Post-Emergency, Multi-Hazard Health Risk Assessment in Chemical Disasters
PEC

Deliverable D.B.4

Multi-hazard contamination

ECHO/SUB/2015-713844-PREV11 - PEC: Post-Emergency, multi-hazard health risk assessment in Chemical disasters
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1 INTRODUCTION

Scope of this report is to develop a methodology to develop a “multi-hazard contamination risk map” that allows describing the risk, associated to equipment of analyzed chemical Plants, caused by all the identified initiating events.

Particularly, this report has been based on the results of deliverables DB.1 “Seismic risk assessment”, DB.2 “Flood risk assessment” and DB.3 “Man-made risk assessment” where the likelihood of potential loss of containment scenarios, caused by the occurrence of internal (corrosion, mechanical defect, process deviation) or external events (terrorist attack, flood, earthquake) has been assessed and evaluated. These frequencies will be combined together with the effects of each analysed release of toxic compound in order to build a specific risk value in order to develop a risk priority map. The consequences of toxic releases will be assessed in deliverables of Task C.

2 IDENTIFICATION OF CASCADING EVENT SEQUENCES

The first task to be performed is to analyze the potential events analyzed in previous deliverables in order to define the possible sequences of cascading events. Such an analysis has been performed by means of a guided brainstorming through the application of the workflow illustrated in the following picture.

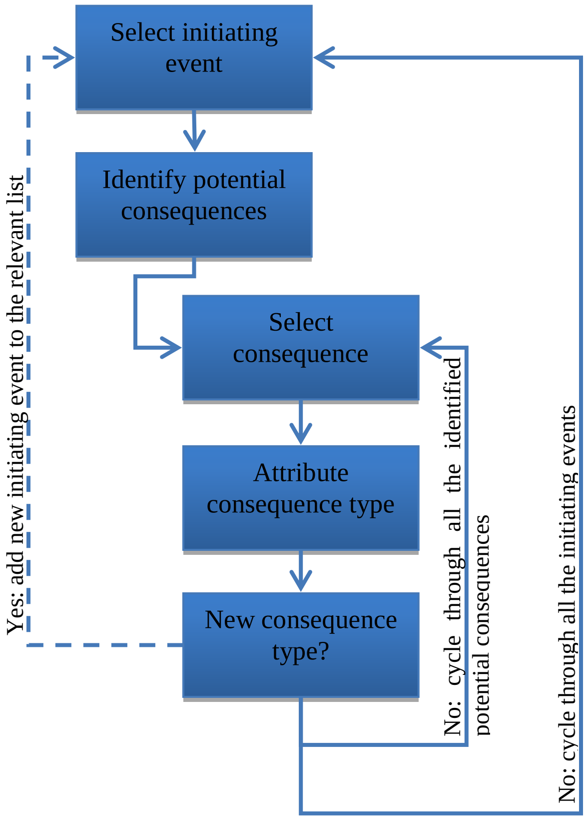


Figure 1: Workflow for potential cascading sequences identification

The main steps of the methodology are detailed in the following:

- Initiating event refers to the root causes of the cascading sequences; all the initiating causes considered in the project (Man Made, Seismic events and Flooding) have been included in the review;
- For each initiating event a list of potential consequences has been identified and relevant type has been attributed (e.g. fire event, structural damage, atmospheric dispersion etc.)
- If a new consequence type is identified, it is added to the list of "initiating event" to be reviewed for potential cascading effects (consequences);
- If the consequence type already exists in the list, relevant potential cascading sequences are already covered by the analysis; analysis is repeated for each potential consequence and for each initiating event.

Results of the methodology application are reported in the following figure.

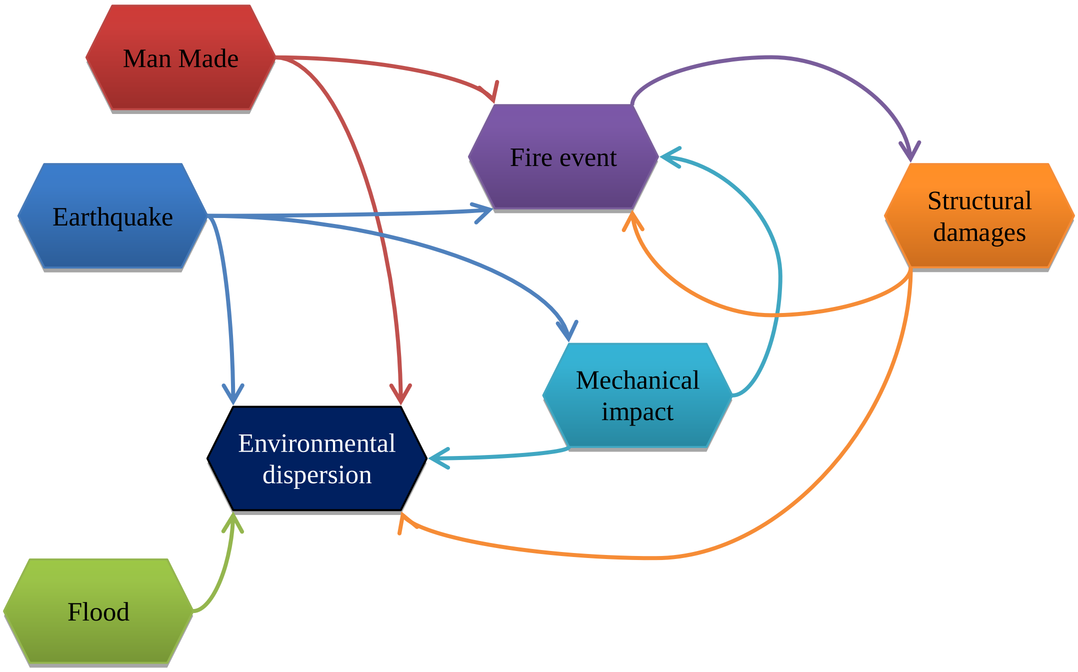


Figure 2: Map of potential cascading event sequences

Connectors represent potential cascading event sequences: for example, starting from a Man Made initiating event a Fire event can be configured; the cascading sequence can be further developed, moving to Structural damages, back to Fire event or to Environmental dispersion.
To ease the readability of the graph, connectors have been drawn with the same color of the relevant initiating cause.
It is important to underline that the Map of potential cascading event sequences has been worked out considering Scenarios in Plant A and Plant B; as a consequence, such a map is specific for the case studies included in this project; alternative maps could be worked out for different scenarios through the application of the methodology detailed in Figure 1.
Identified connections between cascading events are defined as "potential": probability of escalation from one event to the following one depend on specific parameters which must be quantitatively assessed in order to provide a probabilistic assessment of each sequence (for example: probability of fire event depend on the type of release fluid, release rate, presence of ignition sources etc.).
Expected frequency of final events is therefore calculated by combination of:

- Initiating event frequency, as assessed in DB1, DB2 and DB3 (Chapter 3);
- Calculation of conditional probabilities (Chapter 4)
- Probabilistic assessment of the identified sequences of cascading events, performed by means of dynamic event tree approach (Chapter 5).

3 FREQUENCY OF OCCURRENCE OF INITIATING EVENTS

In the following a resume of the frequencies of occurrence of different initiating events leading to loss of containment are provided. These frequencies are extracted from related Deliverable of the PEC Project (Ref. to DB1, DB2 and DB3).

3.1 *Errors in design, construction, maintenance*

The frequencies of occurrence of events related to these causes have been calculate by means of the statistical databases OGP Report 434-1 and 434-3 through the parts count method. Typical items have been identified on Plants PFDs and, for each of them, a leak frequency and an exceedance probability (for the diameters identification) has been worked out.

Typical	**Frequency of loss of containment [ev/y]**	**Probability [-]**				
		2 mm	**5 mm**	**25 mm**	**100 mm**	**250mm**
TYP01	9.25E-03	0.67	0.23	0.08	0.01	0.01
TYP02	6.13E-03	0.67	0.23	0.08	0.01	0.01
TYP03	9.70E-03	0.69	0.23	0.07	0.01	0.01
TYP04	7.66E-03	0.71	0.21	0.06	0.01	0.01
TYP05(1)	3.60E-06	0.00	0.00	0.00	0.00	1.00

(1) Data derived from OGP Report 434-3 "Process Storage Frequencies" and associated to the catastrophic rupture of the tank (i.e., immediately release of the whole inventory contained)

3.2 *Not voluntary errors by plant operators*

Not voluntary errors by plant operators have been analyzed starting from the procedures developed for tasks that require a significant operator action. For each task a dedicated "What-if Analysis" has been developed and from the results potential hazardous scenario (called Top Event) have been identified, analyzed and quantified in terms of frequency of occurrence by means of Fault Tree Analysis; the following Tables provides the summary of the results.

ID	**Substances involved**	**TOP**	**Frequency of occurrence [ev/y]**
TOP01a	Virgin Naphtha	Release of liquid from flexible hose	1.98E-04
TOP01b	Acrylonitrile		6.24E-05
TOP01c	BK Gasoline		1.32E-04
TOP02a	Virgin Naphtha	Tank overpressurization and potential rupture	3.16E-10
TOP02b	Acrylonitrile		5.01E-11
TOP03a	Virgin Naphtha	Tanker fire due to electrostatic energy	2.75E-05
TOP03b	Acrylonitrile		8.68E-06
TOP03c	BK Gasoline		1.84E-05

ID	Substances involved	TOP	Frequency of occurrence [ev/y]
TOP04a	Virgin Naphtha	Tanker damages for low pressure	9.51E-05
TOP04b	Acrylonitrile		3.00E-05
TOP05a	Virgin Naphtha	Tank overfilling	2.69E-07
TOP05b	Acrylonitrile		8.48E-08
TOP06	BK Gasoline	Tank overpressurization and potential rupture	6.11E-07
TOP07	BK Gasoline	Tank overfilling	1.66E-05
TOP08	BK Gasoline	Tanker damages for low pressure	5.00E-05
TOP09	Metal raw materials / molten metal	Furnace Explosion	6.40E-07
TOP10	Metal raw materials / molten metal	Furnace Overfilling	2.42E-03

3.3 *Sabotage and terrorism*

Assessment of frequencies related to sabotage and terrorism has been developed considering a qualitative approach that allow to analyze main possibile threaths derived by a terrorist attack or a sabotage and to identify the worst in order to consider them in next phases.
In the following Table a summary of the results is provided.

Threat	Substances involved	Description	Frequency of occurrence [ev/y]
Bomb attack	Virgin Naphtha	A bomb placed close to the storage tanks that results in instantaneous release/fire of virgin Naphtha	1.00E-06
Bomb attack	BK Gasoline	A bomb placed close to the storage tanks that results in instantaneous release/fire of BK Gasoline	1.00E-06
Bomb attack	Acrylonitrile	A bomb placed close to the storage tanks that results in instantaneous release/fire of Acrylonitrile	1.00E-06
Bomb attack	Arsenic	A bomb placed close to the pregant solution tank that results in instantaneous release of Arsenic	1.00E-06
Terroristic attack	Virgin Naphtha	A terroristic attack that results in a 250 mm release from storage tank	1.00E-06
Terroristic attack	BK Gasoline	A terroristic attack that results in a 250 mm release from storage tank	1.00E-06
Terroristic attack	Acrylonitrile	A terroristic attack that results in a 250 mm release from storage tank	1.00E-06
Terroristic attack	Arsenic	A terroristic attack that results in a 250 mm release from pregant solution tank	1.00E-06

3.4 Earthquake

Tanks

In the following Table the probabilities of reaching PL1 and PL2 in a time window of 1 year for each class of tank are reported. Furthermore, in next Table the mean annual frequencies of occurrence of PL1 and PL2 for each class of tank are shown.

Probability of reaching PL1 and PL2 in a time window of 1 year for tanks

Class	Prob PL1 (%)	Prob PL1 (%)
Class 1	0.448529	0.080212
Class 2	0.281069	0.050061
Class 3	0.344832	0.06219
Class 4	0.422875	0.079481

Mean annual frequency of occurrence of PL1 and PL2 for tanks

Class	λ PL1	λ PL2
Class 1	0.003791624	0.000675703
Class 2	0.002307472	0.000411213
Class 3	0.003199041	0.000570099
Class 4	0.011055932	0.001970272

Please note that, as described in §**Errore. L'origine riferimento non è stata trovata.**, the classes of storage tanks considered in this project are:

- class 1: $0.7 \leq D/H \leq 1$;
- class 2: $1 < D/H \leq 1.5$;
- class 3: $1.5 < D/H \leq 2$;
- class 4: $D/H > 2$.

Horizontal Vessels

The evaluation of the seismic risk for the horizontal vessels has been carried out by assuming the following two performance levels:

- PL1: corresponds to the first leakage of the fluid content and minor damage to the vessels structure;
- PL2: global collapse of the vessels and consequent complete release of the fluid content.

The horizontal vessels assumed in the present study have been defined by randomly vary the H/R ratio, by assuming three types of connections and three different moment/rotation curves with lower, medium and best estimate soil parameters. The 90 statistically independent vessels defined are not divided in classes but they have been analyzed by means of equivalent linear static analyses in both the principal direction. As a consequence of these assumptions, the values obtained for the probabilities of reaching one of the two performance levels in a time window of 1 year and the corresponding mean annual frequencies of occurrence of PL1 and PL2 have been defined for each loading direction. The mentioned results are reported in the following Tables.

Probability of reaching PL1 and PL2 in a time window of 1 year for horizontal vessels

Class	Prob PL1 (%)	Prob PL2 (%)
Transverse Dir.	0.179904	0.095502
Longitudinal Dir.	0.093867	0.057020

Mean annual frequency of occurrence of PL1 and PL2 for horizontal vessels

Class	λ PL1	λ PL2
Transverse Dir.	0.00180066	0.00095548
Longitudinal Dir.	0.00093911	0.00057036

Vertical Vessels

Also in the case of the vertical vessels, the damage levels (or performance levels PL) taken into account for the evaluation of the seismic risk are the following:

- PL1: corresponds to the first leakage of the fluid content and minor damage to the vessels structure;
- PL2: global collapse of the vessels and consequent complete release of the fluid content.

The set of vertical vessels assumed in the present study are divided into two classes as a function of the H/R ratio. More specifically the following classes have been assumed:

- Class 1: vertical vessels with $4 < H/R \leq 7$;
- Class 2: vertical vessels with $7 < H/R \leq 11$.

By applying the procedure described at the beginning of the chapter, the following values have been obtained for the probabilities of reaching one of the two performance levels in a time window of 1 year and the corresponding mean annual frequencies of occurrence of PL1 and PL2. The mentioned results are reported in the following Tables for both the classes of vessels considered, respectively.

Probability of reaching PL1 and PL2 in a time window of 1 year for vertical vessels

Class	Prob PL1 (%)	Prob PL2 (%)

Class 1	0.331030	0.100850
Class 2	0.288505	0.074485

Mean annual frequency of occurrence of PL1 and PL2 for vertical vessels

Class	λ PL1	λ PL2
Class 1	0.00331580	0.00100901
Class 2	0.00288922	0.00074513

3.5 Flood

As described in DB2, the total probabilities of floatation and shell buckling of the vessels have been calculated by means of Bayesian Network technique. Results are provided in the following Table.

Unit	Floatation	Shell buckling
Virgin naphtha storage tank	4.75E-03	0.00E+00
Cracking Gasoline buffer tank	4.96E-03	0.00E+00
Cracking Gasoline storage tank # 1	5.39E-03	8.07E-04
Cracking Gasoline storage tank # 2	5.71E-03	6.16E-03
Acrylonitrile storage tank	4.96E-03	4.03E-07
Primary fractioner	2.97E-07	6.62E-07
Heavy gasoline stripper	0.00E+00	0.00E+00
Quench column	0.00E+00	0.00E+00
Debutanizer	0.00E+00	0.00E+00
Production reactor	0.00E+00	0.00E+00
Stripping column	1.45E-07	0.00E+00
Unit buffer vessel	0.00E+00	0.00E+00

4 CONDITIONAL PROBABILITIES OF CASCADING EVENTS

Aim of this paragraph is to define a methodology to calculate the conditional probability of cascading events.

4.1 List of potential cascading effects

According to the Map of cascading event sequences worked out in Chapter 2, the following cascading effects have been considered in the analysis:

- Fire event due to Man made initiating event (ref. to Para 3.2);
- Environmental dispersion due to Man made initiating event (ref. to Para 3.2);
- Fire event due to Earthquake event (ref. to Para 3.2);
- Mechanical impact due to Earthquake event (ref. to Para 3.4);
- Environmental dispersion due to Earthquake event (ref. to Para 3.2);
- Environmental dispersion due to Flood event (ref. to Para 3.2);
- Structural damages due to Fire event (ref. to Para 3.3);
- Fire event due to Mechanical impact (ref. to Para 3.2);
- Environmental dispersion due to Mechanical impact (ref. to Para 3.2).

4.2 Ignition probability

Probability of fire event (ignition) or environmental dispersion (no ignition) following a release of process fluid (either due to Man Made, Earthquake, Flood) have been assessed by means of Event tree analysis according to IP-UKOOA methodology (as already detailed in DB1); IP-UKOOA provides empirical correlations between the discharge flow rate and the probability of ignition. Specific correlations are provided for different landscape (plant, rural, offshore etc.).
This approach is considered the state of the art in risk assessment methodology.

4.3 Fire cascading effect

Cascading effects due to fire radiation depends upon two main parameters:

- Fire radiation;
- Duration of radiation.

The values of the two parameters used for the study are listed below (Ref. [1]).

Table 4.1: Asset vulnerability to thermal radiation

Target	Scenario	Exposure time [min]	Thermal radiation [kW/m2]
Process equipment	Jet Fire	5	≥ 37.5
Process equipment	Pool Fire	10	≥ 37.5

If both the parameters are respected, probability of Structural damages due to Fire event is set equal to the geometric probability of the jet/pool fire radiation impinging on the target equipment.

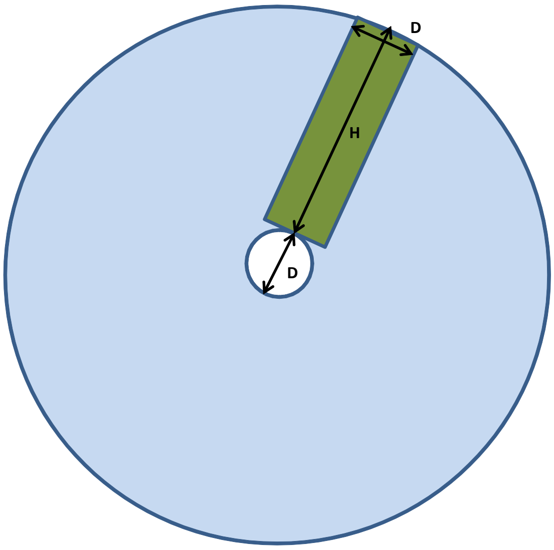
4.4 Fallen item cascading effect

In case of item interested by total disconnection of support in case of catastrophic event (as earthquake), a potential cascading effect is the collapse of the item on the ground with the potential involvement of nearby equipment.

This is particularly critical for items characterized by a ratio H/D > 1 (as columns, separators, etc), since in case of collapse they could affect a significant area.

The probability that, in case of collapse of equipment it can affect another equipment is calculated as follows:

$$P = \frac{(D \cdot H)}{\dfrac{\pi \cdot [(H + D/2)^2 - (D)^2]}{2}}$$



Where

- H: is the height of the fallen item;
- D: is the diameter of the fallen item;

The probability is therefore calculated as the ratio between the area that can be affected by the fallen item (green rectangle in the Figure above) and the total area potentially affected by the fall of the item (light blue annular ring)

5 DYNAMIC EVENT TREE

The assessment of the probability of a cascading event sequences has been assessed by means of the Dynamic Event Tree approach **Errore. L'origine riferimento non è stata trovata.**.
Traditional event trees are a visual representation of the potential evolution of a given starting events; following the initial event different alternatives are considered by means of "branches", each characterized by a given probability of occurrence. Final outcome frequency is therefore calculated by combining the initial event frequency with all the conditional probabilities of each branch leading to the outcome under analysis. The main drawback of such an approach is that conditional probabilities and functional dependencies defined by the risk analyst at the beginning of the analysis are fixed, and the cascade of accidental events is therefore strongly dependent on the initial assumptions. Moreover, interconnected events cannot be properly represented and assessed.
On the other hand, the Dynamic Event Tree approach **Errore. L'origine riferimento non è stata trovata.** allows considering the effect of an event on the conditional probabilities and functional relationship of the following events: graphical representation is given in the next figure ("Starting Event Tree") where relations among Event A, B, C and D are given by means of connector arrows. Probability of each event to progress following a given direction is provided by means of percentage probabilities (for example, Event B has 1% probability of evolving in Event C, Event C has 30% probability of evolving in Event D, etc.). Assuming the failure of Event A, a probabilistic conditioning is observed when probability of following events is modified (probability of occurrence of Event C, for example, is modified as highlighted in red in "Probabilistic conditioning"). A logistic conditioning, on the other hand, will modify functional relationship among following events (for example, failure of Event B may lead to Event D instead of Event C, as highlighted in red in "Logistic conditioning" example).

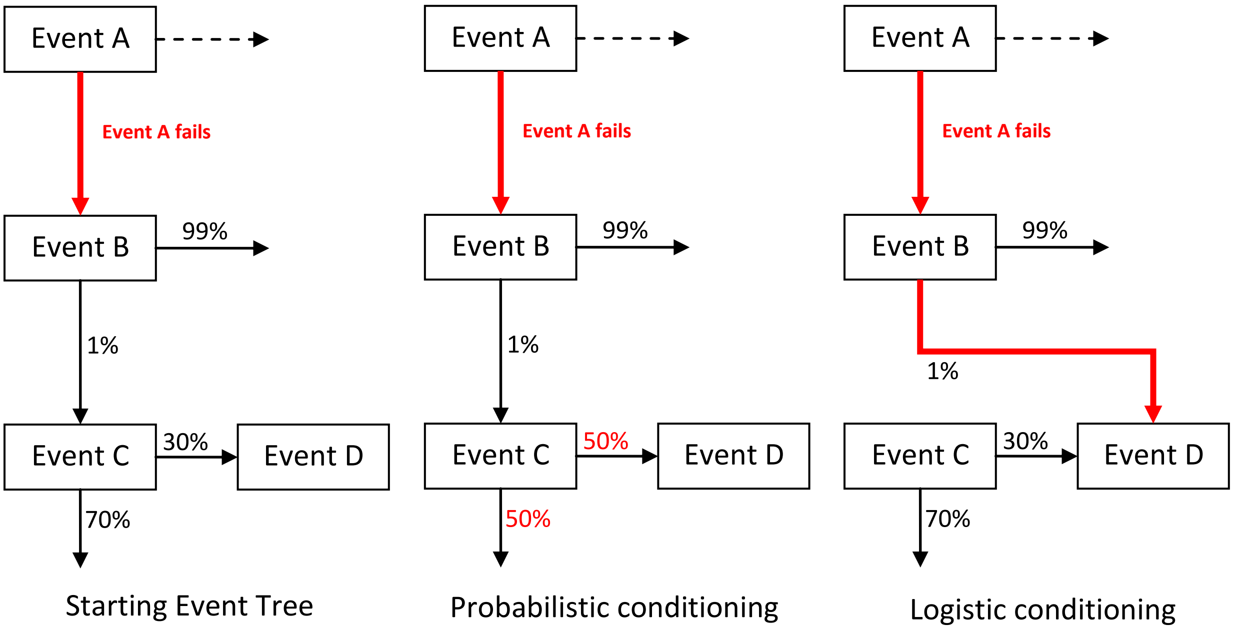


Figure 3: Example of probabilistic and logistic conditioning

As a result of the application of the Dynamic Event Tree approach, the risk analyst is required only to properly identify the conditioning (either probabilistic or logistic) among the identified failure modes, and the cascading event stories will be worked out by the Dynamic Event Tree as a result of the analysis, rather than an input as it occurs in the Static Event Tree.

Implementation of the Dynamic Event Tree approach has been performed by means of dedicated software internally developed.

6 RESULTS

According to the Map of potential cascading event sequences worked out in Chapter 2, Man Made and Earthquake initiating events may develop cascading event sequences: Man Made events may lead to fire event and, in turn to structural damages; Earthquake, on the other hand, may lead to mechanical impact due to tall objects loss of stability.

Flood events, on the other hand, may lead to the atmospheric dispersion of release process fluid, without further development.

Results for the probabilistic assessment through the Dynamic Event Tree approach are summarized in the following Paragraphs.

6.1 Domino from fire scenarios (plant A)

The assessment of cascading event from fire scenarios has been done considering the fire event from one of the pieces of equipment in the plant as potential initiating event. Each piece of equipment has been considered separately, thus meaning that the simultaneous failure of two pieces of equipment has been neglected. Such an occurrence is characterized by a negligible initiating frequency; as a result, the implementation of this kind of scenario would have resulted in a serious increasing of level of complexity of the input file without providing any significant impact on expected results.

A process item impinged by an external fire is potentially subject to a failure due to domino effect, thus releasing, in turn flammable gas. As a result, the primary domino effect may trigger secondary events depending on the flare direction and plant layouts.

Binary relationship has been implemented in the Dynamic Event Tree thus providing the probability of escalation between each pair of process items. Failure of one of the considered pieces of equipment will cause a logistic conditioning to avoid the software counting twice or more the failure of each item (for example, if item A cause a primary domino on item B, the logistic conditioning will intervene to prevent item B causing a secondary domino on item A, which is, in fact, already damaged).

A total of approx. 25000 stories have been calculated out of the Dynamic Event Tree.

Results have been elaborated in terms of frequency of failure, and they have been resumed in the following table.

Table 6.1: Fire cascading event frequency (plant A)

Item	Initiating event frequency	Total failure frequency	Increased vulnerability
Virgin Naphta Storage Tank A	8.64E-08	1.30E-06	1406%
Virgin Naphta Storage Tank B	8.64E-08	1.25E-06	1343%
Primary Fractionator	1.78E-05	1.82E-05	2%
Heavy Gasoline Stripper	1.75E-05	2.79E-05	59%
Quench Colum	2.87E-05	2.94E-05	2%

Item	Initiating event frequency	Total failure frequency	Increased vulnerability
Debutanizer	1.75E-05	1.91E-05	9%
Cracking Gasoline Unit Buffer Tanks	8.64E-08	3.33E-06	3752%
Cracking Gasoline Tank	8.64E-08	2.98E-06	3349%
Cracking Gasoline Tank	8.64E-08	2.82E-06	3168%
Acrylonitrile Storage Tank	8.64E-08	1.98E-06	2189%
Unit Buffer Vessel	1.73E-05	2.06E-05	19%
Elastomer Production Reactor	1.51E-05	1.96E-05	30%
Stripping Column	8.13E-06	1.07E-05	32%

For each item the initiating event frequency is calculated as the frequency of a fire event originated by a failure of the selected item. Failure of the selected item may be caused by any of the failure mode considered in the present analysis as discussed in Chapter 3.

It can be observed that storage tanks are characterized by an initiating event frequency orders of magnitude lower than other process equipment; this is due to the atmospheric pressure in the tanks, leading to significantly smaller frequencies of ignitions (ref. to deliverable ##) and, as a consequence, limited probabilities of causing a domino effect due to a fire event.

Pressurized equipment, on the other hand, are characterized by higher release rates in case of loss of containment and, therefore, higher probability of ignition and fire event.

Total failure frequency is calculated as the total frequency of a fire event originated either due to a failure of the selected item, or as a consequence of a domino effect. Finally the increased vulnerability is calculated as the delta between the total failure frequency and the initiating event frequency, divided by the initiating event frequency.

It could be observed that, given their extremely low initiating event frequency, storage tanks suffer a major increase in their failure frequency when domino cascading effects are considered. Increase may be in the range of two orders of magnitude; early warning, protection and proper fire and gas design for storage tanks is therefore critical to manage risk of fire escalation in the plant.

On the other hand, pressure equipment suffers only minor increase vulnerability (in the range of 2-30%). Fire protection and layout optimization are still important in limiting domino effect, but no significant escalations are to be expected.

6.2 Domino from fire scenarios (plant B)

Since plant B is characterized by water-based slurries (non-flammable fluids), fire scenarios in plant B are not credible. Domino effect from fire scenarios are therefore not possible.

6.3 Domino from earthquake scenarios (plant A)

The assessment of cascading event from earthquake scenarios has been done considering a seismic event potentially impacting on all the process item in the plant under analysis, the failure of each item being completely independent from failures in other equipment.

As a result, first goal of the Dynamic Event Tree has been the assessment of all the potential combination of damaged equipment. Following a major damage of a piece of equipment characterized by an H/D ration higher than 1, the potential domino effect on nearby process items has been assessed has detailed in Chapter 3.

Impact of falling equipment has been conservatively assumed causing a major damage onto the potential targets, thus causing, in turn, a secondary domino effect according to plant layout and geometrical probabilities.

Binary relationship has been implemented in the Dynamic Event Tree thus providing the probability of escalation between each pair of process items. Failure of one of the considered pieces of equipment will cause a logistic conditioning to avoid the software counting twice or more the failure of each item (for example, if item A cause a primary domino on item B, the logistic conditioning will intervene to prevent item B causing a secondary domino on item A, which is, in fact, already damaged).

A total of approx. 50000 stories have been calculated out of the Dynamic Event Tree.

Results have been elaborated in terms of frequency of failure, and they have been resumed in the following table.

Table 6.2: Earthquake cascading event frequency (plant A)

Item	Initiating event frequency	Total failure frequency	Increased vulnerability
Virgin Naphta Storage Tank A	4.04E-02	4.04E-02	0%
Virgin Naphta Storage Tank B	4.04E-02	4.04E-02	0%
Primary Fractionator	6.43E-02	6.43E-02	<1%
Heavy Gasoline Stripper	6.43E-02	6.43E-02	0%
Quench Colum	6.43E-02	6.43E-02	<1%
Debutanizer	6.43E-02	6.43E-02	0%
Cracking Gasoline Unit Buffer Tanks	4.04E-02	4.04E-02	0%
Cracking Gasoline Tank	1.94E-01	1.94E-01	0%

Item	Initiating event frequency	Total failure frequency	Increased vulnerability
Cracking Gasoline Tank	1.94E-01	1.94E-01	0%
Acrylonitrile Storage Tank	4.04E-02	4.04E-02	0%
Unit Buffer Vessel	4.10E-02	4.10E-02	0%
Elastomer Production Reactor	6.43E-02	6.43E-02	0%
Stripping Column	6.43E-02	6.43E-02	<1%

Seismic events are characterized by a higher initiating frequency when compared to fire events; on the other hand, escalation probabilities in case of fire events are close to 1 due to the long impingement distances and the high thermal radiation caused by the combustion of the considered materials. On the other events, conditional probability of major damage to a structure is comparatively lower, and only a part of the considered pieces of equipment may escalated in domino events (process items characterized by an H/D ratio higher than 1). Moreover, geometrical probability further reduces the possibility of domino effect.
As a consequence total failure frequency caused by seismic event is driven only by the initiating natural event; no significant impacts are expected due to following domino effect.

6.4 Domino from earthquake scenarios (plant B)

Probabilistic analysis of domino effect due to earthquake initiating events has been worked out for plant B accounting for the same approach and consideration applied in pant A (refer to Paragraph 6.3).

Results are provided in the following table.

Table 6.3: Earthquake cascading event frequency (plant B)

Item	Initiating event frequency	Total failure frequency	Increased vulnerability
Leaching Tank 1	3.77E-03	3.77E-03	<1%
Leaching Tank 2	3.77E-03	3.77E-03	<1%
Leaching Tank 3	3.77E-03	3.77E-03	<1%
Filter Press (IN)	4.32E-03	4.32E-03	<1%
Precipitation Tank	3.77E-03	3.77E-03	0%
Filter Press (OUT)	4.32E-03	4.32E-03	<1%
Melting Furnace	4.47E-03	4.47E-03	0%
Refining furnace	4.47E-03	4.47E-03	0%
Vacuum distillation	4.32E-03	4.32E-03	0%
Refined Cadmium	4.47E-03	4.47E-03	0%

Item	Initiating event frequency	Total failure frequency	Increased vulnerability
furnace			
CC-2 Distillation	4.32E-03	4.32E-03	0%
Pregant Solution Tank	4.47E-03	4.47E-03	0%
Leach Thickener	4.32E-03	4.32E-03	0%
High shear Pre-oxidation	4.32E-03	4.32E-03	0%
Cyanide Leach Circuit	4.32E-03	4.32E-03	0%
Strip Circuit	4.32E-03	4.32E-03	0%
Large Rotary Vacuum Filters	4.32E-03	4.32E-03	0%
Smelting and Crystalline of Arsenic	4.32E-03	4.32E-03	0%
Distillation Stage	4.32E-03	4.32E-03	0%

7 REFERENCES

[1] WS Atkins Safety and Reliability, “Development of Methods to Assess the Significance of Domino Effects from Major Hazard Sites”, Health and Safety Execute, 1998;

[2] API RP 752, “Management of Hazards Associated with Location of Process Plant Permanent Buildings”, American Petroleum Institute, December 2009;

[3] Demichela M., Camuncoli G., “Risk based decision making. Discussion on two methodological milestones”, Journal of Loss prevention in the process industries, 28 (2014), 101-108