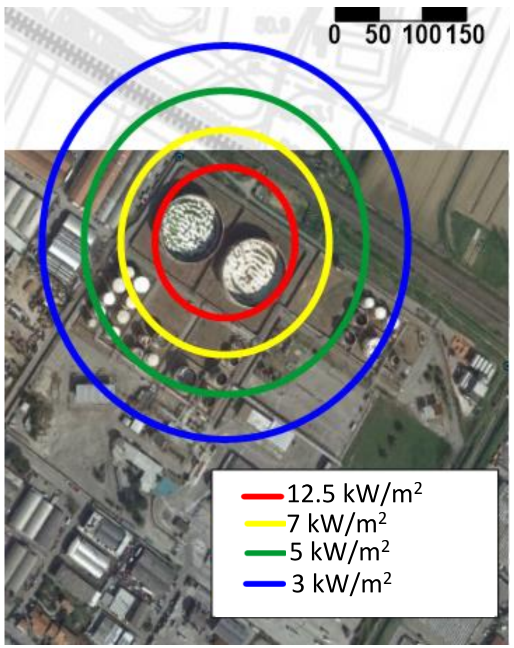
Consequence assessment – “conventional” approach

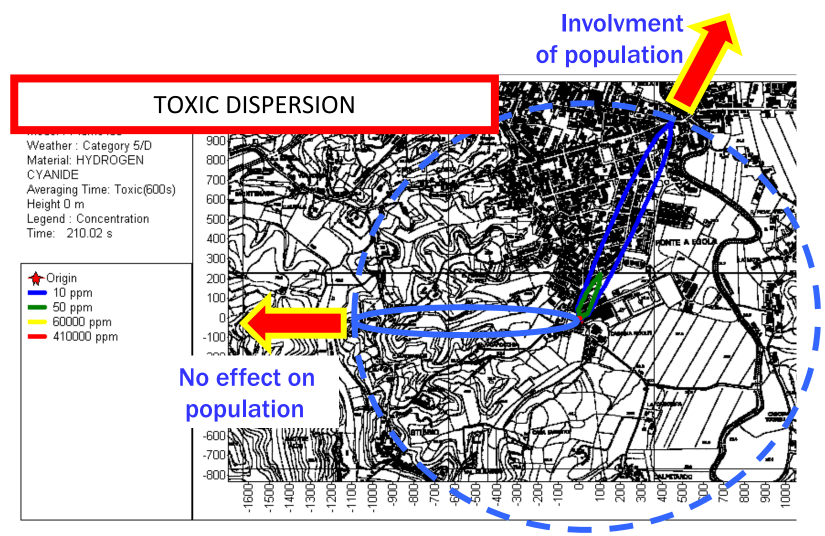
Open issues: advanced modeling

Integral models (lumped parameters)
fires, explosions and toxic dispersion
Commercial packages (DNV GL Phast, TNO Effects, US EPA ALOHA, etc.)







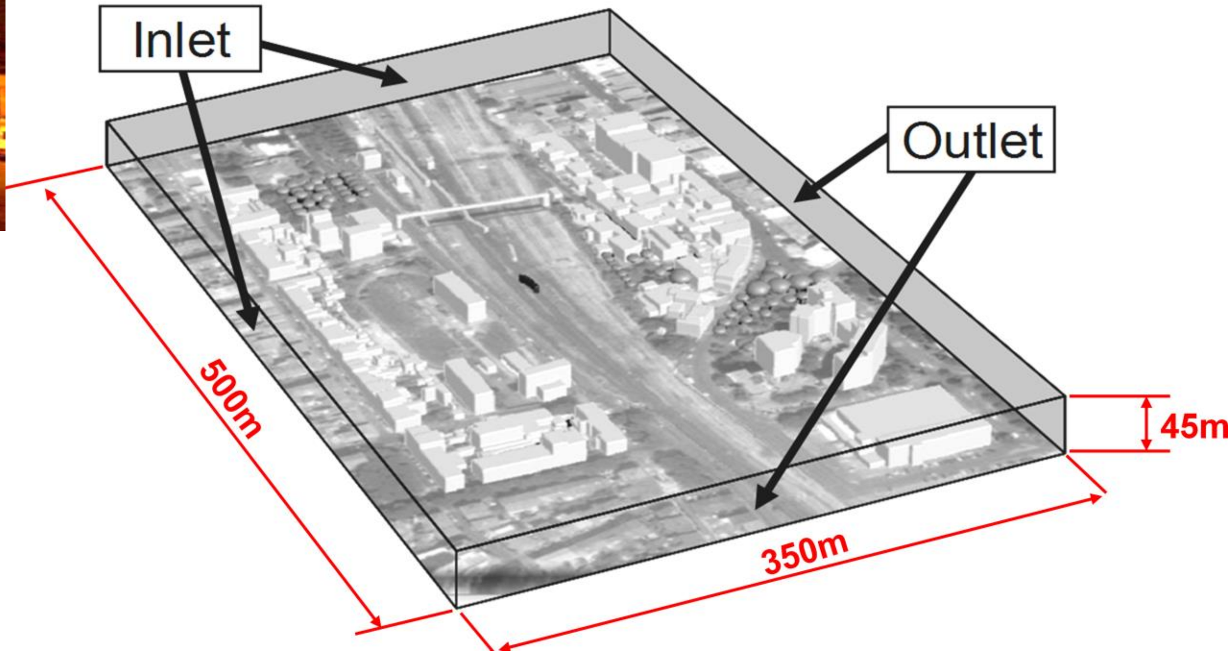


Quantitative Risk Assessment in process safety (5)

Consequence assessment – “advanced” approach (CFD modeling of accident scenarios)

Viareggio accident in Italy (2009)

LPG flash fire after catastrophic release following derailment in urban area (32 fats.)



Quantitative Risk Assessment in process safety (5)

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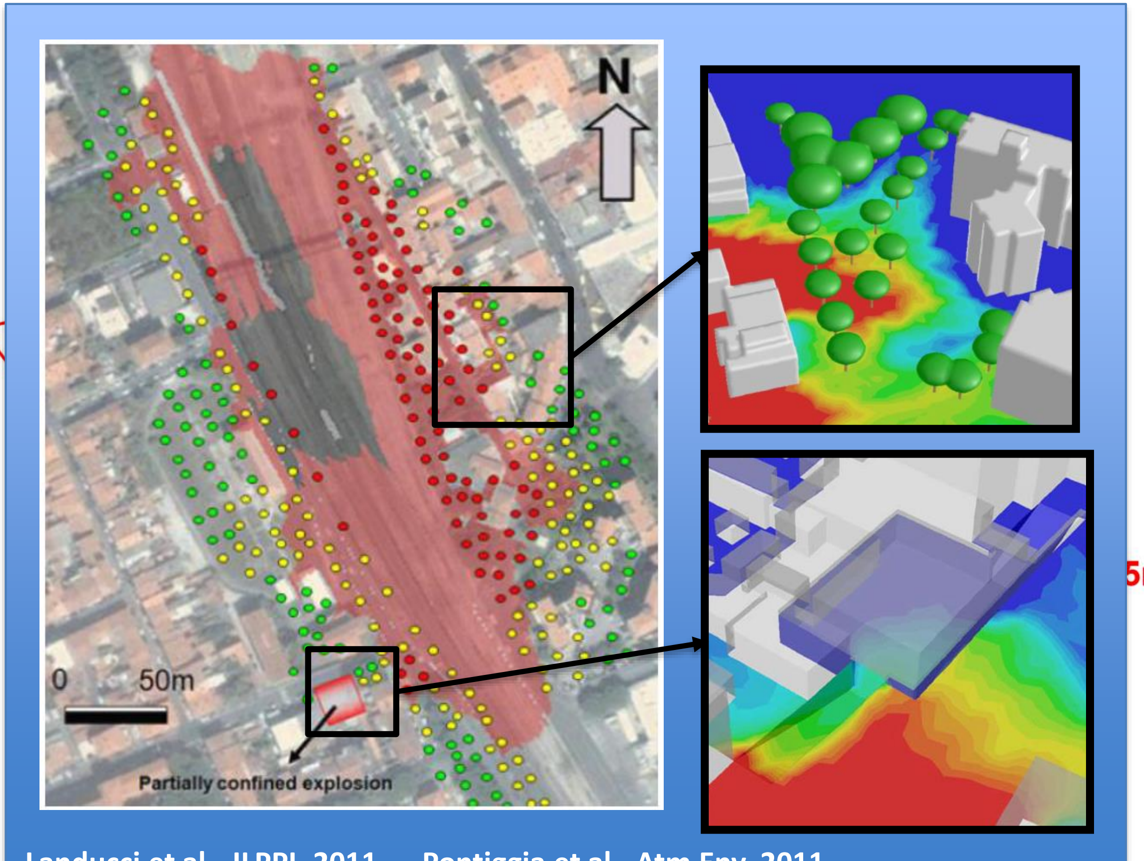


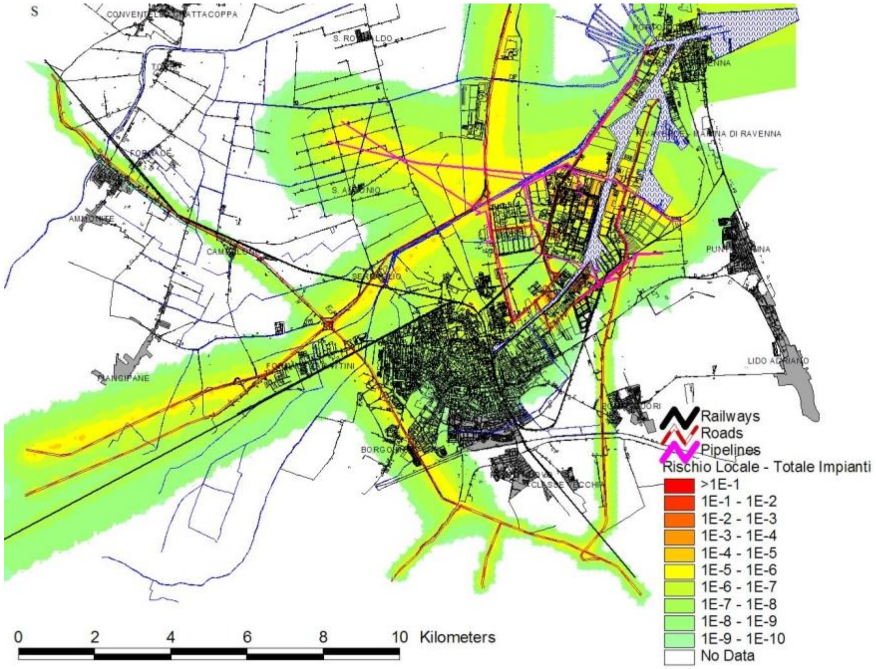
Landucci et al., JLPPI, 2011 Pontiggia et al., Atm Env, 2011

Definition of Risk indexes (1)

LOCAL SPECIFIC INDIVIDUAL RISK - *LSIR*

The risk to a person in the nearby the hazard (point or linear source)

"The expected frequency of the reference damage occurring as a consequence of any accident, to a person who is permanently present (24h a day per one year) in a given point of the area, with no protection and no possibility of being sheltered or evacuated"



$$\Delta IR_{S,M,\varphi,i} = f_S \times P_M \times P_\varphi \times P_i \times P_d$$

Exposure time : the time an individual is subjected to the dangerous concentration

f_S frequency of top event; P_M probability of meteo cond; P_Φ prob wind direction, P_i prob scenario (ignition?); **P_d probability of death**

$$LSIR = \sum_S \sum_M \sum_\varphi \sum_i \Delta IR_{S,M,\varphi,i}$$

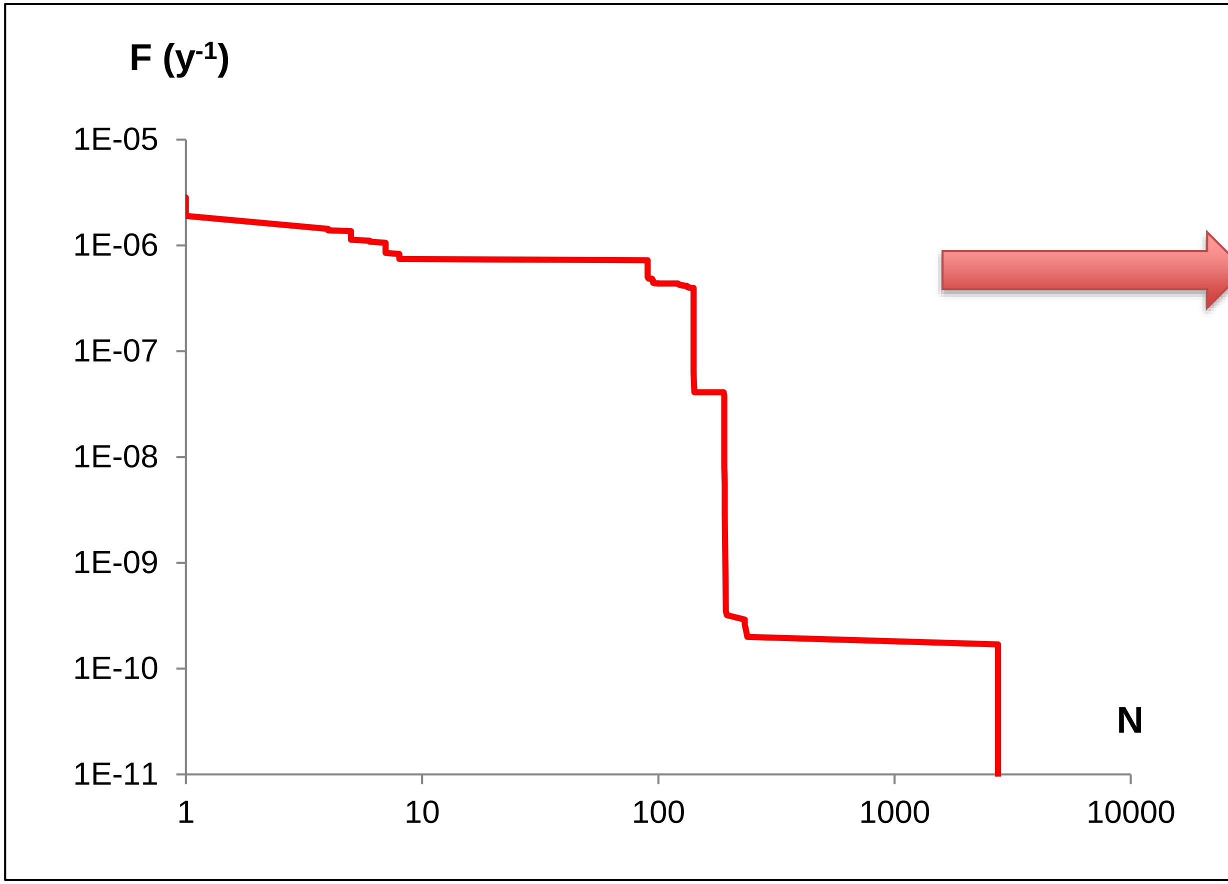
I = heat radiation, kWm^2
C = concentration, mg/m^3
ΔP = peak overpressure, Pa

VULNERABILITY MODELS

DAMAGE PROBABILITY

Definition of Risk indexes (2)

Societal Risk: FN-curves and and related indexes



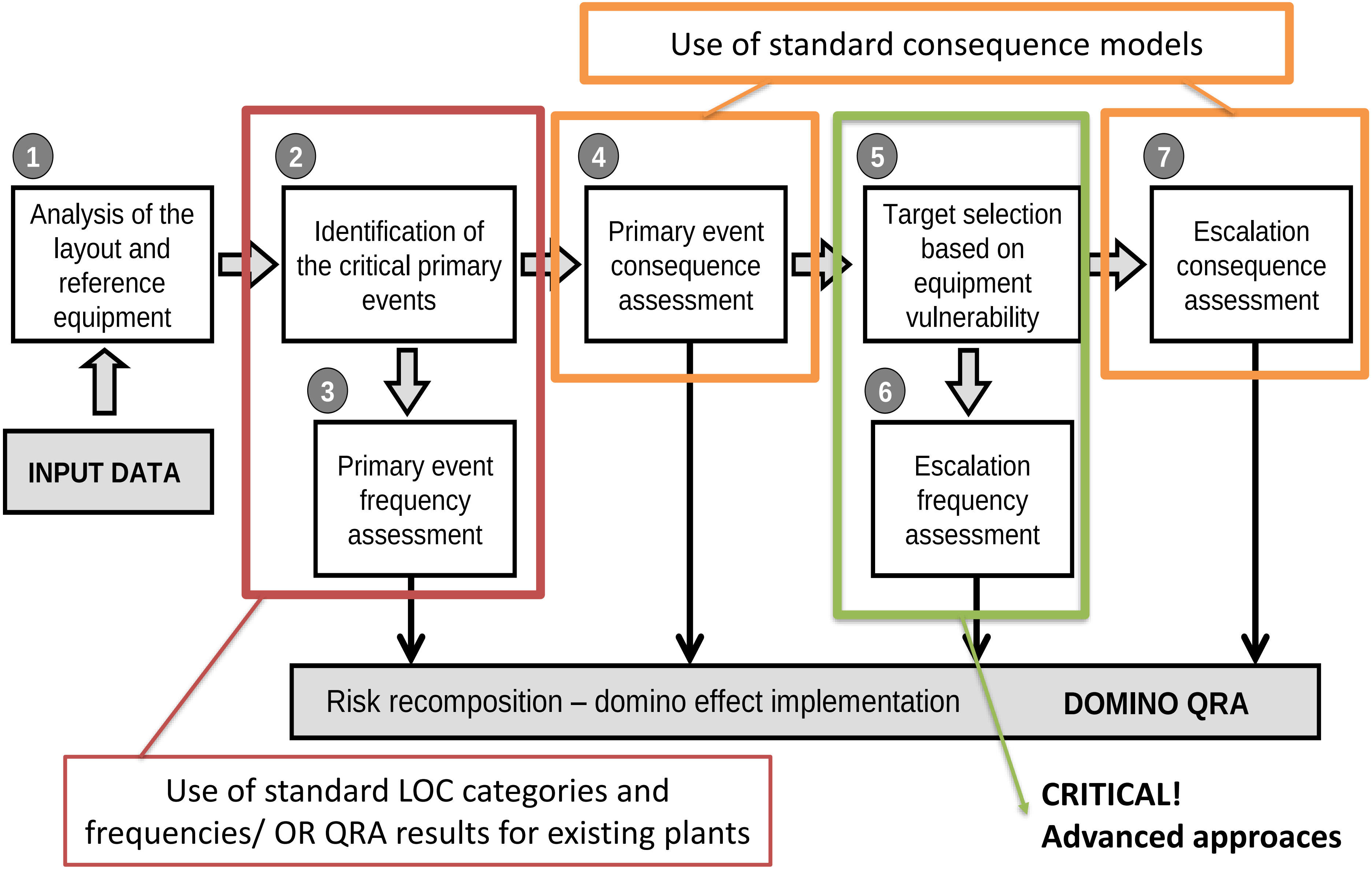
FN-curve shows the exceedance annual probabilities of the potential numbers of fatalities (F(N ≥ n)) on double log scale

$$PLL = \int_0^\infty F(N) \cdot N^{(n-1)} \, dN$$

n = 1 → "potential life loss" (EV)
n = 2 → "expectation value" (RI)

NOTE:
There are other possibilities, either considering the consequences or hybrid methods

QRA and domino events triggered by fire: overview



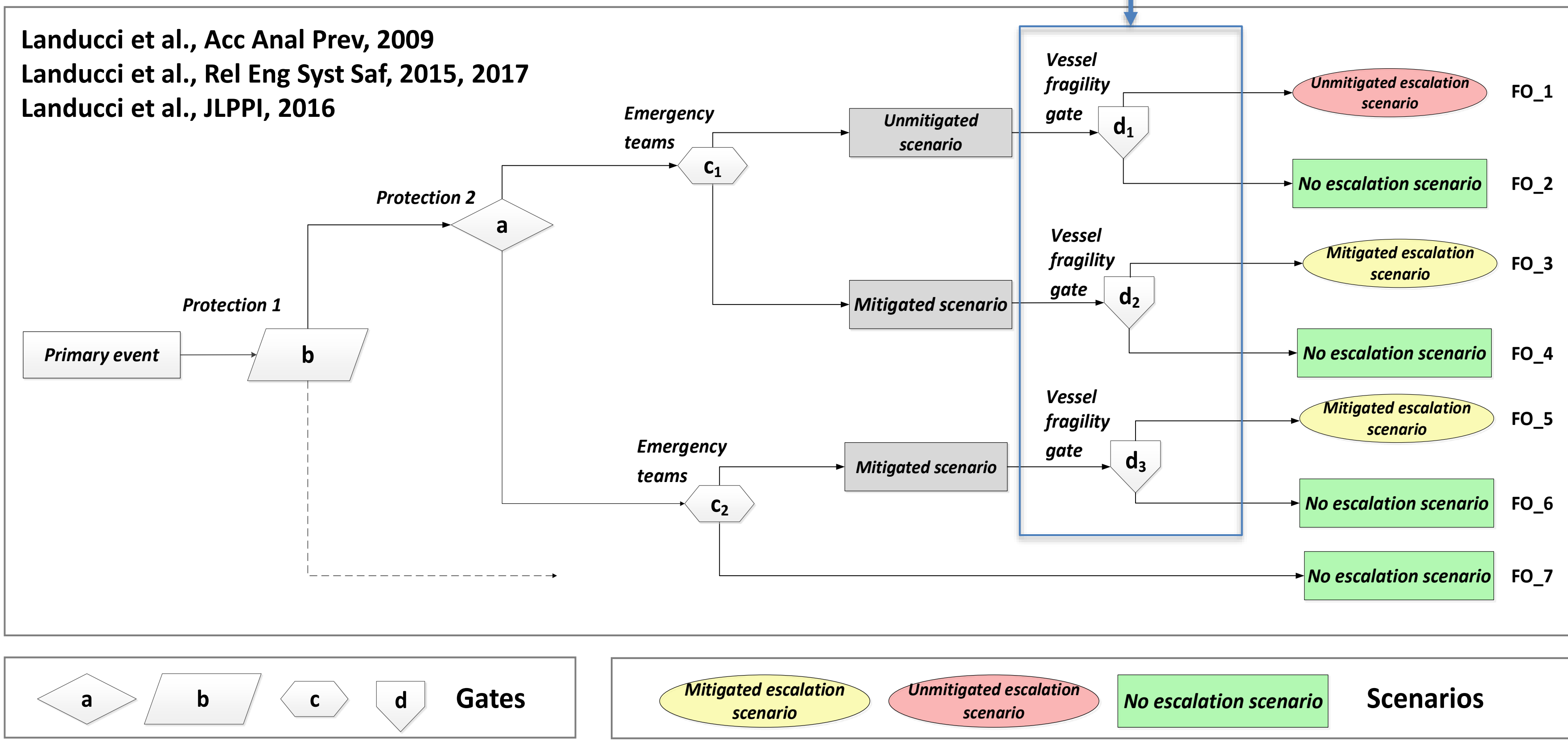
QRA and domino events triggered by fire: safety barriers

Custom event tree analysis

Performance assessment of safety barriers

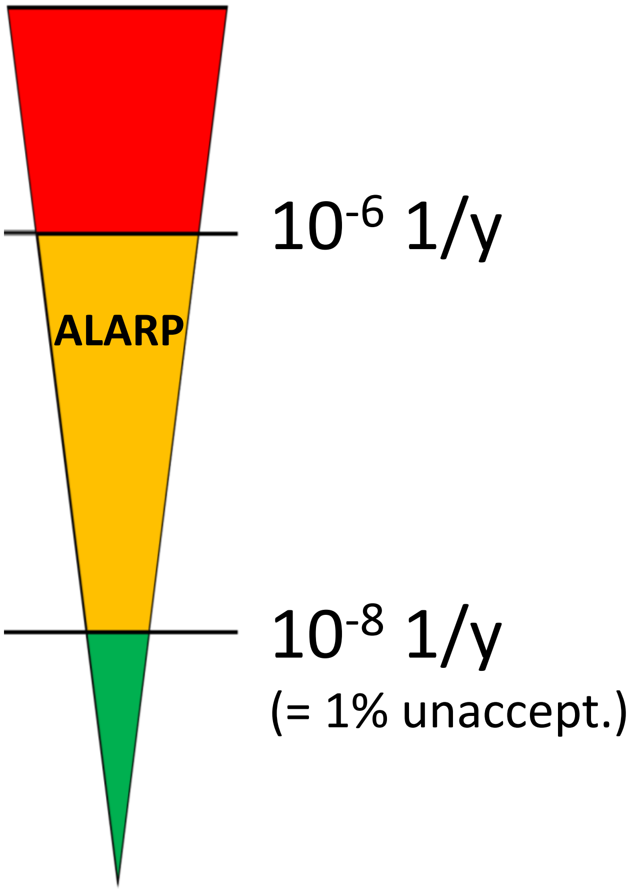
- Availability
- Effectiveness
- **Equipment vulnerability models**

Site-specific probabilistic function typical time required for effective mitigation (TEM) in process industry vs. time to failure (TTF) of the equipment exposed to fire

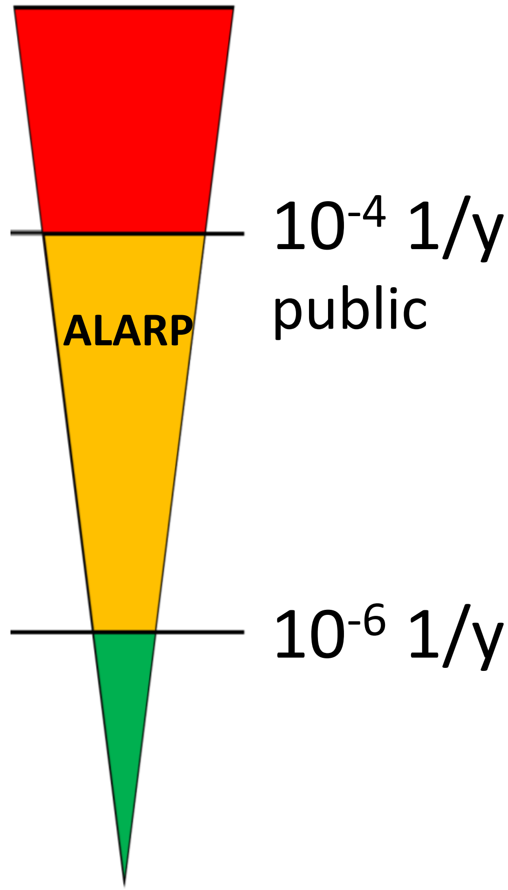


Risk evaluation and management: land use planning (1)

Set risk acceptance criteria for individual risk



SEVESO Land use planning
The Netherlands



SEVESO Land use planning, UK

ALARP

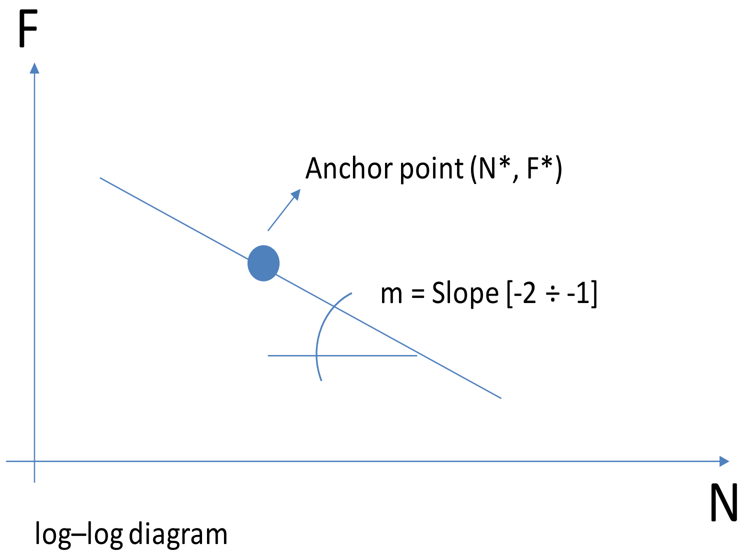
Risks should be managed to be as low as reasonable practicable
(i.e. cost of barriers)

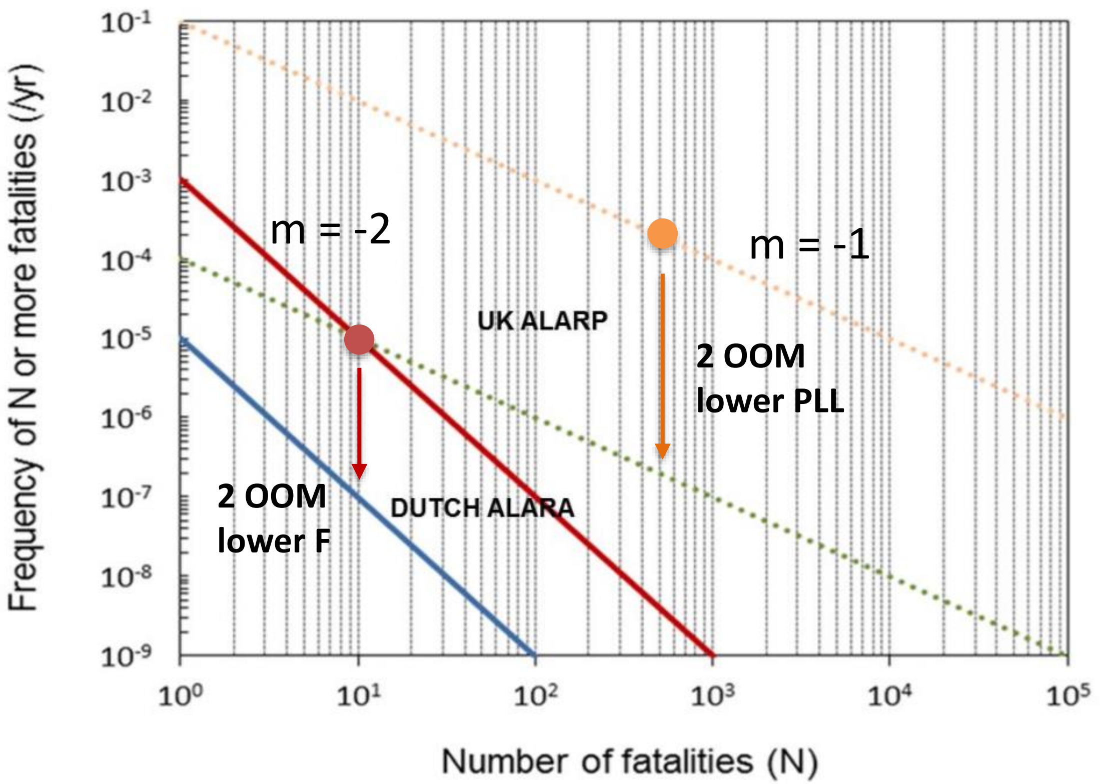
standard measures of practicality to which the risk levels can be compared

Cost vs Risk (cost benefit analysis)

Risk evaluation and management: land use planning (2)

Set risk acceptance criteria for societal risk





m describes the weighting in preference of avoiding large accidents:

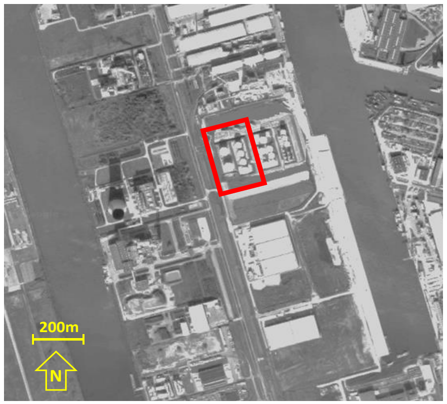
m = -1 Risk neutral;
m = -2 Risk averse

Risk evaluation and management: domino effect (1)

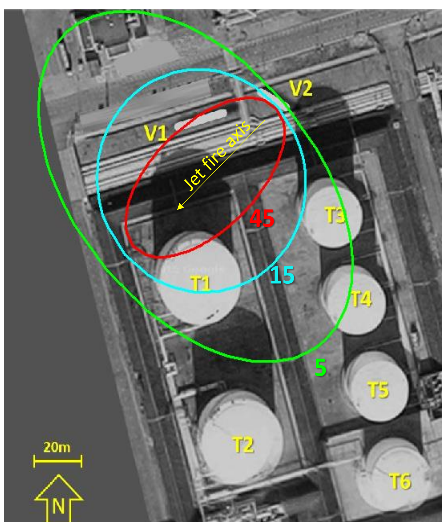
QRA in a chemicals storage plant

- (Case 1) Conventional approach: NO domino
- (Case 2) Simplified approach: domino, no protections
- (Case 3) Novel approach: domino and safety barriers

More details in Landucci et al., RESS, 2017



ID	Diameter (m)	Height (m)	Capacity (m^3)	Design pressure (MPa)	Substance	Inventory (ton)
T1	36.0	9.0	9156	0.1	Petroleum crude	6524
T2	36.0	9.0	9156	0.1	Petroleum crude	6524
T3	24.0	9.0	4069	0.1	Hydrogen sulfide sludge	3357
T4	24.0	9.0	4069	0.1	Sodium chloride sol.	4110
T5	24.0	9.0	4069	0.1	Potassium chloride sol.	4110
T6	24.0	9.0	4069	0.1	Phosphoric acid sol.	4110
V1	3.2	19.4	150	2.0	Propane	67
V2	3.2	12.0	100	2.0	Propane	44

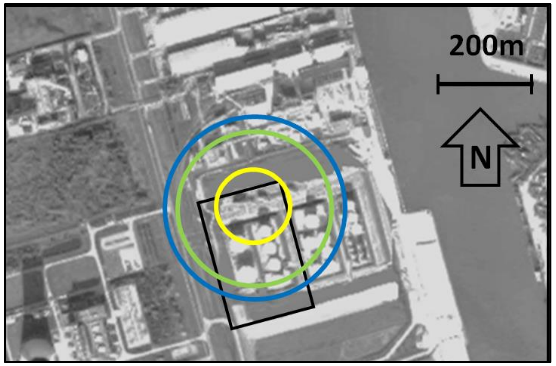


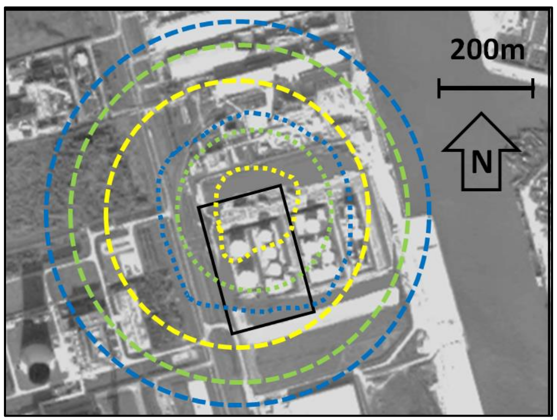
ID	Primary scenario	Radiation (kW/m^2)	ttf (s)	Probit value	Escalation probability	Secondary LOC	Secondary Scenario
T1	-	90	94	8.42	0.9997	Catastrophic release	Pool fire
T3	-	15	819	4.43	0.2827	Catastrophic release	Toxic dispersion
V1	-	90	450	5.53	0.7037	Catastrophic release	Fireball
V2	Jet Fire	-	-	-	-	-	-

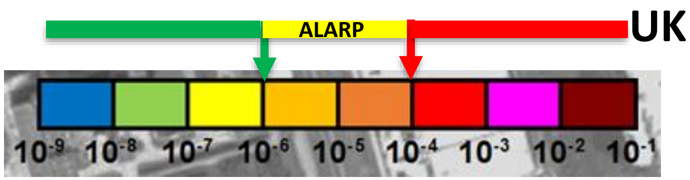
Safety barrier	PFD	Effectiveness	T1	T3	V1
Foam-water sprinkler system	5.43×10^{-3}	0.954	X	X	
Pressure Safety Valve (PSV)	1×10^{-2}	1	X	X	X
Fireproofing coating	0	0.999			X
External emergency intervention	1×10^{-1}	0;1[b]	X	X	X

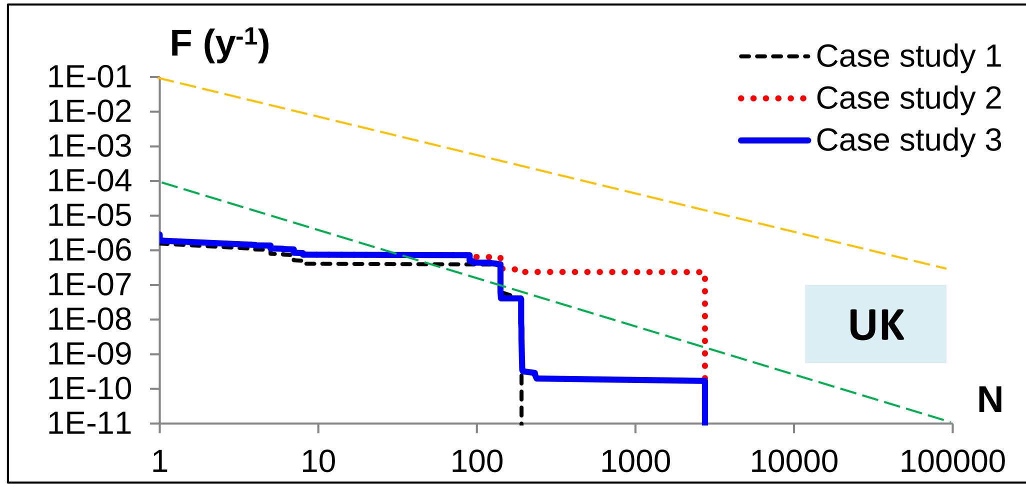
Risk evaluation and management: domino effect (2)

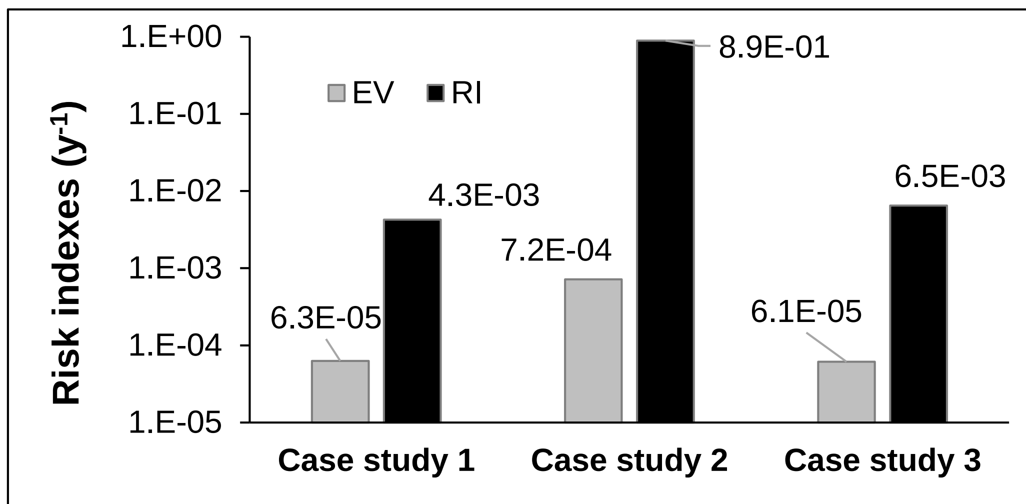
Example of risk reduction achieved trough the implementation of safety barriers











Risk evaluation and management: domino effect (2)

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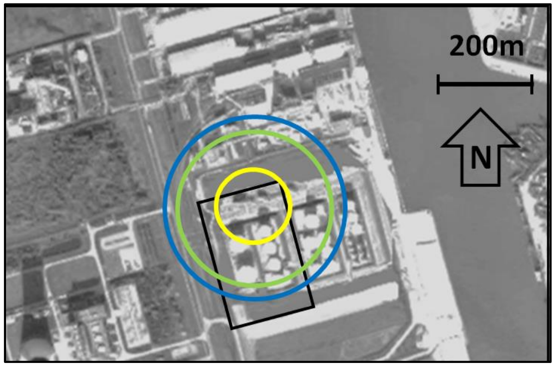
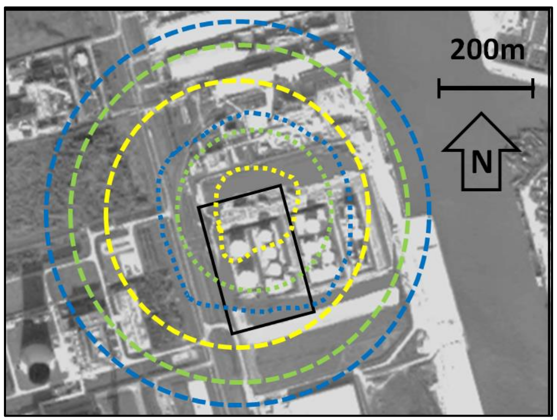
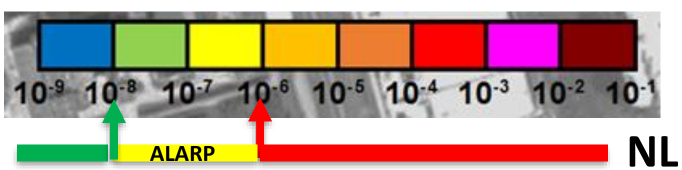
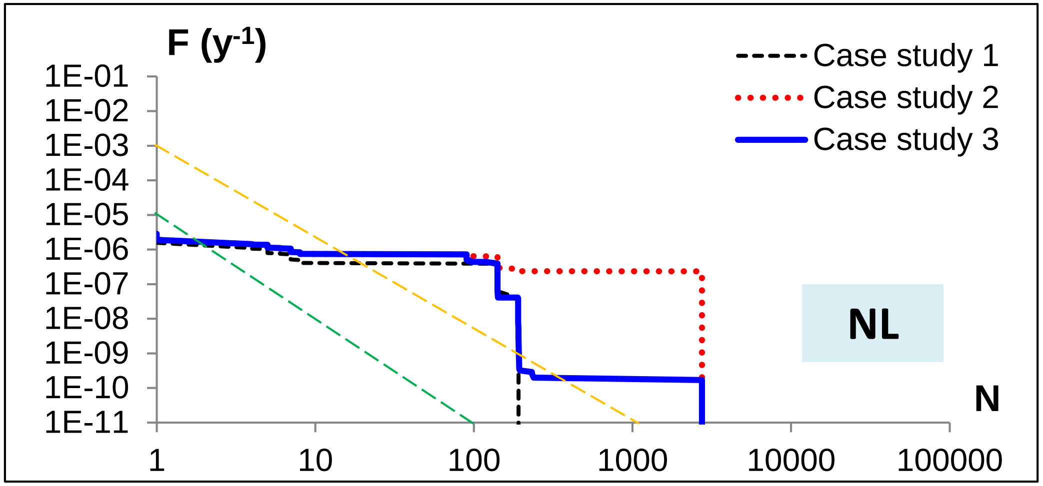
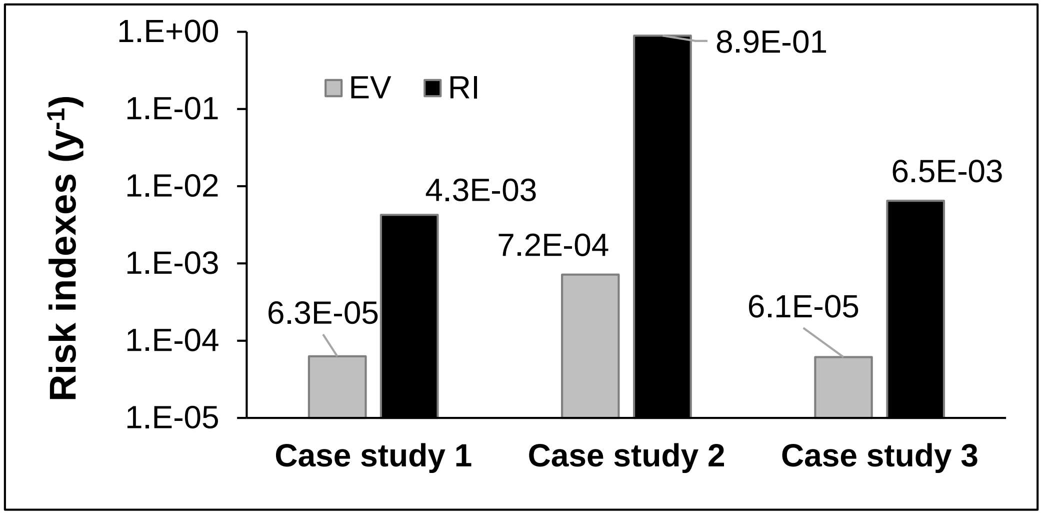










Conclusions

- Quantitative risk assessment in the framework of process facilities was exemplified in “conventional” studies
- Risk metrics and related acceptance criteria in the specific framework are presented
- Based on this framework, detailed methodology for the assessment of domino effect triggered by fire
  - risk reduction due to the safety barriers, availability and effectiveness
- A case study based an actual industrial layout analysis was defined and analyzed

Remarks

- Need of advanced studies and open issues
- Spatial planning in the surrounding of hazardous sources (i.e., chemicals)
- QRA as support to decision making in the selection, application and maintenance of safety barriers and, more in general, industrial facilities

Appendix A

Hazard identification

HAZID
based on brainstorming review of a checklist
comprehension of the highlighted aspects shall be able to identify the predominant hazards at early design stage

Guide Word	Threat	Top Event	Preventive barriers	Consequence	Recovery/ Preparedness - Measures

HAZOP
Brainstorming structured techniques (congruent and complete)
Identify the possible TOP EVENTS, fault chains, detailed design review

Deviation	Causes	Consequence	Safeguards	Actions

Guide word (Less, more, no, etc.) + process parameter (level, temperature, etc.)

Appendix B

(Human) Vulnerability models

I(x,y,z,t) C(x,y,z,t) ΔP(x,y,z,t)

VULNERABILITY MODELS

I = heat radiation, kWm^2

C = concentration, mg/m^3

ΔP = peak overpressure, Pa

t = exposure time, s

<u>DAMAGE PROBABILITY</u>

Threshold models

Scenario	High lethality	Starting lethality	Irreversible lesions	Reversible lesions
Steady fire radiation (kW/m^2)	12.5	7	5	3
Fireball (unsteady radiation)	Fireball radius	350 kJ/m^2	200 kJ/m^2	125 kJ/m^2
Flash fire	LFL	½ LFL		
Explosion overpressure (bar)	0.3 bar (0.6 bar open space)	0.14	0.07	0.03
Toxic exposure	LC50 (30 min, human)		IDLH	

Probit models

Function of dose (D), specific coefficients (k_1,k_2)

$$Pr = k_1 + k_2 \ln D$$

Toxic dose $t\,C^n$

Overpressure ΔP

Thermal dose $t\,I^{4/3}$

Appendix C

Equipment vulnerability models

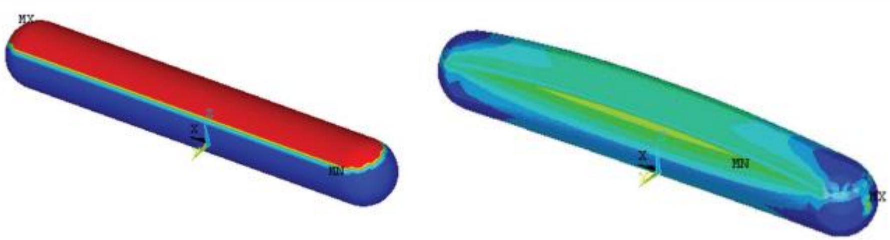
$$Pr = a + b\ln(TTF)$$

(a = 9.25 and b= -1.85)

- ❑ Site-specific probabilistic function
- ❑ Probit constant are derived form site specific factors which take into account the typical time required for effective mitigation (TEM) in process industry fixed installations compared with the time to failure (TTF) of the equipment exposed to fire

TTF is obtained with simplified correlations (Landucci et al. 2009) function of vessel volume (V, m^3) and fire heat load (I, kW/m^2)

Fire exposure model	Correlation for pressurized vessels
Distant source radiation	$\ln(TTF) = -0.95\ln(I) + 8.845\, V^{0.032}$
Full engulfment	$\ln(TTF) = -1.29\ln(I) + 10.970\, V^{0.026}$



Based on sound thermal and mechanical FEM