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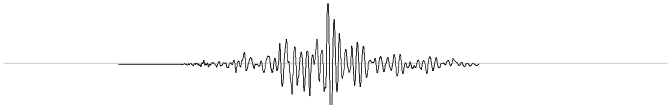

A probabilistic risk assessment of process plants under seismic Loading

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OUTLINE

- Introduction
- Proposal of a procedure for QSRA with MPC capacity
- Quantitative Risk Seismic Assessment by MSC
- Software implementation
- Conclusions

ACKNOWLEDGMENT

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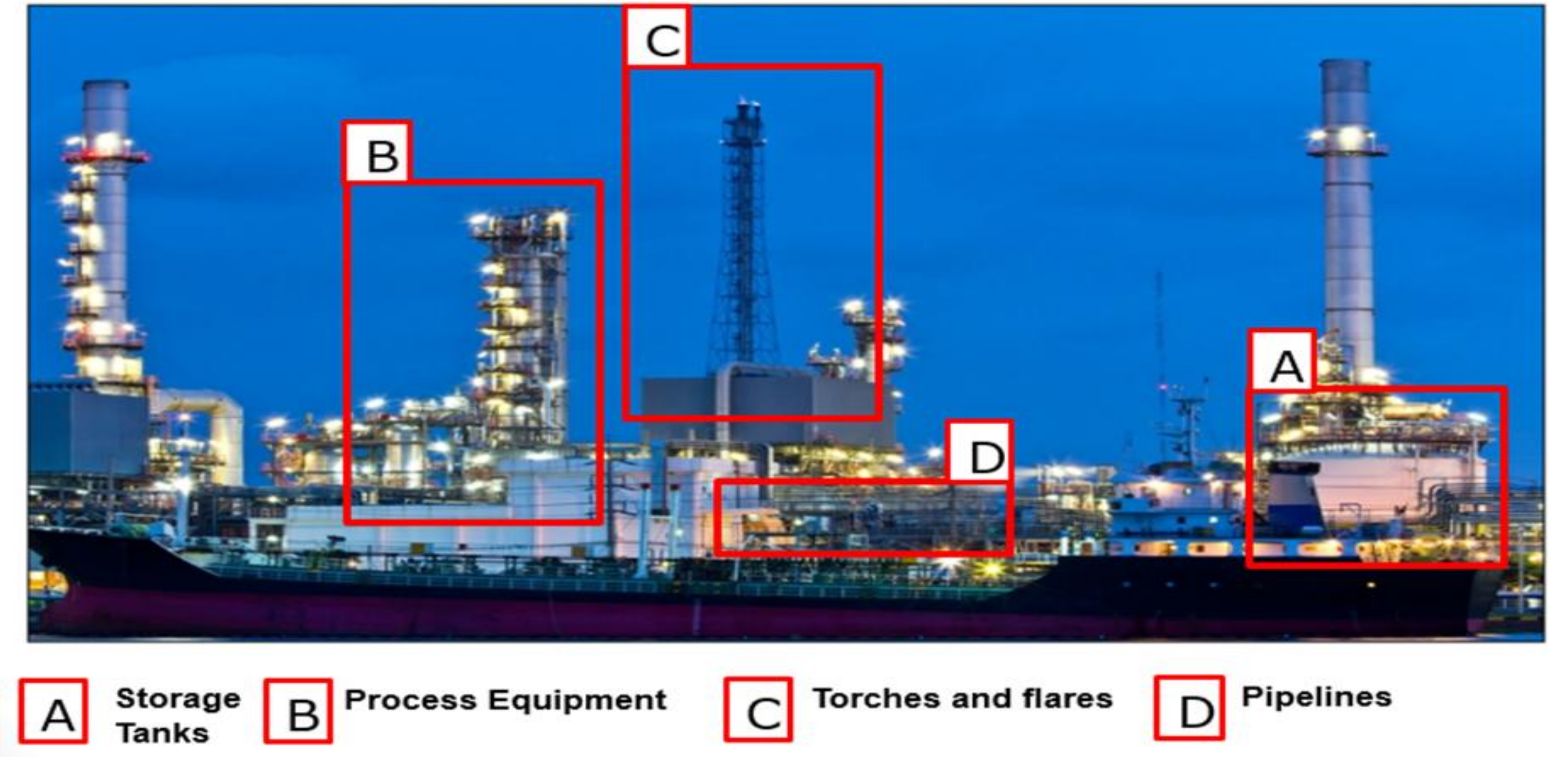
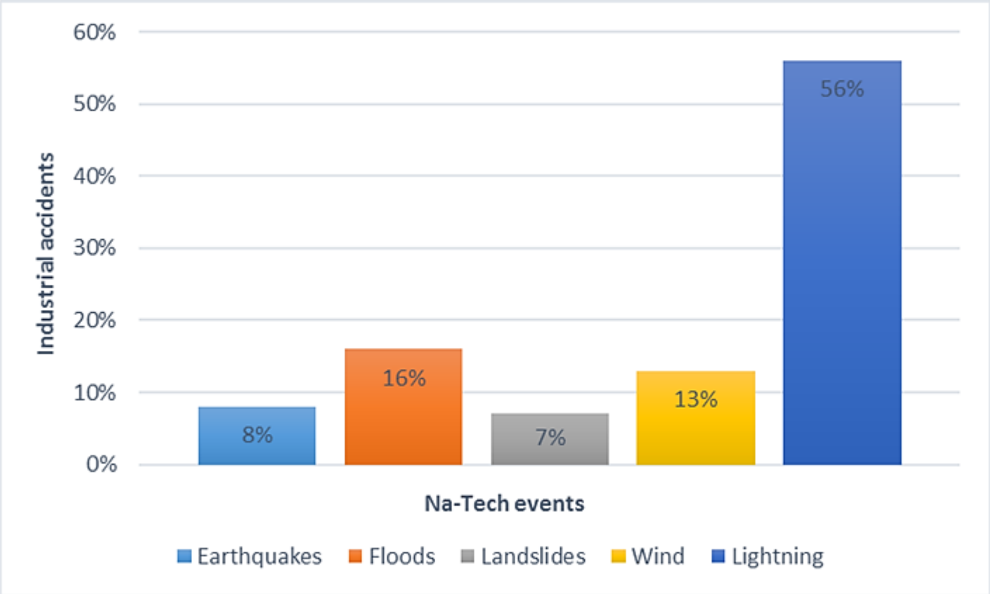
INTRODUCTION

In a world that has a continuous need of petrochemicals, an important role is played by refineries. Once discovered, drilled and brought to the earth's surface, crude oil is transported to a refinery by pipeline, ship or both. At the refinery, it is treated and converted into consumer and industrial products. A petroleum refinery is a complex assembly of individual process plants interconnected with piping and tanks.



NATECH EVENTS

Several accidents occurred in the last decades in industrial sites have evidenced that naturals phenomena may cause severe damages to equipment items, resulting in losses of containment, thus in multiple and extended releases of hazardous substances.



Database: MHIDAS

Past accidents analysis evidences that structural damage to the equipment directly struck by lightning is the more frequent cause of loss of containments accidents, but generally seismic events produces severe consequence because increases the likelihood of **multiple and simultaneous failures** of industrial components.

Typical layout of a Petroleum Refinery

STRUCTURAL CLASSIFICATION OF PLANT COMPONENTS

Structural typology	Critical equipment	Typical seismic observed damages	Other possible damages
Slim vessels	**Columns** **Reactors** **Chimney** **Torch**	• Leakage of fluid in flanged joints • Yielding of anchor bars	**Overturning**
Above-ground squat equipment	Big broad tanks with fixed and floating roof	**Failure of wall-bottom plate welding** **Elephant foot buckling** **Diamond buckling of tank wall** **Settlements of ground** **Impact of floating roof to tank wall.**	**Uplifting** **Overtopping** **Torch fire**
Squat equipment placed on short columns	**Spherical tanks**	**Collapse of structure due to shear failure of columns**	
	Process Furnaces	**Collapse of structure due to shear failure of columns** **Collapse of the chimney** **Detachment of internal pipes** **Detachment of the internal refractory material**	**Leakage from pipes;** **Increase of temperature of Furnace wall**
	Cryogenic tanks	**Collapse of structure due to shear failure of columns**	
Piping systems and support structure	**Steel or R.C. frames**	**Collapse for excessive stresses**	**Damages to supported equipment (pipes, tanks,..)**

*Paolacci F., Giannini R., De Angelis M., (2013), Seismic response mitigation of chemical plant components by passive control systems, **Journal of Loss Prevention in Process Industries**, Volume 26, Issue 5, Pages 879-948 Special Issue: Process Safety and Globalization - DOI:10.1016/j.jlp.2013.03.003.*

NATECH EVENTS: *Earthquakes*

The Kocaeli earthquake caused significant structural damages to the Tupras refinery itself and associated tank farm with crude oil and product jetties and triggered multiple fires in the refinery's naphtha tank farms.

Kocaeli earthquake (Turkey) -17 August 1999 - Magnitudes 7.4

Tupras refinery

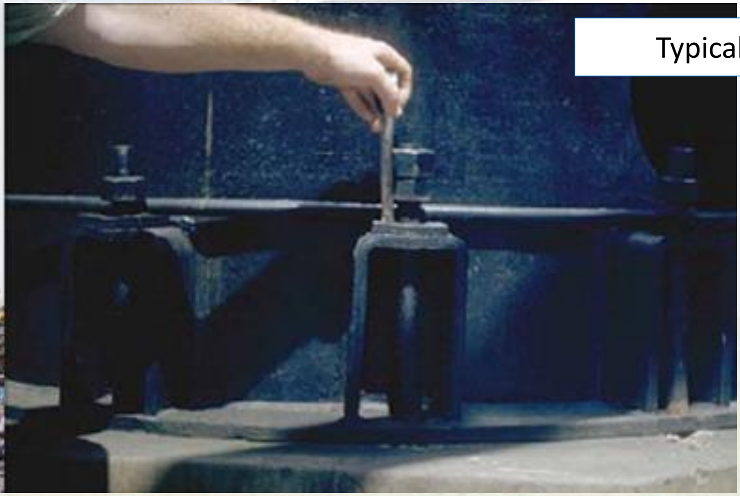
- The majority of the floating roof tanks (30 out of 45) were damaged;
- 250.000 m^3 crude oil and 100.000 m^3 oil product having been exposed to the atmosphere and partially pouring out of the tanks;
- Evacuation order was issued by the crisis centre for a zone of 5 km around the refinery;
- Considerable oil pollution occurred during the incident;
- Total damage is estimated to be around US$ 350 million.

Lession from the past: Extreme vulnerability of the tank farm, importance of the domino effect, damaging of the services and security systems.

SLIM VESSELS



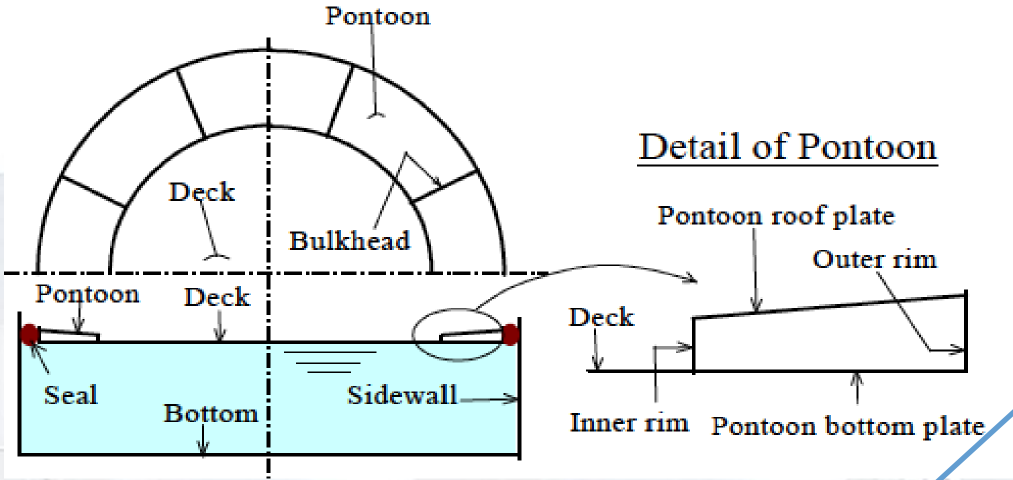




Typical Seismic Damages

ABOVE-GROUND STORAGE TANKS

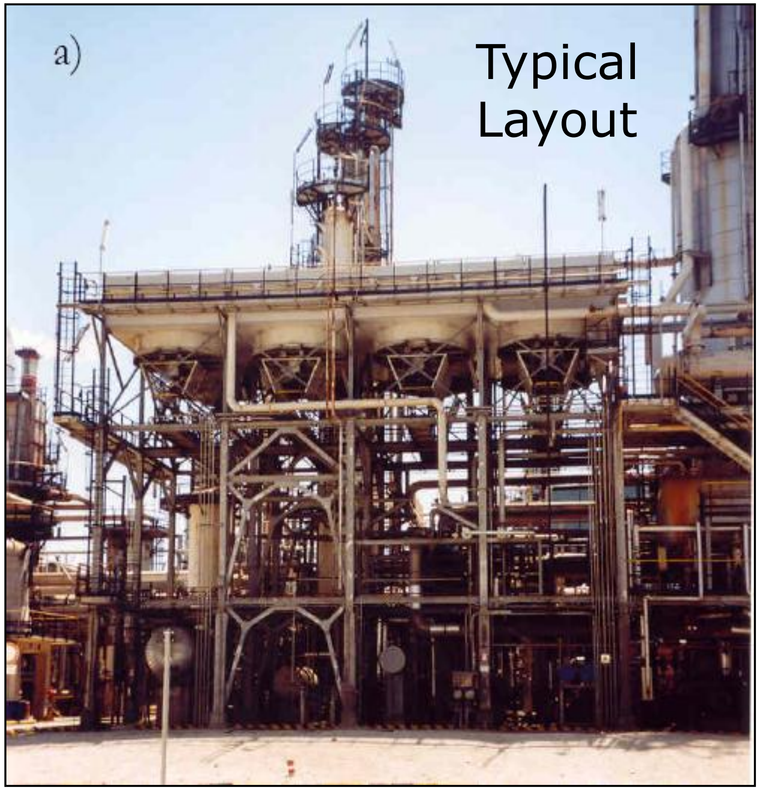
ABOVE-GROUND STORAGE TANKS



Typical Damages in the Floating Roof

ELEVATED STORAGE TANKS

REFINERY PIPING SYSTEMS



NATECH EVENTS: *WHAT ABOUT RISK?*

- Quantitative Risk Assessment (QRA) is an established method utilized for the calculation of risk in process plants based on the logic of consequence analysis described, for instance, in the "**Purple Book**".

- This intrinsically probabilistic method has been thought for **classical accident conditions** in which the damage event and the relevant consequences start from a preselected component and a **predefined LOC**;

- In presence of **Natech events**, like earthquakes, a multisource condition can be caused by multi-damage conditions (**damage in more than one component**), which in turn can generate multiple-chains of events and consequences,

NATECH EVENTS: *WHAT ABOUT RISK?*

In literature several attempts of modifying the classic QRA approach to account for this important aspect have been formalized, but without converging toward a unified approach.

- Cozzani V., et al., 2005, The assessment of risk caused by domino effect in quantitative area risk analysis. Journal of Hazardous Materials, 127:14-30.
- Fabbrocino, G., Iervolino, I., Orlando, F., & Salzano, E. (2005). Quantitative risk analysis of oil storage facilities in seismic areas. Journal of Hazardous Materials, 123(1:3), 61-69.
- Antonioni, G., Spadoni, G. & Cozzani, V., 2007, A methodology for the quantitative risk assessment of major accidents triggered by seismic events, Journal of Hazardous Materials, 147(1-2), 48-59.

The main reason is that the above methods try to assess the overall plant vulnerability due to possible contemporary accident scenarios caused by the release of hazardous materials but **fails to include a systematic procedure to analyze chain of accidents and are based on standard data for LOC frequencies**

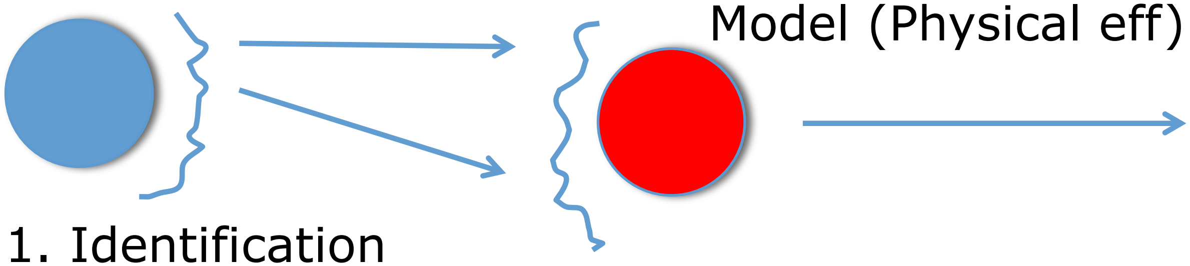
NATECH EVENTS: *WHAT ABOUT RISK?*

The problem of the uncertainties propagation, intrinsically related to **domino effects** triggered by seismic events, has been analyzed in the past by using different approaches, ranging from **analytical** to **numerical** formulations.

- Busini V., Marzo E., Callioni A., Rota R., (2011), Definition of a short-cut methodology for assessing earthquake-related Na-Tech risk, Journal of Hazardous Materials, Volume 192, Issue 1, 15 August, Pages 329-339.
- Huang Y., Whittaker A.S., Luco N., (2011), A probabilistic seismic risk assessment procedure for nuclear power plants: (I) Methodology, Nuclear Engineering and Design, Volume 241, Issue 9, September.
- Alileche N, Olivier D., Estel L., Cozzani V., (2016), Analysis of domino effect in the process industry using the event tree method, doi:10.1016/j.ssci.2015.12.028

These works often either they are not referred to process plants under seismic action or they are for seismic action but referred to different plants like NPP.

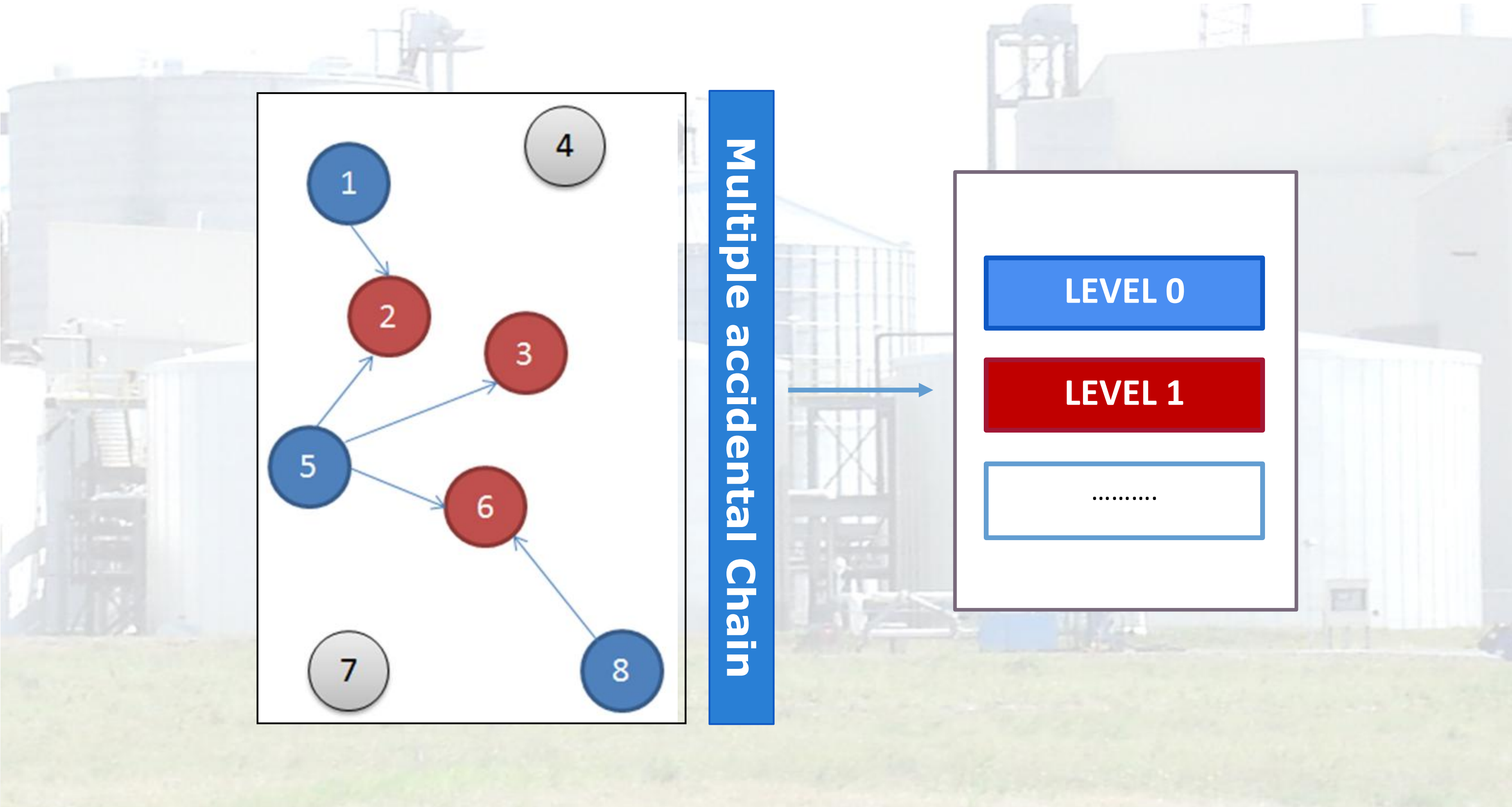
The classical QRA method, described in the Purple book and utilized for the risk assessment of process plants subjected to an industrial accident, basically relies on the following steps:



Multiple chains lead to Domino Effect

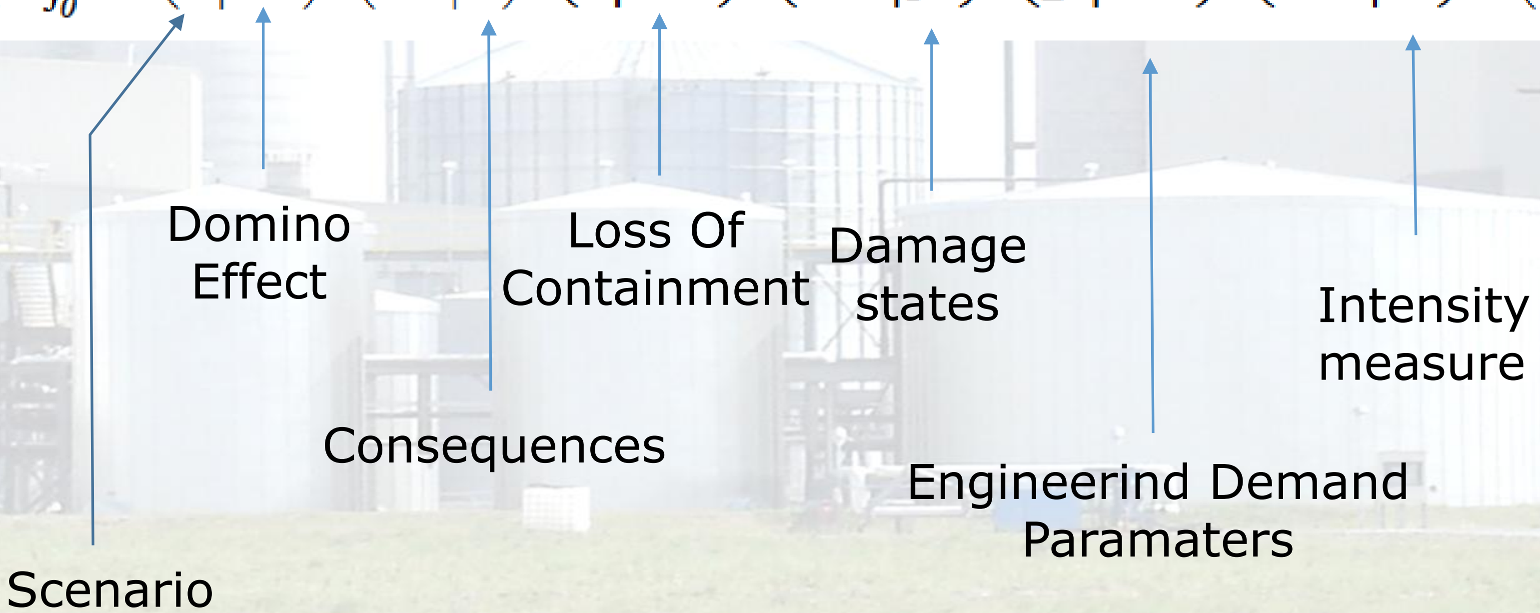
NATECH EVENTS: *WHAT ABOUT RISK?*

In case of **Natech events**, like earthquakes, a multiplicity of chains can be contemporarily triggered and propagated. Therefore, a **series of random initial scenarios** need to be generated and the consequences analysed, including interactions between chains (Multiple levels).



In case of **Natech events**, like earthquakes, a multiplicity of chains can be contemporarily triggered and propagated. Therefore, a **series of random initial scenarios** need to be generated and the consequences analysed, including interactions between chains (Multiple levels).
The probability of a given final scenario can be ideally calculated base on the following general integral

$$P_{tot}=\int_0^{+\infty} P(S\mid DE)\,P(DE\mid C)\,P(C|LOC)\,P(LOC|DS)\,P(LS|EDP)\,P(EDP|IM)\,dP(IM)$$

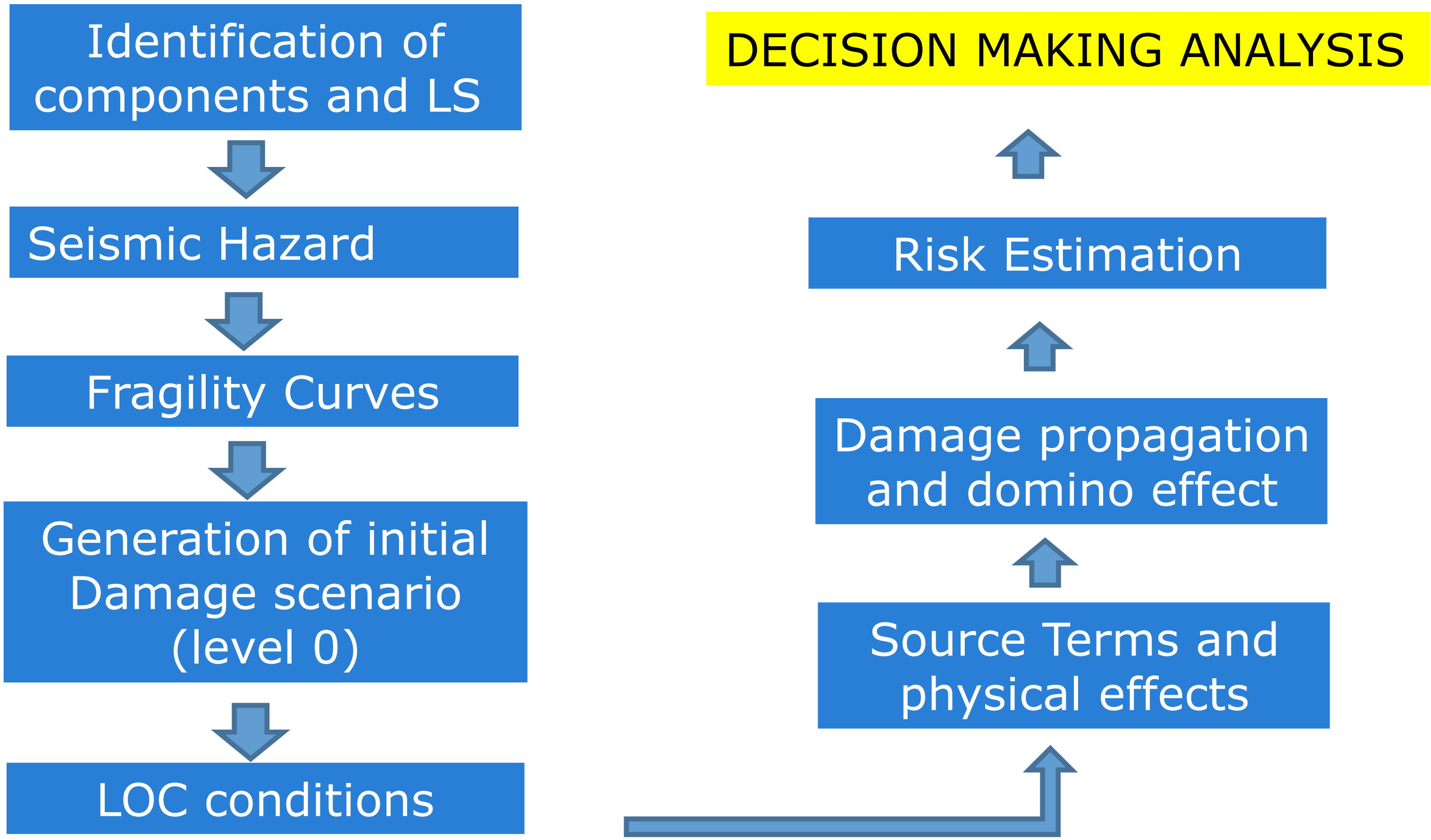


P(X|Y) is conditional probability of X given Y

Proposal of a new procedure for QSRA of petrochemical plants

1. Classification of plant equipment and identification of the relevant limit states and failure modes triggered by earthquake exposure;
2. Seismic Hazard assessment by PSHA and selection of seismic input;
3. Derivation of fragility curves of all equipment;
4. Determination of the initial damage scenario (level 0)
5. Determination of loss of containment (LOC) events for each component damaged by the earthquake according to limit states;
6. Estimation of source terms and physical effects for each seismically damaged unit (consequences);
7. Evaluation of damage propagation (domino effect), which includes the identification of possible damages caused by the earthquake to the undamaged units and derivation of consequences for the next levels (level > 0) until no further units are damaged and the propagation stops;
8. Risk estimation and ranking scenarios.

Proposal of a procedure for QSRA of petrochemical plants



Step 1: Identification of pant components

F. Paolacci, R. Giannini, M. De Angelis, (2013), Seismic response mitigation of chemical plant components by passive control systems, *Journal of Loss Prevention in Process Industries, Volume 26, Issue 5, Pages 879-948 Special Issue: Process Safety and Globalization* - **DOI:10.1016/j.jlp.2013.03.003.**

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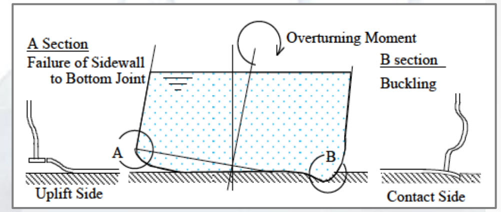
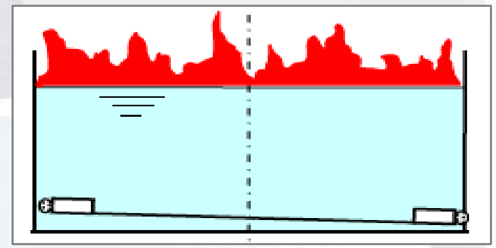
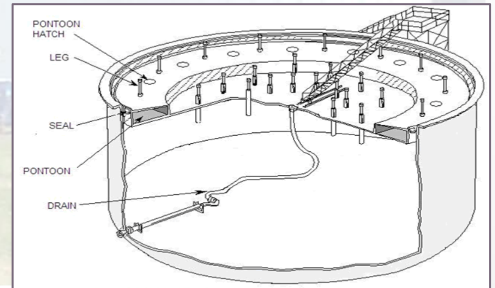
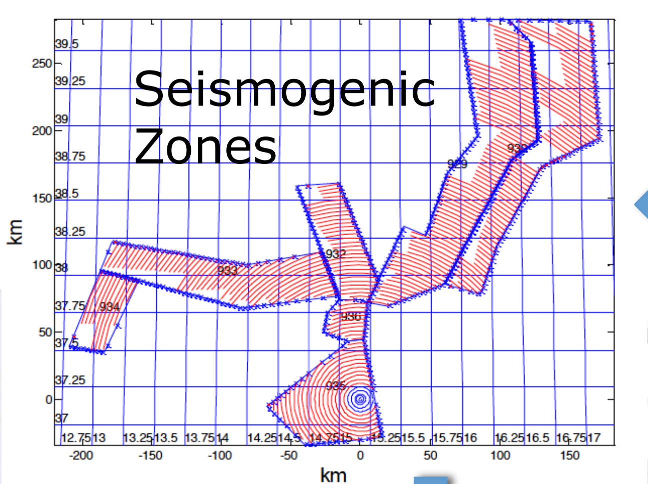


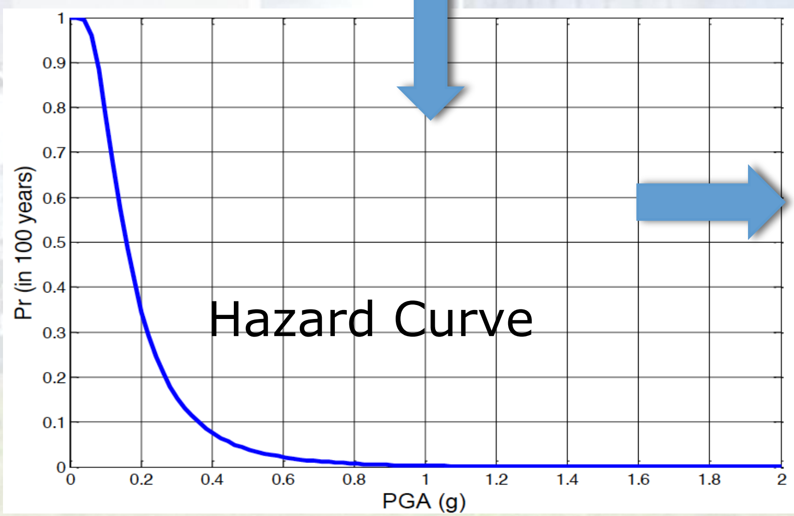


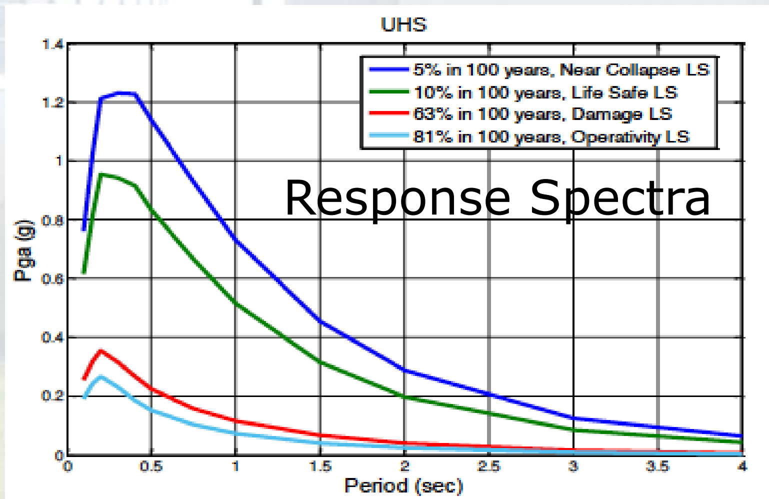


External Floating Roof Tank, single skin roof with pontoons

Step 2: Seismic Hazard







Step 3: Fragility Curves evaluation

For the purpose, only the damages connected to the leakage of the content are considered fundamentals based on which fragility curves can be built.

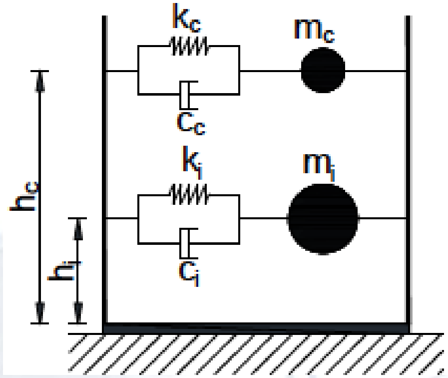
Unanchored tanks

Limit State (LS)	**Engineering Demand Parameter (EDP)**	**Damage Measure (DM)**
Elephant Foot Buckling	Meridional Stress σ_v	Buckling limit σ_{EFP}
Shell fracture	Hoop Stress σ_H	Buckling limit σ_E
Sliding	$F_{sliding} = \mu W$	Total Base Shear
Overturning	Overturning Moment	Overturning Moment limit
Base plate fracture	Max local strain	Strain limit
Roof Damage	Max Vertical displacement of liquid	Free-board height

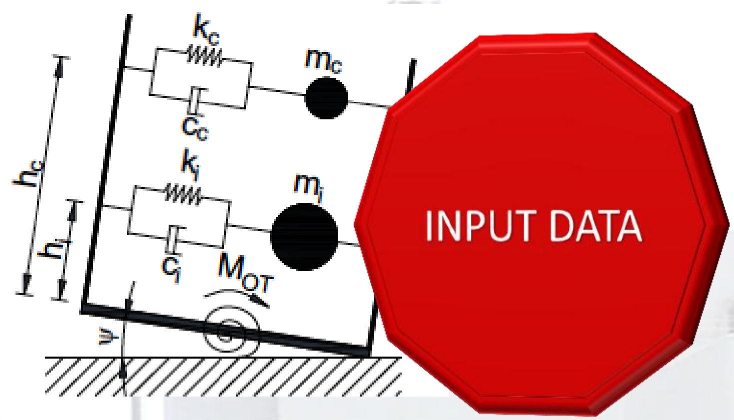
Anchored tanks

Limit State (LS)	**Engineering Demand Parameter (EDP)**	**Damage Measure (DM)**
Elephant Foot Buckling	Meridional Stress σ_v	Buckling limit σ_{EFP}
Shell fracture	Hoop Stress σ_H	Buckling limit σ_E
Roof Damage	Max Vertical displacement of liquid	Free-board height

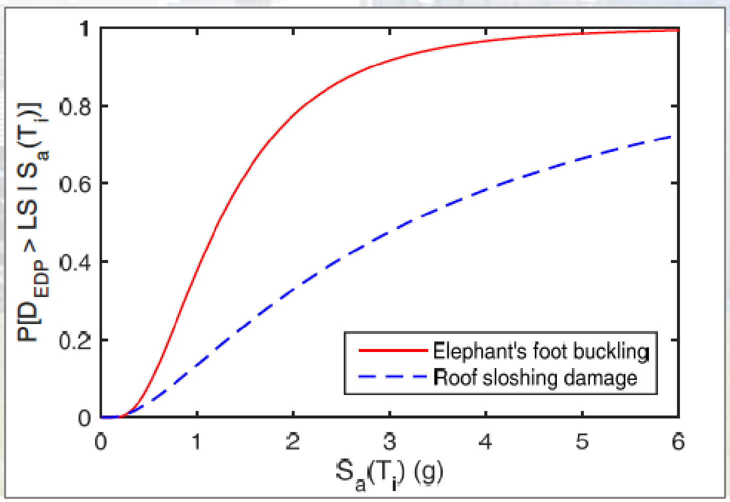
Step 3: Fragility Curves evaluation

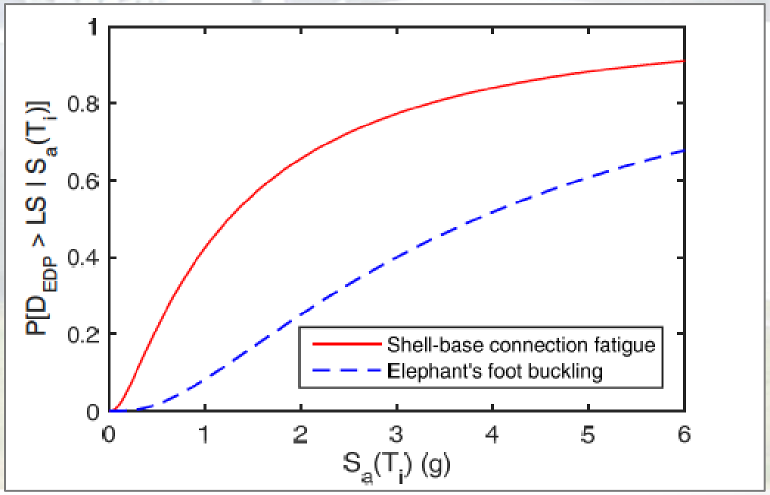


Anchored



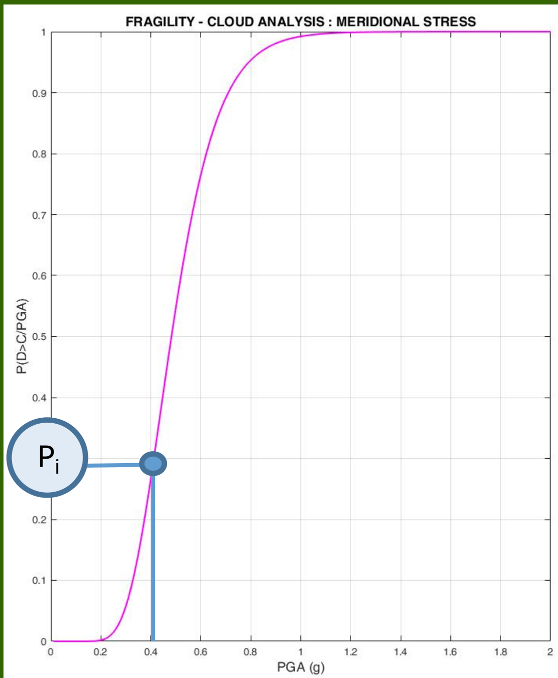
Unanchored





Step 4: Damage scenarios at level 0

For each component: possibles damage typology are randomly generated, damage typologies are considered independently each other and if more damages occurs , conservatively, is considered the more unfavorable.



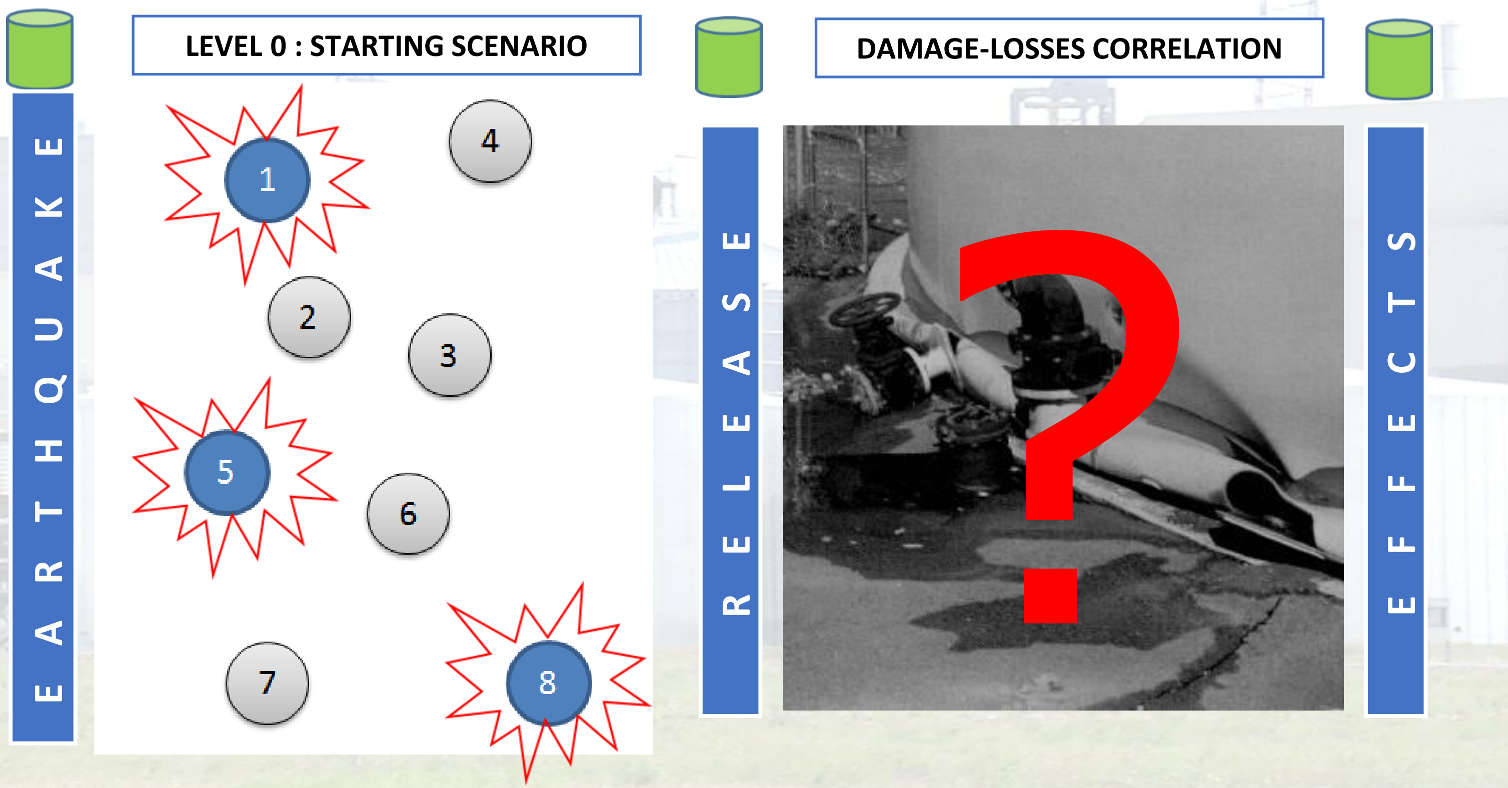
For each equipment and for each limit state, a number 0 ≤ n ≤ 1 is randomly generated by using a uniform probability function.

For the desired LS and IM (PGA) the equipment is considered damaged if:

$$n > P_i$$

Step 5: Determination of LOC events

Several accidents occurred in the last decades evidenced that the impact of seismic events in industrial plants may trigger accidental scenarios involving the release of relevant quantities of hazardous substances.



Step 5: Determination of LOC events

- The criteria to estimate risk level of an industrial facility are based on the type of stored material and on the quantity of material release connected to the type and level of damage

- Procedure concerns the evaluation of the corresponding LOC conditions. In principle, LS and LOC shall be considered both as random variables. Consequently, the determination of the probability of occurrence of a LOC condition given a certain LS would be necessary. However, in the procedure, this relationship will be considered deterministic.

Step 5: Determination of LOC events

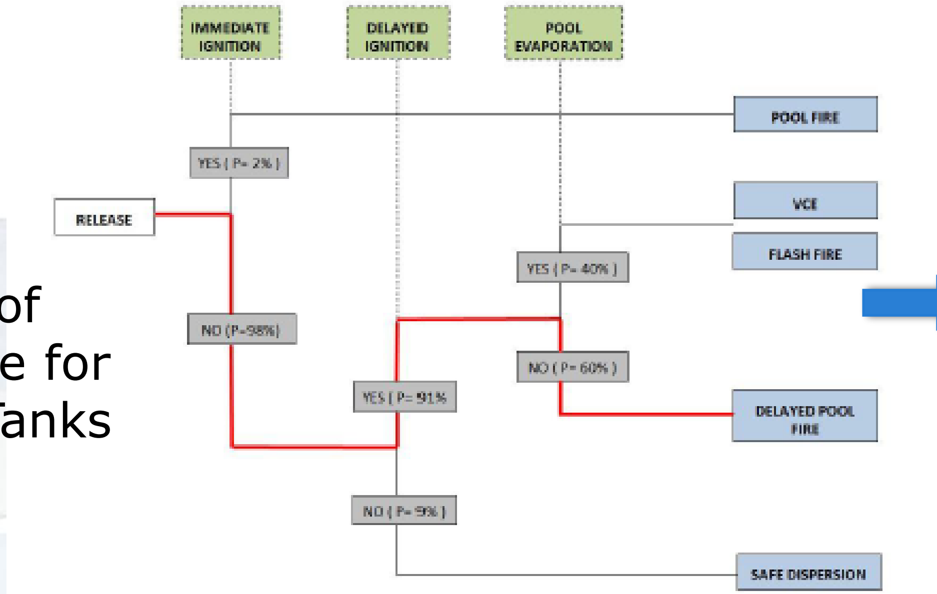
In principle, LS and LOC shall be considered both as random variables. Consequently, the determination of the probability of occurrence of a LOC condition given a certain LS would be necessary. However, in what follows, this relationship will be considered deterministic.

DS/LOC Matrix for anchored tanks

Damage State (DS)	**Engineering Demand Parameter (EDP)**	**Damage State Threshold (LS)**	**LOC1 Continuous release from a 10mm hole**	**LOC2 Continuous release from a full bore of the pipe**	**LOC3 Instantaneous release of full content**
Elephant Foot Buckling	Meridional Stress σ_M	Buckling limit σ_{EFB}	No	Yes	No
Diamond Shape buckling	Hoop Stress σ_H	Buckling limit σ_E	Yes	No	No
Sliding	Total Base Shear	$F_{sliding} = \mu W$	No	Yes	No
Overturning	Overturning Moment	Overturning Moment limit	No	No	Yes
Base plate fracture	Max local strain	Strain limit	No	No	No
Roof Damage	Max vertical displacement of liquid	Free-board height	No	No	No

Step 6: Physical Effects

Example of Event Tree for Storage Tanks



Pool Fire

Bleve and Fire Ball

Jet Fire

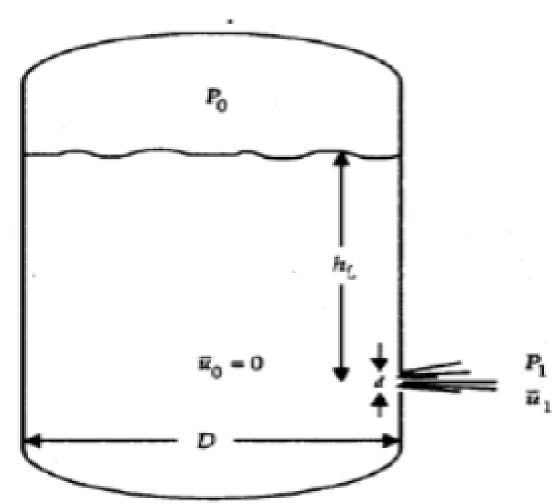
Vapour Cloud Explosion

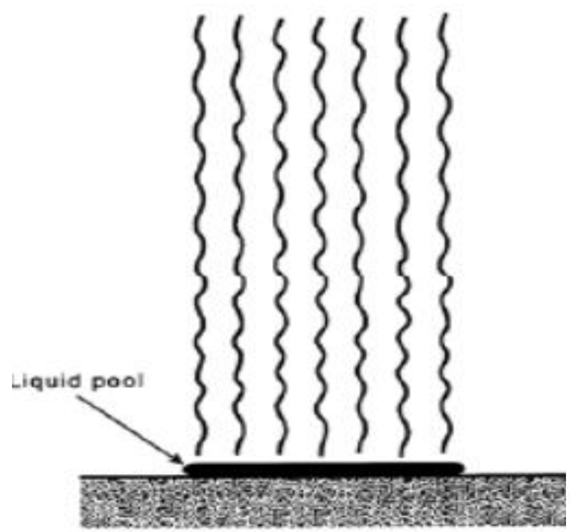
Step 6: Physical Effects

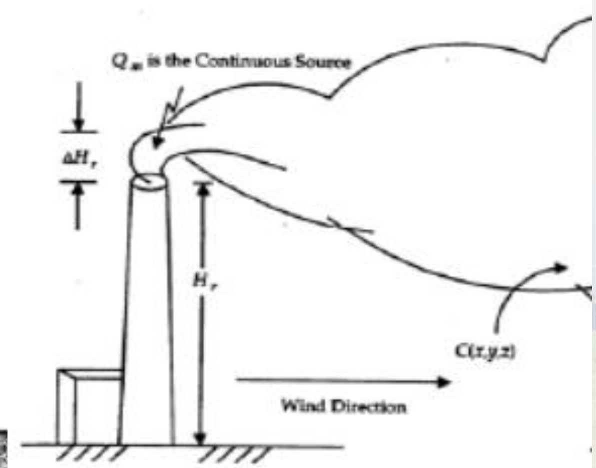
Modelling source terms and dispersion

After having definied the loss of containment events for a **single event**, the source terms and the dispersion in the environmental have to be calculate.

Outflow and spray release	Pool evaporation	Vapor cloud dispersion







Step 6: Physical Effects

Modelling source terms and dispersion

From an instantaneous or continuous release very different consequence can be developed.

Heat flux from fires

Pool Fire	Jet Fire	Fireball



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Step 6: Physical Effects

Modelling source terms and dispersion

From an instantaneous or continuous release very different consequence can be developed.

Explosion

↓

VCE

Step 6: Physical Effects

Modelling source terms and dispersion

From an instantaneous or continuous release very different consequence can be developed.

Toxic exposure

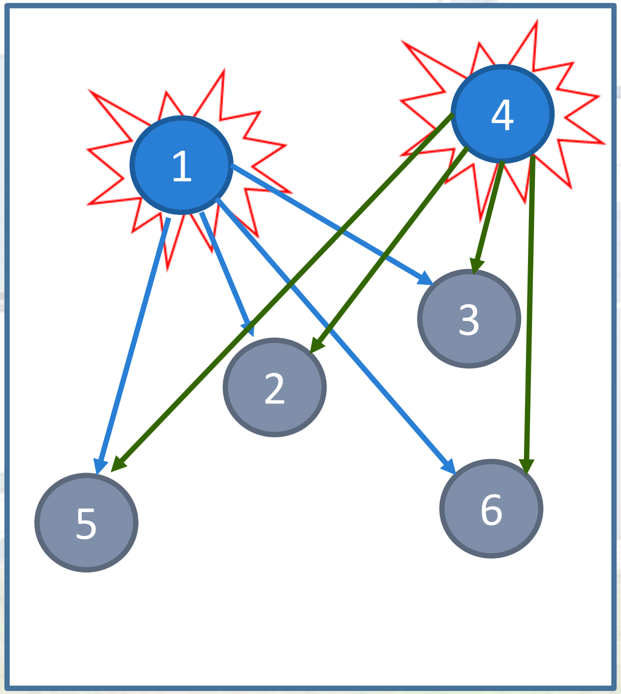
↓

Pollution of the air and soil

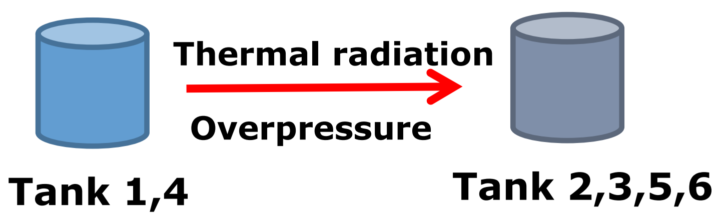
Step 7: Damage propagation and domino effect

Logical sequence of domino effect : for each seismically damaged unit, the procedure includes the damage evaluation in the remaining undamaged units.

LEVEL 0 : STARTING SCENARIO



LEVEL 1 : DOMINO EFFECT



Possible effects on target units :

Tank 1: Thermal radiation Tank 4: Thermal radiation	Target: Sum of Thermal radiations
Tank 1: Thermal radiation Tank 4: Overpressure	Target: Worse effect
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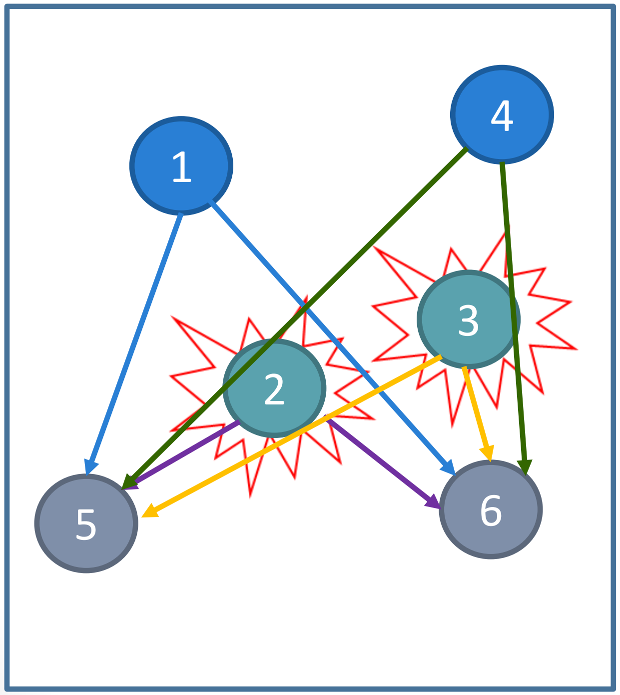
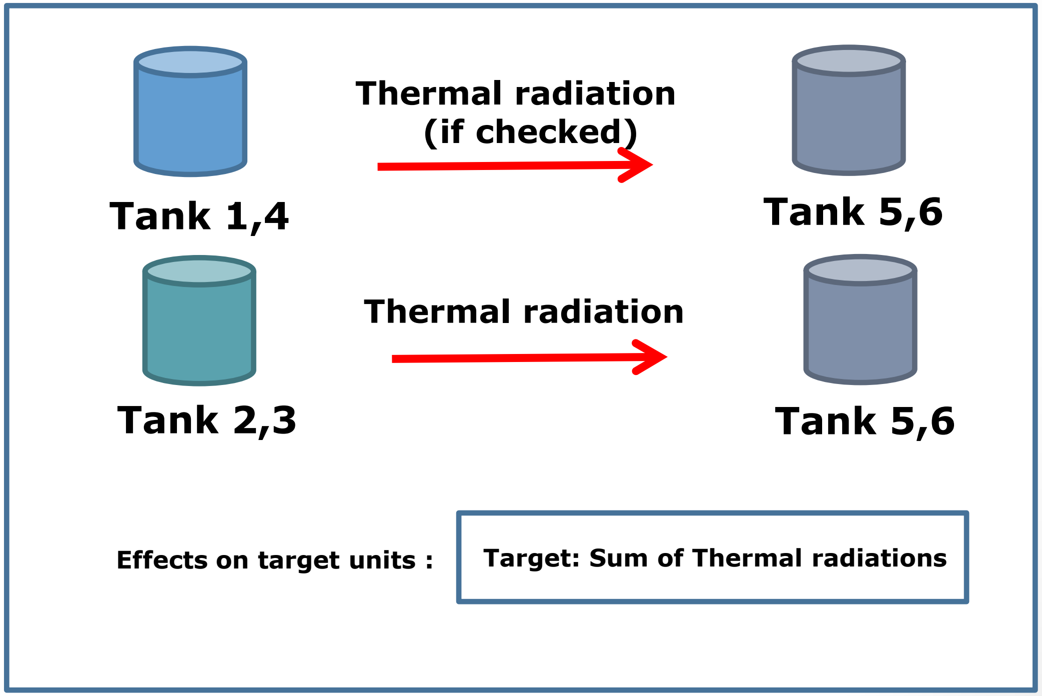


LEVEL 2 : DOMINO EFFECT



Step 7: Damage propagation and domino effect

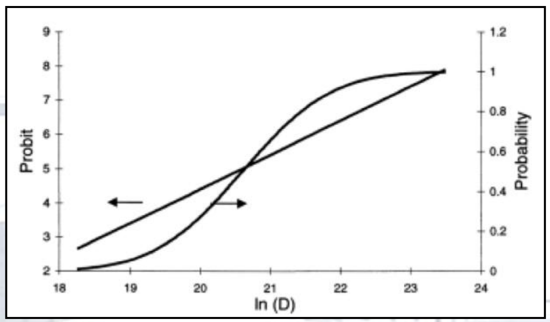
For each seismically damaged unit, after the quantification of the physical effects (pressure, thermal radiation, etc..) due to a LOC event, the procedure includes the damage evaluation in the remaining undamaged units.

Thermal radiation

Overpressure

SOURCE UNIT

Level 0



Probabilistic target damage <u>on weakened structures</u> <u>(Probit models)</u>

Thermal radiation

TARGET UNIT

Level 1

$$P = 0.5\left[1 + \mathrm{erf}\left(\frac{Pr - 5}{\sqrt{2}}\right)\right]$$

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt$$

Step 7: Damage propagation and domino effect

The proposed procedure allows three different types of seismic analysis of the plant: **scenario, fragility** and **risk analysis .**

- The first approach defines the seismic scenario corresponding to the occurrence of an earthquake with a given magnitude M at a given distance D from the site with soil conditions S (e.g., the most likely event producing a given value of the Intensity Measure (IM) at the site, obtained by a deaggregation analysis); therefore, the outcomes are conditioned to the occurrence of the selected earthquake.
- Differently, the fragility approach consists in calculating the probability of occurrence of damage scenarios and consequence for a given set of IMs. This approach can be adopted to investigate the behaviour of the plant to increasing seismic intensities.
- Finally, the third approach consists in a complete risk analysis of the plant.

Step 7: Damage propagation and domino effect: Scenario

If a scenario or a fragility analysis is selected, the probability of occurrence of a given damage scenario, conditioned, respectively, to the seismic scenario or a given value of the IM (e.g. PGA) can be calculated with the relation P[S|PGA], where N is the number of simulations and I_i is the indicator function of the event i for a damage d .

$$P[S \mid PGA] = \frac{\sum_{i=1}^{N} I(d)}{N}$$

Similarly, the expected cost L reads where Cij (dj) indicates the reparing/substitution cost of the j-th unit of the plant that, at the i-th sampling, is subjected to the damage dj ; the second summation is extended to all damaged elements

$$C[L \mid PGA] = \frac{\sum_{i=1}^{N} \sum_{j} C_{ij}(d_j)}{N}$$

Step 7: Damage propagation and domino effect: Scenario

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Probability of a scenario

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$$C[L \mid PGA] = \frac{\sum_{i=1}^{N} \sum_{j} C_{ij}(d_j)}{N}$$

Economic losses

Step 7: Damage propagation and domino effect: Risk

When the risk analysis option is selected, the Magnitude (m) of the seismic event and the distance (R) of the site form the epicenter or the fault are randomly sampled. The PGA is then determined by using a proper seismic attenuation relationship.

- The Magnitude is sampled by using the Gutemberg-Richetr law
- The distance is sampled from a uniform distribution fuction p=dA/A
- The seismic activity is sampled by assuming a uniform annual rate of occurence

To improve the efficiency of MCS the **importance sampling technique** is used

$$p = \frac{\sum_{i=1}^{N} I(d) w_{Ri} w_{Mi} w_{SZi}}{N}$$

$$w_m = \frac{\beta e^{-\beta m}(m_{max} - m_{min})}{e^{-\beta m_{min}} - e^{-\beta m_{max}}}$$

$$w_R = \frac{dA(R)}{A}$$

$$w_{SZ} = \nu_0 \frac{e^{-\beta m} - e^{-\beta m_{max}}}{e^{-\beta m_{min}} - e^{-\beta m_{max}}}$$

Step 7: Damage propagation and domino effect: Risk

When the risk analysis option is selected, the Magnitude (m) of the seismic event and the distance (R) of the site form the epicenter or the fault are randomly sampled. The PGA is then determined by using a proper seismic attenuation relationship.

- The Magnitude is sampled by using the Gutemberg-Richetr law
- The distance is sampled from a uniform distribution fuction p=dA/A
- The seismic activity is sampled by assuming a uniform annual rate of occurence

To improve the efficiency of MCS the **importance sampling technique** is used

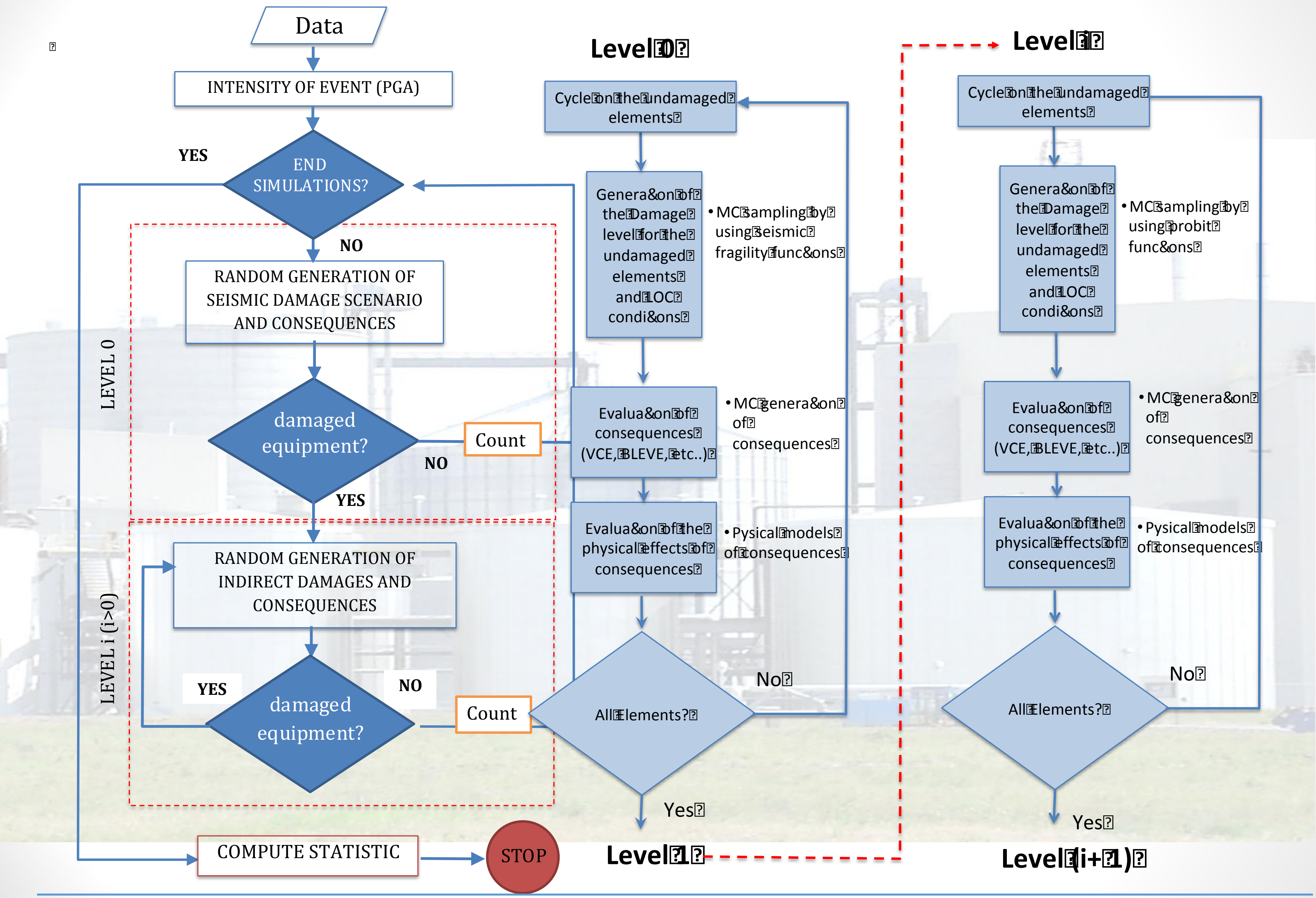
$$C = \frac{\sum_{i=1}^{N} \sum_{j} C_{ij}\left(d_j\right) w_{Ri} w_{Mi} w_{SZi}}{N}$$

$$w_m = \frac{\beta e^{-\beta m}\left(m_{\max} - m_{\min}\right)}{e^{-\beta m_{\min}} - e^{-\beta m_{\max}}}$$

$$w_R = \frac{dA(R)}{A}$$

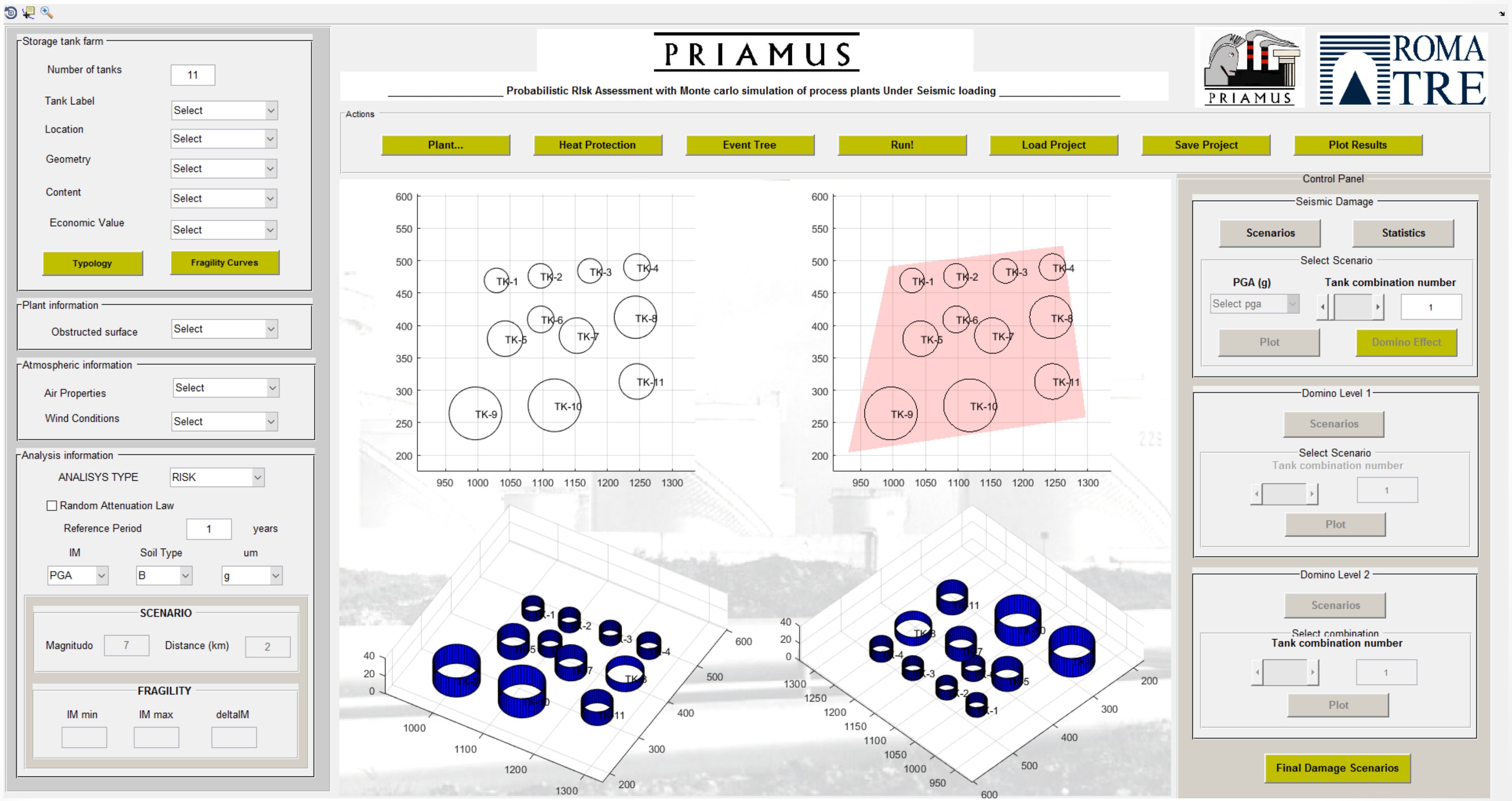
$$w_{SZ} = \nu_0 \frac{e^{-\beta m} - e^{-\beta m_{\max}}}{e^{-\beta m_{\min}} - e^{-\beta m_{\max}}}$$

FLOW-CHART OF THE PROPOSED METHOD

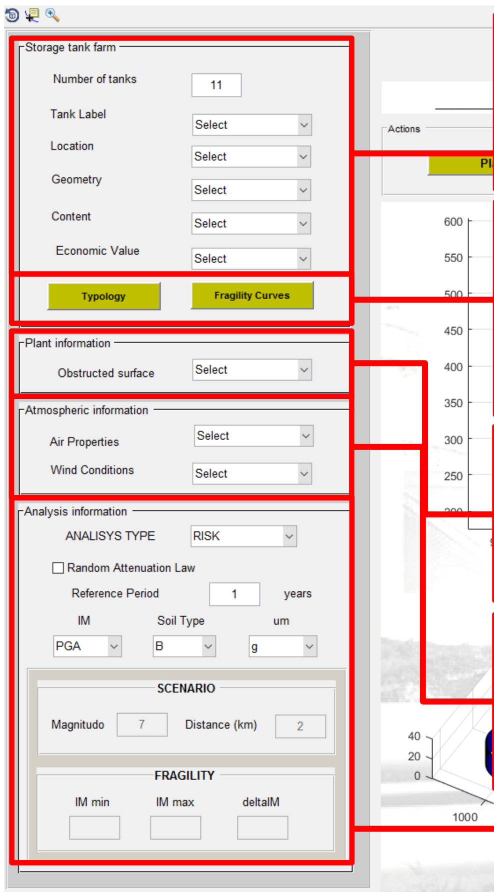


PRIAMUS SOFTWARE

PRIAMUS was developed in MATLAB environment, which allows to define a quantitative probabilistic seismic risk analysis of petrochemicals plants with economic and domino effect evaluation.



Architecture of the software



"Tank information" - This section is dedicated to the definition of the characteristics of the storage tank farm: number of tanks, locations, geometries, typology of content, economic value. The software allows the input of the data through prompt or excel files.

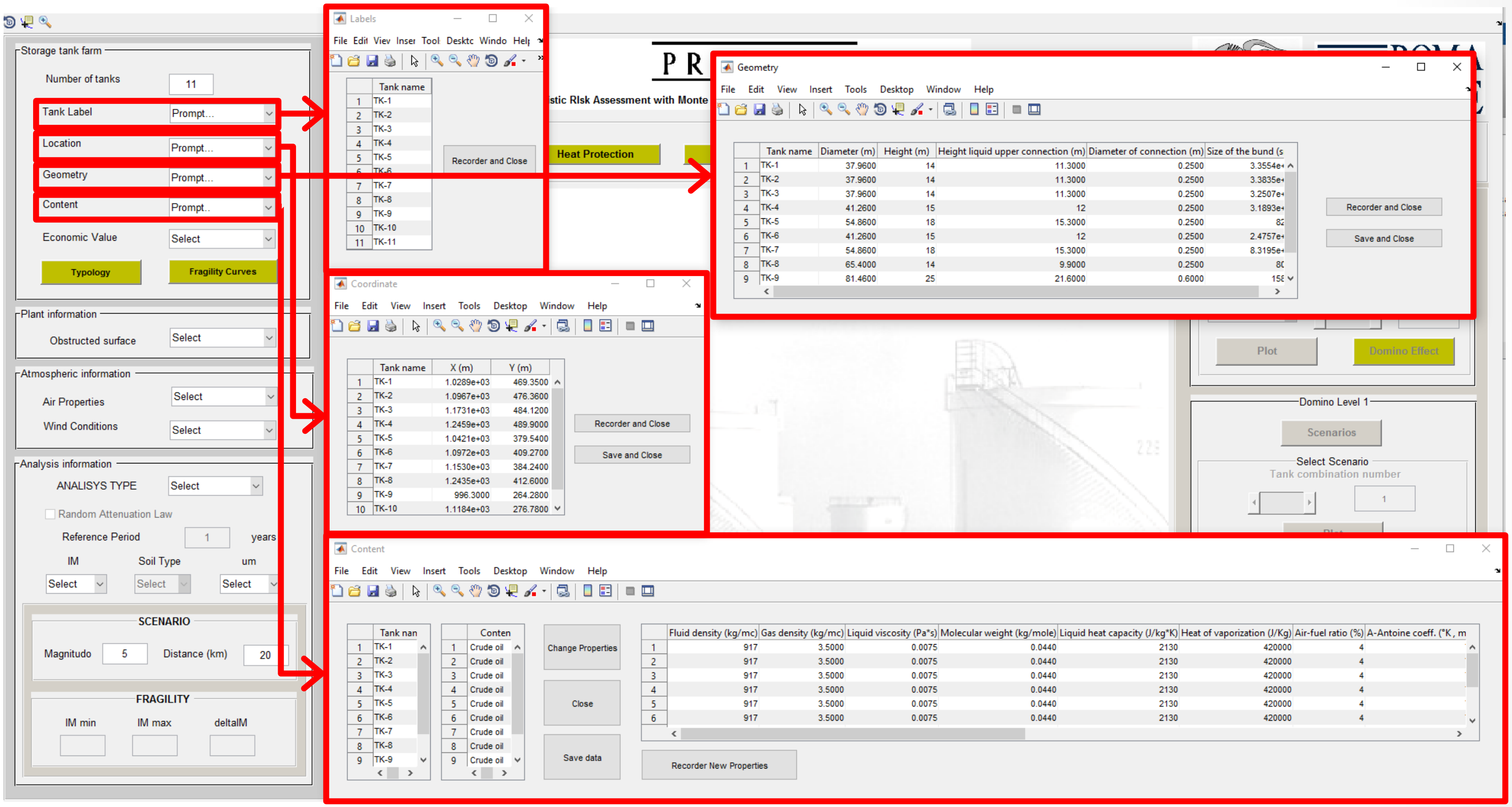
"Vulnerability of tanks"- in this section user can define the typology of each tank (anchored, unanchored or elevated, with fix or floating roof). For each structural damage typology that causes loss of containment, user must define the parameters of fragility curves (medium value and standard deviation).

"Plant information"- This part is dedicated to the definition of the vertex of obstructed area, the volume of components inside and the component maximum height inside the zone for the definition of VCE effects.

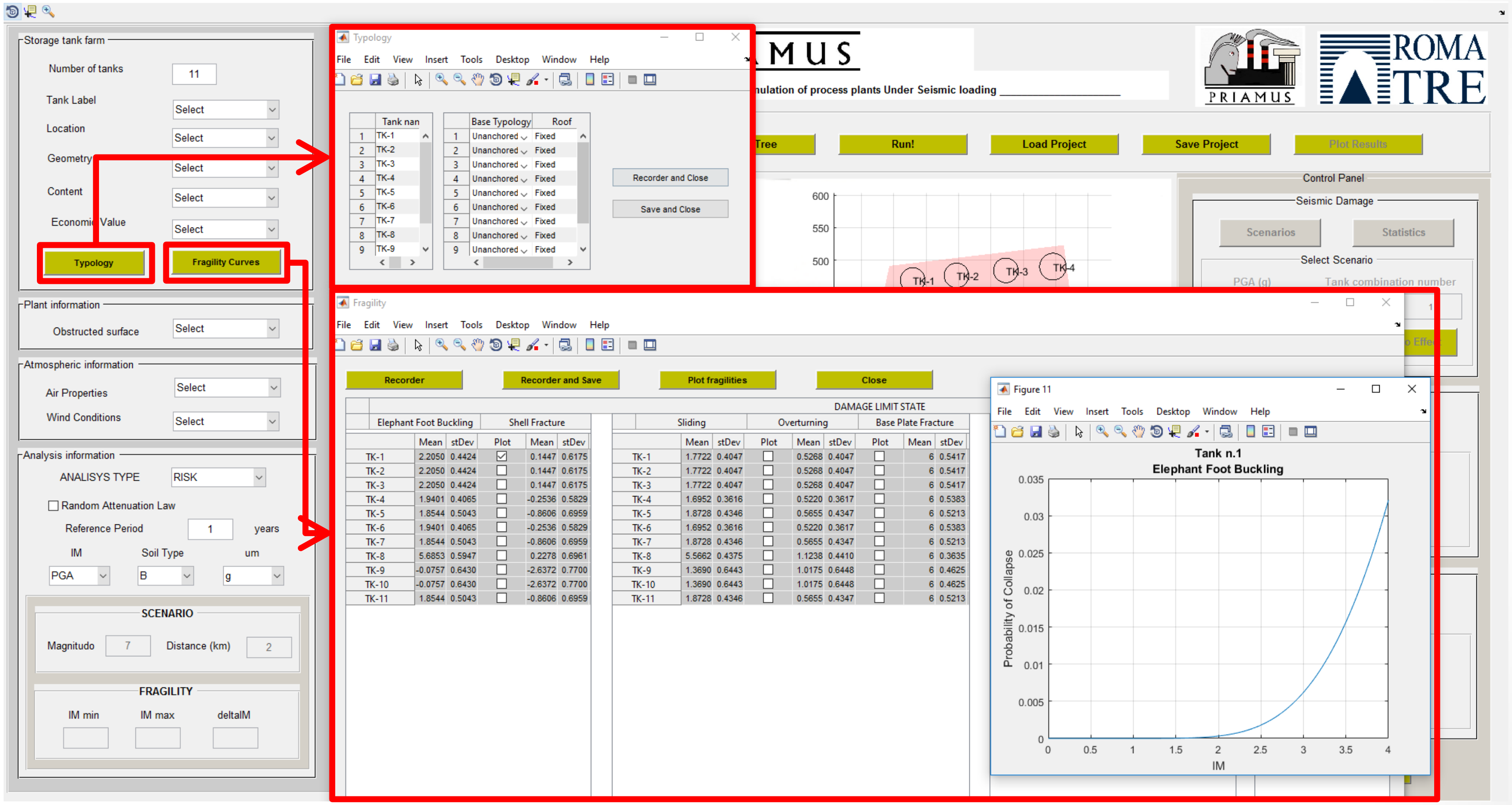
"Atmospheric information": the statistics of atmospheric conditions are entered. Monthly mean value of air humidity, air temperature and wind velocity are needed. The wind direction is defined in terms of probability for each month

"Analysis information": user can choose the typology of seismic analysis (risk analysis, scenario analysis, analysis for a range of intensity measure).

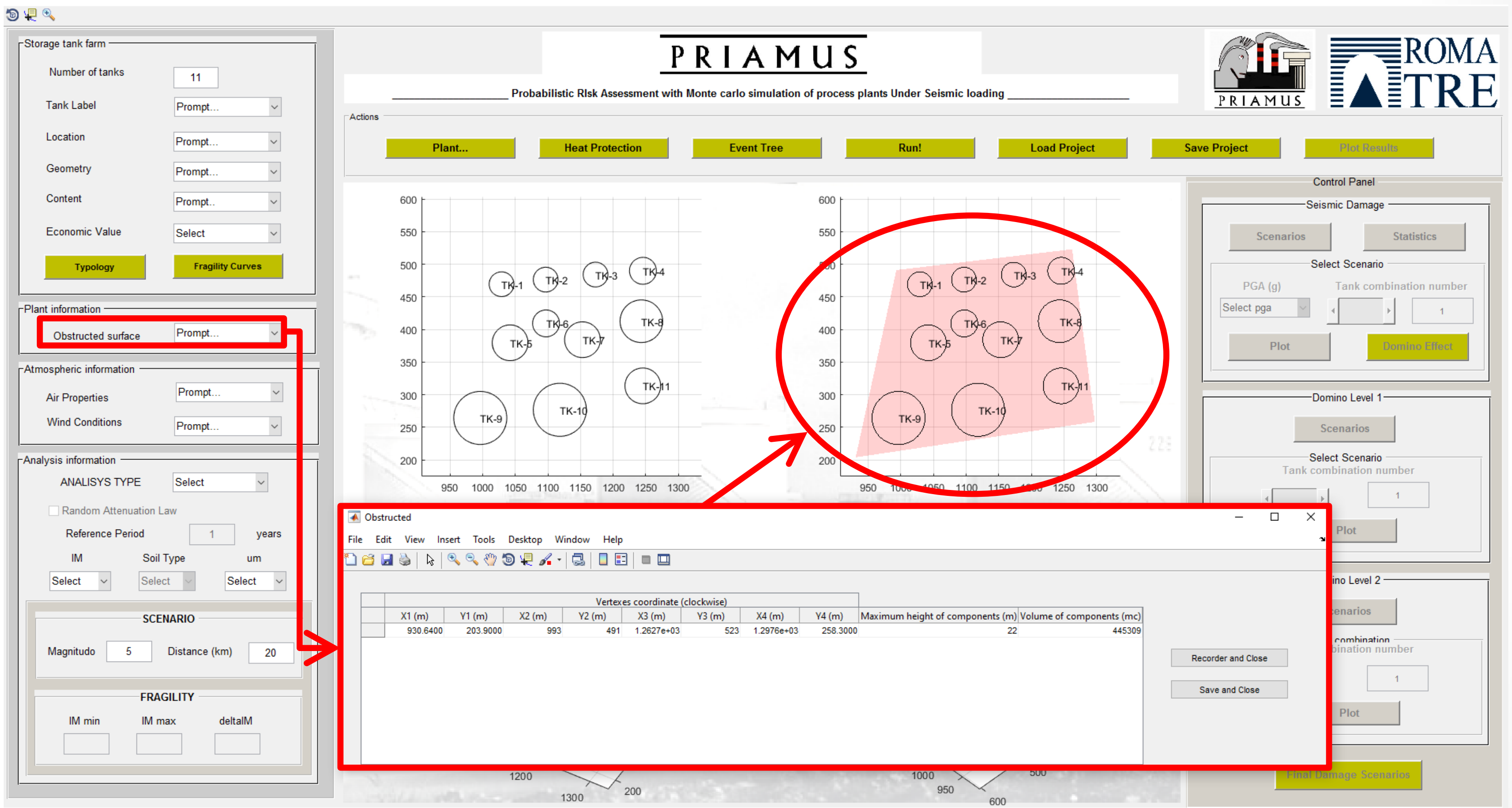
Architecture of the software



Architecture of the software

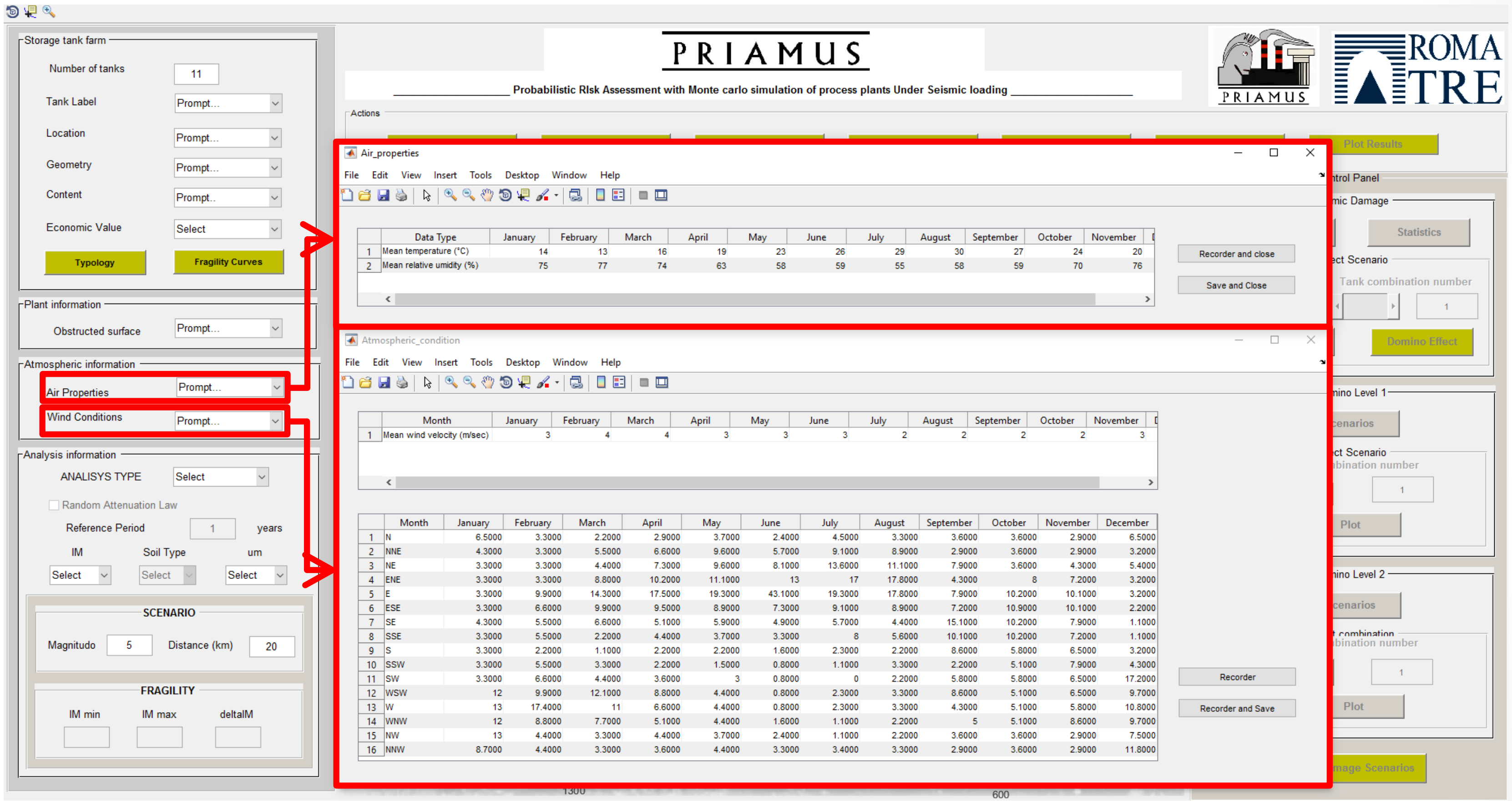


Architecture of the software

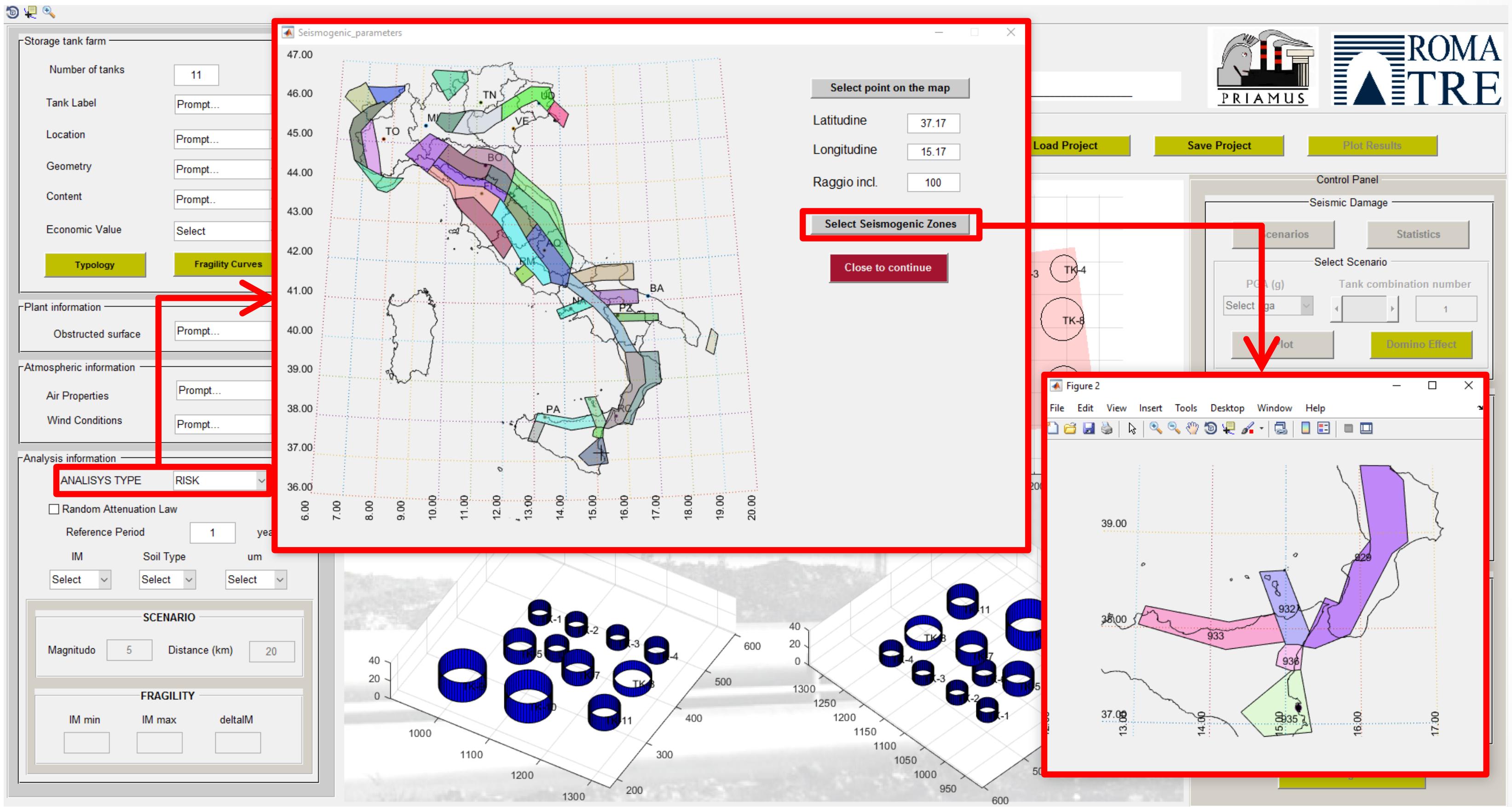


PRIAMUS SOFTWARE FOR QSRA

Architecture of the software

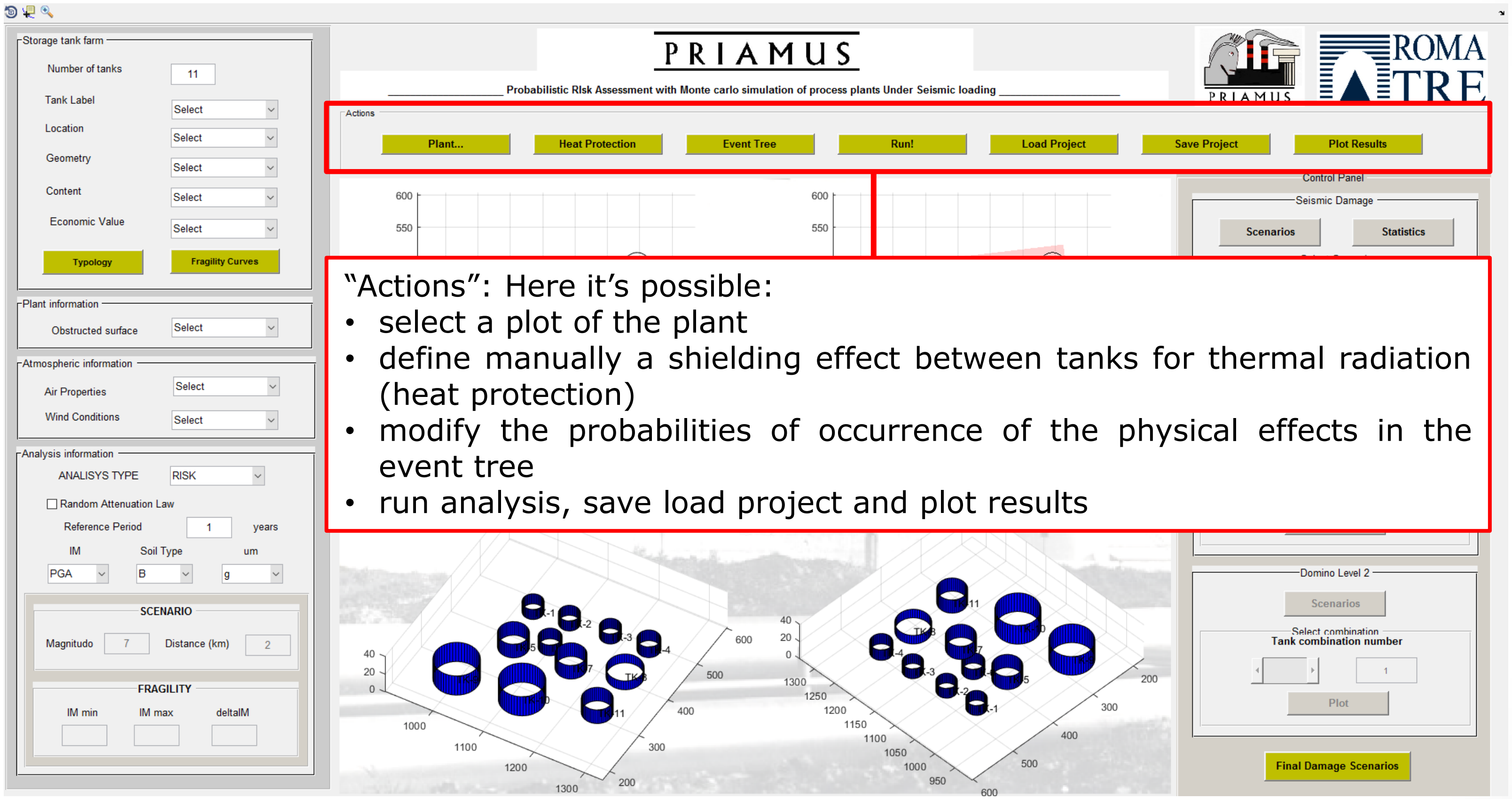


Architecture of the software



PRIAMUS SOFTWARE FOR QSRA

Architecture of the software

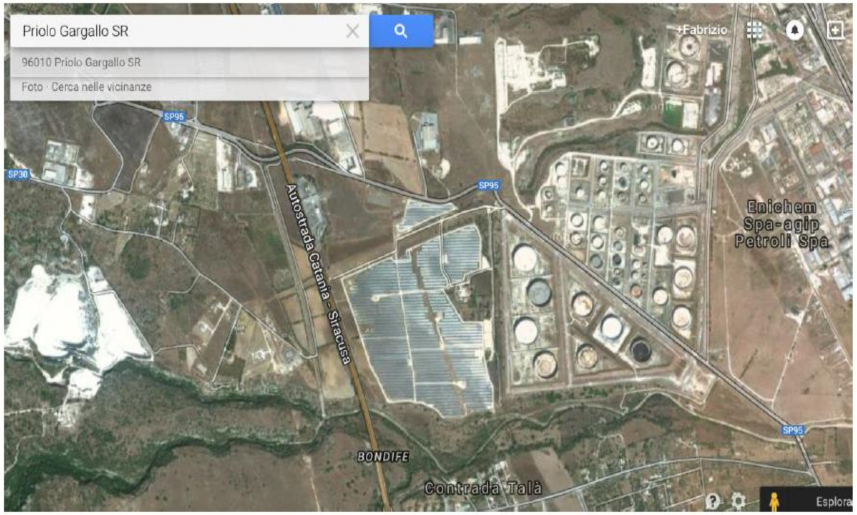


"Actions": Here it's possible:

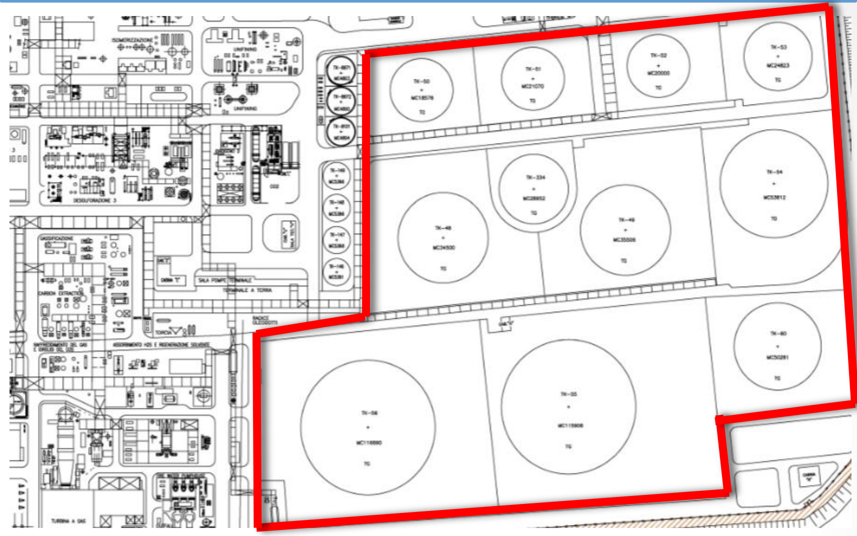
- select a plot of the plant
- define manually a shielding effect between tanks for thermal radiation (heat protection)
- modify the probabilities of occurrence of the physical effects in the event tree
- run analysis, save load project and plot results

PRIAMUS SOFTWARE FOR QSRA: EXAMPLE

SITE : PRIOLO GARGALLO (SR) - ITALY



TANK FARM SELECTED



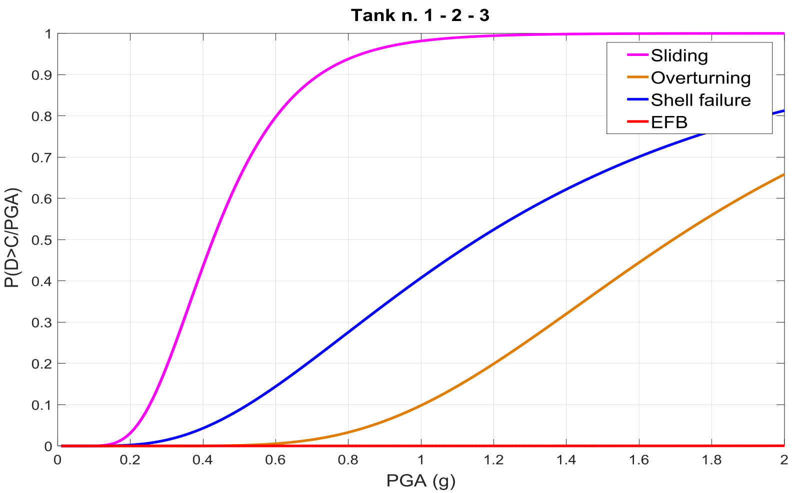
FEAUTURES OF TANKS

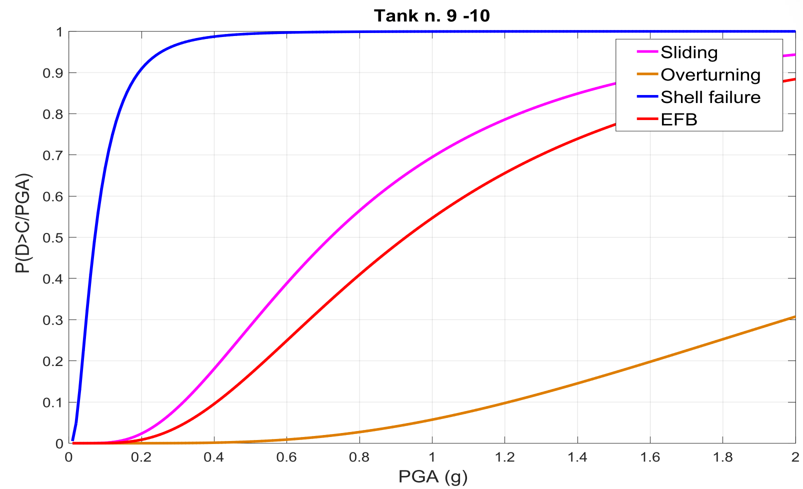
Content : Crude oil

	TK1	TK2	TK3	TK4	TK5	TK6	TK7	TK8	TK9	TK10	TK11
Diameter (m)	37.96	37.96	37.96	41.26	54.86	41.26	54.86	65.4	81.46	81.46	54.86
Liquid Level (m)	11.3	11.3	11.3	12	15.3	12	15.3	10	21.6	21.6	15.3
Height (m)	14	14	14	15	18	15	18	14	25	25	18
Yielding strength (MPa)	345	345	345	345	345	345	345	345	345	345	345
Shell equiv. thick. (m)	0.013	0.013	0.013	0.013	0.0185	0.013	0.0185	0.014	0.026	0.026	0.0185
Shell base thick. (m)	0.02	0.02	0.02	0.02	0.0295	0.02	0.0295	0.0295	0.04	0.04	0.0295
Annular plate thick. (m)	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.016	0.016	0.008

PRIAMUS SOFTWARE FOR QSRA: EXAMPLE

FRAGILITY ANALYSIS OF STORAGE TANKS



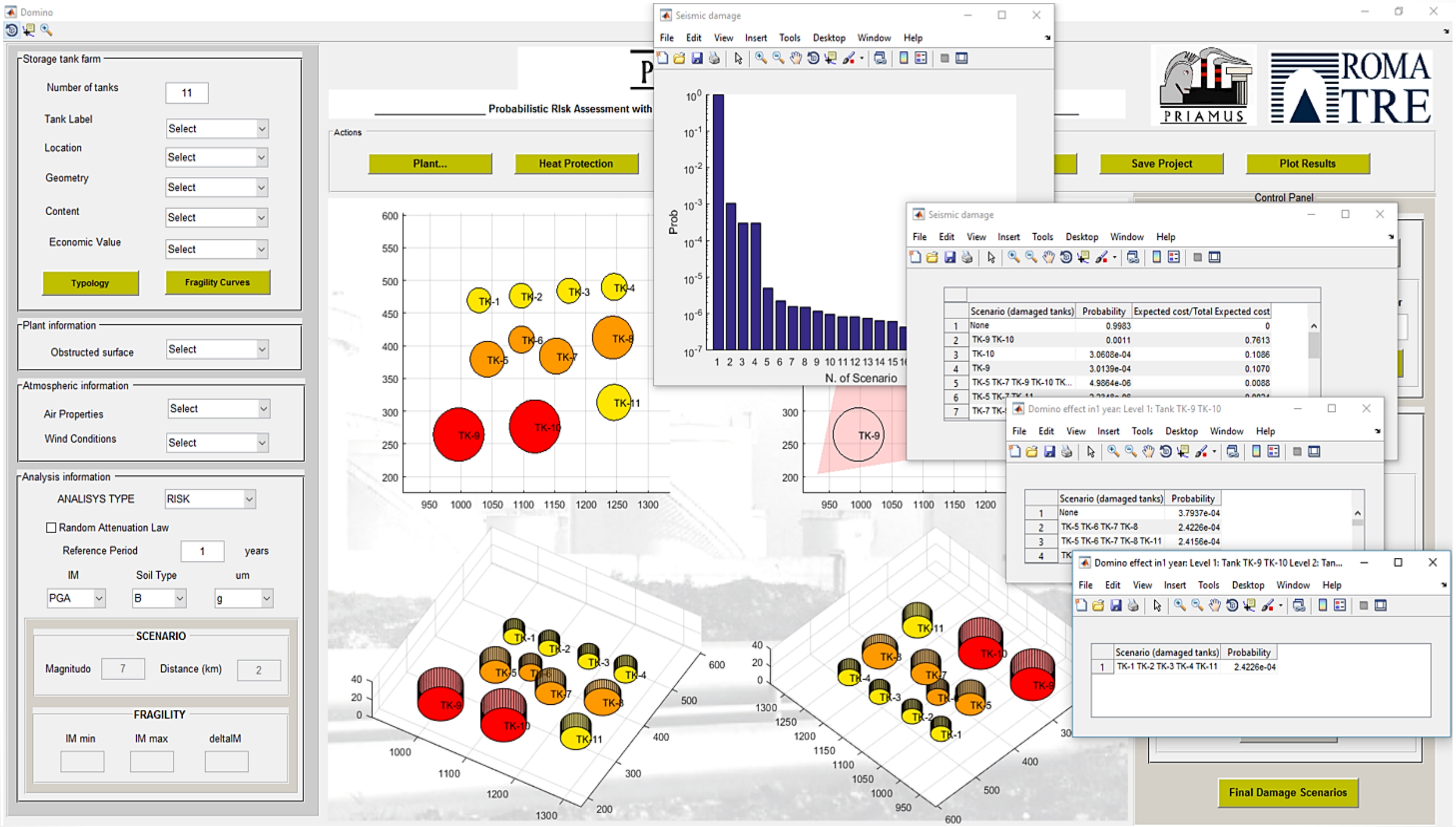


Damages	Parameters	TK-1	TK-2	TK-3	TK-4	TK-5	TK-6	TK-7	TK-8	TK-9	TK-10	TK-11
Shell fracture	Mean	0.145	0.145	0.145	-0.254	-0.861	-0.254	-0.861	0.228	-2.637	-2.637	-0.861
	St. dev.	0.618	0.618	0.618	0.583	0.696	0.583	0.696	0.696	0.77	0.77	0.696
EFB	Mean	2.205	2.205	2.205	1.940	1.854	1.940	1.854	5.685	-0.076	-0.076	1.854
	St. dev.	0.442	0.442	0.442	0.406	0.504	0.406	0.504	0.595	0.643	0.643	0.504
Sliding	Mean	1.772	1.772	1.772	1.695	1.873	1.695	1.873	5.566	1.369	1.369	1.873
	St. dev.	0.405	0.405	0.405	0.362	0.435	0.362	0.435	0.437	0.644	0.644	0.435
Overturning	Mean	0.527	0.527	0.527	0.522	0.565	0.522	0.565	1.124	1.017	1.017	0.565
	St. dev.	0.405	0.405	0.405	0.362	0.435	0.362	0.435	0.441	0.645	0.645	0.435

PRIAMUS SOFTWARE FOR QSRA: EXAMPLE

RESULTS

The most likely seismic damage scenarios (Level 0) along with the relevant frequency of occurrence together with the most likely chain of accidents can be identified.

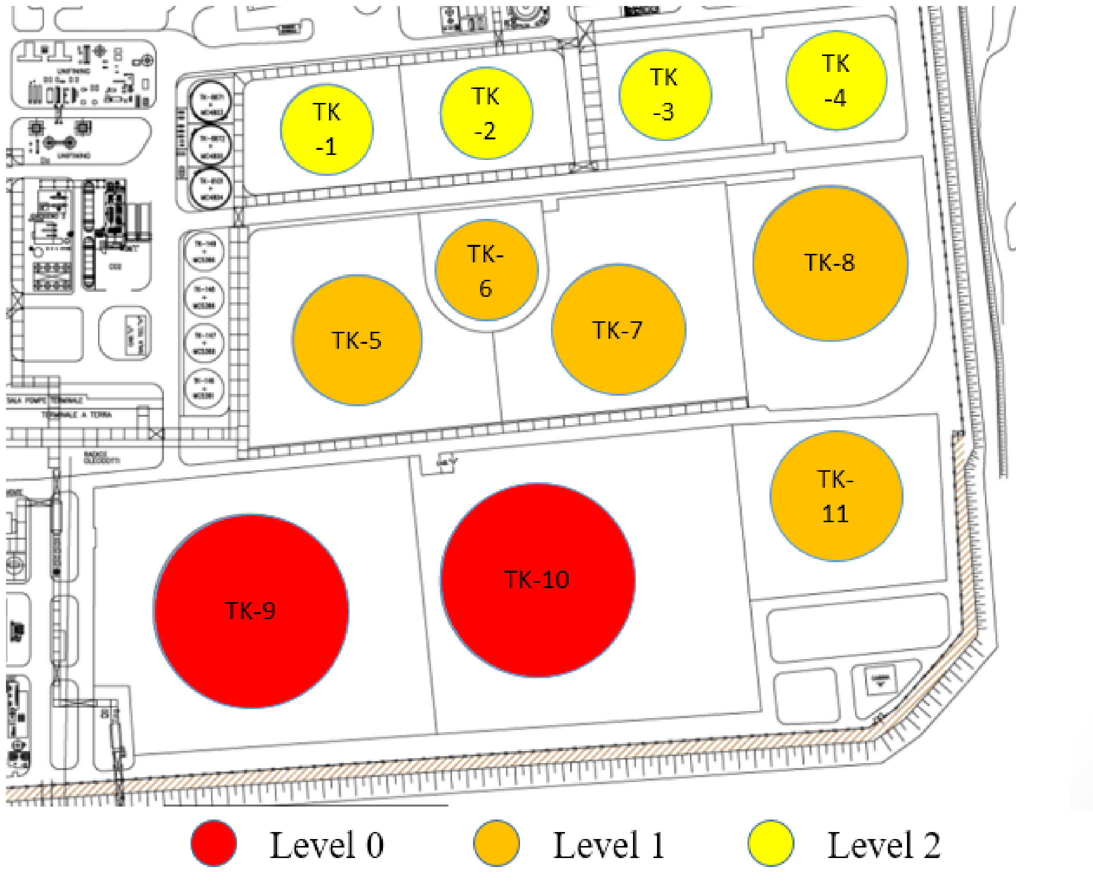


RESULTS

The most likely seismic damage scenarios (Level 0) along with the relevant frequency of occurrence together to the more likely chain of accidents can be identified.

INITIAL DAMAGE SCENARIO		
N°	Sismic Damage Scenario (damaged units)	Probability
1	None	0.998
2	TK-9 TK-10	1.10e-03
3	TK-9	3.0802e-04
4	TK-10	2.8989e-04
5	TK-5 TK-7 TK-9 TK-10 TK-11	4.4430e-06

Accidental Chain #2, P=2.37E-04



CONCLUSIONS

- A new procedure for the Quantitative Risk Analysis of process plants subjected to NaTech events, in particular seismic loading, has been presented and discussed.

- The evolution of the domino effect within a process plant struck by an earthquake has been reproduced assuming that the accident dynamics may be represented by a sequence of propagation steps, called “levels”.

- Each propagation level includes a subset of process units directly damaged by units belonging to the previous levels. The first level (level 0) characterises the initial damage conditions directly induced by the seismic action to the single units of the plant.

- Eventual subsequent levels (level > 0), that is the domino effect, may be generated by material releases (LOC) that follow specific seismic damage conditions, hererecognized by a new Damage/LOC matrix. This latter has been specifically proposed for storage tanks, as the one of the most seismically vulnerable units in process plants.

CONCLUSIONS

With respect to other methods the following key aspects characterize the proposed approach:

- An automatic generation of random initial scenarios based on the probability of occurrence of seismic damage in the plant components (fragility curves), is employed;
- A direct association of Damage states (DS) and loss of containment (LOC) events by proper DS/LOC matrix is proposed;
- An automatic generation of consequences due to LOC events is performed; this allows the propagation of any number of multiple accidental chains that is completely independent of the analysed plant.
- The possibility to adapt the risk output to the needs. For example, it has been shown how to easily evaluate economic losses or damage scenarios simply based on a certain number of simulations.
- The method can be implemented in any computer programming environment and employed for any type of process plant;

CONCLUSIONS

- The proposed methodology has been implemented in Matlab¨ environment (**PRIAMUS**) and used for the computation of the seismic risk of a typical tank farm belonging to a petrochemical plant ideally located in the south of Italy (Sicily).

- The results demonstrated the flexibility of the software in providing either the probability of occurrence of a given damage scenario or the total risk of the tank farm in terms of annual probability of lost volume or the annual probability of occurrence of critical damage scenarios.

- It has been shown that the proposed software can also be usefully employed to estimate the probability of occurrence of specific damage propagation effects (domino effect).

Thank you very much for your attention

Questions?